Field Trip Guide 2 Karst Features of the Northern Black Hills, South Dakota and Wyoming, Karst Interest Group workshop, September 15, 2005

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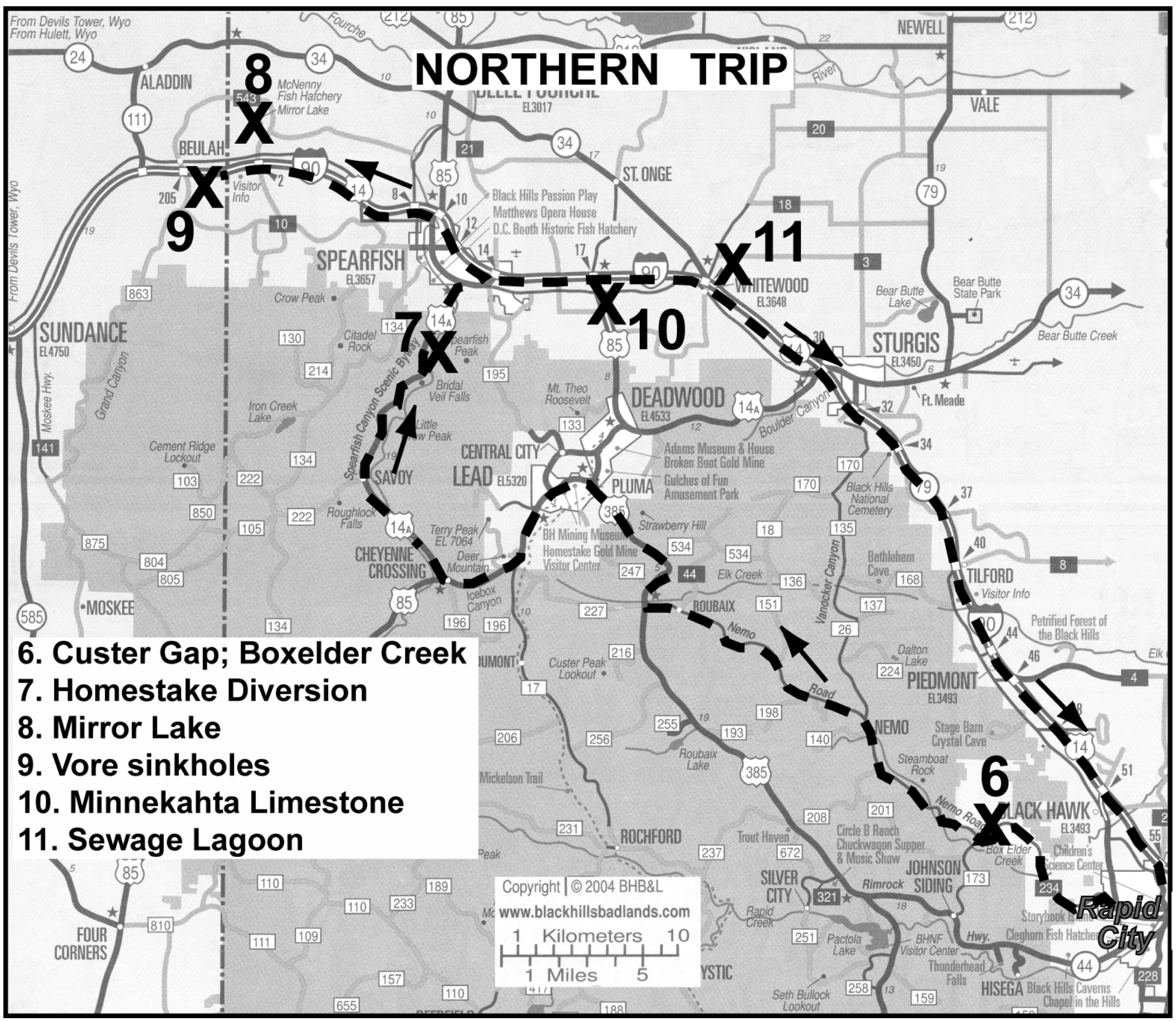

Figure 1. Route map to karst localities in the northern Black Hills.

Field trip originates from the headquarters at the Holiday Inn-Rushmore Plaza, 505 North Fifth Street, Rapid City, SD.

0.0 **0.0** Leave Holiday Inn parking lot, turn right on North 5th Street.

0.2 **0.2** Turn right on Omaha Street.

0.7 **0.5** Intersection with East Blvd, continue straight on Rte 44 West/79 North. Ahead, water gap in “Dakota hogback” comprising Lower Cretaceous and Jurassic rocks.

1.8 **1.1** Stoplight at Deadwood Avenue, continue straight on West Chicago Street.

2.4 **0.6** South Dakota Cement Plant on right, utilizes Minnekahta Limestone quarried nearby to the north.

2.9 **0.5** Stoplight, continue straight on West Chicago St.

3.6 **0.7** Road turns right and becomes Nemo Rd. (County Rd. 234).

4.5 **0.9** Road cut through Minnekahta Limestone, the major material for aggregate, cement, and lime in the Black Hills. It is a thin (averaging about 40 feet), laminated limestone with minor karstic features including joint solution widening and precipitation of calcite, sinkholes, and small caves. Secondary porosity enhanced in places by small scale faulting and folding (fig. 2). Opeche Shale exposed under the Minnekahta just up the road.

Figure 2. Typical small-scale deformation in the Minnekahta Limestone and associated jointing which produce a secondary porosity in the limestone.

5.3 **0.8** Sandstone near the top of the Minnelusa Formation.

5.6 **0.3** Red beds in the Minnelusa.

6.3 **0.7** Brecciated red and yellow sandstones in the Minnelusa. Caves higher in the cliff. Burnt trees from 1988 forest fire on left.

8.4 **2.1** Red shale in the Minnelusa on left are probably the “red marker”, interpreted to be an unconformity and soil horizon near the Permian-Pennsylvanian boundary (Fahrenbach and Fox, 1996).

9.0 **0.6** Cross Boxelder Creek.

9.5 **0.5** “Red marker?” on left.

9.9 **0.4** Brecciated Minnelusa.

11.5 **1.6** About 150 feet to south of road is the grave of Pvt. James A, King who died in 1874 during General Custer’s first visit to the Black Hills.

11.6 **0.1** Entering Black Hills National Forest.

12.2 **0.6** Pahasapa Limestone exposed in creek on left.

12.5 **0.3** Pahasapa Limestone.

12.8 **0.3** Cross Boxelder Creek.

13.2 **0.4** Custer Gap is the small ravine in the Pahasapa Limestone on right through which the General Custer expedition exited the central Black Hills. About 300 feet west of the ravine is the exposed contact of the Pahasapa Limestone and Englewood Formation. The flow of Boxelder Creek normally sinks into the Pahasapa several hundred feet to the east during the fall and winter.

STOP 6: CUSTER GAP, DYE TRACING IN BOXELDER CREEK
Leaders: Foster Sawyer

Exposures of the Pahasapa Limestone form the cliff walls along Boxelder Creek at this stop near Custer Gap named for the 1874 expedition of George Armstrong Custer who utilized this break in the canyon walls to exit the Black Hills with his wagon train. The Pahasapa Limestone, also known as the Madison aquifer, is approximately 300 to 400 feet thick (91-122 m) in this vicinity, and consists of medium-crystalline, white, beige, and gray limestone and dolomite with thin chert beds, local solution breccia, and caves (Cattermole, 1969; Fahrenbach and Sawyer, 2001). Published stream gage data (Hortness and Driscoll, 1998) indicate that this reach of Boxelder Creek loses up to 50 ft^3/s (1.42 m^3/s) of streamflow to the underlying limestone which constitutes the largest streamflow loss zone in the Black Hills uplift. Field observations and geologic mapping over a distance of several miles along Boxelder Creek have resulted in identification of at least six areas underlain by swallow holes (Sawyer and Jarrell, 2000; Strobel and others, 1999; Fahrenbach and Sawyer, 2001). Streamflow is lost to swallow holes (fig. 3) and partially regained from springs multiple times as water moves downgradient through this complex disappearing stream system.

Figure 3. Boxelder Creek disappearing into the alluvium overlying swallow holes in the Pahasapa Limestone near Custer Gap (From Rahn and Gries, 1973).

Previous dye-tracing activities (Rahn and Gries, 1973; Greene, 1999) have illustrated some of the mechanics of surface-water and ground-water interactions associated with this series of swallow holes along Boxelder Creek, as well as with adjacent surface-water drainage basins. In the spring of 1968, 1 lb (0.45 kg) of fluorescein dye in 2.5 gal (9.5 L) of water was injected into a swallow hole (figs. 4 and 5) in this vicinity. The dye appeared downgradient at Gravel Spring in 1 hour and 8 minutes, traveling a distance of about 2,200 ft (670 m) at a subsurface velocity of approximately 0.37 mi/hr (0.60 km/hr). The dye also appeared at Doty Spring in 3 hours and 2 minutes, much faster than the surface-water flow rate from Gravel Spring to Doty Spring, and it reached Dome Spring in 6 hours and 35 minutes. Another dye test in the fall of 1968, using 15 gal (56.8 L) of Rhodamine WT dye, demonstrated that water lost to swallow holes in one drainage basin can reappear in an adjacent drainage basin when the dye appeared within 34 days at City Springs, approximately 6 mi (10 km) away in the Rapid Creek watershed (Rahn and Gries, 1973). Subsequent dye tests in 1993 (Greene, 1999) detected dye in four wells within the Madison aquifer in the Rapid City area between 26 and 49 days from the initial injection time.

Figure 4. Injecting dye in 1968 into the swallow hole in the Pahasapa Limestone along Boxelder Creek near Custer Gap (From Rahn and Gries, 1973).

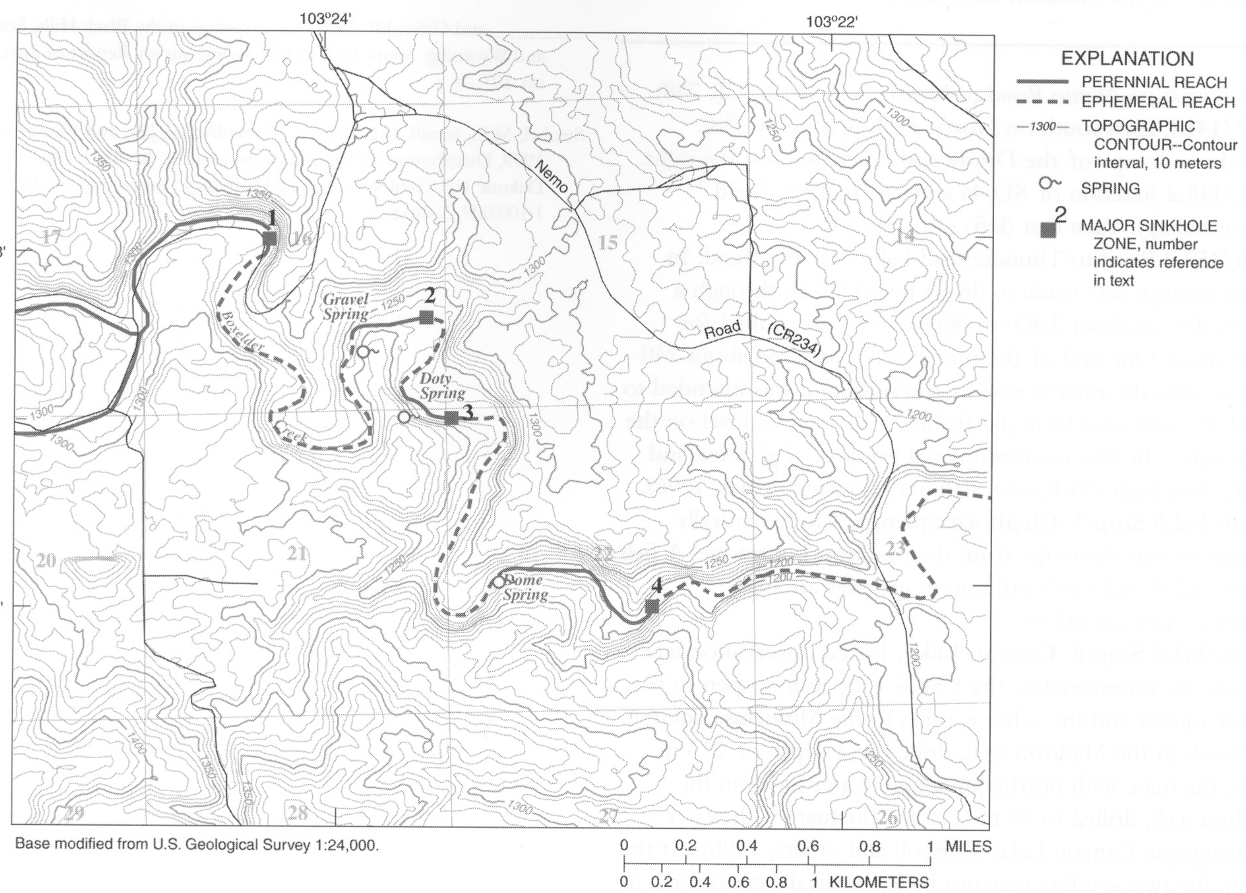

Figure 5. Map of Boxelder Creek swallow hole are (from Strobel and others, 1999).

Numerous dye tests at Custer Gap have also yielded information regarding the effect of the discharge rate of Boxelder Creek on ground-water velocity and flow paths within the Pahasapa Limestone (Rahn 1992, Strobel and others, 2000). Figure 6 shows dye travel times from Custer Gap to Gravel Spring from 11 dye tests under varying discharge conditions. Dye that was injected during discharge rates greater than approximately 10 ft^3/sec (0.28 m^3/sec) had a relatively constant first appearance time of about 60 minutes; however, dye that was injected during discharge rates of less than 10 ft^3/sec (0.28 m^3/sec) usually took two hours or more to arrive at Gravel Spring and sometimes did not appear at all. Under low discharge conditions the entire water table may be at a lower level causing the dye to take a different pathway through the limestone and the dye may never reach Gravel Spring (fig. 7).

