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Bulletin No. 21

Department of Geology and Geological Engineering

Geologic Field Trips in the Black Hills Region, South Dakota

Editors:
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Rapid City, South Dakota
2010

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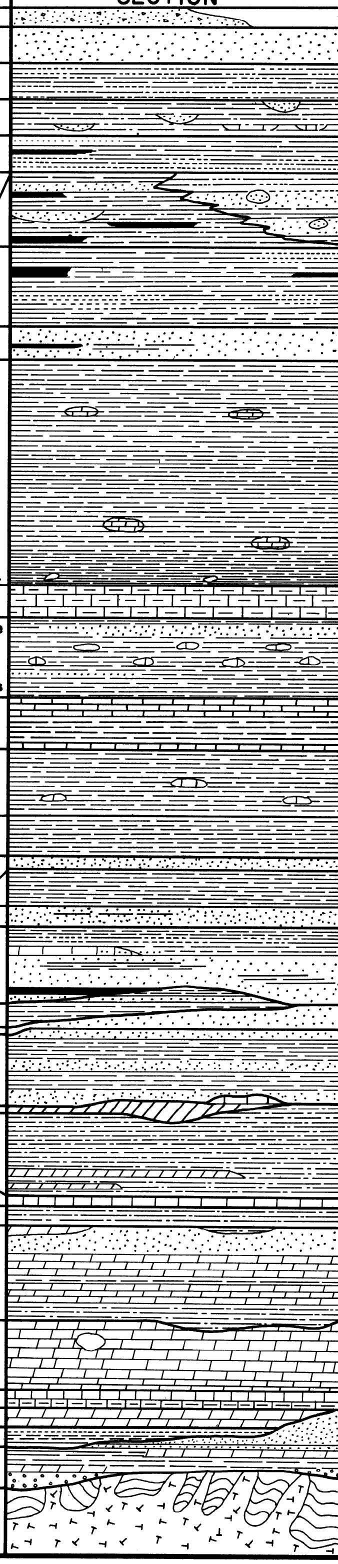
GENERAL OUTCROP SECTION OF THE BLACK HILLS AREA

Age	Formation	Thickness in feet	Description
QUATERNARY	SANDS AND GRAVELS	0-50	*Sand, gravel, and boulders.*
TERTIARY — PLIOCENE	OGALLALA GROUP	0-100	*Light colored sands and silts.*
TERTIARY — MIOCENE	ARIKAREE GROUP	0-500	*Light colored clays and silts. White ash bed at base*
TERTIARY — OLIGOCENE	WHITE RIVER GROUP	0-600	*Light colored clays with sandstone channel fillings and local limestone lenses*
TERTIARY — PALEOCENE	FORT UNION FORMATION: TONGUE RIVER MEMBER	0-425	*Light colored clays and sands, with coal-bed farther north.*
TERTIARY — PALEOCENE	FORT UNION FORMATION: CANNONBALL MEMBER	0-225	*Green marine shales and yellow sandstones, the latter often as concretions.*
TERTIARY — PALEOCENE	FORT UNION FORMATION: LUDLOW MEMBER	0-350	*Somber gray clays and sandstones with thin beds of lignite.*
?			
CRETACEOUS — UPPER	HELL CREEK FORMATION (Lance Formation)	425	*Somber-colored soft brown shale and gray sandstone, with thin lignite lenses in the upper part. Lower half more sandy. Many loglike concretions and thin lenses of iron carbonate.*
CRETACEOUS — UPPER	FOX HILLS FORMATION	25-200	*Grayish-white to yellow sandstone*
CRETACEOUS — UPPER	PIERRE SHALE; Sharon Springs Mem.	1200-2000	*Principal horizon of limestone lenses giving teepee buttes* *Dark-gray shale containing scattered concretions.* *Widely scattered limestone masses, giving small tepee buttes* *Black fissile shale with concretions*
CRETACEOUS — UPPER	NIOBRARA FORMATION	100-225	*Impure chalk and calcareous shale*
CRETACEOUS — UPPER	CARLILE FORMATION; Turner Sand Zone; Wall Creek Sands	400-750	*Light-gray shale with numerous large concretions and sandy layers.* *Dark-gray shale*
CRETACEOUS — UPPER	GREENHORN FORMATION	(25-30)	*Impure slabby limestone. Weathers buff.*
CRETACEOUS — UPPER		(200-350)	*Dark-gray calcareous shale, with thin Orman Lake limestone at base.*
CRETACEOUS — UPPER	GRANEROS GROUP: BELLE FOURCHE SHALE	300-550	*Gray shale with scattered limestone concretions.* *Clay spur bentonite at base.*
CRETACEOUS — LOWER	GRANEROS GROUP: MOWRY SHALE	150-250	*Light-gray siliceous shale. Fish scales and thin layers of bentonite*
CRETACEOUS — LOWER	GRANEROS GROUP: NEWCASTLE SANDSTONE	20-60	*Brown to light yellow and white sandstone.*
CRETACEOUS — LOWER	GRANEROS GROUP: SKULL CREEK SHALE	170-270	*Dark gray to black shale*
CRETACEOUS — LOWER	INYAN KARA GROUP: FALL RIVER [DAKOTA (?)] ss	10-200	*Massive to slabby sandstone.*
CRETACEOUS — LOWER	INYAN KARA GROUP: LAKOTA FM; *Fuson Shale*; *Minnewaste ls*	10-188 0-25 25-485	*Coarse gray to buff cross-bedded conglomeratic ss, interbedded with buff, red, and gray clay, especially toward top. Local fine-grained limestone.*
JURASSIC	MORRISON FORMATION	0-220	*Green to maroon shale. Thin sandstone.*
JURASSIC	UNKPAPA SS	0-225	*Massive fine-grained sandstone.*
JURASSIC	SUNDANCE FM: Redwater Mem; Lak Member; Hulett Member; Stockade Beaver; Canyon Spr. Mem	250-450	*Greenish-gray shale, thin limestone lenses* *Glauconitic sandstone; red ss. near middle*
JURASSIC	GYPSUM SPRING	0-45	*Red siltstone, gypsum, and limestone*
TRIASSIC — ? — PERMIAN	SPEARFISH FORMATION; Goose Egg Equivalent	250-700	*Red sandy shale, soft red sandstone and siltstone with gypsum and thin limestone layers.* *Gypsum locally near the base.*
PERMIAN	MINNEKAHTA LIMESTONE	30-50	*Massive gray, laminated limestone.*
PERMIAN	OPECHE FORMATION	50-135	*Red shale and sandstone*
PERMIAN; PENNSYLVANIAN	MINNELUSA FORMATION	350-850	*Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite.* *Red shale with interbedded limestone and sandstone at base.*
MISSISSIPPIAN	PAHASAPA (MADISON) LIMESTONE	300-630	*Massive light-colored limestone. Dolomite in part. Cavernous in upper part.*
DEVONIAN	ENGLEWOOD LIMESTONE	30-60	*Pink to buff limestone. Shale locally at base.*
ORDOVICIAN	WHITEWOOD (RED RIVER) FORMATION	0-60	*Buff dolomite and limestone.*
ORDOVICIAN	WINNIPEG FORMATION	0-100	*Green shale with siltstone*
CAMBRIAN	DEADWOOD FORMATION	10-400	*Massive buff sandstone. Greenish glauconitic shale, flaggy dolomite and flatpebble limestone conglomerate. Sandstone, with conglomerate locally at the base.*
PRE-CAMBRIAN	METAMORPHIC and IGNEOUS ROCKS		*Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.*



