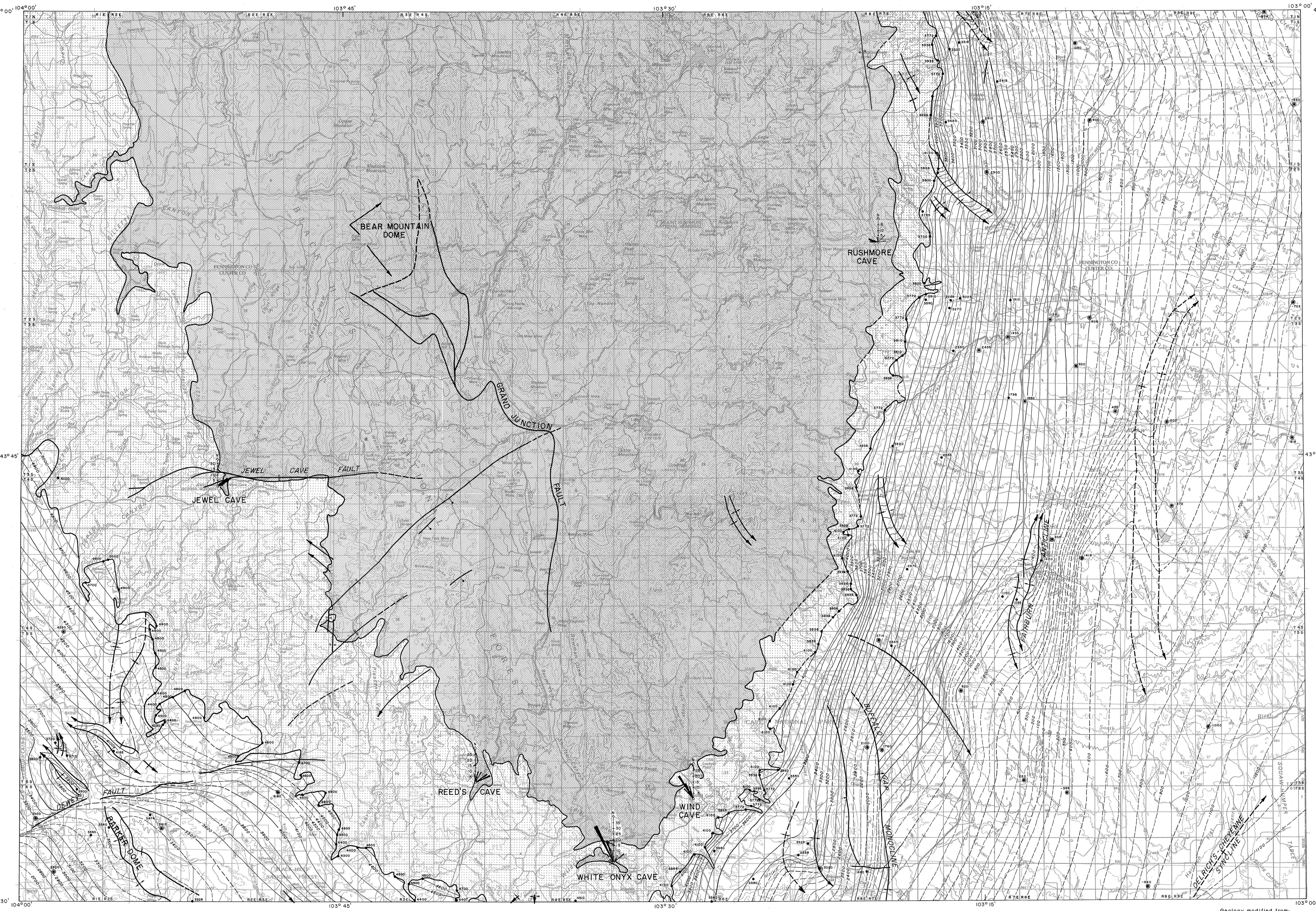
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

