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.

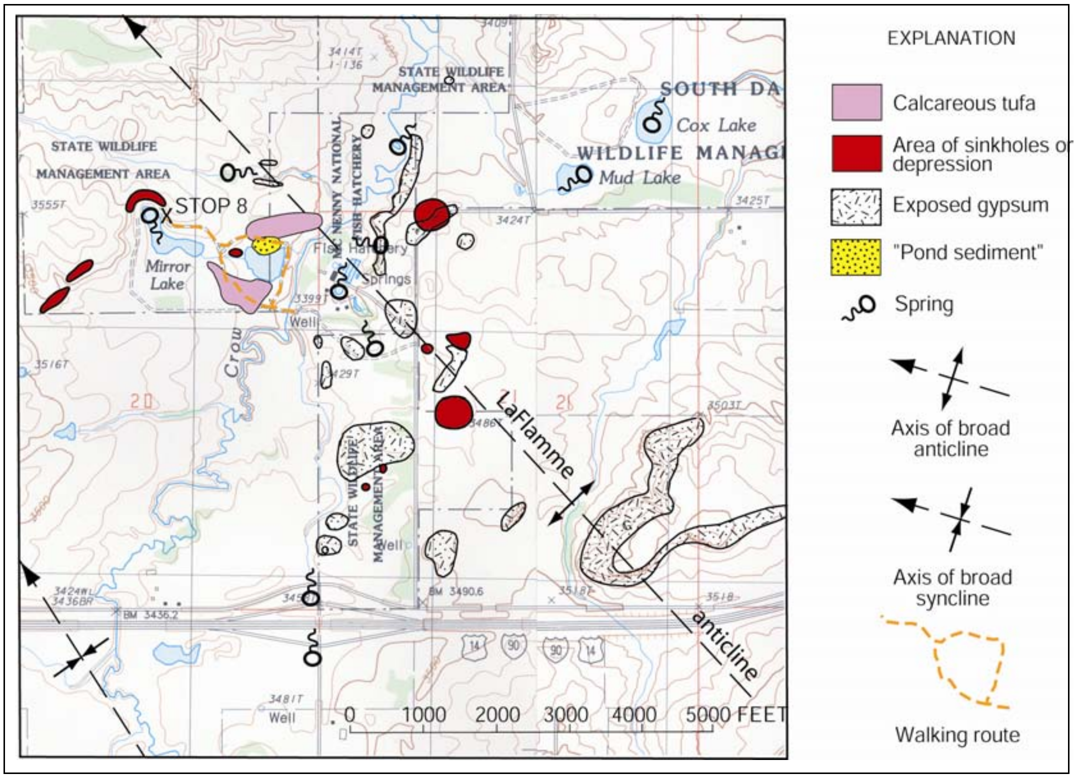

Figure 15. Karst features in the McNenny National Fish Hatchery area at Stop 8. The abundance of sinkholes suggests that there is a labyrinth of open conduits near the base of the Spearfish Formation. Base from Beulah, WY.-S.D. and Chicken Creek, WY. 7.5' topographic maps, 1984.

Figure 16. Air photograph showing karst features in the McNenny Fish Hatchery area.