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DEPARTMENT OF GEOLOGY AND GEOLOGICAL ENGINEERING

SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY

RAPID CITY, SOUTH DAKOTA

Geologic Setting, Black Hills, South Dakota

JACK A. REDDEN and ALVIS L. LISENBEE *Department of Geology and Geological Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701*

[reprinted and reformatted from Paterson, C.J., and Lisenbee, A.L., 1990, Metallogeny of Gold in the Black Hills, South Dakota: Society of Economic Geologists Guidebook series, v.7, p. 1-9, with permission of the Society of Economic Geologists]

INTRODUCTION

The extensive deposits of gold in the Black Hills which have been mined for more than 100 years led to early investigations of the geology and especially the geology as related to the gold deposits (Newton and Jenney, 1880, Van Hise, 1890). Basically the Black Hills consists of an elongate dome of Phanerozoic sedimentary rocks unconformably overlying a core of Precambrian metamorphic and igneous rocks. The core is largely Proterozoic in age and only about one percent is Archean. In the northern Black Hills are sizable areas of Tertiary igneous rocks representing shallow intrusions in Phanerozoic sedimentary rocks or the roots of such intrusions in the Precambrian rocks.

The dominantly stable platform-setting Phanerozoic sedimentary rocks were uplifted during the Laramide orogeny and erosion scoured into the Precambrian basement so that the physiography of the early Oligocene was similar to the present. Oligocene White River deposits then blanketed much of the dome but subsequent erosion has largely removed these deposits.

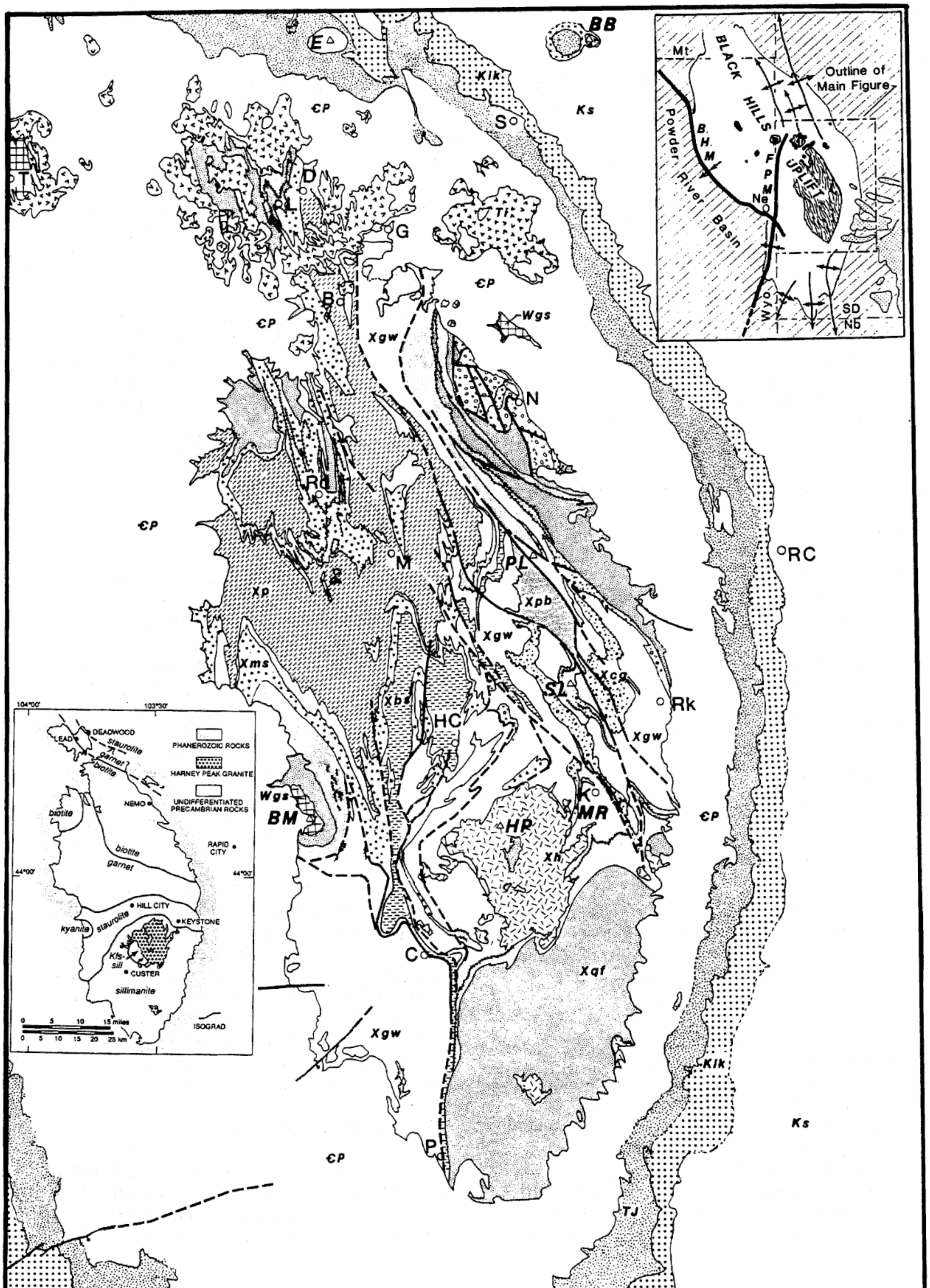
The geology of the world class Homestake gold mine was studied intensively during the early days of mining and, as the complexity of the ore deposit was realized, the necessity of a competent geological staff for handing ore became apparent. In fact, Homestake's geologic staff became a model for many mining companies and undoubtedly led to an especially active role for geologists in Homestake management.

The first detailed comprehensive description of the geology of the Black Hills was published in 1925 as the classic U.S. Geological Survey Central Black Hills Folio (Darton and Paige, 1925). Many additional publications consider various aspects of the geology of the area but the most recent complete summary covering most aspects of the geology is to be found in the assessment of the mineral resource potential of the Black Hills National Forest by DeWitt et al. (1986). The most complete review of the structural development of the Precambrian rocks and their ages is given by Redden et al. (1990). Another paper by Redden and French (1989) basically summarizes the geologic setting of the gold deposits throughout the Black Hills. Lisenbee (1988) presents a general review of the Laramide tectonic setting of the uplift. The following summary of the geology of the Black Hills uses data from these particular publications freely.

