Field Trip Guide 1 Karst Features of the Southern Black Hills, South Dakota, Karst Interest Group Workshop, September 12, 2005

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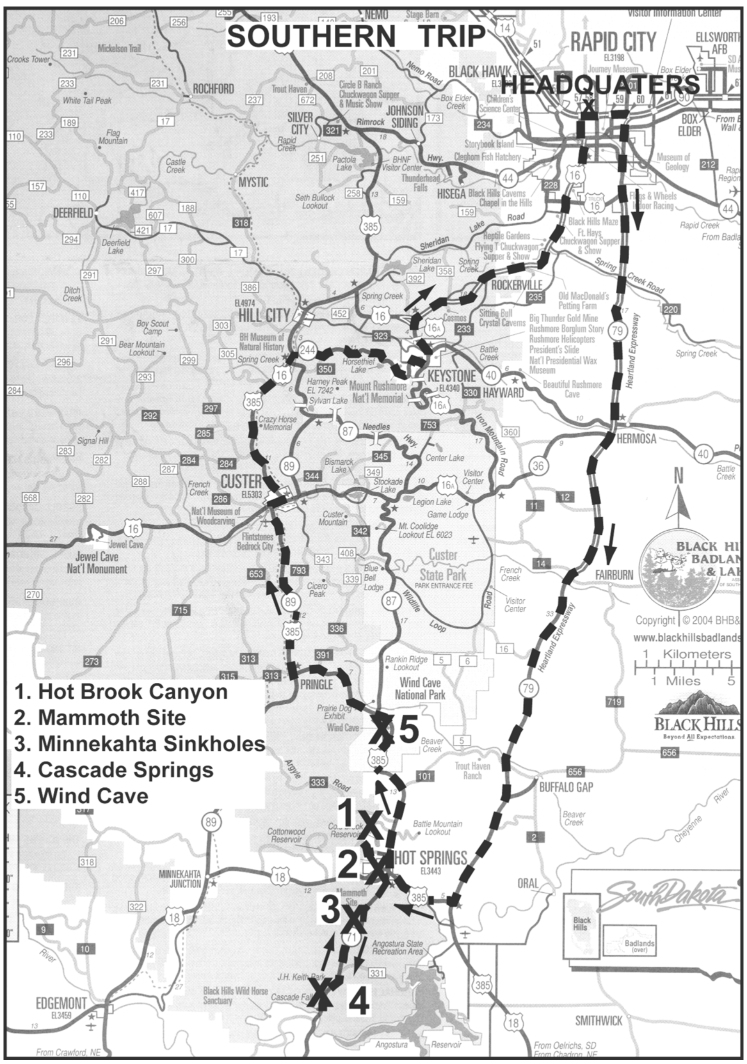

Figure 1. Route map to karst stops in the southern Black Hills.

The field trip originates from the headquarters at the Holiday Inn-Rushmore Plaza, 505 North Fifth Street, Rapid City, South Dakota. The first number is total miles from start and the second number is the miles from the last stop.

0.0 **0.0** Leave Holiday Inn parking lot. Turn right on 6th Street.

0.2 **0.2** Cross Omaha Street.

0.4 **0.2** Cross Main Street.

0.5 **0.1** Turn left on St. Joseph Street.

1.3 **0.8** South Dakota School of Mines and Technology on right. Museum of Geology contains excellent mineral and paleontologic exhibits (free admission).

1.5 **0.2** Geology building to right.

1.7 **0.2** O'Harra stadium on right. Hills underlain by black shales of the Belle Fourche Shale of Late Cretaceous age.

2.6 **0.9** Bear right and merge onto Route 79 South.

3.7 **1.1** East Minnesota Street. Hills in distance to right underlain by rocks in the "Dakota hog-back", defining the physiographic boundary of the Black Hills. The Dakota Sandstone was a earlier name for rocks now termed the Inyan Kara Group. The structural boundary of the Black Hills, however, extends farther out into the surrounding Upper Cretaceous sediments in the Great Plains.

5.8 **2.1** Climbing to top of terrace, underlain by Quaternary gravels disconformably overlying the Belle Fourche Shale.

10.3 **4.5** Cross Spring Creek. Streamflow in Spring Creek near Highway 79 at USGS gaging station 06408500 for 56 years of record (US. Geological Survey, 1949-75; U.S. Geological Survey, 1976-2004) was less than 1 cubic feet per second about 54 percent of the time. Most of the base flow in Spring Creek, which originates in the higher elevations of the Black Hills, is lost to swallow holes as the stream crosses outcrops of the Pahasapa Limestone and Minnelusa Formation that are located about 6 miles upstream.

11.3 **1.0** Road ascends Belle Fourche Shale unconformably overlain by tuffaceous deposits of the White River Group of Oligocene-Miocene age. Martin and others (1996) describe these rocks along this route.

13.2 **1.9** Harney Peak comprising Precambrian granite in distance to right, highest point in the Black Hills (7,242 feet).

14.5 **1.3** Pine-covered hills to right held up by sandstones of the Inyan Kara Group (Early Cretaceous) dipping moderately to the east on the east limb of the Black Hills uplift.

16.8 **2.3** Custer County.

18.2 **1.4** US 40 to Keystone on right, continue on 79 south.

18.9 **0.7** US 36 towards Custer State Park on right, continue straight on 79.

26.9 **8.0** Road to Fairburn on left.

29.7 **2.8** Road to Fairburn on left.

30.2 **0.5** Cross French Creek. Gold was first discovered along this creek near Custer, SD, which heralded the gold rush to the Black Hills.

34.9 **4.7** Greenhorn Limestone (Late Cretaceous) holds up hill on left. It is an argillaceous limestone with no known karstic features. Moderately dipping beds of the Fall River Formation of the Inyan Kara Group at 1 o'clock.

39.0 **4.1** Inyan Kara hogback to right dipping eastward towards us; smaller hill of Greenhorn Limestone on left dipping less steeply in the Greenhorn "piggyback".

40.0 **1.0** The valley narrows here between the Inyan Kara and Greenhorn because the dips of the beds have steepened. See Martin and others (1996) for a description of the Greenhorn here. Abundant oysters are found in the limestone, possibly edible with the proper cocktail sauce.

42.4 **2.4** Beaver Creek.

42.9 **0.5** Road to Buffalo Gap on left. The small canyon to the left is Calico Canyon in which decorative variegated sandstone has been quarried from the Unkpapa Sandstone of Jurassic age.

44.2 **1.3** Road to Buffalo Gap on left.

45.0 **0.8** Fall River County line.

46.2 **1.2** Elm Creek.

47.4 **1.2** Pine trees favor the siliceous Mowry Shale of Late Cretaceous age in this area.

48.8 **1.4** Greenhorn piggyback on left.