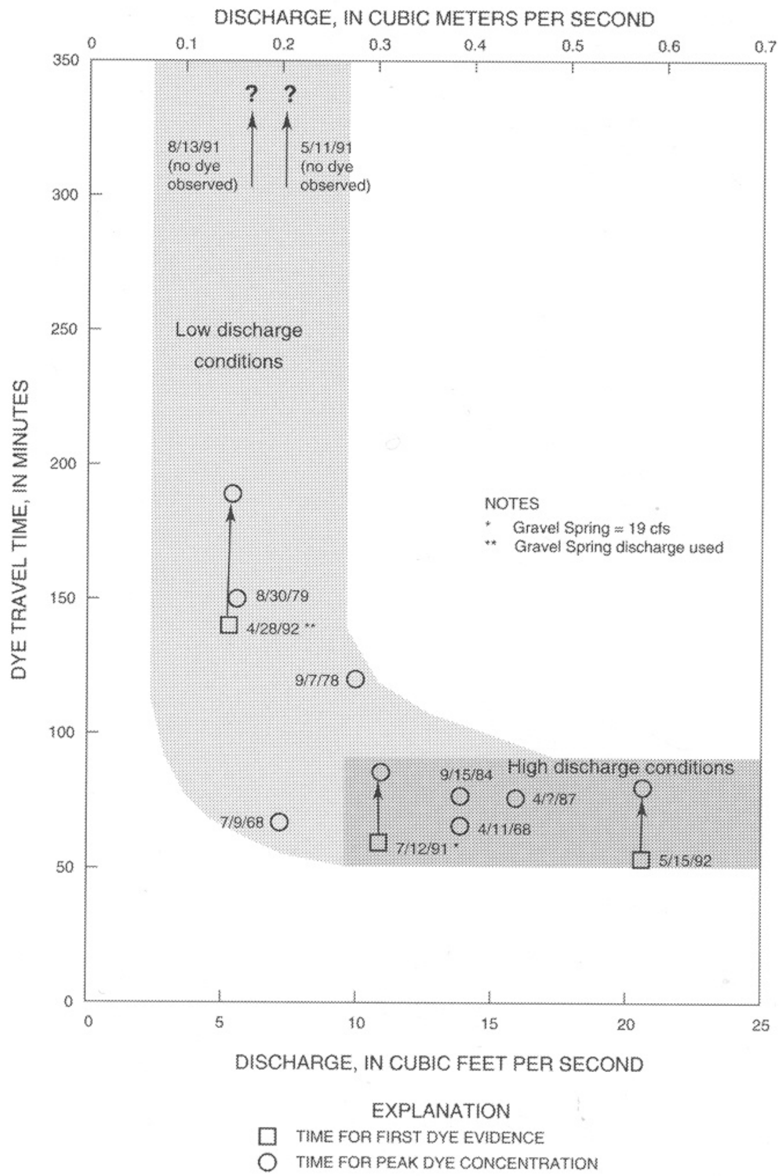

Figure 6. Boxelder Creek discharge and dye travel time from Custer Gap to Gravel Spring (from Strobel and others, 2000).

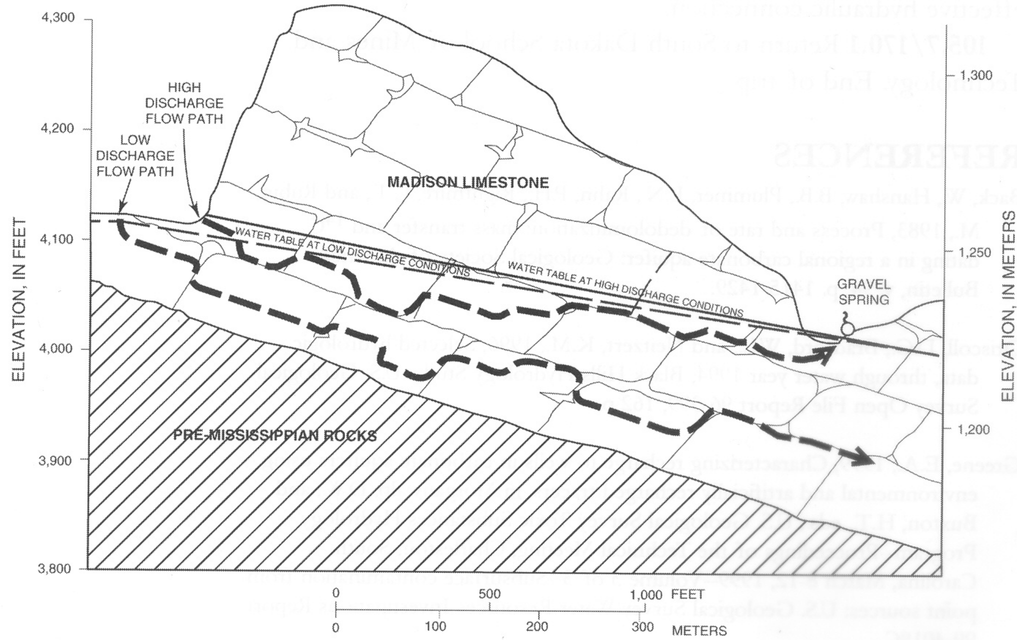

Figure 7. Generalized hydrogeologic section from Custer Gap to gravel Spring, showing conceptualized ground water flow paths for high water table and low water table conditions (from Strobel and others, 2000).

The rapid ground-water velocities associated with the Pahasapa Limestone (Madison aquifer), and the variable subsurface flow paths that allow ground water within the limestone to migrate across surface water drainage basin divides, pose significant challenges to protection of drinking water for cities and communities that utilize this highly productive aquifer. Streamflow loss zones such as the one along Boxelder Creek at Custer Gap are particularly vulnerable to contamination, and could essentially function as locations of point recharge to the aquifer for microbial or chemical contaminants resulting from spills, leaks, accidents, intentional contamination, or malfunctioning septic tanks and drain fields (Davis and others, 2000).

Continue northwest on Nemo Road.

13.9 **0.7** Knobbly weathering sandstone in Deadwood Formation on right.

15.4 **0.5** Cross Boxelder Creek. Deadwood Formation exposed.

15.7 **0.5** Boxelder Creek.

15.3 **0.6** Boxelder Creek.

15.6 **0.3** Meade-Pennington County line.

15.7 **0.1** Cambrian-Precambrian unconformity. For the next 33 miles the road will traverse many Precambrian rocks (see Redden and Fahrenbach, 1996).

16.8 **1.1** Metagabbro sill on right.

17.2 **0.4** Cross Boxelder Creek. Deadwood exposed on left.

17.8 **0.6** Steamboat Picnic Ground.

19.3 **1.5** Pahasapa Limestone forms cliff to right, overlying covered slope of the Englewood Formation, then reddish sandstone of the Deadwood Formation below.

19.7 **0.4** Estes Rd. (FS 208) on left. Open cut mine to northeast is in banded iron formation which produces iron ore as an additive for the State Cement Plant seen at mileage 2.4.

20.8 **1.1** Estes Creek Road.

21.2 **0.4** Town of Nemo.

21.6 **0.4** Basal Deadwood sandstone on left.

21.8 **0.2** Wonderland Cave to right.

24.5 **2.7** Town of Novak.

26.1 **1.6** Cross Boxelder Creek.

32.7 **6.6** Elk Creek. Old Cloverleaf (Uncle Sam, Anaconda) gold mine dumps on left. Production of $900,000 in gold associated with galena, sphalerite, pyrite, and chalcopyrite in milky quartz was from 1878-1937.

34.2 **1.5** Junction, turn right on US 385 North. Deadwood Formation on right.

34.9 **0.7** Cross Bear Butte Creek.

40.8 **5.9** Yates shaft of Homestake gold mine visible to northwest.

41.6 **0.8** Deadwood.

41.7 **0.1** Turn left on US85 South and enter Lead.

43.1 **1.4** Homestake gold mine on right. Visitors park on right shows beautiful exposures of Tertiary rhyolite dikes cutting Precambrian rocks parallel to foliation, then intrudes as sills in the lower Deadwood Formation which caps hills to north. The present underground workings extend to the 8,000-foot level. Total gold production since 1876 exceeds 39 million ounces. Time permitting we will hop out for a quick view of the open pit. Proceed through Lead on Main street.

43.7 **0.6** Stop Light, turn left on US85/US15A.

48.9 **5.2** Road to Terry Peak on right

49.4 **0.5** Pahasapa Limestone to right.

50.2 **0.8** Whiteport Dolomite on right.

50.3 **0.1** Green shale in the Icebox Shale of the Winnipeg Group on right.

50.5 **0.2** Deadwood-Winnipeg contact on right.

51.4 **0.9** Cheyenne Crossing, turn right on US 15A into Spearfish Canyon. Area of smaller trees on left mark the location of a landslide.

52.9 **1.5** Townsite of Elmore.

55.7 **2.8** Dam diverting water to Homestake Hydroelectric No. 2 aqueduct.

56.0 **0.3** View of Pahasapa Limestone cliffs rimming the canyon ahead.

56.6 **0.6** Town of Savoy and Spearfish Falls.

STOP 7: HOMESTAKE MINING COMPANY AND SPEARFISH CREEK
Leaders: Larry Putnam, Andrew Long, Ron Koth

Walk down trail to see abandoned aqueduct and Spearfish falls.

The Homestake Gold Mine was one of the early enterprises associated with the Gold Rush of 1876 in the northern Black Hills of what was then Dakota Territory. The mining community of Deadwood was the center of the gold fever, with tents, sawmills, log houses, and salons springing up seemingly overnight. But the real action would happen three miles away "over the hill" where brothers Fred and Moses Manual and their partner Hank Harney located their Homestake claim on April 9, 1876. Moses liked what he saw of an outcropping of a vein of ore, referred to as a lead and pronounced "leed." Soon more prospectors materialized, and no time was lost in selecting a site for a new town (Severson, 2005).

With a population of 8,392 in 1910, Lead was the second largest community in South Dakota. The employment opportunities for not only miners, but also laborers and mechanics, were excellent. Throughout the decades to come, the City of Lead and the Homestake Mine were confronted with challenges ranging from an epidemic of Spanish influenza, nearby forest fires, and even a fire in the mine, which was extinguished by a deliberate flooding of the mine and subsequent dewatering with no ill effects to the mine or its equipment. But on the whole, the city and its residents prospered as a result of the mine. In the early 1930s, as the rest of the nation suffered economic hardship throughout the Great Depression, the management of Homestake set a shorter work week with an increase in wages and provided end of year bonuses to workers (Severson, 2005).

Today, the mine reaches a depth of 8,000 feet, and its network of 370 miles of underground workings provides direct access to a subterranean volume of rock totaling nearly 8 cubic miles. Prior to closing in December 2001, the Homestake mine had been in continuous operation for 125 years and had produced more than 40 million ounces of gold, ranking it among the largest gold deposits in the world (Duke, 2005).

Water and power were important resources to new technologies incorporated in the mining enterprise. George Hearst pursued numerous legal suits in consolidating mining claims to build control of the Homestake Lode; however, he also vigorously pursued water rights recognizing the importance of water in building an industrial gold mine (Fielder, 1970). The adjacent Spearfish Creek drainage basin with numerous headwater springs discharging from the Pahasapa Limestone was a promising water resource.

The Spearfish Creek drainage basin above the streamflow gage at Spearfish (06431500) encompasses about 168 sq. mi. (fig. 8). About 70 percent of this area includes the outcrop of the Pahasapa Limestone. Average precipitation on the drainage basin ranges from about 23 to 28 inches per year with the higher values in the central part of the basin (Driscoll and others, 2000). Average recharge to the Pahasapa Limestone ranged from about 4 in/yr in the north part of the basin to about 8 in/yr in the south and central part of the basin (Carter and others, 2001b). The land surface altitude in the basin ranges from about 7,000 feet at the highest peaks in the south to 3,640 feet above sea level at the streamflow gage in Spearfish.

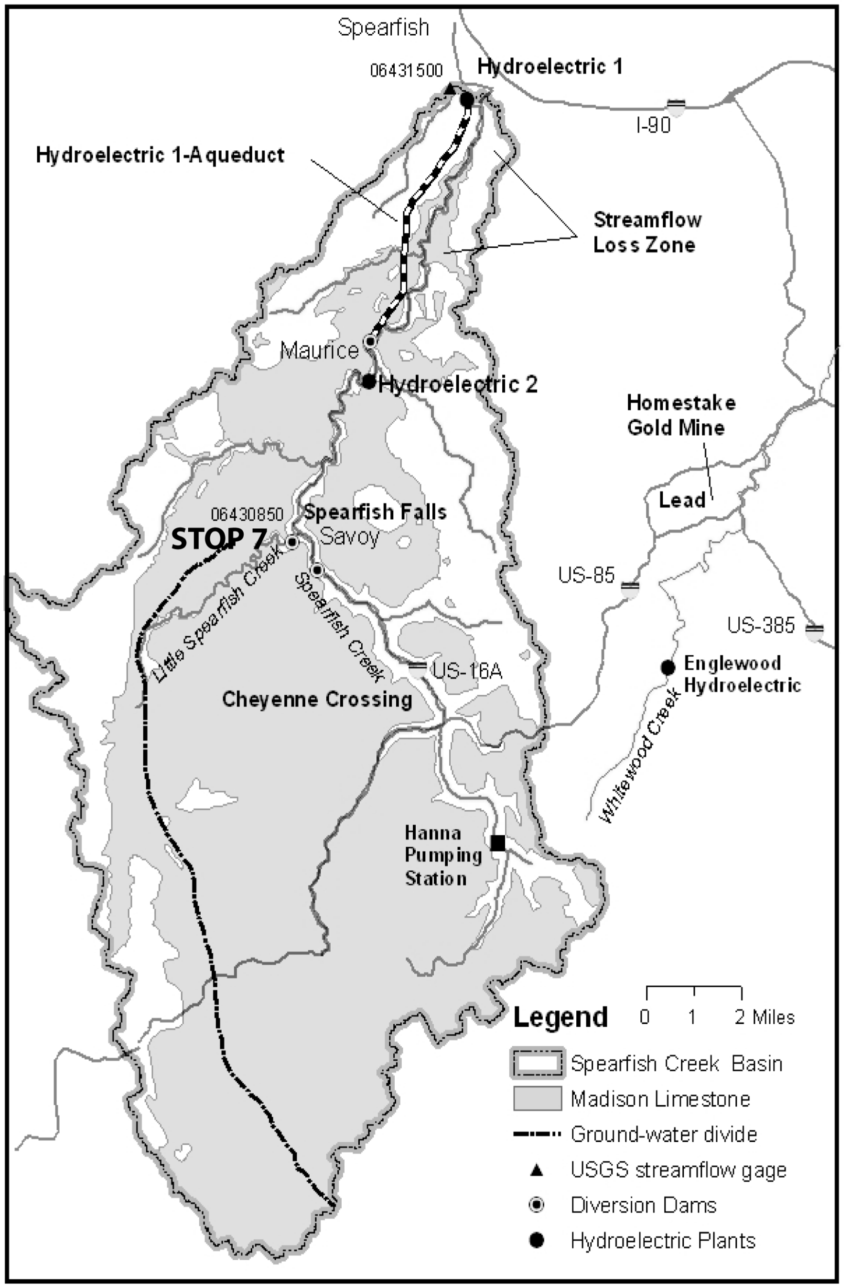

Figure 8. Location of Spearfish Creek and selected hydrologic features.

Recharge to the Pahasapa Limestone west of the ground-water divide (Carter and others, 2001a) flows to the west where ground-water merges with eastward regional flow, then turns to the north or south, and then east around the Black Hills. This recharge is a potential source of water for the numerous artesian springs northwest of Spearfish, some of which will be visited in STOP 8.