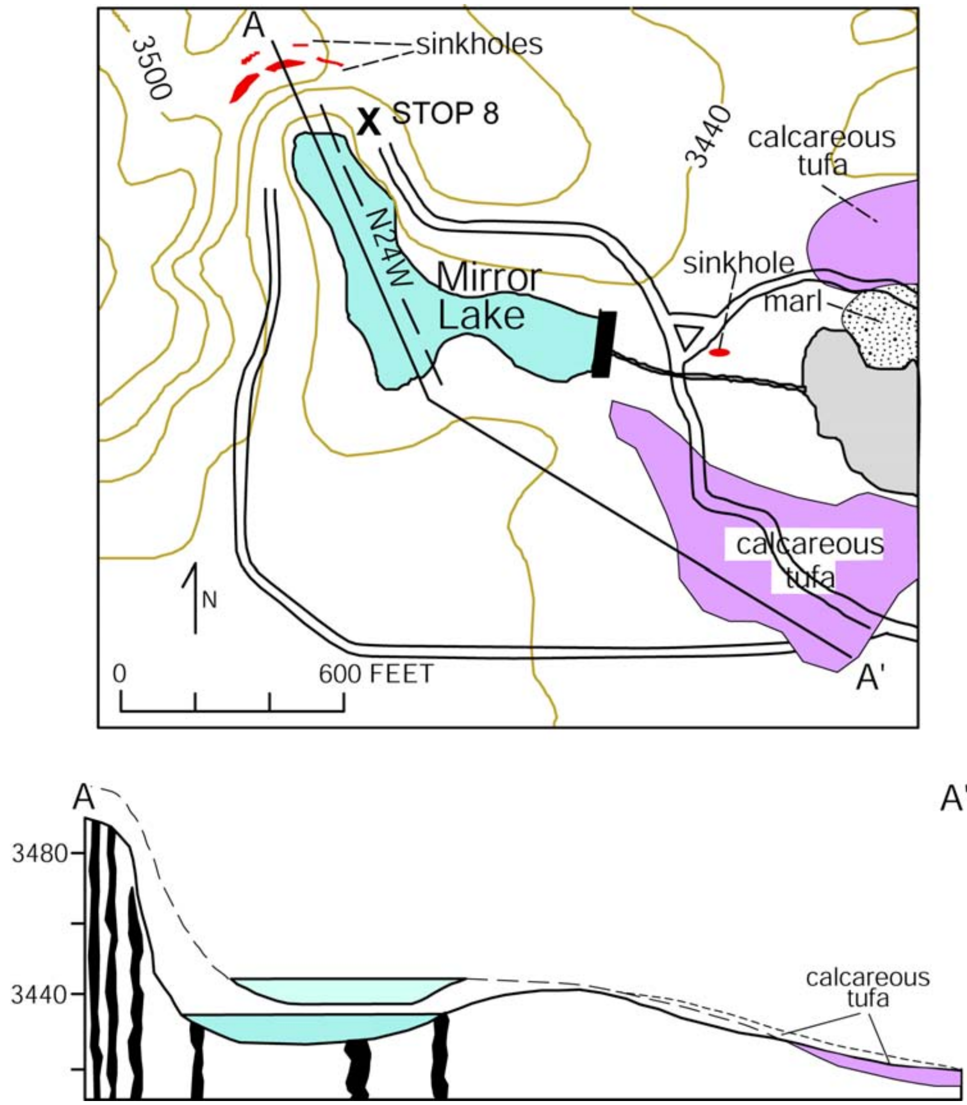

Figure 17. Map and cross section (vertical exaggeration 10x) showing sinkholes at the north end of Mirror Lake (black outlines) and inferred earlier topography (dashed line) in which calcareous tufa was deposited. Contour interval 20 feet.

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.