Prepared in cooperation with the
SOUTH DAKOTA DEPARTMENT OF WATER AND NATURAL RESOURCES
and the
BLACK HILLS CONSERVANCY SUBDISTRICT

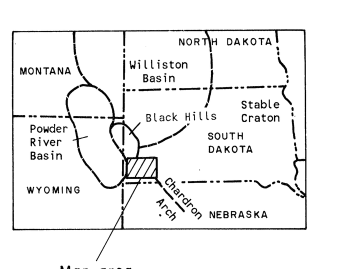
WATER RESOURCES INVESTIGATIONS
REPORT 86-4167



Base from U.S. Geological Survey
Mount Rushmore, South Dakota
quadrangle, 1977

Geology modified from:
Darton and Paige (1925)
Braddock (1963)
Lisenbee (1985)
DeWitt and others (1989)

Scale 1:100,000



Map area

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INTRODUCTION

The U.S. Geological Survey, in cooperation with the South Dakota Department of Water and Natural Resources and the Black Hills Conservancy Subdistrict, began an investigation of the sedimentary aquifers in the Black Hills in 1981 in anticipation of increased use of ground water for municipal and industrial supply. The purpose of the 3-year investigation was to determine the availability and quality of ground water in the sedimentary bedrock aquifers in the Black Hills of South Dakota and Wyoming. The investigation was limited to three bedrock units, which are in order of increasing age: the Cretaceous Inyan Kara Group, Permian and Pennsylvanian Minnelusa Formation, and Mississippian Madison (or Pahasapa) Limestone.

The primary purpose of this report is to show the geologic structure and the altitude of the top of the Minnelusa Formation in the southern Black Hills. It can be used in conjunction with topographic maps to estimate the depth to the Minnelusa Formation at a specific site. The Minnelusa Formation was mapped because it is the deepest aquifer for which there is extensive data. Similar maps for the northern Black Hills and Bear Lodge Mountains and the northeastern Black Hills also have been prepared by Peter and others (1985a, b).

The secondary purpose of this report is to describe the possible effects of geologic structures and hydrologic conditions on cave formation in the Madison Limestone, which underlies the Minnelusa Formation. Two hypotheses of cave formation were tested by investigating five caves. Caves are large-scale examples of secondary permeability in the Madison Limestone. The relationship of secondary permeability to geologic structures has been determined to have significant relation to water development (Lattman and Parizek, 1964, and Siddiqui and Parizek, 1971). It has been suggested that caves in the Bighorn Basin in Wyoming were formed as the result of a steep hydraulic gradient imposed on a uniformly jointed limestone (Huntoon, 1985, p. 443). The orientation and length of the passages in the five caves were measured and qualitatively compared to mapped structural features in the vicinity to identify any relation.

SOURCES OF DATA

The geologic data used to compile this map were obtained from geologic maps and logs of water wells and oil-and-gas exploration wells. This information is on file in offices of the South Dakota Department of Water and Natural Resources in Pierre, South Dakota, and the U.S. Geological Survey in Rapid City, South Dakota. In areas where there were no wells completed in the Minnelusa Formation, the depth to the top of the Minnelusa was estimated from logs of shallow wells and from maps of surface geology. The depth to a shallower geologic unit, usually the Cretaceous Fall River Formation of the Inyan Kara Group, was added to the thickness of the geologic formations between the shallow unit and the top of the Minnelusa Formation to obtain an estimate of the depth to the top of the Minnelusa. Thickness measured in the nearest well was used in the estimates because some geologic formations vary in thickness by more than 100 ft within the map area. Many of the well sites were verified during the study. The altitude of the land surface was obtained from topographic maps with contour intervals of either 10 or 20 ft.