51.0 **2.2** Junction with US 18/US 385; turn right towards Hot Springs.

51.6 **0.6** Fall River Falls historic marker on left. Springflow accounted for about 97 percent of the streamflow in Fall River during 1987 to 1996 (Carter and others, 2001).

FALL RIVER FALLS HISTORIC MARKER

"The eight mile long Fall River, winding through Fall River Canyon after the joining of Cold and Hot Brook streams above the city of Hot Springs, tumbles below over an outcropping of sandstone falling about 50 feet to form Fall River Falls, as viewed from the gazebo.

In 1907 the city of Hot Springs built a low dam above the falls directing the 89°F water through a flume of native wood staves banded with iron rods and wire wrapped. Older residents remember as children walking the 4,700 foot flume to a point below the falls. Upon leaving the flume the water dropped 115 feet to a small hydroelectric plant which supplied part of Hot Springs' electric power until the late 1960's. The white power house and part of the staircase are still visible in the canyon.

There exists, however, a dark undercurrent to the picturesque scene lying below. Multiple drownings have occured in the waters beneath the falls, and in August of 1995 a tragic triple drowning took place over a two day period. Later, a temporary diversion of the falls revealed a small cave beneath which creates a whirlpool effect in the water that can trap even strong swimmers."

51.7 **0.1** Passing through the Dakota hogback. Contact between the Fall River Sandstone and Skull Creek Shale on right, dipping 8^o to east.

51.8 **0.1** Cross Fall River, type locality of Fall River Sandstone seen on right.

52.6 **0.8** Fall River sandstones to right.

53.9 **1.3** Lakota Formation

54.7 **0.8** Entering Hot Spring. Historic marker on right.

HOT SPRINGS, SOUTH DAKOTA HISTORIC MARKER

"Tribal tradition states that as long ago as the 16th century the Fall River Valley and canyon area were seldom without groups of tipis belonging to the North American Plains Tribes. They knew the curative value of the warm springs located there and used them for bathing their sick and lame.

Exploration of the area by white men in 1874-75 led to settlement and discovery of 75 geothermal springs. The crystal clear water issues from clefts in rocks or bubbles out of the ground. Bathhouses, swimming plunges, hotels, hospitals and sanitariums were built turning the City of Hot Springs into an early national health resort. Some of these structures still exist, including a sanitarium now used as the VA Center, and the South Dakota Soldiers Home.

Cowboys and others crippled by rheumatism and other afflictions would arrive in wagons or trains and leave on horseback after three weeks in the springs.

From this point the rushing Fall River can be seen and heard."

55.1 **0.4** Truck Route US 18 to left, continue straight.

55.8 **0.7** Traffic light, continue straight.

56.0 **0.2** Bear left on US 385.

56.1 **0.1** Bear right on US 385.

56.3 **0.2** Coarse terrace gravels to left are about 50 feet thick,consisting of massive and crossbedded gravels with angular to well rounded clasts of limestone, sandstone and some chert as much as one foot long from the Minnekahta Limestone and Minnelusa Formation in a tan to reddish calcareous sand matrix. The gravels dip 13^o to the south. So far, no one has given an explanation for the dip. The brownstone buildings in this area date back to the late 19th century when that area developed into a major health spa because of the many hot springs. The sandstones were derived from the surrounding Fall River Sandstone.

The gazebo across the creek to left was built in 1920, protecting Kidney Springs, one of 179 springs within the Hot Springs Valley. A metal plaque proclaims "Useful in the treatment of chronic diseases of the gastro-intestinal tract, diseases of the liver and biliary passages disorders of the genito-urinary tract and sluggish conditions of the alimentry tract." The following chemical analysis (in part per million) is also given: Sodium Chloride, 242.60; Potassium Chloride, 68.44; Magnesium Chloride, 118.00; Lithium Sulphate, 15.21; Calcium Sulphate, 703.99; Calcium Phosphate, 2.76; Silica, 23.64;Total solids, 1174.64.

56.5 **0.2** Nice exposure of coarse terrace gravels along sidewalk to right.

56.7 **0.2** Stop sign. Continue straight across US 385. White gypsum in Spearfish redbeds to right.

56.8 **0.1** Evans Plunge on right built in 1890. The building houses a recreation pool deriving water from several springs in the creek bed with a total flow of 5,000 gallons per minute. The history of Evans Plunge and an analysis of the water is shown on the sign to left:

> "Long before the white man discovered the valley of healing waters, the Sioux and Cheyenne Indian tribes fought for possession of the natural warm water springs. Legend tells us that the battle raged on the high peak above the springs and the Sioux emerged victorious.
>
> The Mammoth spring at the north end in the interior of the plunge is known as the "Original Indian Spring". Here the Indians drank and bathed in its warm healing water.
>
> The Evans Plunge was built in 1890 over numerous small sparkling springs and one mammoth spring of mineral water with a temperature of 87 degrees and of medicinal qualities proclaimed, on good authority, to be superior to that of the famous Warm Springs, Georgia.
>
> From the inflow of 5,000 gallons of water per minute from the springs arising out of the pebble bottom, there is a complete change of water 16 times daily, thus insuring clean, fresh, living water at all times.
>
> The pool, 50 x 200 feet, ranges in depth from 4 feet to 6 feet with two shallow enclosures for children."

CHEMICAL ANALYSIS

Water temperature....	87 degrees
Total residue	87.9995
Inorganic & non-volatile	4.9160
Organic & volatile......	8.050
Sulphate of sodium ...	8.824
Sulphate of potassium	3.331
Sulphate of calcium...	16.290
Nitrate of magnesium	0.150
Iron susqui-oxide.......	0.260
Alumia	0.021
Silica	1.830

56.9 **0.1** "Y" in road. Continue straight on Fall River Co 18B. Terrace gravels cap Spearfish Formation to left.

57.0 **0.1** Minnekahta Limestone on left.

57.1 **0.1** Small cave high up in Minnekahta on left. The Minnekahta here is about 50 feet thick.

57.3 **0.2** Minnekahta Limestone rises above purplish shales at the top of the underlying Opeche Shale. One belief is that the purple shales were produced during weathering and is an ancient soil, but another explanation is that it is due to bleaching from water percolating downward from the overlying Minnekahta (see Stop 10 of Northern Trip).

57.5 **0.2** Note undulations in the Minnekahta on left, due to differential collapse in the underlying Minnelusa.

57.7 **0.2** Brecciated uppermost Minnelusa (see figure 2A).

58.0 **0.3** Brecciated Minnelusa with distorted bedding overlain by Opeche Shale and Minnekahta Limestone straight ahead (see figure 2B).