Direct surface runoff from parts of the basin where the Pahasapa Limestone outcrops is rare with most streams gaining flow from springs discharging from the Pahasapa Limestone. The mean streamflow (WY 1947-2004) for Spearfish Creek at Spearfish was 55.6 ft^3/s, with the highest annual mean of 106 ft^3/s and the lowest annual mean of 27.1 ft^3/s (U.S. Geological Survey, 2005). The drainage area for Little Spearfish Creek, a tributary to Spearfish Creek, includes mostly Pahasapa Limestone and the mean streamflow (WY 1997, and 1999-2004) was 16.7 ft^3/s, with the highest annual mean of 23.1 ft^3/s and the lowest annual mean of 11.7 ft^3/s (U.S. Geological Survey, 2005). The stream reach from Spearfish to about 5 miles south of Spearfish is a losing reach with a maximum loss rate of about 21 ft^3/s when streamflow is present (Hortness and Driscoll, 1998).

Streamflow that recharges the Pahasapa Limestone in this losing reach rapidly moves downgradient to the north through conduits. Dye injected in 2003 when streamflow was present in the upper reaches of the loss zone arrived in 6 days at a public supply well completed in the Madison aquifer and located north about 2 miles. Dye also was detected within a few months at several Spearfish public supply wells completed in the Madison aquifer and located about 3 to 4 miles north of the dye injection site.

Headwater springs in the Spearfish Creek basin above Cheyenne Crossing were collected by Homestake Mining Company with an extensive system of flumes and ditches and a pumping station that delivered water to Lead. As the mining enterprise grew, water for the growing communities of Lead and surrounding towns increased along with the water needed for the mining and milling operations. Many miles of cast iron tile and wood stave pipeline, included in the water conveyance system, were installed by hand and horse labor (Fielder, 1970). A replication of a section of a redwood stave pipe is shown in figure 9.

Figure 9. Replication of wood stave pipe.

Homestake Mining Company was well established as an industrial gold mine by the beginning of the 1900’s and was actively bringing new technologies to the mine. An important change involved the conversion from steam to electrical power.

Three hydroelectric power plants were constructed beginning with the Englewood hydroelectric located in the Whitewood Creek Basin (fig. 8) in 1906. Water for the Englewood hydroelectric originates from springs in the upper reaches of the Spearfish Creek Basin and is delivered by flumes and ditches to the Hanna Pumping Station. From there the line is joined by gravity flow from collection lines in other draws and continues to the Englewood hydroelectric station. From there the water travels to a reservoir above Lead (Johnson, 1931).

The early experiments with converting mining equipment to electric power using the generation station at Englewood were successful and the transition to electric power continued. Though the cost would be about a million dollars, plans were begun for the building of Spearfish Hydroelectric Plant No. 1. About four miles of tunnel work divided into eight sections would be necessary to divert the water in Spearfish Creek for industrial use (Fiedler, 1970). A dam constructed near Maurice diverted water through the tunnel (fig. 10). The Spearfish Hydroelectric Plant No. 1was finished in 1912 and was capable of diverting all of the streamflow in Spearfish Creek except during very high flow conditions.

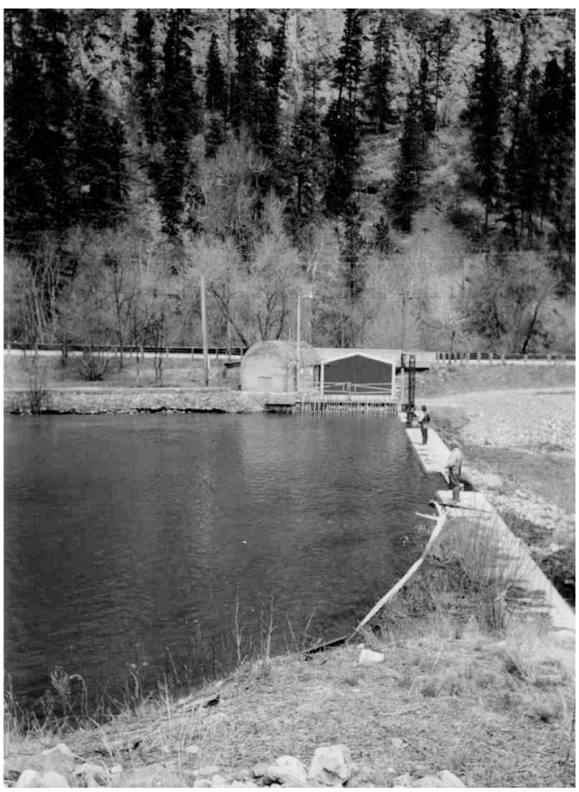

Figure 10. Diversion dam for Hydroelectric 1.

The diversion of water through the aqueduct probably caused a decline in the potentiometric surface in the Madison and Minnelusa aquifers because of reduced recharge in the early 1900's (Greene and others, 1999). A report by Dr. B.W. Evermann in 1896 to the U.S. Commissioner of Fish and Fisheries documenting investigations for potential fish hatchery sites described several springs in the Spearfish area (U.S. Commission of Fish and Fisheries, 1896). He characterized the site at Spearfish in this way: "If fish cultural work should ever be undertaken at any place in the Black Hills, the most satisfactory natural conditions could probably be found here." The D.C. Booth Historic National Fish Hatchery, formerly Spearfish National Fish Hatchery, was established in 1896. By the 1940s, the water supply at Spearfish had become increasingly undependable. This resulted in the acquisition of land 12 miles west of Spearfish from Judge McNenny and the State of South Dakota specifically to rear fish (near springs described in STOP 8). The Booth hatchery ceased operations in the mid-1980s and reopened with a new mission and partnerships to help preserve the U.S. Fish & Wildlife Service's historic and cultural heritage (U.S. Fish and Wildlife Service, 2005). The springs that Evermann described are no longer present suggesting that the Madison and/or Minnelusa aquifers were the source for the springs.

In 1916, Homestake began plans for a second hydroelectric plant (fig. 8) located farther upstream; the plant was completed in 1918 (Fiedler, 1970). Flumes and ditches rather than a tunnel were used to transmit the water to the plant. Wood stave and steel pipes built on shelves excavated on the hillside were used for many of the flumes. The water was diverted from Little Spearfish Creek and Spearfish Creek (fig.1) above Savoy bypassing Spearfish Falls to Hydroelectric 2, which is located about 6 miles downstream. Most of the streamflow was diverted around this 6 mile reach of stream.

Economic development in the northern Black Hills occurred over 80 years with these water diversions in place. With the closing of the mine, potential changes in this water conveyance system involve several hydrologic and environmental issues. The hydroelectric 1 diversion resulted in water being transmitted downstream around the loss zone for about 80 years. The result was a decrease in recharge to the Pahasapa Limestone. Returning the stream to the natural channel would change the character of the stream that has been flowing through the city of Spearfish, especially during low flow conditions. Downstream irrigation would also be affected. Water reentering the loss zone would increase Madison aquifer water levels over time. However, estimation of potential spring discharges in the Spearfish area and water-level responses are difficult because of the complex geologic processes involved in spring formation around the Black Hills.

The diverted streamflow for Hydroelectric 2 is being returned to Spearfish Creek and Little Spearfish Creek as part of the Final Conceptual Restoration and Compensation Plan for Whitewood Creek and the Belle Fourche and Cheyenne River Watersheds, South Dakota (South Dakota Department of Game, Fish and Parks and others, 2005). The plan was developed as a guide for selection and implementation of site-specific activities to best compensate the public for lost, injured or damaged trust resources and services due to hazardous substance releases into State waters from the Homestake Mining Company of California, Incorporated. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund, is the federal law guiding this process and defines restoration in various ways in order to best compensate the public. As a result of this agreement, Homestake has transferred its water right on Little Spearfish Creek.

South Dakota Department of Game, Fish and Parks restored the natural flow of Little Spearfish Creek and Spearfish Falls in November 2003 for the first time since 1917 (fig. 11). The increase in flow in the stream reach below Savoy has improved trout habit in a very scenic part of Spearfish Canyon. SD Game, Fish and Parks biologists anticipate the potential for the naturally reproducing population of rainbow trout previously restricted to the 1-mile reach below Hydroelectric 2 to move upstream into this reach.   Below the Maurice intake for about 3.5 miles, a base flow exists in Spearfish Creek that allows for small numbers of trout to maintain a naturally reproducing population. With cooperative management, this 3.5-mile reach of stream could be improved to host a much improved trout population and fishery if about 10 ft^3/s were allowed to bypass the Maurice intake.

Figure 11. Spearfish Falls where Little Spearfish Creek joins Spearfish Creek.

Continue north on US 16A

56.7 **0.1** Intersection with FS 222 to Roughlock Falls on left. The falls drop over the type locality of the Roughlock Member of the Winnepeg Formation (Ordovician). Continue straight on US 16A.

57.2 **0.5** Cliff with Pahasapa Limestone overlying the pink-colored Englewood Formation ahead. Road continues along Spearfish Creek and following the Deadwood-Winnipeg contact.

58.4 **1.2** Cross Iron Creek.

58.6 **0.2** Outcrop on left exposes rocks of the Winnipeg Formation through Pahasapa Limestone (Fahrenbach and Fox, 1996, Stop 3).

60.0 **1.4** Whitewood Dolomite up through Pahasapa Limestone exposed on left.

60.5 **0.5** Two car-sized blocks of Pahasapa Limestone fell into Spearfish Creek in 1994 on right (fig. 12).

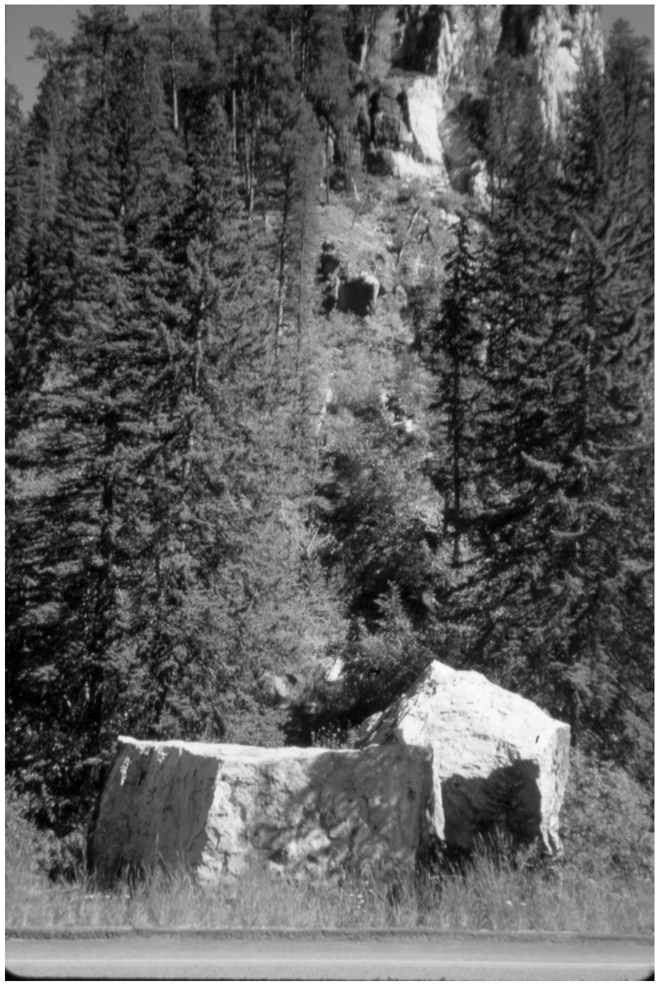

Figure 12. Avalanche chute and rock-fall boulders derived from Pahasapa Limestone.

60.8 **0.3** Tertiary phonolite sill concordant with Winnipeg strata on left.

61.5 **0.7** Winnipeg strata between phonolite sills on left.

61.7 **0.2** Homestake Mining Company Hydroelectric Plant No. 2

62.1 **0.5** Landslide on left due to heavy spring rains in 1995.

62.6 **0.5** Homestake Dam diverting water through four-mile tunnel to Hydroelectric Plant No. 1 in Spearfish.

63.0 **0.4** Landslide.

63.4 **0.4** Large roadcut on left in Deadwood Formation contains interbedded glauconitic sandstone, shale, intraformational conglomerate, carbonate beds, and horizontal burrows. The section is capped by *Skolithos* (vertical burrows) sandstone. A vertical fault with about 3 ft of displacement is in the middle of the roadcut. A small flexure at south end is probably the result of Tertiary intrusion.

63.6 **0.2** Deadwood Formation on left.

63.8 **0.4** Bridal Veil Falls on right. A Tertiary sill and dike of nepheline syenite within the Deadwood Formation is resistant to erosion and forms this waterfall on Rubicon Creek (Lisenbee and others, 1996, p. 126).

64.5 **0.7** Small adit in Deadwood Formation on left follows a porous conglomerate.

65.0 **0.5** Roadcut on left in steeply dipping Deadwood Formation crosscut by dikes along west flank of a phonolite laccolith.

65.9 **0.9** Roadcut on left at sharp bend exposes the upper Englewood Formation and lower Pahasapa Limestone.

66.4 **0.5** Dry creek bed of Spearfish Creek--now a losing stream.

67.5 **1.1** Minnelusa Formation overlies Pahasapa ahead.

68.1 **0.6** Leaving Black Hills National Forest.

68.4 **0.3** Spearfish Creek; brecciated Minnelusa to left.

68.6 **0.2** Minnekahta Limestone on Opeche Shale overlying Minnnelusa on right.

69.3 **0.7** Winterville Drive on left leads to D.C. Booth National Fish Hatchery, a worthwhile visit. Spearfish production well on left completed in the Madison aquifer to a depth of 842 feet and production of about 2,000 gallons per minute.

69.4 **0.1** Spearfish Formation on left. Lookout Mountain straight ahead.

69.6 **0.2** Stop sign. Turn right on US 15A.

71.1 **1.5** Stop sign. Turn left towards I-90.

71.3 **0.2** Turn left on I-90 West, Exit 15. Crow Peak at 11 o'clock, a Tertiary intrusive.

72.3 **1.0** Lookout Mountain to right capped by sandstone of the Lakota Formation (Cretaceous). Housing development to right makes use of a terrace in gypsum of the Gypsum Spring Formation.

73.0 **0.7** Exit 12. City of Spearfish. To left is a hill composed of old landslide debris derived from all units in Lookout Mountain. Old topographic maps show that the hill is an erosional outlier and is not a result of I-90 excavation.

73.5 **0.5** Lookout Mountain to right exposes red beds of the Spearfish Formation (Triassic) at bottom, overlain by prominent white gypsum of the Gypsum Spring Formation (Jurassic), then green shale and yellow sandstone of the Sundance Formation (Jurassic), and capped by sandstone of the Lakota Formation (Cretaceous) in the core of a syncline. During construction of I-90 solution cavities in the gypsum had to be filled for stability (Rahn and others, 1977).

74.9 **1.4** Exit 10. US 85N to Belle Fourche. Continue on I-90W. Gypsum beds in the Gypsum Spring Formation.

In 1972, the City of Spearfish constructed a sewage lagoon two miles north of here. The lagoon leaked into sinkholes and was abandoned in favor of a water-treatment plant (Rahn and Davis, 1996; Davis and Rahn, 1997). The city considered 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 (fig. 13), similar to one prepared by Davis (1979, fig. 4) showing that at least ten sinkholes, one of which is about 1,000 feet long, had developed in the gypsum. This hydrogeologic information was subsequently used by the city planners in their decision to abandon the project.