ARCHEAN ROCKS

Archean rocks are limited to two small areas in the central Black Hills; one area is in a small erosional window along Little Elk Creek north of Nemo; and the other in the core of a small dome at Bear Mountain along the west edge of the Precambrian core (Plate II). Both areas (Wgs, Plate II) include granite dated at approximately 2.5 Ga (Zartmanand Stern, 1967, Ratte', 1986, Gosselin et al., 1988) but the granite is texturally quite dissimilar in the two areas. The older country rocks consist of schist and gnessic rocks, which are, at least in the Little Elk Creek area, derived from relatively coarse-grained clastic sedimentary rocks. Thin units of oxide banded iron-formation are also known in the latter area.

In the Tinton area on the Wyoming-South Dakota boundary Plate II), there are small pegmatite bodies and biotite schists which differ considerably in appearance from the Proterozoic rocks and may be Archean in age. In the Bear Lodge Mountains farther to the northwest, but still on the Black Hills uplift, are relatively large screens of Archean granite (2.63 Ga) which have been rafted upward by Tertiary intrusions (Staatz, 1983). No mineralization is known to occur in these Archean rocks.


BB
E
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Xpb
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Xcg
SL
Rk
RC
Xbs
HC
BM
K
MR
HP
Xh
C
Xqf
P
TJ
Mt
BLACK HILLS UPLIFT
Outline of Main Figure
Powder River Basin
B.H.M.
F.P.M.
Ne
Wyo
SD
Nb
DEADWOOD
LEAD
staurolite
garnet
biotite
NEMO
PHANEROZOIC ROCKS
HARNEY PEAK GRANITE
UNDIFFERENTIATED PRECAMBRIAN ROCKS
RAPID CITY
HILL CITY
KEYSTONE
kyanite
Kfs-sill
CUSTER
sillimanite
ISOGRAD
104°00'
103°30'
44°00'
15 miles
25 km

EXPLANATION

Ti — Tertiary igneous rocks

Ks — Rocky Mountain geosyncline; marine shales

Kik — Rocky Mountain geosyncline; Inyan Kara Group

TJ — Mesozoic continental and shelf sequence

€P — Paleozoic shelf sequence

EARLY PROTEROZOIC ROCKS

Xh — Harney Peak Granite

Xp — Phyllite-schist; thin-bedded locally graphitic--Garnet-bearing above garnet zone

Xms — Mica schist and metamorphosed volcaniclastic rocks--Laminated mica phyllite/schist in area to the south and to the east of Mystic; mainly volcaniclastic rocks in Rochford and Lead areas

Xbs — Biotite phyllite/schist; typically thin bedded, some distal turbidites, garnet-rich above garnet isograd

Xcg — Metaconglomerate and volcanoclastic rocks--Typically has included units of carbonate-silicate iron-formation

Xif — Iron-formation--Includes chert and carbonate-silicate facies iron formation

Xgw — Quartz-mica schist or phyllite derived from turbidite deposits

Xpb — Laminated slate/phyllite garnet schist and greenstone/amphibolite--Derived from pillow basalts and interflow deposits

Xqf — Quartzite and fanglomerate--fanglomerate restricted to Nemo area; shelf quartzite interbedded with phyllite and sillimanite schist in area southeast of Custer

Xmg — Metagabbro--Gravity differentiated sill shown in Nemo area only; many small metagabbro sills/dikes of younger age not shown

Xqi — Quartzite, fluvial conglomerate and fanglomerate including overlying oxide facies banded iron-formation--Restricted to Nemo area

LATE ARCHEAN ROCKS

Wgs — Archean granite and schist

Contact

Fault, dashed where approximately located

PLATE II. Generalized geologic map of the Black Hills in South Dakota. Geographic locations and towns are: B Brownsville; BB Bear Butte; BM Bear Mountain; C Custer; D Deadwood; E Elkhorn Peak; G Galena; HC Hill City; HP Harney Peak; K Keystone; L Lead; M Mystic; MR Mount Rushmore; N Nemo; P Pringle; PL Pactola Lake; RC Rapid City; Rd Rochford; Rk Rockerville; S Sturgis; SL Sheridan Lake; T Tinton. Precambrian isograd map prepared by E. Duke. Abbreviations on Tectonic Sketch Map: BHM Black Hills monocline; FPM Fanny Peak monocline; Ne Newcastle. Stippled pattern along east side of uplift in upper right hand inset shows approximate location of Oligocene White River Group.

PROTEROZOIC ROCKS

Proterozoic rocks constitute about 99% of the exposed Precambrian rocks in the Black Hills. At least two separate depositional sequences are 1.87-1.97 and ca. 2.2 Ga in age. These were intruded by the Harney Peak Granite at approximately 1.7 Ga. The latter is the youngest of Precambrian rocks and more than a billion years of the younger Precambrian record is missing. The oldest Proterozoic rocks occur in the Nemo area in the northeast part of the Precambrian core (Plate II). These have been described in detail by Redden (1981) and are shown as a single unit (Xqi) in Plate II. The unit includes conglomerate, fanglomerate, quartzite and other rock types of the Boxelder Creek Formation and an overlying oxide banded iron-formation (bif). In this report and on the map original rock names are used instead of metamorphic names wherever the rock prototype is evident. Part of the Boxelder Creek Formation includes a fluvial tongue of uraniferous and auriferous pyritic conglomerate which has been described by Redden (1988). The fanglomerate and coarse clastic rocks are characterized by rapid lateral facies changes suggesting a tensional rift environment along the western margin of an interior basin. An unconformity above the Archean rocks is not exposed but is inferred to exist to explain refolded structures in clasts of bif and quartzite clasts in these oldest Proterozoic rocks. Lateral facies changes in the fanglomeratic rocks indicate western sources which, if correct, indicates that the earliest depocenter for the Black Hills was to the east of the present core. A gabbroic, gravity-differentiated layered sill (Xmg) intrudes these oldest rocks and has a 2.17 + 0.1 Ga age (Redden et al., 1990) thus making the enclosing rocks somewhat older.

These oldest Proterozoic rocks then experienced folding, faulting, and uplift so that an angular unconformity developed across three listric fault blocks. Marine fanglomerate of the Estes Formation is as much as 3 km thick adjacent to one of these growth faults but thins drastically and changes facies a short distance to the west away from the faults (Xqf). The tensional faults progressively migrated eastward into the highland source bordering this basin which apparently became the main central Black Hills depobasin. The coarse clastic environment near the growth faults changed upward to a narrow shelf carbonate environment along the western boundary of the Nemo area.

After deposition and deformation of the Nemo-area rocks including the development of the angular unconformity, all rocks were overturned to the southeast and now dip steeply to the northwest. The presumably considerably younger north-northwest trending folds and nearly vertical foliation typical of most of the Black Hills Precambrian, have been superposed on these overturned rocks of the Nemo area.