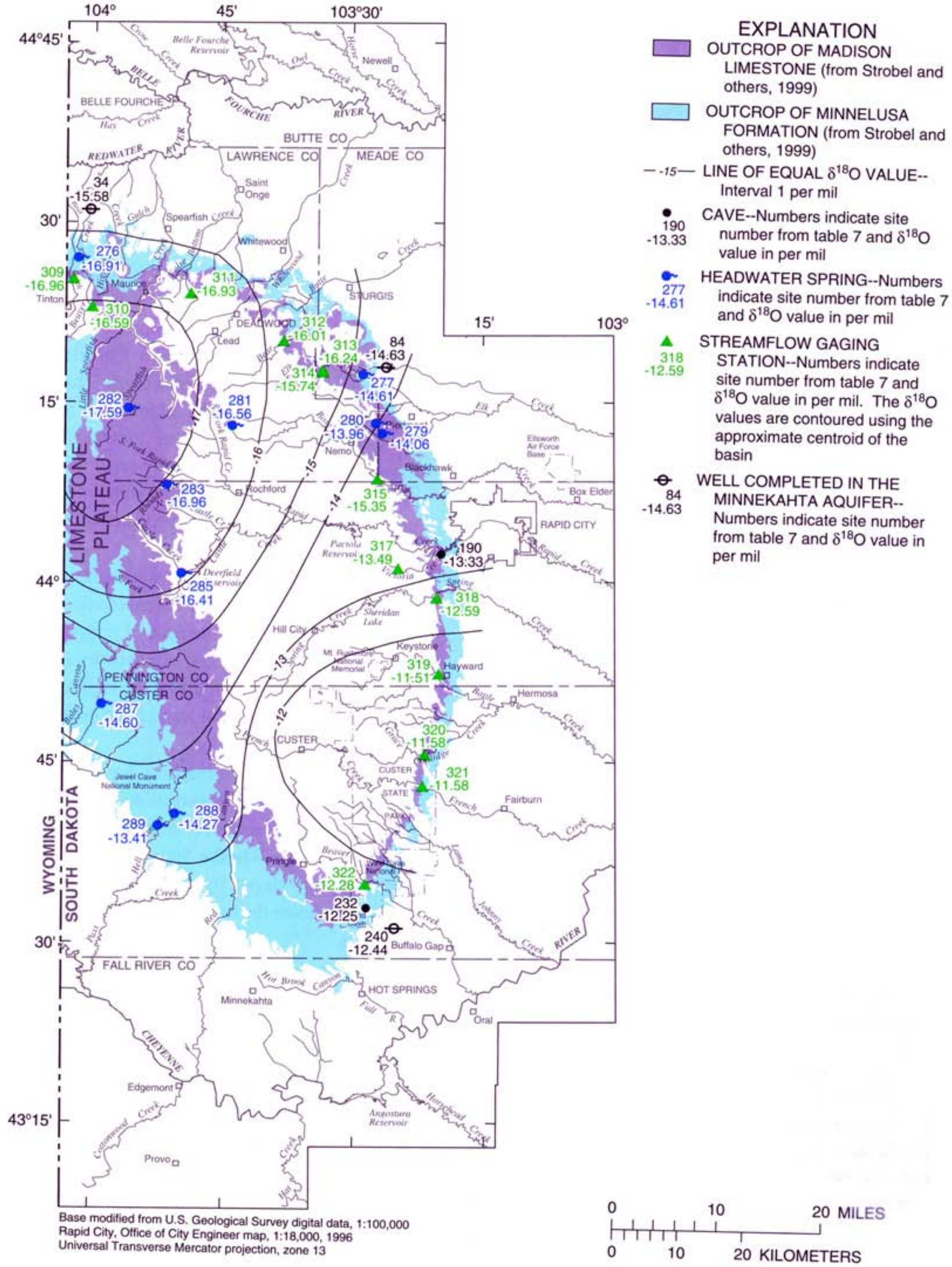

Figure 20. Generalized distribution of $\delta^{18}O$ in surface water and ground water in near-recharge areas. From Naus and others, 2001.

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 (^{3}H) 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.

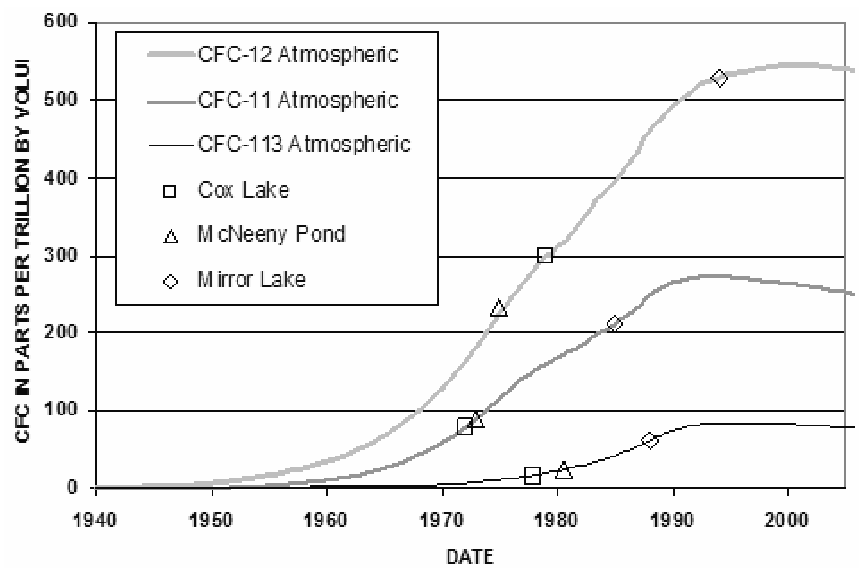

Figure 21. Comparison of CFC concentrations for Mirror Lake, McNenny Pond, and Cox Lake with atmospheric concentrations by year.