58.9 **0.9** **Buses pull off to the side of the road at curve.**

STOP 1: HOT BROOK CANYON: MINNELUSA EVAPORITE KARST
Leaders: Mark Fahrenbach and Jack Epstein

The Minnelusa Formation comprises interbedded sandstone, limestone, dolomite, shale, and anhydrite, and ranges from more than 1,000 feet thick in the southern Black Hills to about 400 feet thick in the northern Hills (Jarrell, 2000). As much as 235 feet of anhydrite has been observed from well logs describing the subsurface near Jewel Cave, occurring mainly in the middle of the formation (Braddock, 1963; Brobst and Epstein, 1963). In Hot Brook Canyon about 300 feet of the Minnelusa is exposed, the lower part of the formation and the contact with the Pahasapa Limestone are covered. The red shale, siltstone, and sandstone of the overlying Opeche Formation, and the succeeding Minnekahta Limestone, are visible at the very top of the cliff. Minnelusa and Opeche are the Lakota names for Rapid Creek and Battle Creek respectively, and Minnekahta is the Lakota word for hot springs.

The Minnelusa Formation is an important stratigraphic unit in a geologic mapping project of five quadrangles located between Jewel and Wind Caves in the southern Black Hills (Wind Cave, Pringle, Argyle, Fourmile, and Jewel Cave quadrangles). The Minnelusa can be subdivided into six stratigraphic units. The initial mapping, which began as a cooperative venture between the National Park Service, the U.S Geological Survey and the South Dakota Geological Survey, covered units 1-4 of the Minnelusa Formation to see if there was any correlation with the Minnelusa units and cave development in the underlying Pahasapa Limestone. This is one of several methods to determine the location of undiscovered cave passages in the Jewel Cave-Wind Cave area that will be discussed at this KIG Conference. Fracture orientations were also measured to see if these trends were visible or controlled passage orientation in Jewel Cave. Subsequently, it was decided to map units 5 and 6 of the Minnelusa Formation, with the long term goal of mapping the entire quadrangles.

No evaporites are present at the outcrop of Stop 1. They have been removed by solution at depth, resulting in foundering of the overlying beds. Characteristic evaporate dissolution features that are produced are collapse breccias, breccia pipes, distorted bedding, and cavities (fig. 2C). Elsewhere, such as in Redbird Canyon, 12 miles southeast of Newcastle, WY, collapse sinkholes are present in the cliff faces (Epstein, Field Trip Guide 3, Western Black Hills, this volume, fig. 8).

In Hot Brook Canyon, the position of the anhydrite that has been removed and is clearly deciphered on the canyon wall by the disrupted bedding, with approximately 200 feet of the upper Minnelusa being brecciated. Below the steep covered slope in the middle of the exposure at this locality, the beds are undisturbed (fig. 2B). The anhydrite, therefore, was positioned at the level of the covered slope above the undisturbed beds.

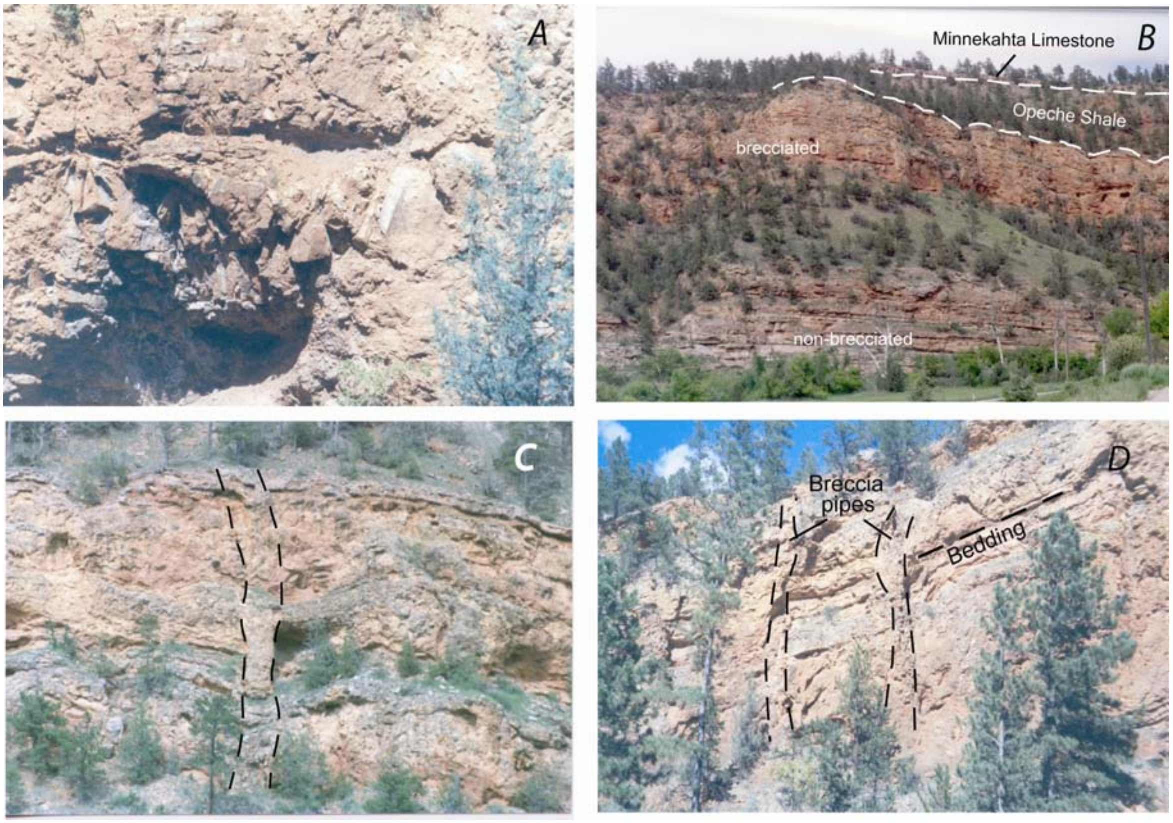

Figure 2. Evaporite karst features in the Minnelusa Formation, Hot Brook Canyon, Hot Springs, Fall River Co., SD.

A, Angular clasts of all sizes form a characteristic breccia in the upper part of the formation.

B, The position of many tens of feet of anhydrite that were removed from the Minnelusa is indicated by brecciated rocks above and non-brecciated rocks below the covered slope. The uppermost Minnelusa beds are wavy due to subsidence, as are the beds in the Minnekahta Limestone above.

C, Breccia pipe extending to the top of the Minnelusa.

D, Near-vertical breccia pipes (short dash) in moderately dipping (15^{o}) beds (long dash) of the Minnelusa Fomation, at mileage 59.3, suggesting that the beds were tilted prior to pipe formation.