Cave maps were obtained from published and unpublished sources. Maps of Wind and Jewel Caves were obtained from the Wind Cave/Jewel Cave Historical Association. Maps of Rushmore, Reeds, and White Onyx Caves were obtained from the Pahasapa Grotto at the South Dakota School of Mines and Technology, Rapid City, South Dakota. Cave-passage orientations and lengths were measured by drawing centerlines along approximately straight passage segments and then measuring the centerlines.

GEOLOGIC STRUCTURE

The map shows the configuration of the structural features in part of the southern Black Hills. The Black Hills are surface features of the Black Hills uplift, an irregular, dome-shaped anticlinal uplift trending northwest, formed during the Laramide Orogeny. All formations in the area older than Oligocene were folded and faulted. The largest anticlines are Fairburn anticline, in T. 4 S. and T. 5 S., R. 7 E. and R. 8 E., and Barker Dome in T. 6 S., R. 2 E. Buffalo Gap monocline, in T. 5 S. and T. 6 S., and R. 6 E. and R. 7 E. extends as much as 12 mi to the south, outside the study area (Lisenbee, 1985).

Smaller anticlines and synclines parallel the Minnelusa Formation outcrop in the southern Black Hills. Some folds were interpreted from logs of units shallower than the Minnelusa Formation because there are no wells penetrating the Minnelusa Formation in the vicinity of these folds. As a result, the location and configuration of these folds, such as the large parallel anticline and syncline northeast of the Fairburn anticline are only approximated.

There are two large faults in the area. Jewel Cave Fault, in T. 3 S. and T. 4 S.; R. 2 E., and R. 3 E., extends at least 12 mi (Lisenbee, 1985). Dewey Fault, in T. 5 S. and T. 6 S., R. 1 E. and R. 2 E., extends at least 20 mi; the west end is outside the study area (Lisenbee, 1985). Braddock (1963, pl. 20) shows drag along these faults of as much as one-half mile, in a more detailed structure contour map of the base of the Hulett Sandstone Member of the Sundance Formation of Jurassic age. A fault approximately 1 mi in length offsets the Buffalo Gap monocline in T. 6 S., R. 6 E., and R. 7 E.

ALTITUDE OF THE TOP OF THE MINNELUSA FORMATION

The Minnelusa Formation crops out in the southwestern and east-central parts of the area. In the eastern one-half of the map area, the Minnelusa Formation generally dips southeasterly, from the Black Hills uplift toward the Chadron arch, which is southeast of the study area. In the western one-half, it dips southwesterly, toward the Powder River Basin. The rock units dip more steeply than does the land surface. As a result, although the top of the formation crops out in the Black Hills at an altitude of about 3,500 to 5,000 ft above sea level, it is about 1,100 ft below sea level, or about 3,800 ft below land surface, in the southeastern corner of the study area.

LITHOLOGY OF THE MINNELUSA FORMATION

The Minnelusa Formation consists mostly of interbedded sandstone, sandy dolomite, and limestone, with some shale, siltstone, gypsum, and anhydrite. The upper part of the Minnelusa Formation, above the red mudstone informally called "the red marker," is Permian in age and the remainder is Pennsylvanian (Braddock, 1963, p. 220).

The Minnelusa Formation is overlaid by the Opeche Formation or Shale and is underlaid by the Madison Limestone, which is called the Pahasapa Limestone in the Black Hills. The top of the Minnelusa Formation is relatively easy to identify during drilling or from lithologic descriptions because the uppermost bed is a buff, yellow, or pink sandstone and the lowermost bed of the Opeche Formation or Shale is red shale, or sandstone. Although there are limestone beds in the lower part of the Minnelusa, they are gray, and commonly bedded, whereas Madison (or Pahasapa) Limestone in the subsurface is buff or cream and massive, with bedding not distinguishable. The contact between the Minnelusa Formation and the Madison Limestone is unconformable (Cattermole, 1969).