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.

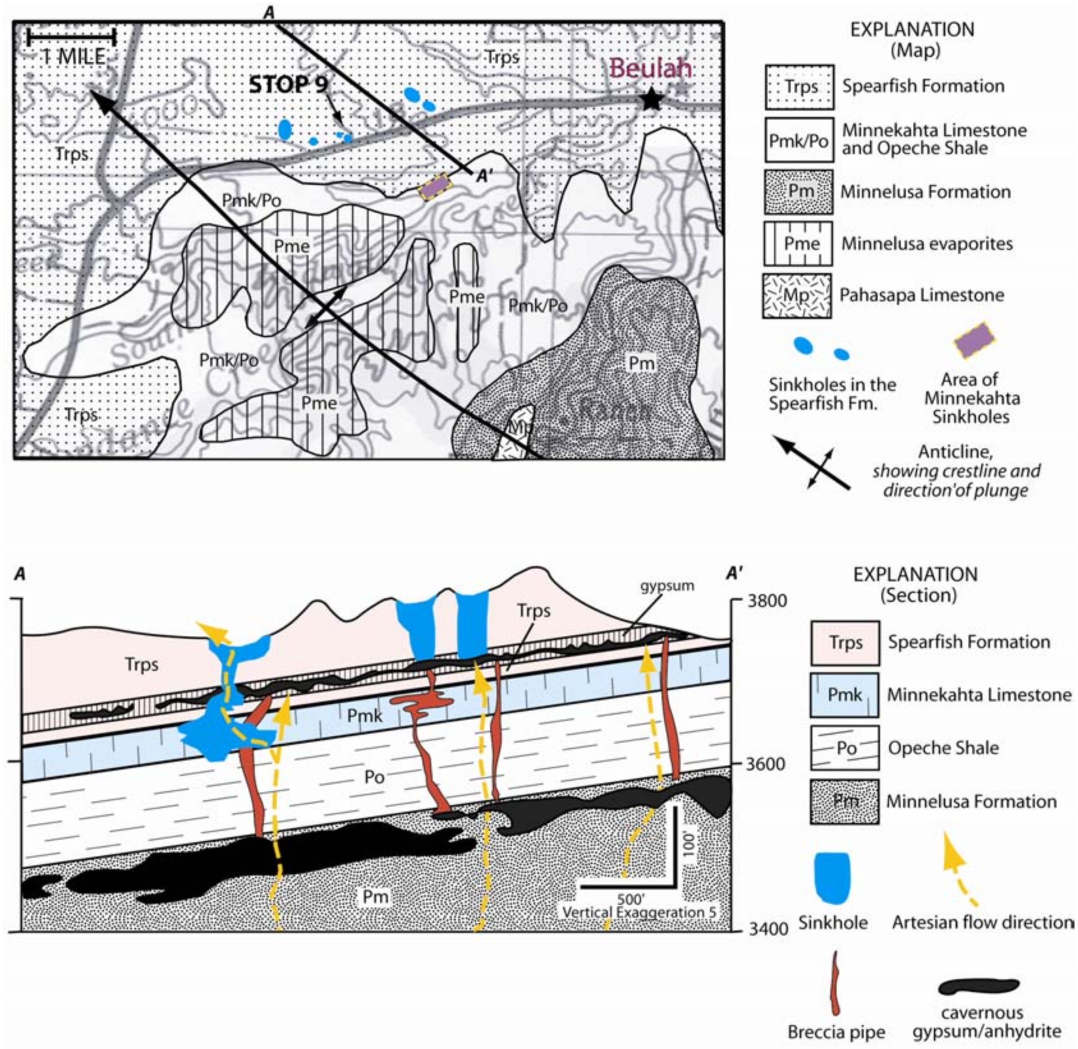

Figure 23. Geologic map (modified from Brady, 1958) and section of the Beulah, Wyoming, area, showing the location of sinkholes at Stop 9, cavernous gypsum in the basal Spearfish Formation, area of outcropping sinkholes in the Minnekahta Limestone, dissolution zone at the top of the Minnelusa Formation 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.