Outside the Nemo area extensive shelf-derived quartzite and intercalated siltstone are distributed along the eastern edge of the Black Hills. To the southeast these are now quartzite and sillimanite schist. These rocks are considered to be lateral equivalents of the Estes Formation. Likewise, in the Bear Mountain dome on the western edge of the Precambrian rocks, conglomerate, quartzite, arkose and carbonate rocks unconformably overlie the Archean basement and are considered also to be equivalent to the Estes Formation of the Nemo area. This implies encroachment of the Black Hills basin onto the Wyoming Archean craton. Following the shelf facies rocks, tholeiitic volcanism was initiated along the east-central part of the Black Hills. Interflow lithologies include carbonate-silicate iron-formation and lenticular chert, both chemical sediments believed to be products of deposition by oceanic hot springs. The individual volcanic flows pinch out to the northwest into black shale characterized by high sulfide, graphite, ribbon chert, and iron-carbonate content and the two major lithologies are included as the single unit (Xpb). Similar rocks are exposed as the oldest rocks in the Lead dome, where they have been named the Poorman Formation (Hosted and Wright, 1923), and are overlain by the Homestake and Ellison Formations. The Homestake Formation is a carbonate-silicate-sulfide facies iron-formation which is host of the gold mineralization in the Homestake mine. No age data are available from the mafic volcanic rocks but zircon from tuffaceous beds in the Ellison Formation give a U-Pb age of 1.97 +.01 Ga which suggests that this early volcanism occurred about 2.0 Ga (Redden et al., 1990).

Following volcanism, apparent deepening of the basin led to classic turbidite deposits (Xgw). The metamorphosed equivalents make up the most abundant rock type of the Proterozoic. Near Rockerville and Keystone the turbidites are split into two units by a well developed debris flow unit (Xcg) which includes lenticular quartzite, shale, carbonate-silicate iron-formation, massive chert, metagabbro bodies, and thin mafic volcanic units as well as mud-matrix conglomerates. Some evidence indicates that an episode of deformation preceded the debris flow unit but this is not fully documented. Certainly the unit indicates steep slope conditions to the southeast and a decrease in igneous activity to the west where the debris flow unit apparently changes facies to more typical turbidite deposits.

In the central and southern part of the core, an extensive thin bedded shale (Xbs) is intercalated with more proximal turbidite deposits and probably is itself mainly a distal deposit. In the same area and also in the Rochford area is a combined unit of dominantly mica schist and other schist derived from volcaniclastic material. The mica schist part of the unit is widely distributed in the central and southern part of the central Black Hills where it is generally intercalated with graywacke. It changes facies gradually to the north and to the extreme east, however, where it cannot be distinguished from distal turbidites. The mica schist portion is very aluminous, has thin laminae of chert and manganiferous garnet and chalcopyrite-bearing laminae. It is believed to be derived from a weathered tuffaceous unit which changes laterally to dominantly coarser volcaniclastic material in the Rochford area. In the Rochford area the unit includes small lensoid pillow lava units and very small amounts of ash fall tuff. The latter has been dated at 1.88 + .03 Ga (Redden et al., 1990). The tuff is associated with carbonate-silicate facies iron-formation (Montana Mine Formation, Bayley, 1972). The iron-formation and associated rocks were included by Bayley (1912) in the Flag Rock Group which is correlated with rocks overlying the Ellison Formation in the Lead dome. The available ages of the Ellison Formation in the Lead area (1.97 Ga) and the tuff-iron-formation (Flag Rock) of the Rochford area (1.88 Ga) indicate an unconformity or tectonic break. Based on the limited evidence for an unconformity in the turbidite section in the central and southeastern part of the central Black Hills core, the existence of an unconformity is favored over an unrecognized major fault. Such an event would have preceded the deposition of the diverse debris flow unit (Xcg).

The youngest Proterozoic metasedimentary unit (Xp) is a thick sequence of shale metamorphosed to graphitic slate and phyllite that underlies the northwestern part of the central Black Hills. The unit lacks distinctive subunits and is probably considerably repeated by folding. It apparently underlies a major synclinal axis which in general trends east-northeasterly but has been later cross folded in a north-northwesterly direction.

Small metagabbro bodies intrude most of the metasedimentary rock units but are not shown on Plate II. These tend to be most abundant in the older rocks and especially those having submarine basaltic flows. Several different ages are present ranging between 1.87 Ga and 1.97 Ga. Associated basaltic volcanic rocks probably have the same general range in ages.

The youngest Proterozoic rock is the post-tectonic Harney Peak Granite in the southern Black Hills (Plate II). It is approximately 1.7 Ga (Riley, 1970, Redden et al., 1990) and consists of a highly complex group of sills and dikes of peraluminous S-type granite and pegmatite (Redden et al., 1985).

Metamorphism accompanied the development of the north-northwest trending fold pattern (F2) which was superposed on earlier northeast-trending probable nappe-like folds (F I). The earliest folds, noted only in the oldest Proterozoic rocks in the Nemo area, preceded the unconformity in the Proterozoic rocks and presumably had northerly trends. All of these Nemo rocks were subsequently overturned, as previously noted, possibly by the northeast-trending Fl folding.

Additional Abukuma-type metamorphism accompanied the emplacement of the Harney Peak Granite forming a major domal structure. Metamorphic mineral textures and the relatively wide thermal aureole suggest that the isotherms have been bowed upward considerably as the dome developed and that considerable heat was transferred to the country rock by fluid evolved from the pegmatitic Harney Peak Granite. Many zoned pegmatites with commercial value in the surrounding schists are sources of nonmetallic deposits and rare elements such as Be and Li.

PHANEROZOIC ROCKS

Introduction

The Phanerozoic history of the Black Hills region is dominated by epeirogenic warping punctuated only by Early Tertiary Laramide orogenesis. This history is revealed in strata and the numerous unconformities which separate them as exposed in elliptical outcrop patterns of the Black Hills uplift. These strata are divisible into several litho-tectonic packages based upon their differing environments of deposition (Lisenbee, 1985). The Early Tertiary igneous suite separates the last two major litho-tectonic packages.

Paleozoic Shelf Sequence

Shallow, warn seas covered the region during much of Paleozoic time although numerous disconformities within the section indicate intermittent transgressions and regressions. Epeirogenic movements in the Black Hills area resulted from relative elevation and depression of the Williston basin to the north, the Trans-continental arch to the south and the Cordilleran miogeocline to the west. Deposited onto this shelf along the western part of the North American craton during much of the Paleozoic were beach, shallow marine, carbonate bank and mud-flat, sabkha, and evaporite units (CP, Plate II). These units form the inner part of perimeter rocks surrounding the core of the Black Hills.

The geologic record is far from complete. The strata show an overall thinning from approximately 940 m on the north end of the uplift in Montana to 400 m at the south end near the South Dakota - Nebraska border as a result of thinning or the pinching out of individual formations. Rocks of Silurian age are absent, and to the south so are those from much of the Cambrian, Ordovician, and Devonian, and part of the Mississippian, Pennsylvanian, and Permian.