The Minnelusa Formation was described by Darton and Paige (1925, p. 9) in a typical section cropping out in Beaver Creek Canyon near Wind Cave:

	Thickness, in feet
Shale, red, Opeche Formation	4
Limestone, impure, gray	15
Sandstone, orange, limy	50
Sandstone, yellow to buff, limy	10
Sandstone, red	20
Limestone, purplish, sandy	10
Bed mostly covered, shale above, sandstone below	60
Sandstone, buff, limy	10
Sandstone, massive, reddish, contains flint nodules . .	3
Sandstone, light yellowish, buff, and pinkish, mostly thin-bedded with a few 0.5-inch beds of light-colored flint	50
Limestone, pinkish, fine grained, contains a few beds of clay and two 8-inch beds of black shale about 10 feet apart; 3-inch layer of black flint at base . .	30
Quartzite and covered slope	25
Sandstone, massive, brownish and buff with mudstone . .	50
Shale, buff, sandy	12
Sandstone, buff	25
Limestone, drab, with flint streaks	30
Sandstone, massive, pink limy, with calcite veins . . .	15
Mudstone, purplish drab	12
Sandstone, massive, pink, limy, with calcite veins . . .	25
Limestone, massive, drab	18
Limestone, slabby, pink, sandy	8
Sandstone, red, shaly; lies on Madison (or Pahasapa) gray limestone	25
	497

Anhydrite, known to be present in the subsurface but not present in Beaver Creek Canyon, generally is missing in and near the outcrop, because of dissolution by ground water. The solution appears to be incomplete 5 to 10 mi downdip and downgradient from the outcrop as the concentration of sulfate in the water in the Minnelusa aquifer changes from less than 100 mg/L (milligrams per liter) near the outcrop to more than 1,000 mg/L at this distance (U.S. Geological Survey, unpublished records, Rapid City, South Dakota). Breccia caused by collapse in solution areas is typical of the upper part of the Minnelusa outcrop. As a result, the Minnelusa is thinnest in the outcrop.

The thickness of the Minnelusa Formation in the study area varies from 600 to 1,100 ft, based on sections reported by Darton and Paige (1925, p. 8-9), Braddock (1963, p. 221), and lithologic and geophysical logs. In the eastern one-half of the map area, the Minnelusa thickens from the north where it is about 600 ft thick, to the southeast, where it is about 800 ft thick. In the western one-half of the map area, the Minnelusa generally thickens westward, from 900 to 1,100 ft.

HYDROLOGY

The upper part of the Minnelusa Formation contains more permeable beds and breccias and yields water to wells, whereas the lower formation is less permeable and is a confining or semi-confining unit separating the Minnelusa and the underlying Madison aquifer. Coarse-grained sandstone, solution openings, and breccias are the principal sources of permeability in the upper part of the Minnelusa.

ORIENTATION OF MAPPED CAVE PASSAGES

In all five of the caves measured, the majority of cave passages approximately parallel dip as well as structural features within 10 mi of the cave. It is possible a regional anisotropic permeability exists, produced by the same forces that result in the larger (and, therefore, more likely to be mapped) structures.

Four of the caves do not appear to be near (within 1 mi) known geologic structural features. Approximately 32 percent of the passages in Rushmore Cave, measuring a total of 3,146 ft, are oriented between N. 70° W. and due west. Of the 17,055 ft of passage measured in Reeds Cave, approximately 64 percent are oriented between N. 5° W. and N. 70° E. In Wind Cave, of the 24,908 ft of passage comprised of segments exceeding 100 ft in length, 60 percent are oriented in the range of N. 25° W. to N. 45° W. Approximately 60 percent of the passages in White Onyx Cave, measuring a total of 370 ft, are oriented in the range of N. 15° W. to N. 30° W. Though there is not an obvious parallelism between cave-passage and structural-feature orientation, there may be as yet unidentified structures that effect fracture patterns and secondary permeability, and thus cave formation.