Brecciation, caused by removal of anhydrite at depth, was undoubtedly initiated after the Black Hills were uplifted and the Minnelusa breached after the Late Cretaceous. Dissolution probably occurred within a zone about 1,000 feet below the ground surface based on breccia pipes extending as high as the Lakota Formation and the total thickness of these overlying formations.

A short distance west of Stop 1, to be seen as the buses continue up the canyon to turn around, there are near-vertical breccia pipes cutting beds that dip 15^{o} westward (fig. 2D). If the brecciation occurred prior to tilting, the pipes, which would have formed vertically, would have been rotated by the tilting. Clearly, because the pipes are vertical, they formed after the beds were tilted. Similar relationships can be seen elsewhere in the Black Hills (Epstein, 2005b, figure 8).

Close-up examination of the Minnelusa shows extensive fracturing and brecciation producing angular blocks of many sizes (fig. 2A). Effects of brecciation appear to decrease upwards in the formation, and the effects of collapse in the overlying formations are not dramatically apparent. The resistant, thin, Minnekahta Limestone, overlying the red beds of the Opeche Shale above the Minnelusa, contains only scattered collapse features such as sinkholes (Stop 3) and brecia pipes that may be ascribed to foundering in the underlying Minnelusa (Stop 4). The most significant effect on the Minnekahta is the undulation of beds visible in outcrop throughout the Black Hills. The limestone may have a local relief of several tens of feet, and basins and saddles are common. The soft sediments of the Opeche may have acted as a buffer between the Minnekahta and Minnelusa, absorbing some of the differential settlement. Bedding in the Opeche is not generally visible because of poor exposure.

Resume driving west on Hot Brook Canyon Road.

59.3 **0.4** Vertical breccia pipe in brecciated Minnelusa beds that dip 15^{o} to the west indicate that brecciation occurred after the deformation that formed the Black Hills uplift (fig. 2D; Epstein, *this volume*, figure 8).

Turn around and retrace route back to Hot Springs.

60.7 **1.4** Closer view of Minnelusa breccia to left.

62.1 **1.4** Stop sign. Continue straight along US 385 South into Hot Springs.

62.7 **0.6** Bear left on US 385 South towards Mammoth Site.

62.8 **0.1** Bear right on US 385 South.

62.9 **0.1** Stop light, continue straight.

63.7 **0.8** Turn right (west) on Truck US 16 towards route 71.

64.5 **0.8** Intersection with Route 71 on left, continue straight ahead. Mammoth Site, historic sign:

MAMMOTH SITE OF HOT SPRINGS, SOUTH DAKOTA HISTORIC MARKER

"Gigantic Mammoths, ancestors of the elephants of today once roamed freely across the High Plains of North America. A repository of their remains, along with other prehistoric animals, lay undisturbed until their discovery over 26,000 years later, in June of 1974.

Limestone deposits beneath the Earth's surface dissolved in water from underground springs. The land then collapsed and the resulting sinkhole filled with 95 degree water that lured mammoths to drink or feed on vegetation. Once in the water they could not go up the slippery, steep incline. Death by starvation or drowning was the fate of most animals that came to the sinkhole. Along with the mammoth, remains of the giant short faced bear, white-tailed prairie dog, fish and other associated fauna have also been found at this site.

As centuries passed the sinkhole gradually filled. Rain, snow and wind deposited soil leaving a hil1 of buried skeletons. This hill remained undisturbed until1974 when excavation for a housing project by Phil and Elenora Anderson revealed bones and tusks of these huge animals.

In 1975, Mammoth Site of Hot Springs, South Dakota, Inc. was formed as a non-profit corporation dedicated to the preservation of the fossils, protecting and developing the site as an insitu (bones left as found) exhibit.

The Mammoth site is quite different from most museums. It is not merely a display of collected items; most of the excavated bones remain exactly were they were found. Visitors also witness the complete process of paleontology from start to finish. Along with the scientists, they will see for the first time bones of animals that lived before any person walked the land.

In 1980 the Mammoth Site was designated as a Registered National Landmark by the Department of the Interior. The Mammoth Site of Hot Springs is truly a gift from Nature—our inheritance held in trust for over 26000 years. We would diminish ourselves if we failed to perceive the historical and scientific value of this discovery."

Turn into parking area and park.

STOP 2: THE MAMMOTH SITE: A PLEISTOCENE FAUNA SINKHOLE TRAP
Leaders: Kris Thompson and Larry Agenbroad

The Mammoth Site is located within the southern city limits of Hot Springs, South Dakota. The site represents a hydrologic-geologic natural trap of late Pleistocene fauna. Located within the Spearfish Formation, which is exposed at the margins of the interior Black Hills, the surface expression is that of a low hill. This topographic feature is the result of inverse topography, in that the former topographic sink became a topographic high due to differential erosion. The sedimentary fill of the sinkhole containing Pleistocene fossils was more resistant than the surrounding Spearfish Formation.

The sinkhole formation is interpreted as a consequence of extensive dissolution and removal of up to 76 m of anhydrite in the Minnelusa Formation by ground water. The Minnelusa Formation is stratigraphically located approximately 60 m below the Spearfish Formation. Post-solution collapse within the Minnelusa initiated subsidence and the upward development of vertical breccia pipes, as much as 76 meters in diameter. Down hole collapse within these breccia pipes has produced numerous steep-walled sinkholes in the Black Hills since early Tertiary. The Mammoth Site at Hot Springs resides in one of these sinks.

In addition to the physical formation of the breccia pipe and resulting sinkhole, a critical factor in producing an animal trap in what would otherwise be just another sinkhole was the presence of an artesian spring. Groundwater in the Minnelusa flowed up the conduit formed by the breccia pipe, producing the spring and contributed to the standing body of water. The water was warm, estimated at 35^{o}C (95^{o}F) based on biological and sedimentary evidence.

The sinkhole deposit is located on the fourth terrace above the modern bed of Fall River (fig. 3). The Mammoth Site sinkhole is roughly an elliptical feature measuring 150 by 120 feet (~46 m by ~37 m). The Spearfish Formation walls are very steep, measuring greater than 60^{o} slopes. A large spring conduit was identified in the northeast section of the deposit, with minor conduits in the south-southwest and north-northwest areas of the sinkhole.

In 1978, the South Dakota Geological Survey drilled three test holes in the sinkhole fill (fig. 4). The deepest hole (test hole no. 3) was stopped at 65 feet (~20 m) below the drill surface. At that depth, bones and fill sediment were still being retrieved. We do not currently know the total depth of the fossiliferous fill deposits. Three recognized episodes of fill are classified in the deposit; phases I, II, and III. Phase I is the initial collapse including marginal gravels derived from river terraces incorporated as the walls fell in. Phase II sediments reflect a pond environment with fine-grained, laminated depositional units. Phase III reflects a declining water table-probably due to lateral migration to the entrenched Fall River. The sinkhole sedimentation was reduced, and the depression became essentially a bioturbated mud hole (fig. 5).