In the northern Black Hills this sequence is intruded by Late Laramide alkalic plutons (described below) and locally mineralized. Base and precious metal deposits related to this mineralizing event are most abundant within the clastic and carbonate units of the Cambrian Deadwood Formation and only traces persist into the overlying massive carbonates of the Mississippian Pahasapa (Madison) Limestone. Paleoplacer gold is found locally at the base of the Cambrian Deadwood Formation.

Mesozoic Continental and Shelf Sequence

Throughout Triassic and Jurassic time epeirogenic activity continued on the shelf at the eastern margin of the Cordilleran seaway. Fluctuations between continental and marine deposition produced channel, flood plain, dune, beach, and shallow marine clastic units, and minor amounts of evaporites, whose cumulative thicknesses range from 300 to 365 m. Numerous disconformities are present, but form no obvious breaks in the strata.

These units are exposed today in the annular ring of the "red valley" (TJ, Plate II) which surrounds the pine covered core of the Black Hills. White gypsum and red-colored siltstone, sandstone and shale of the Permo-Triassic Spearfish Formation underlie the valley floor, as seen during a drive along Interstate 90 northward from Rapid City to Spearfish. They are overlain by shallow marine clastic rocks of the Sundance Formation, the channel and floodplain deposits of the Morrison Formation and dune deposits of the Unkpapa Formation which underlie the outer slopes.

Rocky Mountain Geosyncline

In late Early Cretaceous time the North American craton flexed downward such that seas advanced slowly from the north and south and ultimately joined near the southern margin of the present Black Hills uplift. This through-going sea remained until the end of the Late Cretaceous at which time the shoreline retreated slowly southward from the Black Hills. The residues of this great seaway may be described loosely as a sandwich composed of lower and upper stacks of sandstone separated by a shale middle. The lower sandstone unit (KiK, Plate II) consists of channel, flood plain, beach, near-shore, and shallow marine deposits and hosts classic roll front sandstone uranium deposits in the southern Black Hills. The overlying shale, and minor carbonate units (Ks, Plate II), represent marine deposits formed in the central portion of the seaway. The original thickness of this package may have been as much as 1,900 m in western South Dakota.

Although these strata are removed from the crest of the uplift, remnants remain along the margins. The outermost, continuous ridge of the Black Hills is underlain by sandstone of the Lower Cretaceous Inyan Kara Group (Kik, Plate II) which lies unconformably on the Triassic-Jurassic strata (TJ, Plate II). A part of the thick section of Upper Cretaceous shale remains in the eastern part of the area described here. The uppermost sandstone units are present to the northeast, outside of this area. Because the inclination of these strata decreases away from the uplift, flat-lying shale is present at the surface far to the east to beyond the Missouri River where it is covered by Pleistocene glacial deposits.

Laramide Orogenesis

Broad upwarping which resulted in retreat of the Cretaceous sea was followed by fracturing of the craton and the formation of the crustal-scale blocks of the Powder River basin and the Black Hills uplift. The latter is the easternmost of the Laramide foreland uplifts and contains the Black Hills which are the easternmost chain of the Rocky Mountains. The uplift extends from southeastern Montana to the South Dakota-Nebraska border, a distance of approximately 200 km. The maximum width is 120 km and the maximum structural relief is 2100 m.

Monoclines, distinctive features throughout the Laramide orogenic zone, are common here and two of the largest (he Black Hills and the Fanny Peak structures) separate the uplift from the Powder River Basin to the west (Plate II, inset). This structural style contrasts strongly with the eastern flank where the Proterozoic basement is warped into a large half dome. It is this half dome which is shown in the geologic map of Plate II and which comprises most of the topographic Black Hills. From the latitude of Newcastle, Wyoming, the Fanny peak monocline continues northward onto the uplift separating it into eastern and western blocks.

With only two exceptions all monoclines are west vergent. As a result of the regional dip those on the eastern block have the form of asymmetric anticlines. Three large folds plunge from both the northern and southern ends (Plate II). Other smaller examples are present along the eastern margin of the uplift, but are generally lacking on the western block. The structural patterns suggest formation due to regional compression although Shun and others (1988) interpret some components of strike-slip along the Fanny Peak and Black Hills monoclines.

Uplift began in the Paleocene and probably continued in the Eocene although it is possible that more than one episode of movement occurred. Sand ratio maps (Lewis and Hotchkiss, 1981) and paleocurrent directions (Flores and Ethridge, 1985) for the Powder River basin indicate a source terrane in the Black Hills area during deposition of the Paleocene age Tullock Member of the Fort Union Formation at approximately 63 Ma b.p. Erosion had probably cut to the level of the Cretaceous Mowry Formation by 56 Ma b.p. (Lisenbee and Roggenthen, 1990), and had removed the entire Phanerozoic section from the core of the Black Hills by 37 Ma b.p. (Lisenbee, 1981) prior to deposition of the Oligocene White River Group.

Late Laramide Alkalic Plutons

Following at least the initial stage of uplift, dikes, stocks, sills, laccoliths, breccia pipes, diatremes, and ring dikes, some with carbonatitic affinities, were emplaced in a west-northwesterly-trending belt (Plate II) across the northern part of the uplift. This igneous activity, which occurred during the period 38 to 62 Ma (Paleocene and Eocene), was alkalic in nature and emplaced rhyolite, quartz latite, trachyte, and phonolite as the most common rock types. Base and precious metal mineralization is found near, or within, some of these bodies, especially those of trachytic character. Intrusions are not equally distributed, and tend to occur in clusters. Within the area discussed here these clusters form two major domes in the basement and seven laccolithic centers in the Phanerozoic strata. Individual intrusive bodies occur in the Phanerozoic strata or as dikes in the basement. One additional dome affecting Precambrian basement is present west of the map area of Plate II in Wyoming.

Emplacement of dike swarms and stocks combined to forcefully swell the basement and to produce the 15 to 18 km diameter Lead-Deadwood and Tinton domes. The dikes follow the general north-northwesterly trend of schistosity in the basement and are locally so abundant as to be recognized only by thin screens of schist found between them. Examples of the dikes are seen to greatest advantage in the Homestake open cut mine in Lead. Laccolithic clusters also form composite domes in the Phanerozoic strata. The clusters are 10 to 15 km across and composed of numerous individual laccoliths having an average diameter of about 2 km. Most intrusions within a cluster are of similar compositions, e.g., rhyolite at the Theodore Roosevelt and Woodville groups, trachyte and phonolite in the Carbonate and Terry Peak groups, and quartz latite in the Vanocker group. Minor variations are generally present, however.

