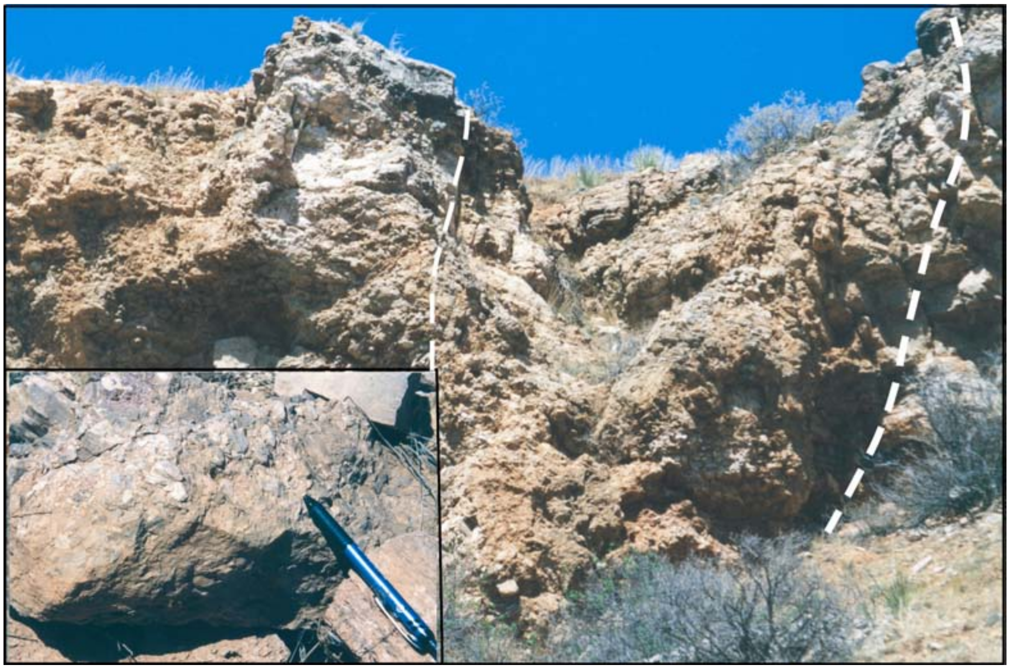

Figure 24. Collapse sinkhole (dashed line) in a zone of brecciated Minnekahta Limestone along Redwater Creek, one mile southeast of Stop 9. Inset shows details of breccia.

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).

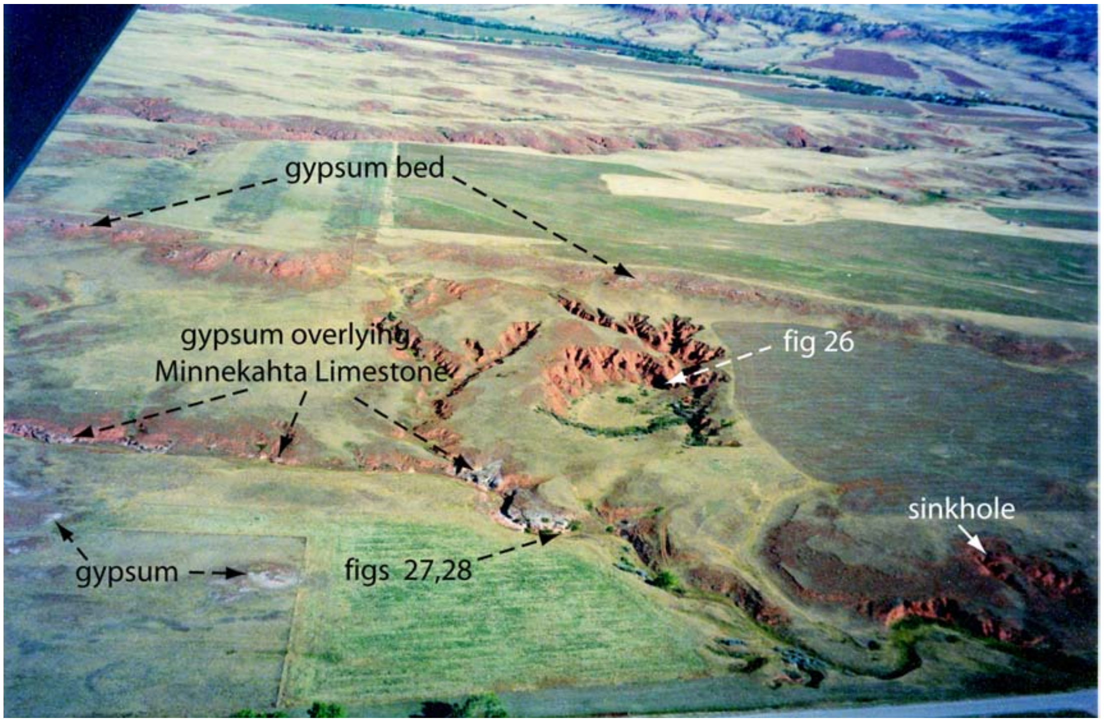

Figure 25. Karst features northwest of the Vore Buffalo Jump, Stop 9. Deep sinkhole in figure 26 lies within larger, flat-bottom sinkhole in center of photo (see figure 33 at mileage 94.8). Another sinkhole lies in the lower right corner. Small blind valley shown in figure 27 in lower center. The lower 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 (figure 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 (figure 34).

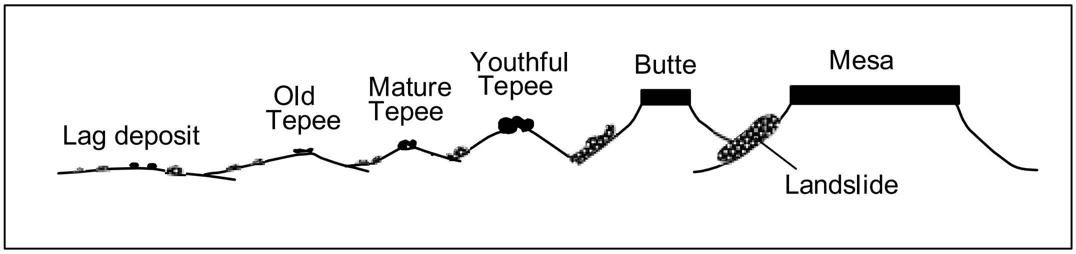

Figure 34. Stages in the development of lag boulders derived from the Lakota Formation in the northern Black Hills. Isolation from the tableland capped by the Lakota results in formation of a mesa and then a butte. Disruption of the Lakota forms isolated sandstone blocks protecting the underlying shale 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.