Late Pleistocene fauna are included in all phases of sedimentation (fig. 6). The trap was a burial place for late Pleistocene mammoths, plus 47 associated fauna (7 extinct, 40 extant). Worldwide there is no comparable deposit known as a repository for mammoths. To date, we have identified 50 Columbian mammoths (*Mammuthus columbi*) and 3 woolly mammoths (*Mammuthus primigenius*) in the excavations that represent approximately 40% of the known sinkhole fill area (fig. 7).

There is a paucity of reported Pleistocene sites in the Black Hills. As a result, paleoenvironmental interpretations for the Black Hills are limited. In summary, the Black Hills are an important but inadequately understood region, and thus an ideal place to study the invertebrate and vertebrate faunas of the present as well as the recent glacial past. The approximately 26,000 yr B.P. faunal remains recovered from the Mammoth Site provide a rare glimpse into the middle Wisconsinan environmental conditions in the northern Great Plains/Black Hills southwest of the Laurentide ice sheet.

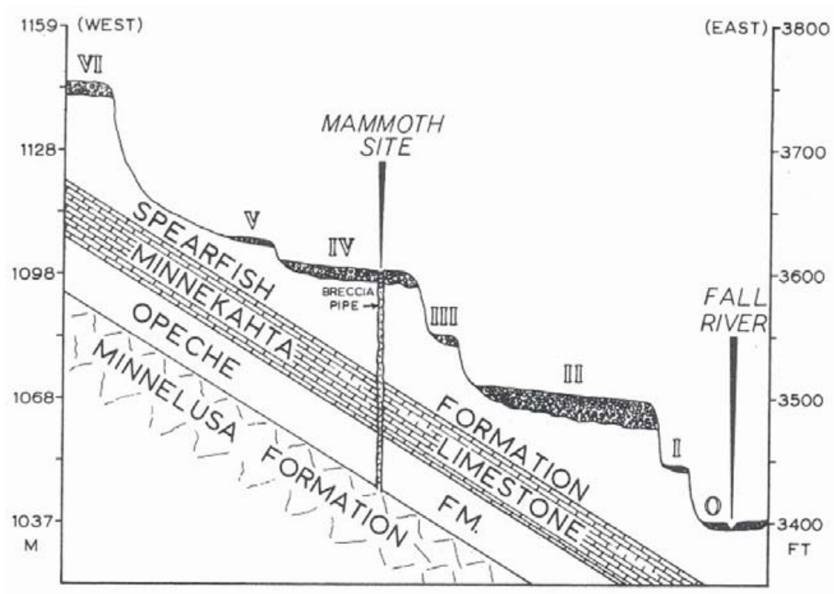

Figure 3. Simplified geologic and physiographic setting of the Mammoth Site sinkhole. Terrace 0 is the present floodplain of Fall River. The city of Hot Springs is built on all six terraces. Horizontal distance not drawn to scale. From Laury (1980).

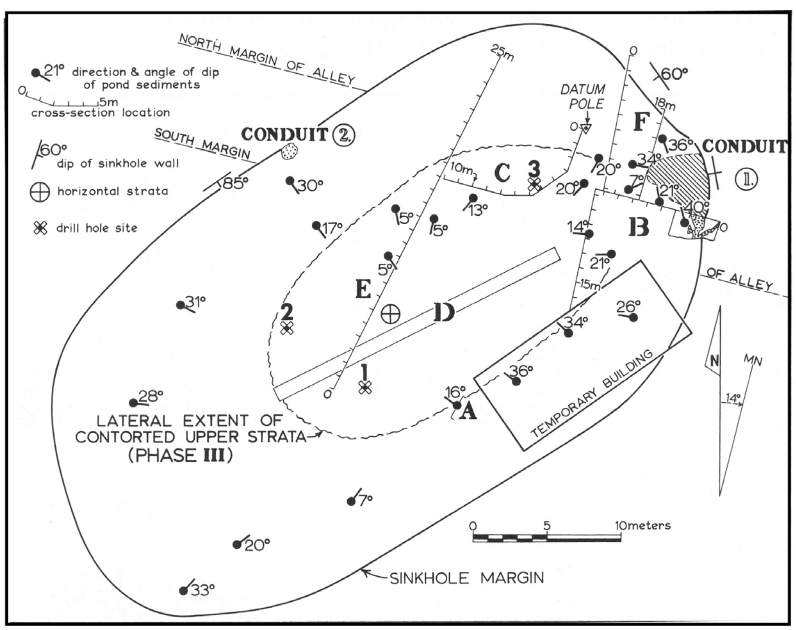

Figure 4. Map of the Mammoth Site sinkhole located in the Spearfish Formation, showing dip of pond sediments, slope of sinkhole wall, and drill-hole sites. (From Laury, 1980).

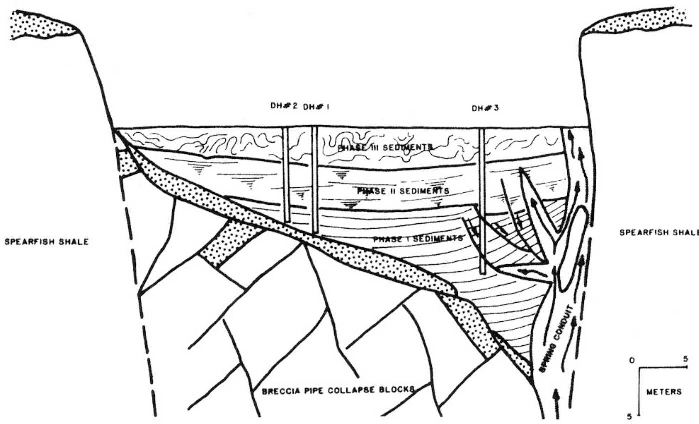

Figure 5. Schematic showing the physical character of the Mammoth Site sinkhole hydraulics, sedimentary fills, and host breccia pipe. From Agenbroad (1994).