Post-Laramide Continental Clastic Sequence

Erosion in the early Tertiary removed the arched strata from the uplift and exposed the Precambrian core, the entire Phanerozoic section and the Tertiary igneous rocks. Channel, flood plain, and lacustrine deposits of the Oligocene White River Group were laid down with angular unconformity across this substrate. A maximum thickness of 73 m of this material remains, mostly in paleovalleys which radiate from the uplift (Plate II, inset) or locally curve around the laccoliths and stocks. In addition, tuffaceous units similar to those of the Badlands to the east, form local remnants.

REFERENCES CITED

Bayley, R. W., 1972, A preliminary report on the geology and gold deposits of the Rochford district, Black Hills, South Dakota: U. S. Geol. Survey Bull. 1332-A, 24 p.

Darton, N. H., and Paige, S., 1925, Central Black Hills [quadrangle], South Dakota: U.S.

Geol. Survey Geologic Atlas of the United States, Folio, 219, 34 p.
DeWitt, E., Redden, J. A., Wilson, A. B., and Buscher, D., 1986, Mineral resource potential and geology of the Black Hills National Forest, South Dakota and Wyoming, with a section on Salable commodities by J.S. Dersch: U. S. Geol. Survey Bull 1580, 135 p.
Flores, R. M., and Ethridge, F. G., 1985, Evolution of intermontane fluvial systems of Tertiary Powder River Basin, Montana, Wyoming: Cenozoic Paleogeography of the West-central United States: Rocky Mountain Section Soc. Econ. Paleontologists and Mineralogists, Denver, p. 107 -126.
Gosselin, D. C., Papike, J. J., Zartman, R. E., Peterman, Z. E., and Laul, J. C., 1988, Archean rocks of the Black Hills, South Dakota; reworked basement from the southern extension of the Trans-Hudson orogen: Geol. Soc. America Bull. v. 100, p. 1244-1259.
Hosted, J. O., and Wright, L. E., 1923, Geology of the Homestake ore bodies and the Lead area of South Dakota: Eng. Min. Jour., v. 115, p. 793-799, 836-843.
Lewis, B. D., and Hotchkiss, W. R., 1981, Thickness, percent sand, and configuration of shallow hydrologic units in the Powder River Basin, Montana and Wyoming: U. S. Geol. Survey Misc. Inv. Series, Map I-1317.
Lisenbee, A. L., 1981, Studies of the Tertiary intrusions of the northern Black Hills Uplift, South Dakota and Wyoming, a historical review: Geol. Soc. America, Rocky Mountain Section, 1981, Ann. Mtg,, Rapid City, Geology of the Black Hills, South Dakota and Wyoming, Guidebook, American Geol. Inst., p. 106-125.
Lisenbee, A. L., 1985, Tectonic map of the Black Hills uplift, Wyoming, and South Dakota: Geol. Surv. of Wyoming, Map Series 13, 1:250,000 scale.
Lisenbee, A. L., 1988, Tectonic history of the Black Hills uplift: Wyoming Geol. Assoc. Field Conf. Guidebook, 39th, Casper, Wyoming, Sept. 9-l l, Eastern Powder River Basin-Black Hills Guidebook, p. 45 -52.
Lisenbee, A. L., and Roggenthen, W. R., 1990, Alkalic diatremes and breccia pipes of the northern Black Hills, South Dakota, In Paterson, C. J., and Lisenbee, A. L., eds., Metallogeny of Gold in the Black Hills, South Dakota: Soc. Econ. Geol. Guidebook Series, v. 7, p. 175-181.
Newton, H. A., and Jenney, W. P., 1880, Report on the geology and resources of the Black Hills of Dakota: U. S. Geographical and Geological Survey of the Rocky Mountain Region, 566 p.
Ratte', J. C., 1986, Geologic map of the Medicine Mountain Quadrangle, Pennington County, South Dakota: U. S. Geol. Survey Misc. Investigations Series Map I-1654, scale 1:24,000.
Redden, J. A., 1985, Summary of geology of the Nemo area: Geol. Soc. America Rocky Mountain Section, 1981, Ann. Mtg., Rapid City, Geology of the Black Hills, South Dakota and Wyoming Guidebook (2nd ed.), American Geol. Inst., p. 193-210.
Redden, J. A., Norton, J. J., and Mclaughlin, R. J., 1985, Geology of the Harney Peak Granite, Black Hills, South Dakota: Geol. Soc. America Rocky Mountain Section, 1981 , Ann. Mtg., Rapid City, Geology of the Black Hills, South Dakota and Wyoming Guidebook (2nd ed.), American Geol. lnst., p.225-240.
Redden, J. A., 1988, Uraniferous Early Proterozoic conglomerates of the Black Hills, South Dakota, U.S.A., in Uranium deposits in Proterozoic quartz-pebble conglomerates: Internat. Atomic Energy Agency Tech. Doc. 421, p. 7 5-97 .
Redden, J. A., and French, G. M., 1989, Geologic setting and potential exploration guide for gold deposits, Black Hills, SD: U. S. Geol. Survey Bull., v. 1857-B, p.948-969.
Redden, J. A., Peterman, Z. E.,Zartman, R. 8., and DeWift, E., 1990, U-Th-Pb geochronology and preliminary interpretation of Precambrian tectonic events in the Black Hills, South Dakota: Geol. Assoc. Canada Special Paper on the Trans- Hudson Orogen (in press).
Riley, G. H., 1970, Isotopic discrepancies in zoned pegmatites. Black Hills, South Dakota: Geochim. et Cosmochim. Acta, v. 34, p. 713-725.
Shurr, G. W., Watkins, l. W., and Lisenbee, A. L., 1988, Possible strike-slip components on monoclines at the Powder River basin-Black Hills uplift margin: Wyoming Geol. Assoc. Field Conf. Guidebook, 39th, Casper, Wyoming, Sept. 9-11, Eastern Powder River Basin-Black Hills Guidebook, p. 53-65.
Staatz, M. H., 1983, Geology and description of thorium and rare-earth deposits in the southern Bear Lodge Mountains,

northeastern Wyoming: U. S. Geol. Survey Prof. Paper 1049-D, 52 p.

Zarlman, R. E., and Stern, T. W., 1967 ,Isotopic age and geologic relationships of the Little Elk Granite, northern Black Hills, South Dakota: U. S. Geol. Survey Prof. Paper 575-D, D157-D163.

Van Hise, C. R., 1890, The Pre-Cambrian rocks of the Black Hills: Geol. Soc. America Bull., v, 1. p.203-255.

Geology of Area of the Homestake Gold Mine (Deep Underground Science and Engineering Lab) in Lead, South Dakota

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Introduction

The Homestake gold mine in Lead in the northern Black Hills operated almost continuously from initial discovery in 1876 until final production at the end of 2001. More than 40 million ounces of gold and 8 million ounces of silver were produced, thus making this a giant among world gold deposits. The deposit is hosted by an early Proterozoic iron formation, and has been the subject of numerous scientific studies, yet the understanding of the factors responsible for its origin is incomplete. Questions arise regarding sources of the gold and fluids, timing of fluid migration, and controls on ore deposition.