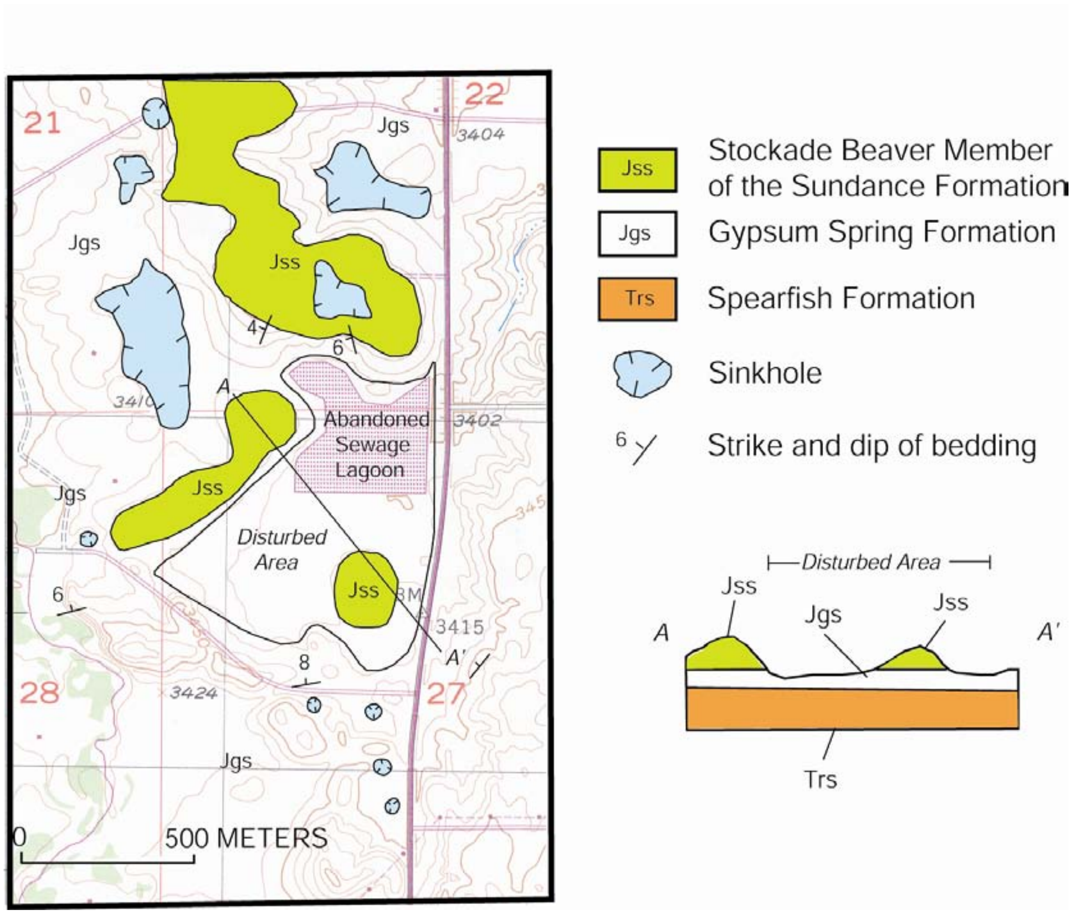

Figure 13. Geologic map of the abandoned sewage lagoon area west of US 85, 2 miles north of I-90, Spearfish, SD. (From Epstein, 2003).

77.2 **2.3** Crow Peak to the left comprises an intrusion into the core of the LaFlamme anticline. Dip slope in the Minnekahta Limestone ahead.

78.6 **1.4** Undulations in the Minnekahta Limestone in the wide crestal zone of the LaFlamme anticline probably reflect subsidence in the underlying Minnelusa Formation due to solution removal of anhydrite. Several Pleistocene terraces are well developed in the Red Valley to right.

80.5 **1.9** I-90 curves to the left following the configuration of the Minnekahta Limestone in the LaFlamme anticline.

82.2 **1.7** Minnekahta heads south on the west limb of the LaFlamme anticline. Interbedded gypsum in the Spearfish Formation to right.

82.9 **0.7** Exit 2. Turn right towards McNenny State Fish Hatchery.

83.2 **0.3** Stop sign. Turn right on US 15.

83.4 **0.2** McNenny Road, turn left. Many residual silicified sandstone boulders to right derived from the Lakota Formation and let down approximately 1,000 feet to their present position as the softer sediments of the Spearfish Formation were eroded away.

83.55 **0.15** Flowing well on left and two small sinkholes on right.

84.1 **0.7** Scarps and very shallow depressions in Spearfish due to solution-collapse in gypsum.

84.2 **0.1** Turn left towards McNenny State Fish Hatchery and then left towards Mirror Lake. Hill in distance to west is capped by the Stockade Beaver Member of the Sundance Formation atop the Spearfish in a shallow syncline. Hills to north comprise well-exposed rocks from the Spearfish to the Lakota. Numerous small sinkholes in red beds of the Spearfish formation in field to the southwest and in the entire surrounding area are due to solution of interbedded gypsum (fig. 14).

Figure 14. Many small sinkholes are present in the McNenny Fish Hatchery area, including circular depressions in red beds with some remaining gypsum (top) and solution widening of joint in gypsum resulting in soil collapse in residential parking area (bottom).

84.6 **0.4** McNenny Fish Hatchery, Test Well No. 3 on right. Lithologic log:

Depth	Formation	Principal lithology	Description
0-50	Spearfish	Mudstone	Moderate reddish brown, slightly silty, shale; shaley moderately well cemented, calcareous siltstone; light olive gray, soft mudstone; and trace of clear, poorly cemented, well rounded, fine grained sandstone and grayish orange pink, finely crystalline limestone
50-70	Spearfish	Shale	Moderate reddish brown, slightly silty shale and rare, thin chips of gypsum
70-110	Spearfish	Siltstone and gypsum	Moderate reddish brown and white, moderately well cemented, calcareous siltstone and white to clear gypsum

110-200	Spearfish	Mudstone	Moderate reddish brown, sticky mudstone with traces of gypsum; minor amounts of clear, moderately well cemented, well rounded, fine grained sandstone from 170 to 180 feet and grayish orange green claystone from 180 to 200 feet
200-267	Spearfish	Siltstone	Moderate reddish brown, poor to moderately well cemented, slightly clayey siltstone; abundant white gypsum from 250 to 260 feet
267-295	Minnekahta	Limestone	Pale blue and pale pink to pale yellowish brown, finely crystalline limestone
295-307	Opeche	Shale	Grayish red calcareous shale

Continue straight across wooden bridge over Crow Creek.

84.65 **0.05** Take first right at triple fork in road. Low outcrops of calcareous tufa--spring deposits on left.

84.8 **0.15** On the north side of lower Mirror Lake there are two intervals of marl separated by about 5 to 6 feet of red Spearfish soil. Higher up the slope the interval is replaced by calcareous tufa (see fig. 16).

85.0 **0.2** Turn right at fork in road; 60-foot-long sinkhole to right.

85.1 **0.1** Park in turnaround.

STOP 8: MIRROR LAKE: SINKHOLES, GYPSUM DISSOLUTION FRONT, AND HYDROLOGY OF RESURGENT SPRINGS
LUNCH
LEADERS: Jack Epstein and Larry Putnam

Karst features in the area around Mirror Lake at the McNenny National Fish Hatchery are expressed within red shale, siltstone, and fine-grained sandstone of the Spearfish Formation. The Spearfish is about 615 feet thick at this locality, although the thickness varies by one hundred feet or more in wells nearby. Sinkholes, springs, and spring deposits are located within the lower 500 feet of the formation, and exposures of gypsum, within the lower 350 feet, are scattered over a wide area. The gypsum occurs in well-defined and contorted beds, in veins, and as a weathered crust resembling popcorn. In many places the gypsum has flowed and drapes over underlying rocks. The gypsum is poorly exposed either because it is covered by surficial debris or because it has been removed by solution. All karstic features are located along a zone that parallels the axial crest of the broad, northwest-plunging, LaFlamme anticline. Figure 15 shows the location of these features. Figure 16 is an aerial photograph of the Mirror Lake area, showing the alcove at the head of the lake, sinkholes that border the headwall, sinkholes to the southwest, calcareous tufa, pond sediment, and scattered gypsum exposures. Figure 17 is a map and cross section of the area useful in interpreting the karst development at Mirror Lake and environs.

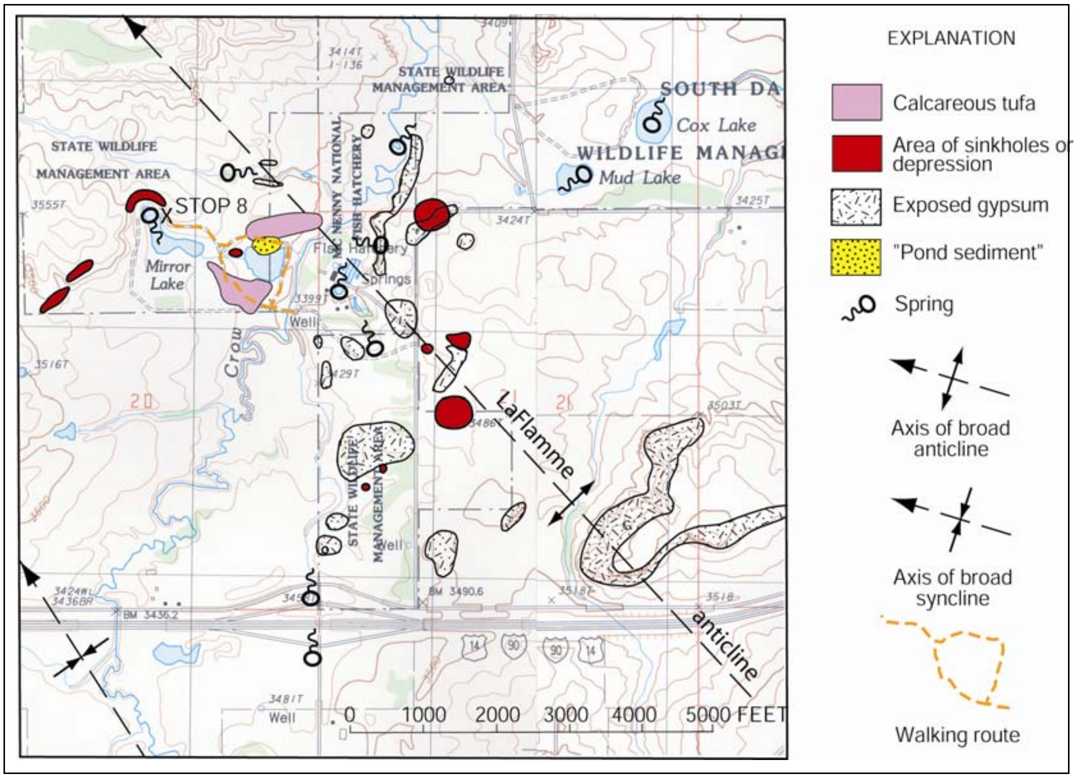

Figure 15. Karst features in the McNenny National Fish Hatchery area at Stop 8. The abundance of sinkholes suggests that there is a labyrinth of open conduits near the base of the Spearfish Formation. Base from Beulah, WY.-S.D. and Chicken Creek, WY. 7.5' topographic maps, 1984.

Figure 16. Air photograph showing karst features in the McNenny fish hatchery area.

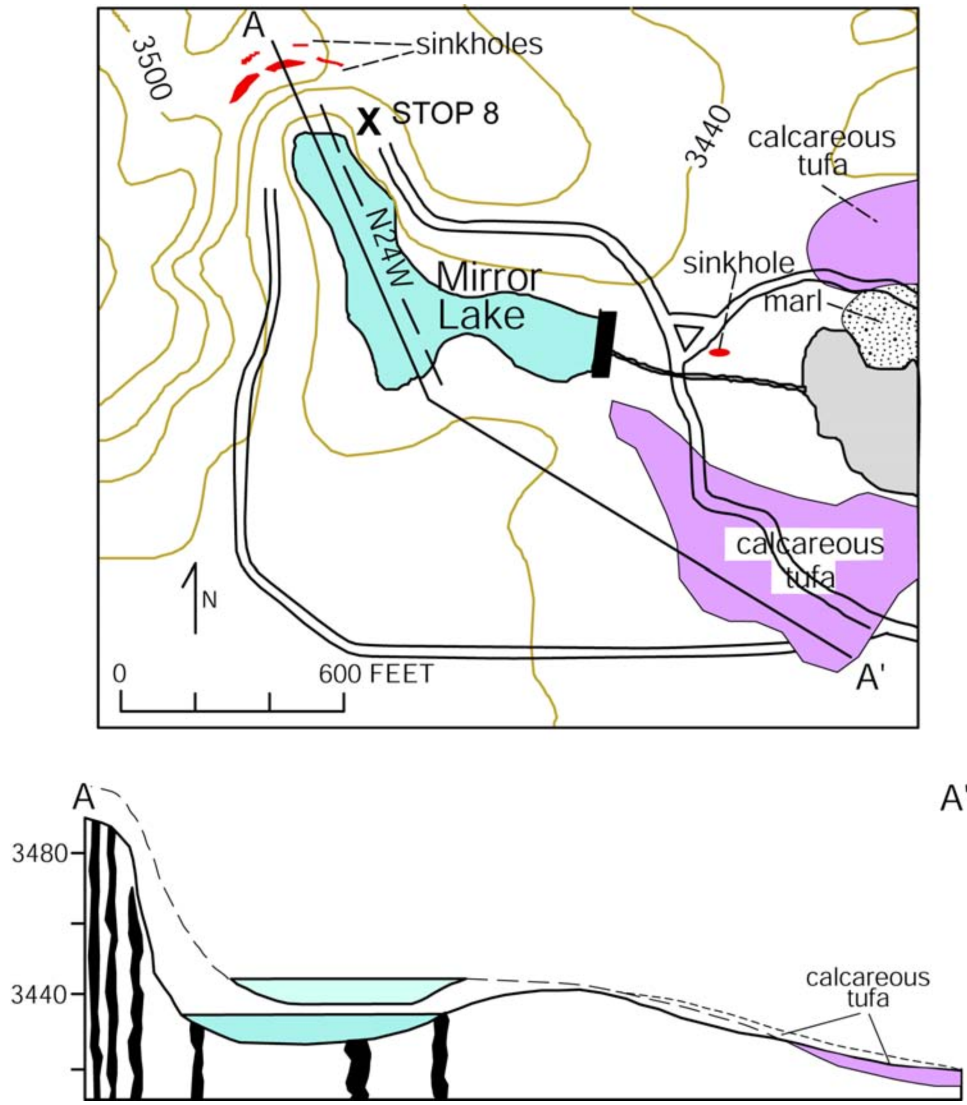

Figure 17. Map and cross section (vertical exaggeration 10x) showing sinkholes at the north end of Mirror Lake (black outlines) and inferred earlier topography (dashed line) in which calcareous tufa was deposited. Contour interval 20 feet.