In only Jewel Cave, do the majority of the passages parallel a nearby (within 1 mi) fold axis or a fault. In the main passage level of Jewel Cave, of the 50,188 ft of passage comprised of straight segments exceeding 100 ft in length, 48 percent are oriented between N. 55° E. and N. 75° E., approximately parallel to a nearby zone of fault and folds, reported by Lisenbee (1985).

The hydrologic conditions that produced the caves may be inferred from Huntoon's (1985) hypothesis and observations of present-day sites of steep hydraulic gradient; that is the large, resurgent springs in the Black Hills. There are numerous springs throughout the Black Hills (Rahn and Gries, 1973), the largest of which are resurgent springs. These springs, which discharge as much as 10 to 20 ft^3/s, are sustained by recharge that originates as streamflow infiltration on the outcrops of the Madison Limestone and to a lesser amount, the Minnelusa Formation. The springs usually are located on the outcrop of the upper part of the Minnelusa Formation or younger rocks. The conditions needed to produce a resurgent spring are:

1. A potentiometric surface in the Madison Limestone that is above land surface,
2. An area where the Madison is sufficiently shallow and the overlying rocks are sufficiently permeable to allow vertical movement of water.

The potentiometric surface of the Madison Limestone is above many of the outcrops of younger rocks because the recharge area of the Madison Limestone is much higher than these outcrops. The Madison Limestone is shallower where a canyon or valley has been eroded; perhaps controlled by an antecedent condition or a structural feature, and as a result many of the resurgent springs are in canyons or valleys. If there is an area of increased vertical permeability in the overlying rocks, possibly as a result of structural deformation or dissolution, there is increased likelihood of a large spring developing. If there is sufficient vertical permeability, the spring may develop where the Madison is more deeply buried, such as on a hillside or in a broad valley.

As Huntoon (1985) described the localization of caves in the Bighorn Basin, the unusually steep gradients that occur between the recharge area and the springs would produce the rapid and voluminous circulation of freshwater that could remove large quantities of limestone and result in cave formation. At the time of the formation of the caves, the Madison Limestone may have had a higher recharge area, analogous to present conditions, and springs may have issued above the caves, perhaps in areas now removed by erosion.

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METRIC CONVERSION TABLE

The following factors can be used to convert inch-pound units in this report to the International System of Units (SI):

Multiply inch-pound unit	By	To obtain SI unit
inch	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

EXPLANATION

MINNELUSA FORMATION--Pattern shows general area of outcrop.

MINNELUSA FORMATION ABSENT

CONTACT--Dashed where approximately located.

ANTICLINE--Showing trace of axial plane and direction of plunge. Dashed where approximately located.

SYNCLINE--Showing trace of axial plane and direction of plunge. Dashed where approximately located.

MONOCLINE--Showing trace of axial plane. Dashed where approximately located.

Anticlinal

Synclinal

FAULT--U indicates upthrown side; D indicates downthrown side. Dashed where approximately located.

FAULT--Bar and ball on downthrown side.

500 STRUCTURE CONTOUR--Shows altitude of the top of the Minnelusa Formation. Dashed where approximately located. Contour interval, in feet, is variable. National Geodetic Vertical Datum of 1929.

CONTROL POINT--Location of water well or oil or gas exploration well.

3660 Top of Minnelusa Formation known--Number is known altitude, in feet, above or below National Geodetic Vertical Datum of 1929 for the top of the Minnelusa Formation.

2100 Top of Minnelusa Formation projected--Number is projected altitude, in feet, above or below National Geodetic Vertical Datum of 1929 for the top of the Minnelusa Formation.

ORIENTATION OF CAVE PASSAGES IN THE MADISON LIMESTONE--Numbers are percent of total passages measured with the orientation shown.

GEOLOGIC STRUCTURE AND ALTITUDE OF THE TOP OF THE MINNELUSA FORMATION AND ORIENTATION OF MAPPED CAVE PASSAGES IN THE MADISON LIMESTONE, SOUTHERN BLACK HILLS, SOUTH DAKOTA

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