About the time that the mine was closing in 2001, initial discussions began regarding the potential for development of an underground facility that would allow continuation of physics research on neutrinos. Neutrino research that began in the 1950's by Ray Davis from the University of Pennsylvania resulted in the receipt of a shared (with Masatoshi Koshiba of Japan, and Riccardo Giaconni of the U.S.) Nobel Prize for physics in 2002. Since 2001, the discussions have evolved into full scale planning for a national Deep Underground Science and Engineering Laboratory (DUSEL) utilizing the existing mine opening down to a depth of about 8000 feet below surface. Although the initial impetus for DUSEL was based on research in physics, research in other disciplines such as geology, hydrology, geomicrobiology, biology, and rock mechanics have become integral to the future of the lab.

When the mine was undergoing closure, the owners, Barrick Gold Corporation, offered to donate the mine and mine buildings to the State of South Dakota. Barrick decommissioned the mine, removing equipment including the pumps that kept the mine dewatered. In 2006, the state legislature provided some funding to begin the process of reinstalling pumps and dewatering the workings that had become flooded to the 4550 level. As of March 2010, the water was down to the 5125 level.

Geologic Setting

The DUSEL site in the northern Black Hills of South Dakota lies within the "Lead window", exposed by removal of approximately 1.5 kilometers of Phanerozoic strata in the Paleocene and Eocene. The window results from two structural events: The first is the broad arching (340 km x 165 km) of the NNW-trending Laramide Black Hills uplift during the interval from 64 to 35 Ma; the second is emplacement of Tertiary alkalic plutons (60-40 Ma) near the axis of the arch, resulting in the 10 km–diameter Lead dome.

Exposed within the erosional window are units of the Precambrian metamorphic basement and the Tertiary plutons, which inflated the basement and formed the dome. Precambrian rocks at the DUSEL are complexly deformed and metamorphosed volcanic and sedimentary strata, including the Poorman Formation, Homestake Formation, and Ellison Formation. All of these units were subject to polyphase deformation and greenschist to amphibolite facies metamorphism that occurred between ~1780 and 1715 Ma. Tertiary plutons at DUSEL are a group of NNW-tending rhyolite dikes that are cut by less common, ENE-trending phonolite dikes.

Structural Geology

There are four major Paleoproterozoic deformation events that have affected rocks in the Precambrian core of the Black Hills including folding about ENE-trending axes during north-directed thrusting (D1) (~1780 Ma), folding about shallow to moderately plunging NW-trending axes and development of steeply east-dipping foliation (D2) (~1750 Ma), folding about steeply E- to SE-plunging axes with development of a NNW-striking steeply E-dipping foliation (D3) (~1750-1715), and doming (D4) (~ 1715 Ma). D4 includes the direct effects of emplacement of S-type granite and pegmatite including the Harney Peak granite (1715±3 Ma) in the central Black Hills and the Crook Mountain granite (1718±22) emplaced 6 km to the NE of the DUSEL site. There is evidence for each of these

Paleoproterozoic deformation events in the exposed rocks of the Lead window and the DUSEL site.

The DUSEL site is located on the axis of a major anticlinorium consisting of the Poorman anticline, the Lead syncline and the Lead anticline. Each of these parasitic structures are also complex anticlinoria and synclinoria that have parasitic fold structures referred to as ledges (Caddey et al., 1991). Even-numbered folds (ledges) are anticlines and odd-numbered ledges are synclines; the numbering increases from east to west. Early ledges were named and include Main ledge and Caledonia ledges, which are exposed in the vicinity of the open cut (Stop 5). Ore grade mineralization is typically restricted to the synclines.

Strain in the major anticlinorium is strongly partitioned into 4 discrete domains that can be mapped based on the style and orientation of structures (Fig. 1a, b). Domain 1 dominates deformation on the west side, has a minimum width of 2.5 km, and is characterized by steeply east- to southeast-plunging stretching lineation defined by mineral aggregate, and minor fold hinges are NNW-striking (Fig. 1b, c; Stop 1). Kinematic indicators are typically east-side-up and left lateral. Domain 2 dominates the Lead syncline and linear features including fold axes, mineral aggregate lineation, quartzite rods, and fold mullion plunge steeply to the SE in a uniform fashion (Fig. 1d). The associated foliation strikes slightly more to the NW (346°) compared to domain 1 (338°). Domain 3 is characterized by shallowly plunging fold axes and mineral aggregate lineation (Fig. 1e). Folds are complex and locally include sheath fold geometries (Fig. 2).