Mirror Lake has a dog-leg shape; the eastward-trending section is partly artificial, formed by a dam at the east end. The northwest-trending, 900-foot-long alcove is cut into a 50-foot-high ridge of the Spearfish Formation. The lake, similar to other lakes in the area (Cox Lake, Mud Lake, and the McNenny springs), occupies a depression formed by dissolution of gypsum at depth. Numerous shallow sinkholes, several feet deep, are found at the north end of the alcove. These presently are active and indicate that the lake is expanding fairly rapidly to the northwest by continued collapse of sediment due to solution of gypsum. Much of the fine sediment derived from the Spearfish Formation is presumably carried away by the emerging spring water. Two deposits of calcareous tufa, more than four feet thick in places, are found about 1,000 feet southeast and east of the lake. They consist of light-brown porous limestone with abundant plant impressions, known as “moss rock” to local ranchers. The deposits dip gently to the east, away from Mirror Lake and was deposited earlier by spring water that emerged from the lake. The lake level was once probably higher at the time the tufa was deposited (fig. 17). Continued downcutting and northwest migration of the headwall has produced the present landform, a pocket valley also termed a “steephead” (Jennings, 1971). The rate of headward erosion could be determined by dating the sediments in the bottom of the lake. Eric Grimm of the Illinois State Museum cored the north end of Mirror Lake at a water depth of 18 feet in 1983 (written communication, 2004) obtaining two AMS dates near the bottom of the core at 11.41-11.45 meters (37 feet). The weighted average of the two dates (1260 +/- 200; 1530 +/- 230) is 1393 +/- 151. While the errors may be large, the data indicate a rapid sedimentation rate of more than 2 feet/ 100 yrs. A line of sinkholes, several hundred feet long to the southwest of Mirror Lake, parallel the eroding slope in the Spearfish (fig. 15, 16, 18**)**. These appear to be part of the process of slope retreat in this area. The sinkholes are characteristically rimmed by a low shrub, western snowberry (*Symphoricarpos occidentalis*).

Figure 18. Elongate sinkholes paralleling the slope southwest of Mirror Lake.

The sediment in Mirror Lake and the other ponds in the area is a very light brownish gray marl consisting of gypsum, calcite, and quartz ((x-ray analyses by John Johnson, USGS). The fine, soft clayey and silty material results from leaching of several bedrock horizons: the red clastic rocks and gypsum of the Spearfish Formation, carbonate rocks and gypsum or anhydrite from the Minnelusa Formation and possibly the Pahasapa Limestone below by upwelling spring water. A scuba diver encountered soft suspended sand at 65 feet and was able to sink a line an additional 20 feet into the soft material at Cox Lake (http://dive.scubadiving.com/members/tripreports.php?s=1051). About 8 feet of similar pond sediment is found to the east of Mirror Lake at a lower level than the calcareous tufa and up to 12 feet above the lower Mirror Lake (fig. 15), indicating a history of pond lowering after the deposition of the tufa.

Epstein (2003) suggested that the sinkholes in the Spearfish are not the result of removal of gypsum within the Spearfish, but that the dissolution occurred in the Minnelusa formation, more than 700 feet below. He presented the following reasons: (1) the sinkholes are deeper than the aggregate thickness of exposed gypsum beds; (2) several of the sinkholes lie below many of the gypsum beds; and (3) the chemical signatures of water in several of the lakes occupying the sinkholes suggests they were derived from the underlying Minnelusa Formation and Pahasapa Limestone (Cox, 1962; Klemp, 1995). However, the distribution of abundant sinkholes in the area of Stops 8 and 9 of this field trip, and localities beyond, and their stratigraphic confinement to the lower part of the Spearfish Formation suggests that there is a labyrinth of open conduits within the lowest Spearfish created by gypsum removal in the lower Spearfish. If the subsidence originated by stoping upwards from the Minnelusa, then sinkholes should be common within the Spearfish. Generally, few sinkholes are known within the Opeche Shale and Minnekahta Limestone (see Stop 3 of this field trip). About five miles southwest of Stop 8 along Sand Creek, the Minnelusa is exposed. This locality is only one of two known in the Black Hills where anhydrite is exposed and brecciation is minimal or non-existent (Brady, 1931, 1951; Martin and others, 1988). This suggests the hypothesis that the Minnelusa is not the only source of subsidence affecting rocks upwards into the Spearfish Formation.

Klemp (1995) noted an irregular northward increase in specific conductance of spring water in the area of Stop 8 which indicated to him a line of anhydrite dissolution in the Minnelusa aquifer. During preparation of this field guide in 2005, significant sinkhole development was found nearby in the Minnekahta, and its significance is discussed at Stop 9. The available evidence shows that karstification within the Spearfish is probably due to a variety of hydrologic and geologic factors. The development of karst in the Black Hills is a multi-tiered process affecting several stratigraphic horizons, much more complicated than generally envisioned.

The gypsum in the Spearfish Formation is commonly folded; it has been injected as veins in a multitude of variably oriented fractures which probably formed as the result of the hydration expansion as well as by the force of artesian pressure, similar to the “hydraulic fracturing” proposed by Shearman and others (1972). Thus, the lower part 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 (fig. 19). Ground water flows through the fractures and solution cavities in the gypsum. Although the entire Spearfish Formation is generally considered to be a confining hydrologic unit, the lower 200 feet of the Spearfish is an aquifer, at least in the northern Black Hills. The upper part of the Spearfish, consisting of red siltstone, shale, and very fine-grained sandstone and lacking gypsum, is a confining layer.

Figure 19. Spring immediately northeast of fish ponds along Crow Creek below zone of gypsum and fractured red beds intruded by gypsum veinlets. The water is perched on top of impermeable red shale and siltstone (arrow) and supports lush vegetation below.

An analysis of several ground-water tracers in water discharging from Mirror Lake, McNenny Springs, and Cox Lake supports the concept of a varied hydrogeologic process controlling the observed karst features in the Spearfish Formation. The analysis of several environmental tracers suggests that ground-water flow from several formations could be involved in the down-dip evolution of karst features.

Stable isotopes of hydrogen and oxygen are useful tools in characterizing source waters for springs in the Black Hills. Because of the effect of the Black Hills uplift on precipitation patterns, the isotopic signature of recharge water varies geographically across the Black Hills.

Stable isotope values are given in “delta notation (δ),”which compares the ratio between heavy and light isotopes of a sample to that of a reference standard. Delta values are expressed as a difference, in parts per thousand, or per mil (‰), from a value reference standard. A sample with a δ value of -20‰ is depleted by 20 parts per thousand (2 percent) in the heavier isotope of the element relative to the standard. In this paper $\delta^{18}O$ ($^{18}O/^{16}O$) are reported in per mil relative to Vienna Standard Mean Ocean Water (VSMOW) and are described as lighter and heavier in relation to each other. The lighter values are more negative relative to the heavier values, which are less negative.

The generalized spatial distribution of $\delta^{18}O$ in surface water and ground water in near recharge areas (fig. 20) shows a progressively lighter isotopic signature heading south from the Mirror Lake area towards the recharge areas for the Pahasapa and Minnelusa outcrops. This distribution of $\delta^{18}O$ values for different outcrop areas is evident from samples from three nested wells completed in the Madison (-17.3), Minnelusa (-17.0), and Minnekahta aquifers (-15.8) aquifers and located about 3 miles south of Mirror Lake (Naus and Others, 2001). The $\delta^{18}O$ values for different outcrop areas for water samples from Mirror Lake (-15.4), McNenny Rearing Pond (-17.2), Cox Lake (-17.0) (Naus and Others, 2001) suggest that the ground-water source for Mirror Lake most likely is a formation above the Pahasapa (Madison) Limestone and Minnelusa Formation and the ground-water source for McNenny Rearing Pond and Cox Lake are most likely from the Pahasapa or Minnelusa.

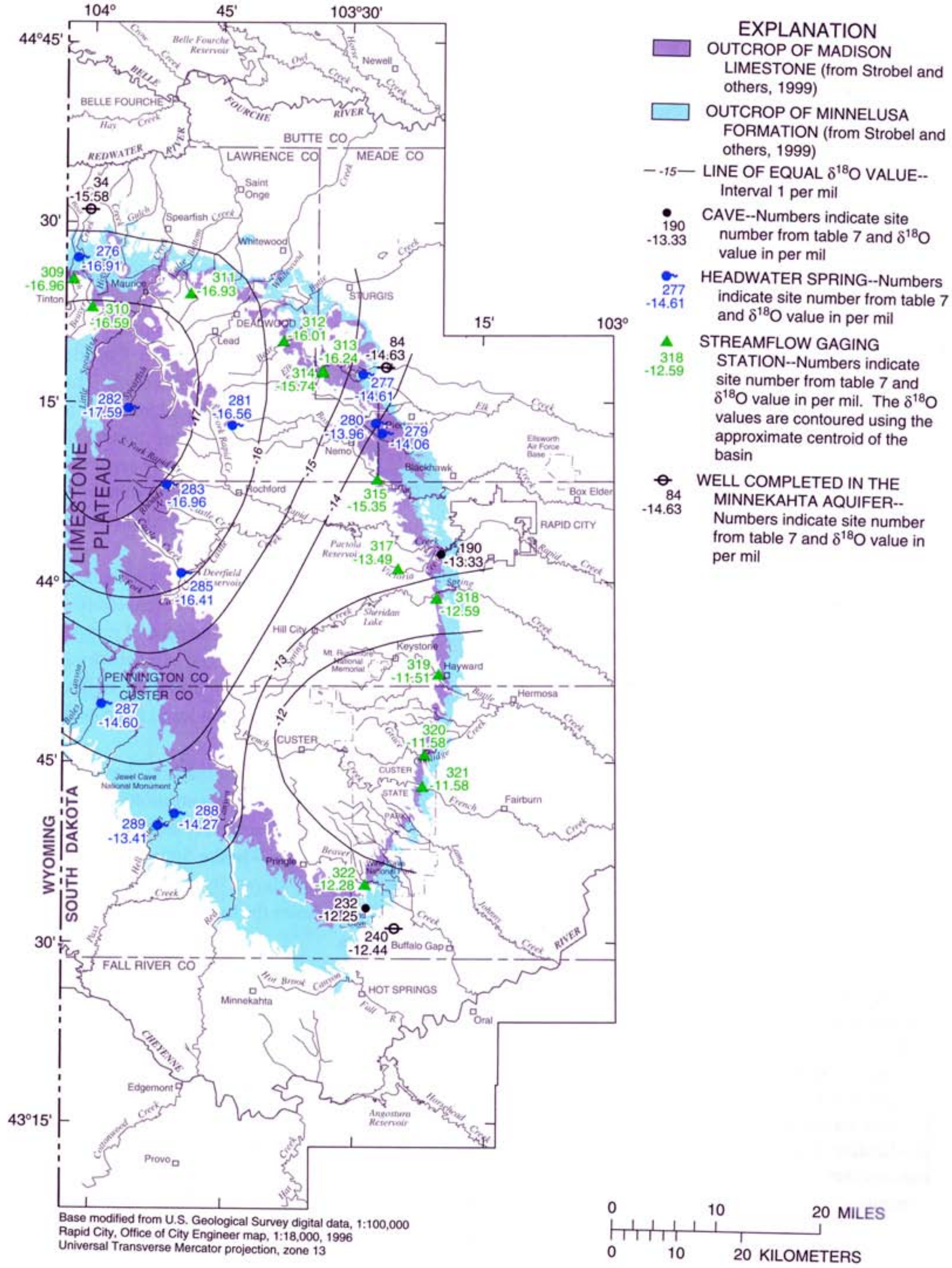

Figure 20. Generalized distribution of $\delta^{18}O$ in surface water and ground water in near-recharge areas. From Naus and others, 2001.

During the past 50 years, human activities have released an array of chemical and isotopic substances to the atmosphere. In the atmosphere, these substances have mixed and spread worldwide. These atmospheric substances, such as tritium (^3H) in water vapor from detonation of thermonuclear bombs in the 1950s and early 1960s, and chlorofluorocarbons (CFCs) from refrigeration and other uses from the 1950s through the 1980s, dissolve in precipitation, become incorporated in the Earth's hydrologic cycle, and can be found in ground water that has been recharged within the past 50 years. The detection of chlorofluorocarbons and tritium in ground water provides valuable information that can be used for dating and tracing young ground water (Plummer and Friedman, 1999).

Water samples from Mirror Lake, McNenny Pond and Cox Lake collected in November, 2001, were analyzed for three CFC's (CFC-11, CFC-12, and CFC-113). The CFC results for the three sites plotted on the atmospheric input curves (fig. 21) shows that the water from Mirror Lake contains a larger fraction of young water and is distinctly different than McNenny Pond or Cox Lake. The apparent age calculated for these water samples assumes plug flow. If that were true, the apparent age indicated by each of the CFC's for each sample would be the same. The offset in these values indicates the possibility of a binary mixture of young and old water (pre-CFC) that represent a combination of flow in conduits and a diffuse matrix. Mirror Lake has a similar pattern in the relation between the three CFC's: however, mixing with some old (pre 1950) water indicates a larger fraction of relatively young water. Water samples from these sites analyzed in 1994 for tritium (Naus and Others, 2001) also shows that tritium unit values are about the same for Cox Lake (21.0), and McNenny Pond (20.7): while tritium ages for Mirror Lake (16.9) show a younger age, similar to findings using other ground-water tracers.

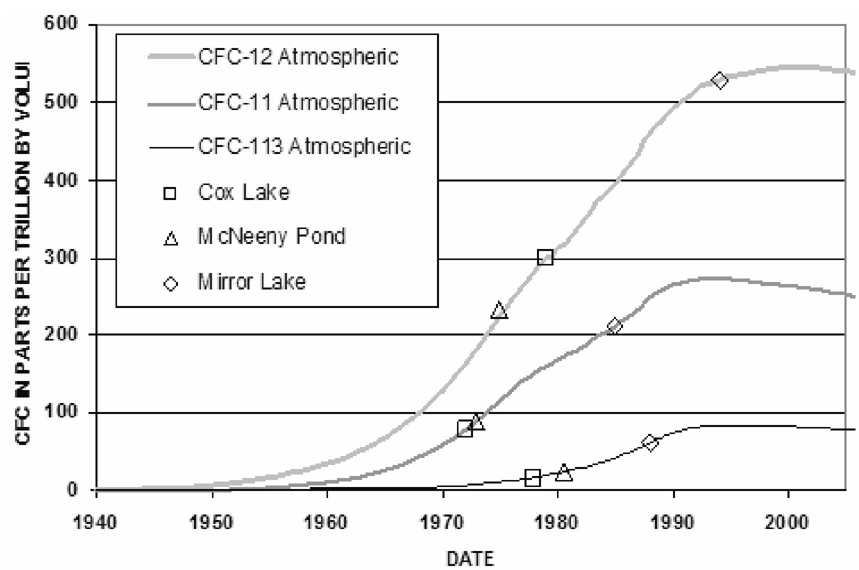

Figure 21. Comparison of CFC concentrations for Mirror Lake, McNenny Pond, and Cox Lake with atmospheric concentrations by year.