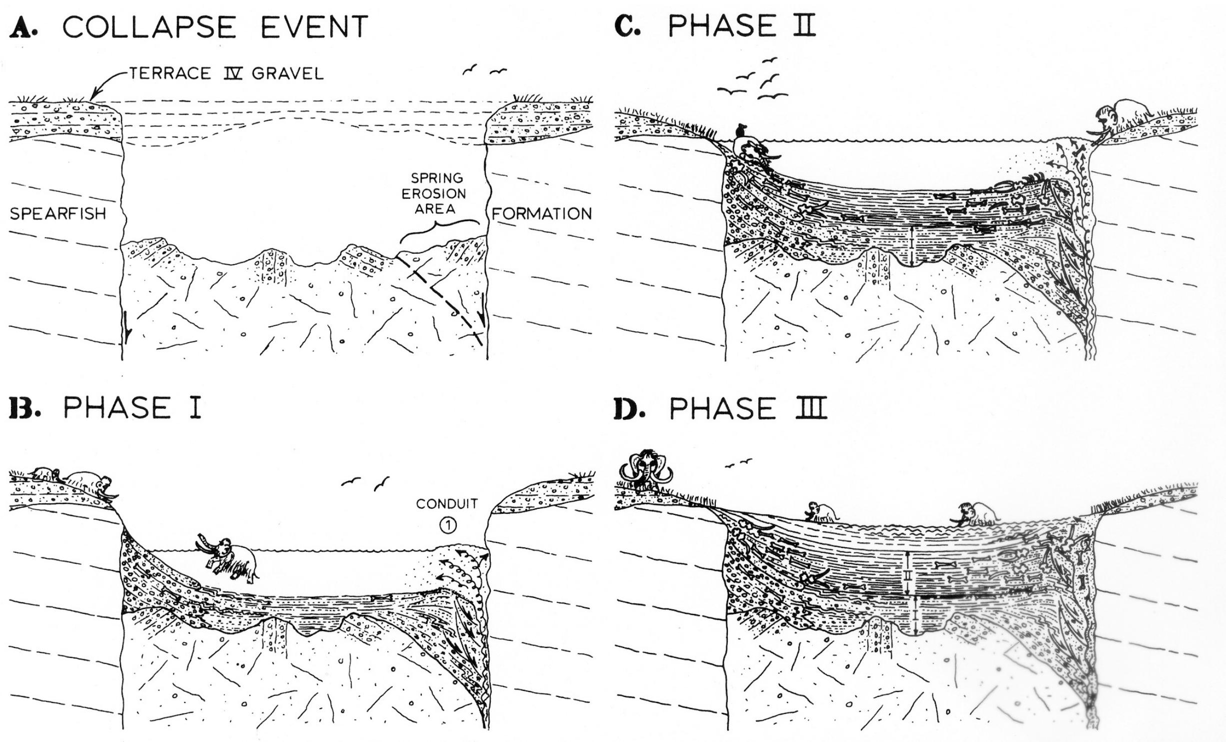

Figure 6. Sequence of events in history of the Mammoth Site sinkhole. Cross sections are simplified northward views. A, Sinkhole as it may have appeared immediately after breccia-pipe collapse. B, End of Phase I sedimentation, a period of rapid wall erosion and pond sedimentation. C, Near end of Phase II sedimentation, a longer period of sedimentation than Phase I in which more mammoths were trapped. D, Late Phase III sedimentation. The water table had dropped during renewed Fall River entrenchment, spring discharge virtually ceased, and the pond was reduced to a mud puddle. (From Laury, 1994).

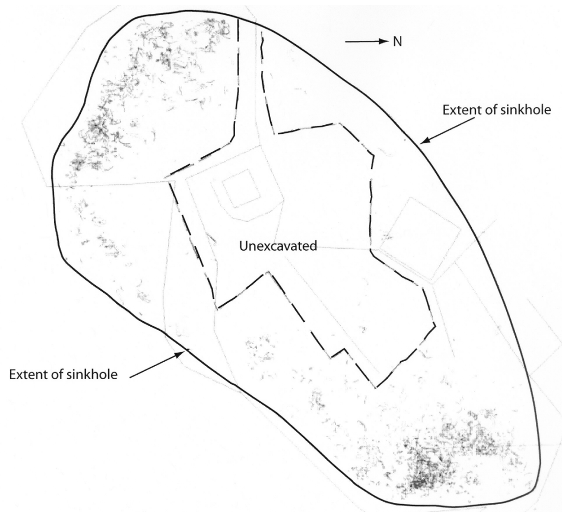

Figure 7. Distribution of bone in the Mammoth Site sinkhole.

65.0 0.5 Resume driving. Leave Parking lot, turn left on truck Route US 16.

65.4 0.4 Route 71 towards Cascade Springs, turn right. Red beds of the Spearfish Formation overlain by Sundance Formation, including pinkish beds, on the higher slope, capped by sandstones of the Inyan Kara Group on left.

67.8 2.4 Pull off to side of road.

STOP 3: MINNEKAHTA SINKHOLES; WHAT IS KARST?
Leaders: Jack Epstein and Rod Horrocks

The Minnekahta Limestone is 40 feet thick in this area, comprising laminated gray limestone with a purplish tinge (light gray, N7 to light reddish gray, 10R 7/1). Three sinkholes are present at this locality, the most prominent one is 60 feet in diameter (fig 8, 9). The depth of the hole is 40 feet and it probably encompasses the entire thickness of the Minnekahta. Two other sinkholes within 100 feet to the west are about 20 feet in diameter with about 4 feet of Minnekahta exposed, and another is 50 feet in diameter with no limestone exposed. It is doubtful that the sinkhole is due to solution within the limestone because the hole extends below the Minnekahta. The shape of the hole is partly controlled by intersecting joint trends, mainly N. 78^{o} E., N. 10^{o} E., and N. 62^{o} E. A sinkhole about 400 feet to the south across the road is about 300 feet in diameter and about 35 feet deep. The sinkhole was probably formed by cover collapse due to anhydrite removal in the Minnelusa Formation, more than 200 feet below. Sinkholes in the Minnekahta are not common in the Black Hills, except locally (Epstein, Davis, and others, 2005, *this volume*, fig. 22). Other sinkholes in this formation have been reported by Darton (1909), see fig. 10) and Gries (1963). The sparce soil cover associated with these sinkholes is quite different from that in much of the humid eastern United States (fig. 11) where sinkhole formation is generally the result of piping and subsidence of soil or uncon solidation overburden (the "plug" that fills or covers the void.

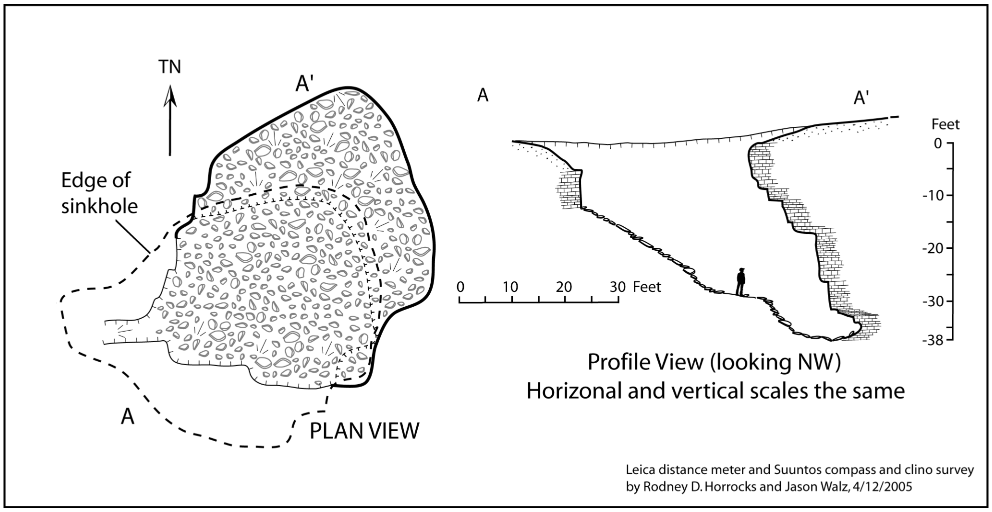

Figure 8. Map and profile of sinkholes in the Minnekahta Limestone at Stop 3. The base of the Minnekahta is probably immediately below the bottom of the pit.