Crow Creek, which flows through the area that includes the LaFlamme anticline (Fig 15), includes contributions from numerous springs that cumulatively amounts to about 40 ft^3/s. The hydrogeologic information at these sites indicates that ground-water flow to these springs includes a complex karst evoltion that could involve several formations including the Pahasapa Limestone, the Minnelusa Formation, the Minnekahta Limestone, and the Spearfish Formation.

Retrace route to McNenny Road.

86.5 **1.4** Turn right on McNenny Road.

86.1 **0.4** Turn right on McNenny Springs Road.

86.7 **0.6** Turn right on US 15.

86.9 **0.2** Continue straight, do not turn left towards I-90.

87.8 **0.9** Approximate position of synclinal axis seen in hill to right.

89.1 **1.3** Enter Wyoming.

90.4 **0.5** Beulah. Continue straight to downtown Beulah.

91.4 **1.0** Contorted gypsum beds in Spearfish to left probably due to hydration expansion of anhydrite.

93.6 **2.**2 "Tumulus", a bowed gypsum bed probably due to gypsum expansion, in gypsum in ravine to right (see fig. 29).

94.1 **0.5** Turn left to Buffalo Jump parking area.

STOP 9: VORE BUFFALO JUMP; SPEARFISH KARST; MULTI-TIERED KARST HYDROLOGIC IMPLICATIONS
LEADER: Jack Epstein

The Spearfish Formation at Stop 9 comprises red shale, siltstone, and fine sandstone with scattered beds of gypsum in the lower half. Many dry sinkholes and springs that occupy sinkholes are located in the lower half of the Spearfish Formation.

The Native Americans that inhabited this area 300 years ago trapped and slaughtered thousands of buffalo for their primary food by herding and stampeding the animals over the steep rim of one of these large sinkholes, the Vore Buffalo Jump (fig 22). The hunters then dispatched the remaining live animals and completed the skinning and meat preparation. The site is now a major archeological dig by the University of Wyoming. Because of the importance of this archeological site, a visitor's center is proposed (http://www.dennisrhollowayarchitect.com/html/Vore1.html). Geologic controls for foundation construction is important in a region affected by karst.

Figure 22. The Vore Buffalo Jump, a 60-foot deep sinkhole. The hole was not readily seen by bison that were stampeded 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. Digital image by D.R. Holloway. (http://www.dennisrhollowayarchitect.com/html/Vore9SiteB.html).

The Vore Buffalo Jump sinkhole is more than 200 feet across and about 50 feet deep. The hole is rimmed by several convoluted, disjoined, and disrupted gypsum beds 8 to10 feet thick. Contortions in the gypsum here and in the surrounding area indicate hydration and expansion of original anhydrite. No gypsum is seen in the base of the sinkhole which is probably less than 50 feet above the Minnekahta Limestone. The Minnekahta crops out about one mile to the west along the service road where a four-foot bed of gypsum lies at the base of the Spearfish. Layers of bones of at least 15,000 bison are found in an excavation 20 feet below the lower level of the sinkhole, indicating rapid sedimentation during the last 300 years. A similar sinkhole in the Spearfish Formation near Hot Springs, SD, was an active trap for large mammals (Stop 2 of the Southern Field Trip, Epstein and Agenbroad, *this volume*).

Several sinkholes in the area of Stop 9 are on the northeast limb of a broad anticline (fig. 23); the average dip of beds is about 2-3 degrees to the northeast, and the Minnelusa Formation is exposed along the crest of the fold. The simplest explanation for the origin of these sinkholes is direct subsidence into voids caused by dissolution of anhydrite in the Minnelusa formation, several hundred feet below the base of the Spearfish. This is the same explanation given for the origin of the Mammoth Site (Stop 2) and Cascade Springs (Stop 4), where outcrops totaling more than 300 feet in the upper half of the Minnelusa are brecciated. Thus, the working hypothesis for subsidence directly into the Minnelusa is quite valid. However, no brecciation in exposed Minnelusa was reported within three miles south of Stop 9 (fig. 23), only one of two areas in the Black Hills where anhydrite is exposed at the surface (Brady, 1951; Martin and others, 1988); although (Brady, 1931) reported 72 feet of poorly bedded cavernous sandstone near the top of the formation, suggesting that that part of the formation is at least partly brecciated. This suggests an alternative working hypothesis, and that is that the Minnelusa may not be the sole cause of subsidence.

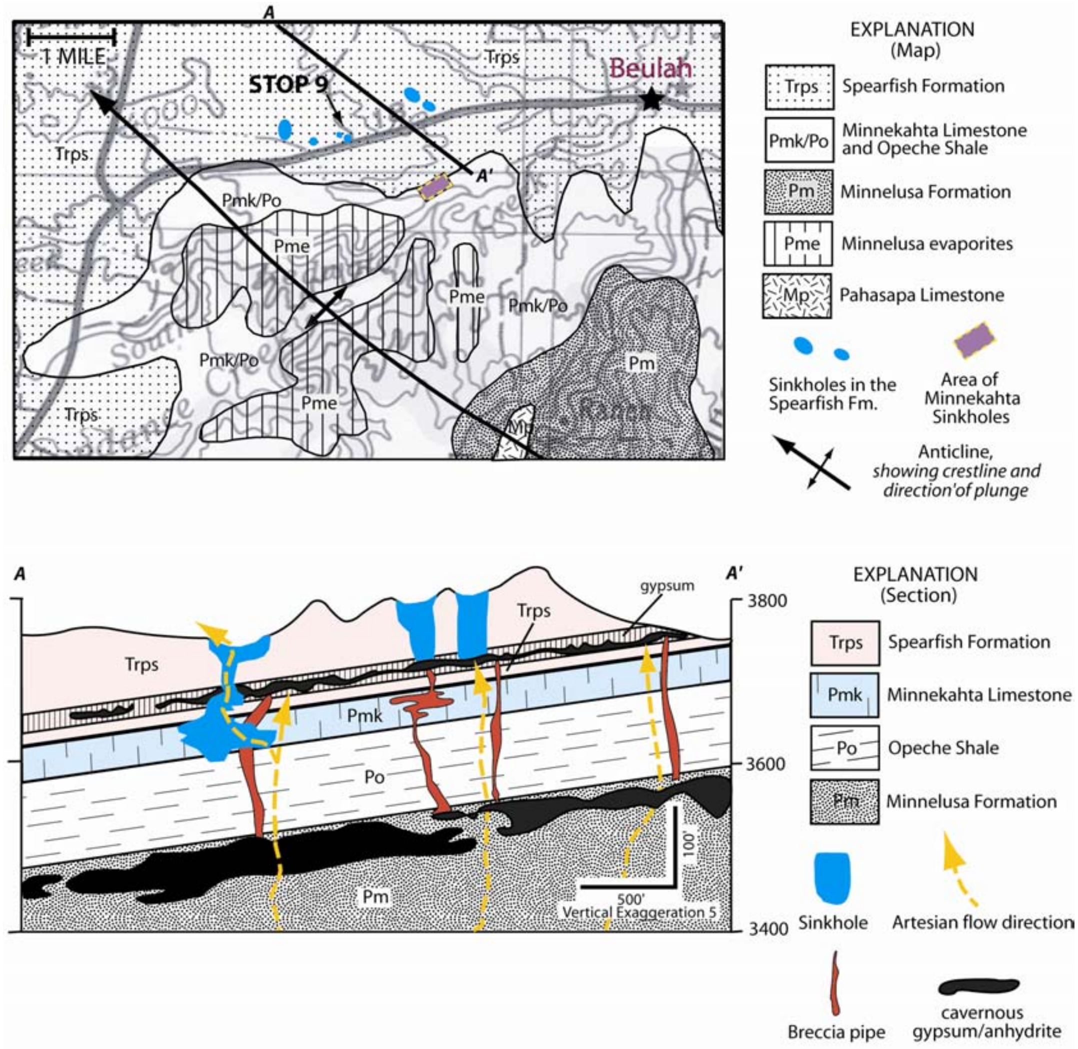

Figure 23. Geologic map (modified from Brady, 1958) and section of the Beulah, Wyoming, area, showing the location of sinkholes at Stop 9, cavernous gypsum in the basal Spearfish formation, area of outcropping sinkholes in the Minnekahta Limestone, dissolution zone at the top of the Minnelusa Formation and vertical dissolution zones (breccia pipes), and artesian flow direction from the Minnelusa Formation and the Pahasapa Limestone. Where the potentiometric surface is below ground level, sinkholes are dry; where it is above ground level, sinkholes contain emergent springs, such as Mirror and Cox lakes seen at Stop 8.

Two observations suggest a complicated pattern of subsurface dissolution affecting several stratigraphic horizons. First, 3.5 miles east of Stop 9, at the junction of Sand Creek and South Redwater Creek, the upper part of the Minnelusa is exposed and the topmost 50 feet or so *is* brecciated. Several miles south in the Sand Creek canyon the beds in the Minnelusa below are not brecciated. No sinkholes are seen in the Minnekahta Limestone above, confirming that here sinkhole development has not extended above the Minnelusa in this area. Second, the Minnekahta is exposed along South Redwater Creek, one mile southeast of Stop 9, where numerous sinkholes are present in a 2,000-foot-long low cliff and the unit is extensively brecciated (fig. 24), and the underlying Opeche Shale is disrupted. These two observations suggest that dissolution has occurred in the Minnelusa, but to a lesser degree than in the southern Black Hills, and that the Minnekahta is locally a zone of sinkhole collapse, affected by subsidence in the Minnelusa below. A short distance to the west of Sand Creek, Martin and others (1988, p. 197) reported that several beds of gypsum occur at and near the top of the Minnelusa which could have been dissolved to form the breccia seen on Sand Creek.

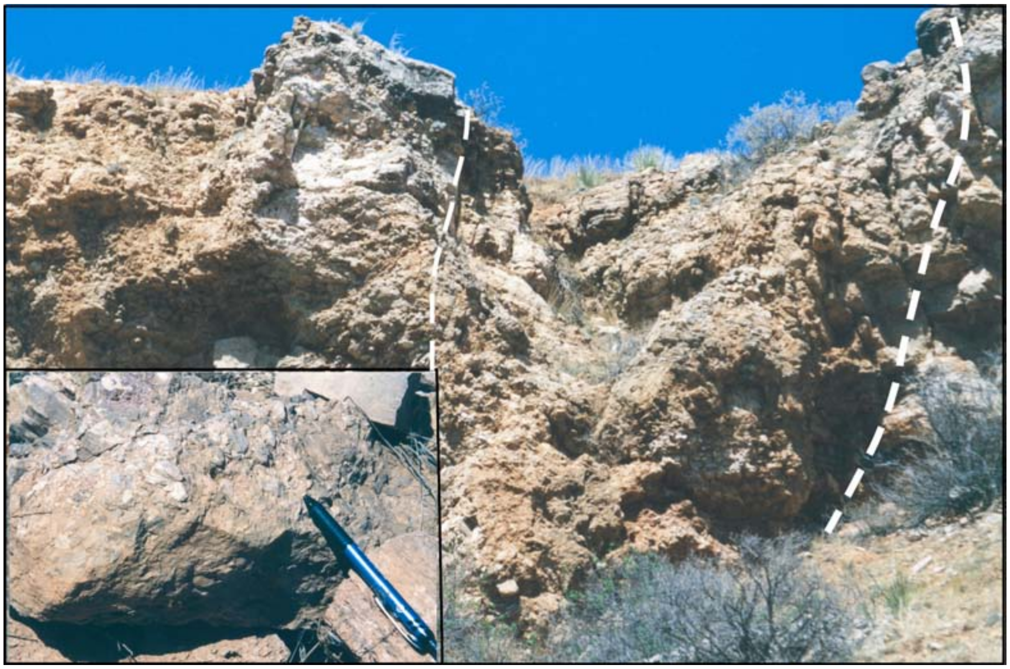

Figure 24. Collapse sinkhole (dashed line) in a zone of brecciated Minnekahta Limestone along Redwater Creek, one mile southeast of Stop 9. Inset shows details of breccia.

While breccia pipes and sinkholes may extend up through the Minnelusa Formation into overlying formations, the evidence suggests that sinkholes in Spearfish in the Beulah-McNenny Fish Hatchery area may not be directly connected to pipes in the Minnelusa below. Whereas, the distribution of the sinkholes seen at Stop 9 suggests that below the red soil there lurks a labyrinth of cavernous passageways developed as gypsum dissolved at the base of the formation and collapse sinkholes developed in the underlying Minnekahta Limestone. One of these passageways can be seen in the bottom of a large sinkhole, 3,500 feet WNW of the Buffalo Jump (fig. 25). The sinkhole is about 500 feet long, flat floored, and contains a narrower 60-foot deep, steep-sided sinkhole in its north end (fig. 26). This deep sinkhole was discovered in 1985 by local ranchers who heard running water in a cavern that extended horizontally beyond the limits of their flashlight beam (Ted Vore, oral communication, 1999). About 11 feet of the Minnekahta Limestone and an overlying gypsum bed are exposed in the gulley in the lower central part of figure 24. These extend to the north and underlie the large sinkhole. The gulley is the site of a blind valley (fig. 27) that is adjacent to disrupted beds in a collapse sinkhole (fig. 28).

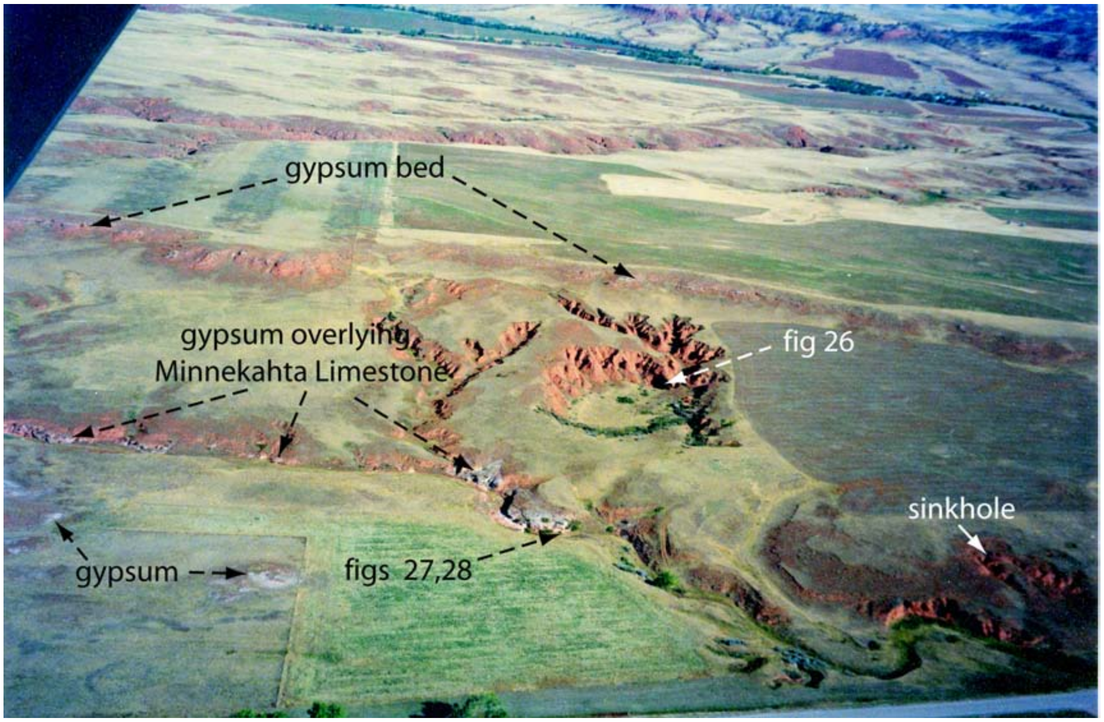

Figure 25. Karst features northwest of the Vore Buffalo Jump, Stop 9. Deep sinkhole in figure 26 lies within larger, flat-bottom sinkhole in center of photo (see figure 33 at mileage 94.8). Another sinkhole lies in the lower right corner. Small blind valley shown in figure 27 in lower center. The lower of two conspicuous gypsum beds lies immediately above the Minnekahta Limestone and also underlies the sinkholes and are probably the source of their collapse.