Figure 9. Steep sided sinkhole in Minnekahta Limestone. The hole is 40 feet deep and encompasses the entire thickness of the formation.

Figure 10. Sinkhole near Four Corners, Wyoming, northwestern Black Hills (Darton, 1909), similar to the one at Stop 3. The hole extends down through the entire Minnekahta.

Figure 11. Typical sinkhole in the humid eastern United States. This one developed by collapse of the residual soil cover in the Beekmantown Formation of Ordovician age in eastern Pennsylvania near a quarry whose pumping has significantly lowered the water table.

Karst is defined as “A type of topography that is formed over limestone, dolomite, or gypsum by dissolving or solution, and that is characterized by closed depressions or sinkholes, caves, and underground drainage” (Gary and others, 1972). At this stop, and especially at Stop 4, we will discuss whether the sinkhole in the Minnekahta as well as other collapse features are truly “karst”, according to the above definition.

Resume driving. Continue south on Route 71.

67.9 **0.1** Large sinkhole to left.

69.2 **1.3** Skeletal remains of cow on slope to right (2004).

72.8 **3.6** Disembark from bus; buses proceed and park at Cascade Springs at 73.1.

STOP 4: CASCADE SPRINGS: HYDROLOGY, GYPSUM SHENANIGANS, PULL APARTS, BIOLOGY. LUNCH
LEADERS: Andy Long, Jack Epstein, and Larry Putnam

73.1 **0.3** Buses park at Cascade Springs.

This stop is located along the west limb of the Cascade anticline at the south end of the Black Hills uplift (fig. 12). First we will examine structures in gypsum in the Spearfish formation along SD Highway 71 (fig. 13*A*), followed by a 100-foot vertical hike to see large fractures in the Minnekahta Limestone (fig.13*B*), and contemplating whether this is related to karst. Then we will discuss the hydrology, origin, and biology of Cascade Springs (fig. 13*C*).

A. Gypsum Shenanigans

In the cascade springs area the Spearfish Formation is 330 feet thick, comprising interbedded red beds and gypsum, the gypsum totaling about 70 feet (Post, 1967). The beds dip moderately to the west on the west limb of the Cascade anticline, ranging between 15 and 50 degrees (fig. 14), the steepest dips are 2,000 feet to the northwest along the highway.

The bottom of the roadside exposure at locality ***A*** is about 75 feet stratigraphically above the base of the Spearfish Formation; the top of the Minnekahta Limestone lies in a ravine just north of the road. About 50 feet of interbedded gypsum and red siltstone and shale are exposed. About 30 feet above the road there is a 2-foot bed of non-calcareous greenish-gray-weathering (5GY6/1) siltstone to fine-grained sandstone. The gypsum is contorted and many veinlets, generally less than one inch thick, extend from the parent beds (fig. 15*A*). The shale at the base of the exposure is highly fractured and bedding is not readily discernable. These features combine to create a secondary porosity in the Spearfish at this locality.

Post (1967) and Hayes (1999) noted two breccia pipes in this exposure; the easternmost one is shown in figure 15*A*. Hayes believed that breccia pipes extending up from the Minnelusa Formation are the conduits for the artesian springs at Cascade Springs. The gypsum bed in figure 15*A* is thickened and downwarped and is immediately underlain by about five feet of breccia containing blocks more than 1 foot long, some of which appear to have risen from below (fig. 15*B*) . To the side of this structure the red siltstone is highly fractured and contains a continuous 4-inch-thick bed of light-olive gray (5Y6/1) siltstone that is incorporated as clasts in the red shale of the breccia and is at a higher position than to the side. The beds immediately above the structure are flat, lying athwart the structure, and do not appear to have subsided. Beds below consist of minutely fractured and brecciated siltstone which is traversed by gypsum veinlets.