Figure 26. Sixty-foot-deep sinkhole within the larger sinkhole shown in figure 25. This hole formed in 1985, examined by Ted Vore, the man in the foreground. He heard running water at depth below the range of his flashlight. This suggests that passageways developed by the dissolution of gypsum at shallow depth. Accompanying this dissolution was the precipitation of thin tabular gypsum injected into the surrounding sediments (seen on the highwall to left), producing a disrupted zone and fracturing allowing for rapid movement of ground water and contributing to continued removal of gypsum.

Figure 27. Blind valley in larger gulley developed by solution at base of laminated gypsum bed overlying the Minnekahta Limestone. Sinkhole in figure 28 lies to the immediate left.

Figure 28. Vertical gypsum (on left) and limestone beds exposed on walls of sinkhole at the Minnekahta-Spearfish contact in gulley 500 feet southwest of large sinkhole shown in figure 25.

Abundant gypsum veinlets are present in the walls of the sinkhole similar to those shown in figure 15A of the Southern Field Trip (Epstein and Agenbroad, *this volume*). These veinlets were probably produced by expansion of gypsum and fracturing of the surrounding bedrock. The pressure exerted by hydration of anhydrite to form gypsum produced an irregular dome above a 25-foot wide void, termed a *tumulus* (fig. 29), 3,200 feet east of the Buffalo Jump. Similar features are common in lava flows where the movement of molten lava pushes the overlying crust upwards.

Figure 29. Tumulus in Spearfish Formation near the Buffalo Jump developed by upward bowing of the gypsum bed due to hydration expansion.

The distribution of the sinkholes near Stop 9, the extension of some of them to a layer of gypsum below, the dissolution of the gypsum forming voids, contortions, and vein-filled fractures, suggest that the sinkholes are formed by collapse into open passageways near the bottom of the Spearfish as well as into the Minnekahta Limestone. One of these passageways in the Spearfish, diagramed by Darton (1909), is a cave in gypsum near Sundance, WY (fig. 30). Additionally, Cox (1962, p. 11) noted a well about four miles east of Mirror Lake that produced from a "Lower Spearfish gypsum cavern". The flat floor of the large sinkhole described above suggests collapse over the entire width of the hole over a void at least 600 feet wide. The gypsum and sediment that has been removed from that void probably was and continues to be flushed to springs in Redwater Creek to the north. Alignment of two sinkholes at the head of a minor drainage (fig. 31) suggests that solution of the underlying gypsum is aligned with the present-day surface drainage.

Figure 30. "Interior of cave in gypsum, near Sundance, Wyo" (Darton, 1909, Plate X). The cave appears to be at least 20 feet high, judging from the height of the person. The water flows on a gypsum bed, possibly 8 feet thick. Above that is a zone of red beds intruded by gypsum stringers. An attempt to locate the cave in 2005 was not successful. See description at mileage 17.2 of the Western Road Log (Epstein, this volume).

Figure 31. Aerial photograph of two sinkholes (arrows), about 500 feet long, aligned along head of gulley suggesting that the present drainage controls the location of the sinkholes. These are 3,700 feet northeast of the Buffalo Jump.

The removal of gypsum by dissolution produced the sinkholes in the Spearfish formation and by collapse of limestone in the Minnekahta. The artesian waters that caused the karstification moved upward from the Minnelusa Formation, from between 100 and 700 feet below (the Minnelusa is slightly more than 600 feet thick in this area, indicated by well data), as well as from the deeper Pahasapa Limestone. The cross section in figure 23 shows the partial dissolution of some anhydrite in the Minnelusa, upward stoping and water flow into the Minnekahta and lower Spearfish gypsum, collapse in the Minnekahta, and removal of gypsum in the Spearfish Formation, creating a system of open voids, and formation of the Spearfish sinkholes.

In the area of the northern Black Hills at least from Spearfish, SD., west to the Wyoming-South Dakota border and beyond, the lower part of the Spearfish Formation has different hydrologic properties than the upper part. The hydration-expansion of gypsum produced secondary fractures in disrupted zones with injection of thin gypsum veins into the surrounding sediments. The lower Spearfish yields water to wells, many springs, and large ponds such as Cox, Mud, and Mirror Lakes, characteristic of a karst aquifer. The overlying rocks, which lack gypsum, are a confining layer.

Turn left and continue on US 15.

94.3 0.2 Large sinkhole on right (figure 32).

Figure 32. Elliptical, 300-foot-long sinkhole northwest of the Buffalo Jump with a smaller deeper hole at arrow.

94.6 0.3 Another large sinkhole on right.

94.8 0.2 Bus slows down to view the 600-foot wide sinkhole in the Spearfish Formation to the right (fig. 33).

Figure 33. Large sinkhole with a flat bottom that is 250 feet wide and 450 feet long (see figure 25). The deep sinkhole shown in figure 26 can be seen in right far corner of the hole (dashed arrow). Smaller sinkholes (solid arrows) are characteristically rimmed with western snowberry.

95.2 0.4 Another large sinkhole to right.

95.6 0.4 Minnekahta Limestone overlain by 4-foot-thick gypsum bed. Ten miles farther east this gypsum interval thins to about 1.5 feet of interbedded red shale and impure gypsum.

96.2 0.6 The Minnekahta Limestone is crushed for stone from quarry on left. The Minnekahta is a valuable aggregate resource throughout the Black Hills.

96.8 0.6 Many silicified and case-hardened sandstone lag boulders of the Lakota Formation are remnants of erosion of about 1,000 feet of sediments overlying the Minnekahta. Geomorphic features to the north show that the boulders are an end result of a series of erosional processes (fig. 34).

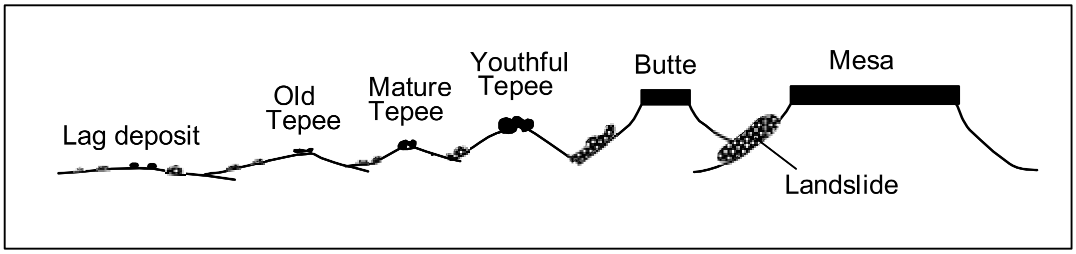

Figure 34. Stages in the development of lag boulders derived from the Lakota Formation in the northern Black Hills. Isolation from the tableland capped by the Lakota results in formation of a mesa and then a butte. Disruption of the Lakota forms isolated sandstone blocks protecting the underlying shale in a series of progressively lowering "tepees." Isolated boulders in a lag deposit is the final stage.

97.7 0.9 Intersection with Wyo. 111. Turn left towards I-90 east. Continuing straight leads to Sundance Wyoming, gateway to Devils Tower.

98.2 0.5 Turn left onto I-90 East.

99.1 0.9 1,000-foot-wide sinkhole we have already seen on the service road to left.

99.7 0.6 Another sinkhole to left

99.9 0.2 Vore Buffalo Jump between I-90 and service road to left.

101.7 1.8 Contorted gypsum in Spearfish Formation to right. These are about 100 feet above the Minnekahta contact.

103.7 2.0 Exit to Beulah, continue straight ahead.

104.9 1.2 Enter South Dakota.

115.7 10.8 City of Spearfish on right. White gypsum in the Gypsum Spring Formation prominent in Lookout Mountain to left.

118.6 2.9 Exit 15. Entrance to scenic Spearfish Canyon. Continue straight.

119.8 1.2 Approximate axis of the Belle Fourche anticline which causes the Gypsum Spring to wander farther north.

121.7 1.9 Gypsum Spring overlies the Spearfish on left.

122.2 0.5 Exit 17, turn right towards US85 south leading to Deadwood and Lead, early Paleozoic stratigraphy.

122.4 0.2 Stop sign. Turn right on US85 South.

125.4 3.0 Park along side of road to right.

STOP 10: MINNEKAHTA LIMESTONE; KARST AND HYDROLOGY
Leaders: Jack Epstein and Larry Putnam

The Minnekahta Limestone is 30 feet thick at this locality, and ranges from 25 to 65 feet thick in the Black Hills. It is a thin-bedded and laminated algal limestone with a purplish tinge (ranges from light gray (N7) to light reddish gray (10R 7/1) through pale red (10R 6/2). The limestone was deposited in intertidal-flat environments during the Permian and is sandwiched between red beds and evaporites of the Opeche Shale and Spearfish Formation that were deposited on supratidal flats and in isolated basins. The resistant limestone characteristically erodes to steep cliffs between the softer fine sandstone, siltstone, and shale above and below, and forms extensive dip slopes throughout its area of exposure. It is the prime aggregate resource and major ingredient in cement in the Black Hills. The Minnekahta Limestone is considered a major aquifer in the Black Hills area (Strobel and others, 1999). Most wells completed in the Minnekahta aquifer yield from 10 to 100 gallons per minute (gal/min) with a few wells yielding from 100 up to 1000 gal/min.

The Minnekahta Limestone has a few karstic features, including joint-solution widening with terra rosa filling, solution pits, with a few rare occurrences of sinkholes and small caves (Stop 3 of the Southern Field Guide, Epstein and Agenbroad, this volume), although locally sinkholes are abundant (fig. 24). One sinkhole was present in the Centennial limestone quarry (previously called the Cole quarry) immediately to the east before it was removed by quarry operations (Cox, 1962, Appendix B). Porosity is governed by bedding parting and fractures, including joints and intraformational faults and folds. The joints range from less than one foot to a few feet apart. Joint sets average about N30^{o}E (most prominent) and N60^{o}W. The basal contact with the Opeche Shale is channeled in places with vertical relief as much as one foot.

The Opeche Shale in the Black Hills region is predominantly moderate reddish brown (10R5/6), but the upper several feet (8.5 feet thick at this locality) has a distinct purplish color (pale grayish red 10R5/2 with a purplish tinge) that is transitional into the beds below through several inches (fig. 35). The Opeche red beds are calcareous. Yellow leached zones (grayish yellow, 5Y8/4) with red and gray liesegang rings (narrow bands due to precipitation within water-saturated rock), as much as 2.5 feet thick, are prominent features under conspicuous joints in the Minnekahta that trend about N30^{o}E. The yellow leaching has removed some of the calcium carbonate from the rock and clearly post-dates the formation of the purple color. During the 1999 summer wet season in the Black Hills, springs were seen in the Centennial quarry to the east, emanating from the prominent northeast-trending joints at the base of the Minnekahta, and obviously causing the leaching of the uppermost Opeche to yellow clay. The chemistry of the color alteration has not been studied.

Figure 35. Minnekahta Limestone in abrupt contact with the underlying Opeche Shale. Dashed outline shows yellow leaching zone below prominent northeast-trending joint shown in fig. 36.

Significant ground-water flow through the open NE-trending joint set is evidenced by a complete lining of calcite crystals (fig. 36). Greene and Rahn (1995) demonstrated that joints created a hydrologic anisotropy and a radial direction of ground-water flow throughout the Black Hills in South Dakota, as well as controlling the direction of cave passages that are abundant in the Pahasapa Limestone throughout the region (fig. 37). The orthogonal joints observed at this site also are consistent with localized orthogonal anisotropy that has been observed in areas where large springs modify the generally radial direction of ground-water flow in the Pahasapa Limestone. These joint trends are prevalent throughout all stratigraphic units in the Black Hills. The anisotropy suggested by the northeast-trending calcite-lined joints in the Minnekahta at this stop agrees exactly with this regional picture, and is shown in figure 35.

Figure 36. Northeast-trending, calcite-crystal-lined joint in the Minnekahta. This trend is shown on the regional fracture pattern in figure 37.

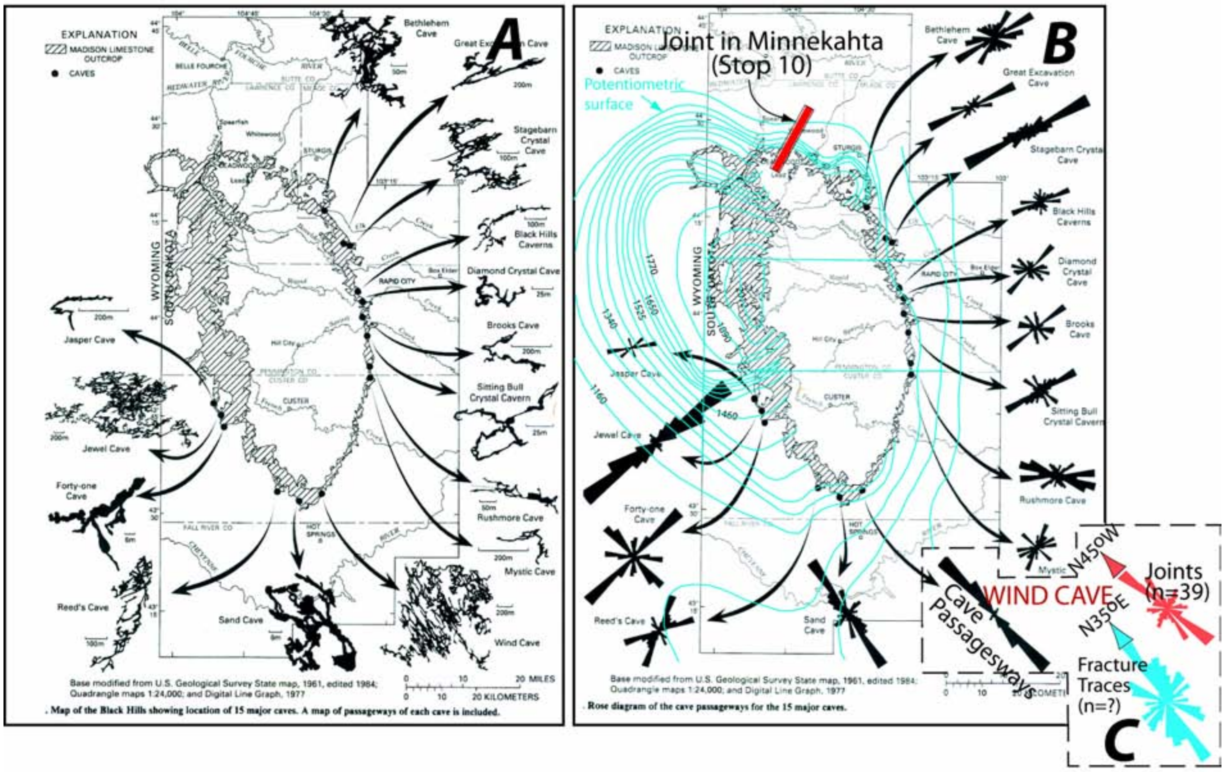

Figure 37. Fifteen major caves in the Black Hills, SD, showing passageways maps (A) and rose diagrams of cave passages (B), and comparison of trends of cave passageways, joints, and fracture traces at Wind Cave, Black Hills, SD (C). Modified from Greene and Rahn (1995). Crystal-lined joint trend in Minnekahta Limestone at Stop 10 is indicated.

The origin of the uppermost purple zone in the Opeche is worthy of investigation (*students at South Dakota School of Mines and Technology take note*). It ranges to about 15 feet in thickness and is present throughout the Black Hills. The color has been attributed to a period of weathering and erosion prior to deposition of the Minnekahta Limestone (e.g., Gries, 1996, p. 258). An alternate possible explanation is that the color is due to staining from chemical leaching in the overlying purplish Minnekahta Limestone. On the east side of the roadcut, the purple zone below the Minnekahta is well exposed and colluvium derived from the Minnekahta extends down the slope to the south (fig. 38). Under the colluvium is another purplish zone that was better exposed than at present. That zone cuts across both the upper Opeche purple zone and the underlying red beds. It is possible that this second purple zone is due to downward percolation of water through the Minnekahta colluvium, staining the underlying rocks, and post-dating the uppermost purple zone. This suggests that the uppermost purple zone in the Opeche throughout the Black Hills may also be caused by chemical alteration by ground water seeping down through the Minnekahta. The chemistry involved has not been studied, and worthy of investigation. A manganese color alteration may be ruled out because Darton (1909, p. 26) reported that manganese was not present in the Minnekahta, but we are unaware of any more recent analyses.

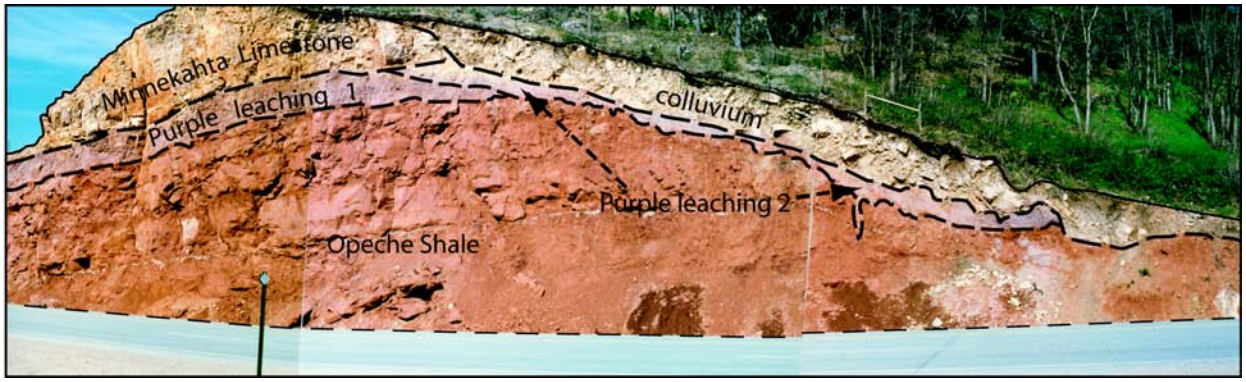

Figure 38. Exposure of the Minnekahta Limestone and upper Opeche Shale on the east side of US 85 at stop 10 showing two purple leach zones in the Opeche.

Turn around heading north on US 85 and retrace route back to I-90.

128.3 2.9 Turn right on I-90 east.

129.3 1.0 Circular hill to right is the Elkhorn dome, rimmed by a circular dip slope of the Minnekahta Limestone and cored by the Minnelusa Formation. Uplift is presumably due to intrusion of a Tertiary laccolith at depth. We are riding on a narrow part of the "red racetrack" underlain by red beds of the Spearfish Formation and with moderately dipping Sundance and Inyan Kara rocks on the left and the Minnekahta to Minnelusa on the right.

133.5 4.2 Turn right on exit 23 towards Whitewood.

133.9 0.4 Stop sign, turn left on Rte 34 west.

134.5 0.6 Turn right on Weyrich Lane.

134.7 0.2 Park in lot of Weyrich Gravel and Service. Walk to top of hill along dirt road.

STOP 11: PROPOSED WHITEWOOD SEWAGE LAGOON AND ARTIFICIAL WETLAND
Leader: Arden Davis

A sewage lagoon and artificial wetland were proposed for the City of Whitewood, South Dakota, at the site of this stop. The geology and hydrology of the proposed wastewater treatment site are similar to that of the failed sewage lagoon site near Spearfish, SD, where two lagoons were built on alluvium above a thick, widespread layer of gypsum in the Gypsum Spring Formation. The lagoons near Spearfish started leaking within a year of their completion; the southern lagoon was abandoned soon after construction, and the northern lagoon could not provide sufficient retention time for proper treatment of sewage (Rahn and Davis, 1996).

At the site of the proposed Whitewood sewage lagoon and artificial wetland (the present stop), surface investigation of the area showed numerous gypsum outcrops, several sinkholes, and a cave entrance nearby (figures 39 and 40). Exposures of thick gypsum in the Gypsum Spring Member were identified within the proposed wetland cells. Sinkholes as deep as 10 meters below the land surface were mapped within 30 m of the proposed wetland (Figures 41 and 42). Subsequent drilling within a proposed wetland cell showed a

9-meter thickness of gypsum. South of the wetland cells, the proposed site of the sewage lagoon was covered by alluvium, but later drilling also showed massive gypsum beneath that site (Davis and Rahn, 1997).

The Lawrence County Commission tabled the proposed Whitewood wetland project, although not without controversy. Eventually the entire site was abandoned as a potential wastewater disposal facility.

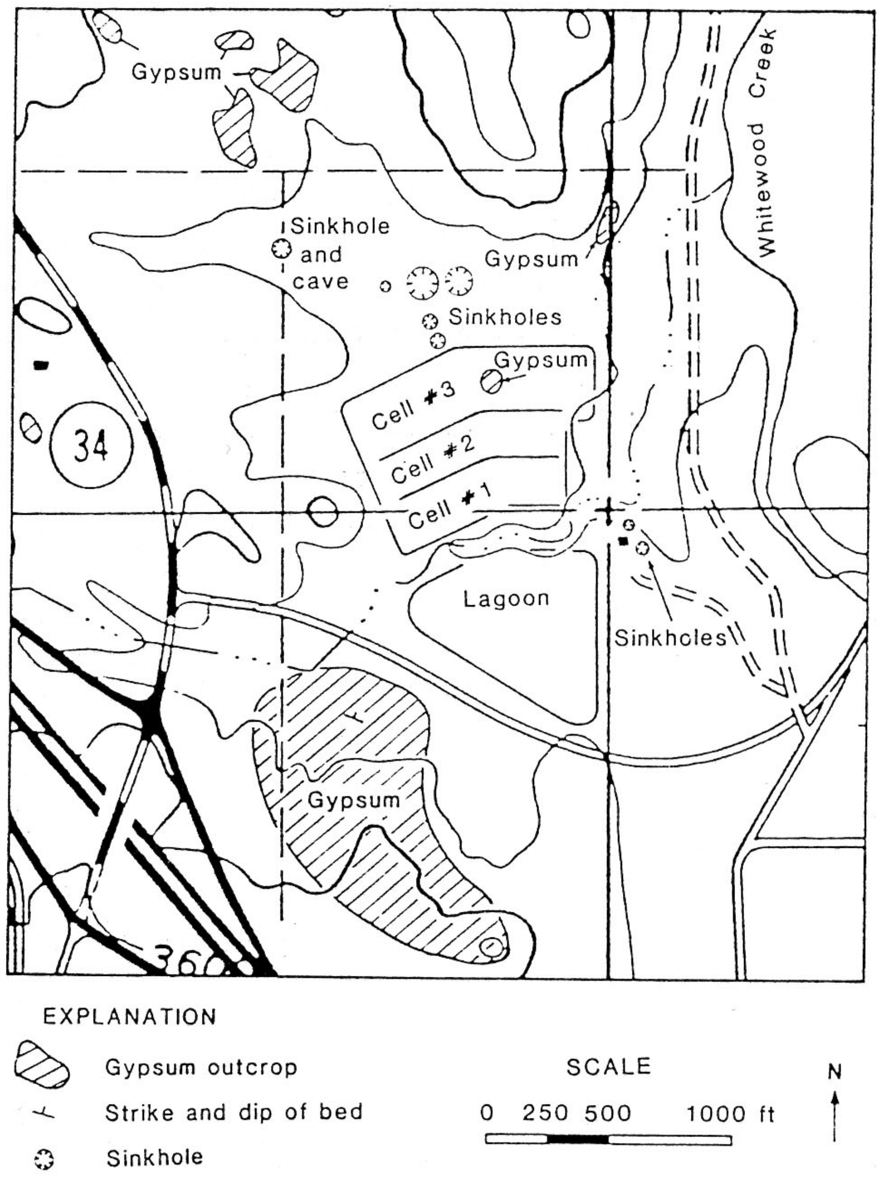

Figure 39. Map of proposed Whitewood sewage lagoon and artificial wetland, showing sinkholes, gypsum outcrops, and cave (from Davis and Rahn, 1997).

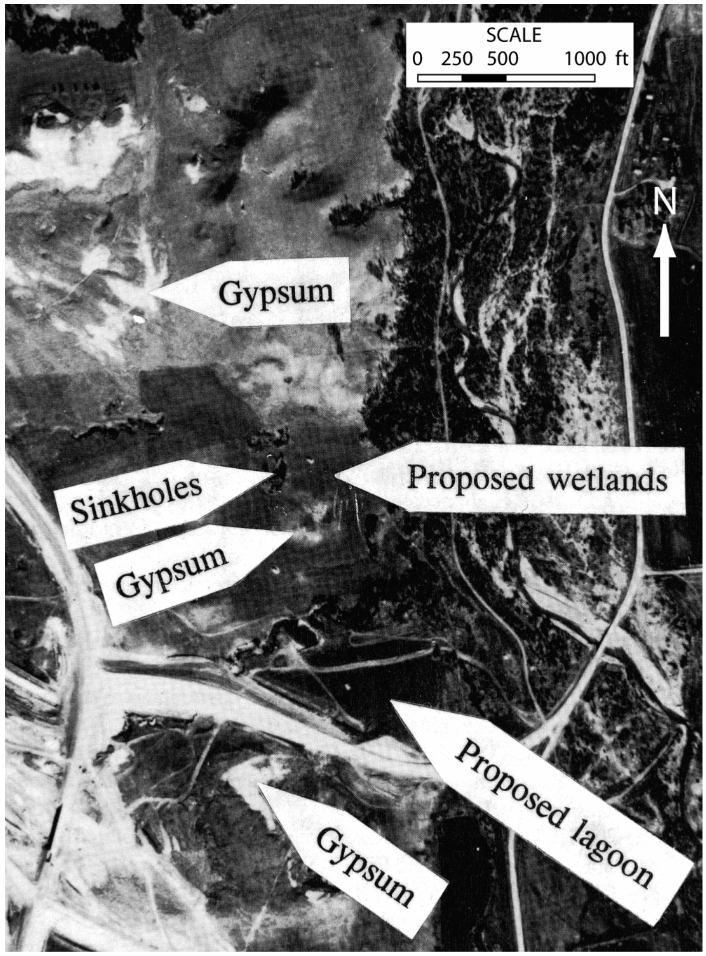

Figure 40. Aerial photograph of proposed Whitewood site (from Davis and Rahn, 1997).

Figure 41. Recently developed sinkhole approximately 100 meters north of proposed wetland cell. Note that the area was being fenced for the safety of cattle and horses (from Davis and Rahn, 1997).

Figure 42. Large sinkhole about 60 meters north of proposed wetland cell. Land surface elevation where person is standing is about 10 meters lower than the elevation at the edge of the sinkhole (from Davis and Rahn, 1997).

Retrace route back to I-90.

135.0 **0.3** Turn left on Rte 34 east.

135.6 **0.6** Turn left on I-90 East.

137.8 2.2 Gypsum Spring gypsum overlies the Spearfish on left. Bear Butte, an exhumed Tertiary laccolith, may be seen in the far distance poking through hills to left.

138.8 1.0 Gypsum caps red beds, both units of the Gypsum Spring Formation to right. Overlain by greenish shale of the Stockade Beaver Member of the Sundance Formation, and overlies red beds of the Spearfish Formation.

150.9 2.1 Hummocky topography typical of landslide on the slope of the hogback on left.

151.6 0.7 Sturgis, Exit 30. Every year during August a multitude of motorcyclists invade the Black Hills for the famous Sturgis Bike Rally. In 2004 there were 515,000 participants, generating 706 tons of garbage, with 133 marriage licenses issued, four deaths, 16 felony drug arrests, 405 jailed, 340 emergency hospital visits, and $1,100,000 taxes collected (From The Official City of Sturgis Rally Website).

156.2 4.6 Exit 34, Black Hills National Cemetery, one of several, including Arlington National Cemetery near Washington DC.

157.2 1.0 In 1963 a roadcut on I-90 triggered a landslide that was stabilized by removing material equal to the amount removed at the toe of the slide (Rahn, 1986, p. 173).

159.2 2.0 Landslide topography on slope ahead to left.

152.6 3.4 Rest area.

153.3 0.7 Gypsum caps Spearfish red beds on left. Minnekahta, Opeche, and Minnelusa rocks dip towards us on right.

159.6 6.3 Exit 48. Stagbarn Canyon Road. Excellent exposure of upper Sundance, Morrison, and lower Lakota Formations along the road up the hill to left.

164.7 5.1 Enter Pennington County.

168.1 3.4 Cut through the Dakota hogback held up by Lower Cretaceous sandstone and underlain by Jurassic sandstone and shale.

168.6 0.5 Turn right onto I-190 South.

169.8 1.2 Turn right on exit 1C towards the Civic Center.

169.9 0.1 Stop Sign. Turn left towards Civic Center.

170.0 0.1 Bear left towards Civic Center passing under I-190.

170.2 0.2 Stop sign. Continue straight.

170.5 0.3 Traffic light. Turn right on 5th Street.

170.7 0.2 Turn right into Holiday Inn. End of trip.

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