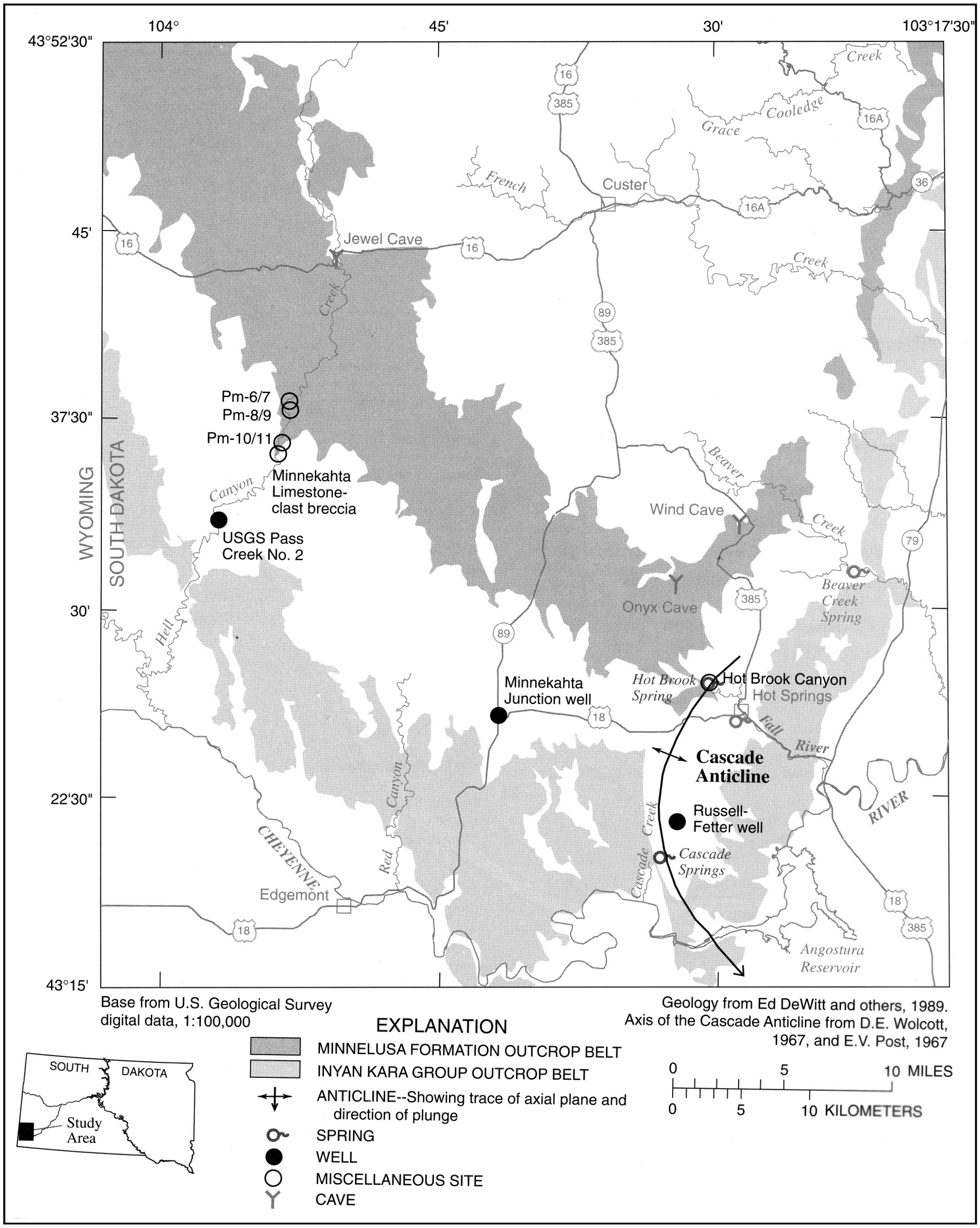

Figure 12. Location map showing Cascade Springs, other nearby springs, and miscellaneous rock and ground-water sampling sites (from Hayes (1999).

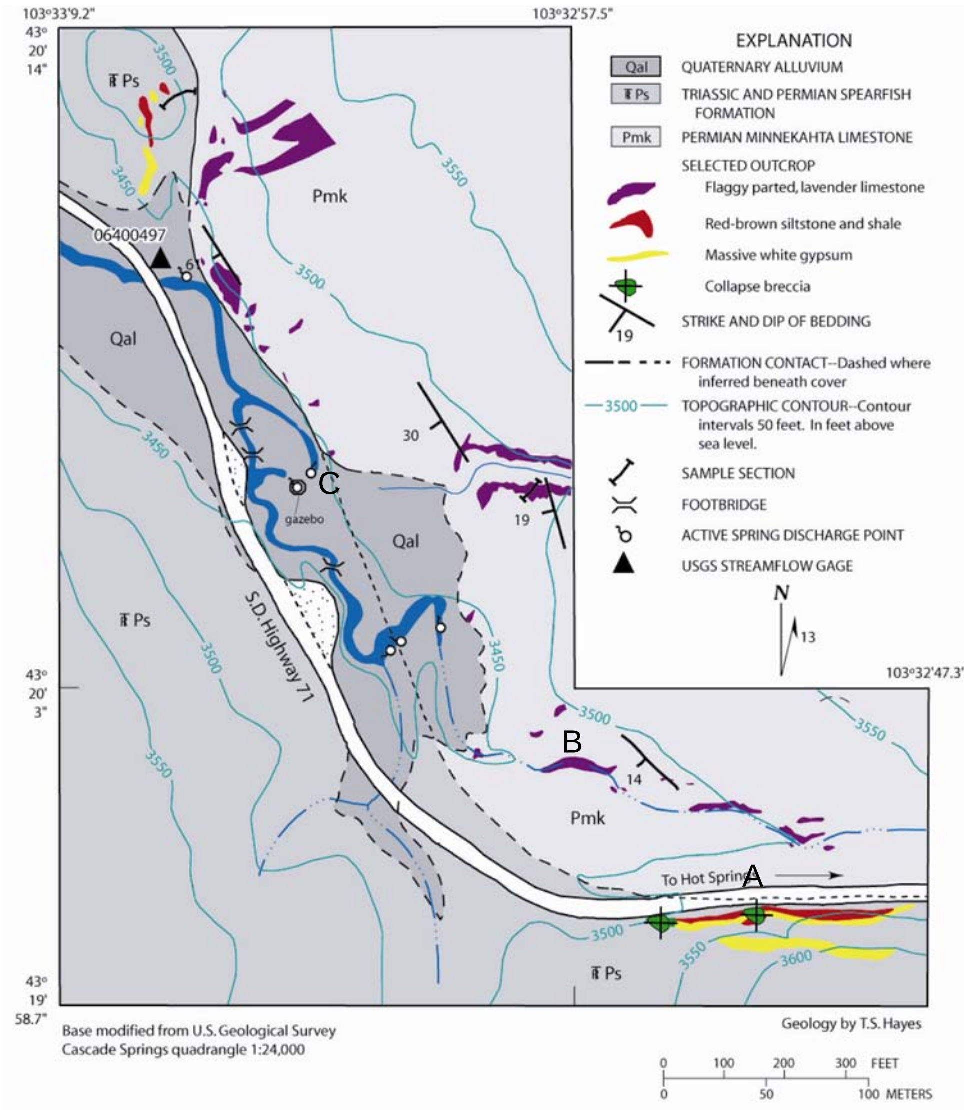

Figure 13. Stop locations at Cascade Springs showing general geology, location of springs and breccia pipes (from Hayes, 1999).

It is interesting to compare this "pipe" with those seen in the Minnelusa at Hot Brook Canyon, Stop 1. The exposure that Post (1967) saw (fig. 15*C*) was different from the one seen now because of subsequent road widening, suggesting that we now see only the edge of the pipe. Post describes the feature thus: "High radioactivity, as much as 35 times background, was noted at a bleached and structurally disturbed zone in the Spearfish Formation on the south side of State Highway 87 in the SW1/4 SE1/4 sec. 20, T. 8 S., R. 5 E. (See fig. 87--*Post's figure*). This disturbed zone is approximately 15 feet wide and extends vertically up the face of the roadcut. Bedding in the zone is obliterated. The rock consists of a mass of disoriented fragments of siltstone, gypsum, and black mudstone. The siltstone, which is the major constituent, has been bleached to a moderate greenish gray from its normal, reddish-brown color. The character of this disturbed zone, its proximity to the hot springs at Cascade Springs, and the presence of caverns in the gypsum at the top of the roadcut just to the east of this zone suggest that the structural disturbance and bleaching were caused by a hot spring similar to those presently active at Cascade Springs. The disturbed zone may, in fact, be the upper part of a breccia pipe similar to those described by Bowles and Braddock (1963)."