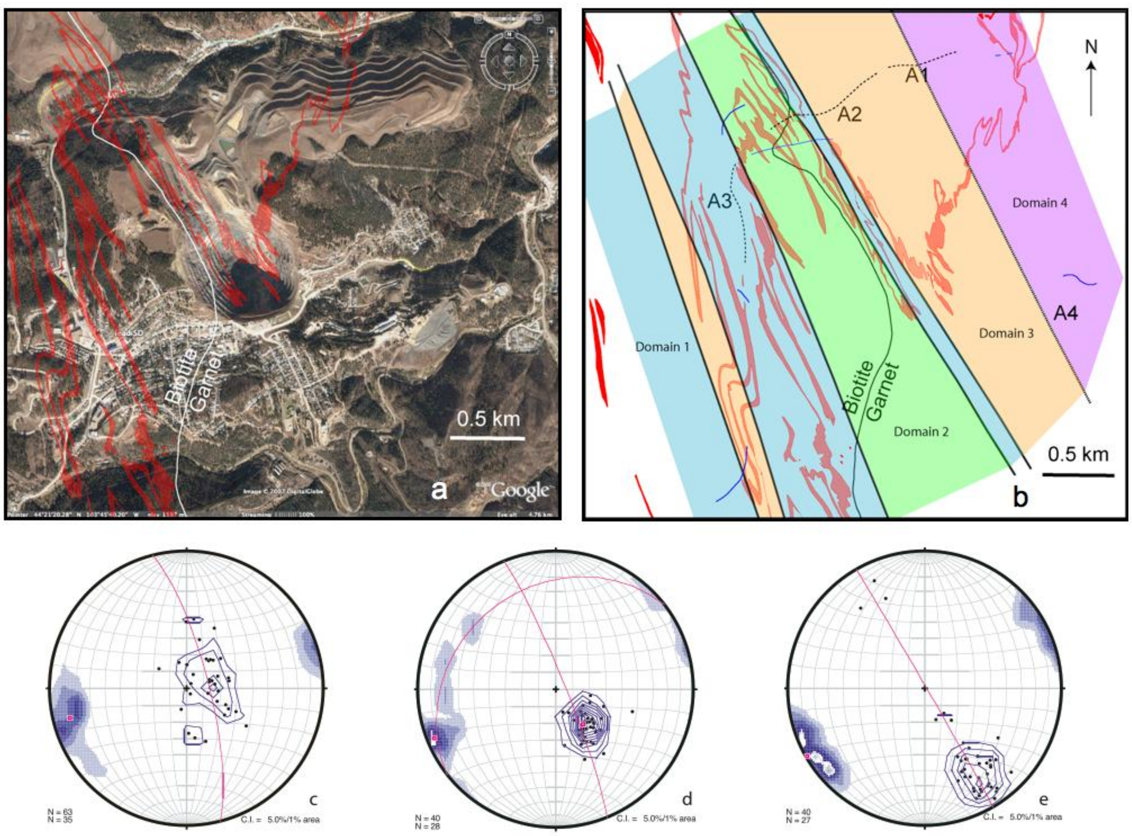

Figure 1. Summary of structural data collected across the anticlinorium. a) Google image of the anticlinorium. Red is the Homestake Formation b) Generalized map of structural domains across the Lead anticline (1, Blue = Domain 1; 2, Green = Domain 2; 3, Tan = Domain 3, and 4, Magenta = Domain 4) and A1-A4 are locations (black dashed lines) where Reid (1982) collected structural data. Blue solid lines are locations where data were collected by Terry et al. (2007). c, d, and e) Lower hemisphere stereonet plots for domains 1, 2 and 3 respectively, showing poles-to-cleavage/layering (shaded contours), hinge lines and mineral aggregate lineations (open contours). Great circles (magenta) show the general orientation of foliation (c, d and e) and best fit to poles-to-foliation (d). All contours are 1% area.

Domain 4 is poorly understood due mainly to the lack of data. This area is currently under a more thorough investigation, and ongoing mapping on the 4850 Level campus in the lab will shed some light on this area. This domain is located on the east limb of the anticlinorium (Fig. 1a, b) characterized by a ESE-plunging folds isoclinal folds and a gently E-dipping foliation (stops 8 and 9). Major structures on the east limb include the City Creek structures (Fig. 1a, b). These structures are cored by Ellison Formation and have very different geometries than the sheath-like folds observed in domain 3.

One important observation made in Figure 1b is that the structural domains and their characteristic geometries are not distributed uniformly across the anticlinorium. Two prominent examples are shown in the map in Figure 1b. Note the narrow strip of domain 3 occurs in a region that has characteristics that are dominantly domain 1 (see stop 2 for details). The most spectacular example of intermixing of domains occurs on the northern end of the open cut (Fig. 1a, b). At this location, a shallowly plunging lineation is folded about steeply plunging axes that are characteristic of domain 1 (Figure 2a, b). Immediately to the east of this location, the lineations, including axes of minor folds and mineral aggregates, are very shallowly plunging (Figure 2 c, d, and e).

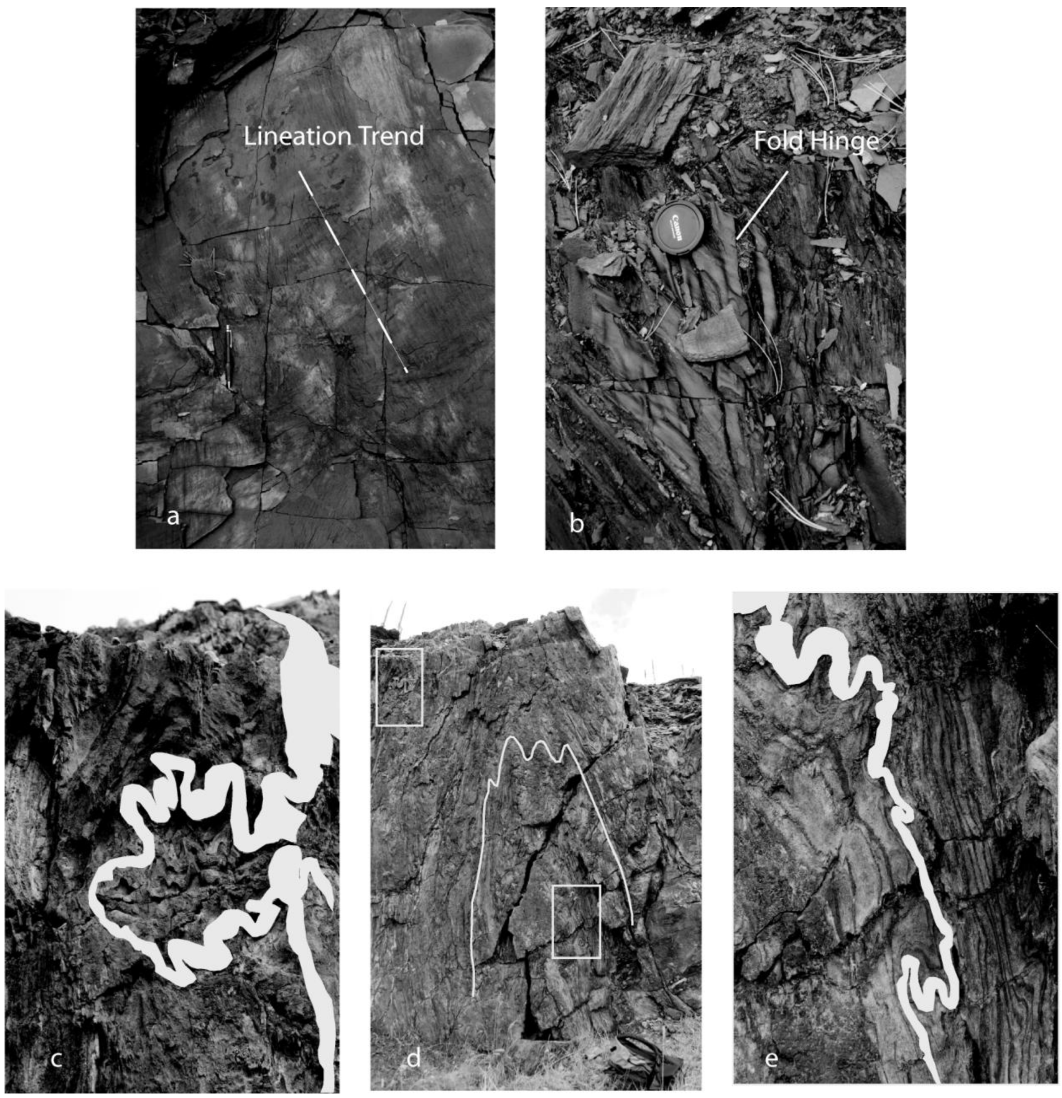

Figure 2. Photos from north open cut (stop 4) showing contrasting structures across domain 1 (a, b) and domain 3 (c, d, e) boundaries. Photos a and b are taken facing west and show steeply-plunging fold hinges and lineation. Photos c, d and e are taking facing south and show shallowly-plunging folds.

In summary, the anticlinorium is a moderately SE-plunging fold with a steeply east-dipping foliation that is correlated with regional D2 deformation. The west limb of the anticlinorium is overprinted by a high strain deformation (D3) associated with domain 1. In the higher strain west area, D3 is associated with steeply plunging NE-trending reclined folds and lineation. Folds are tight to isoclinal and locally have sheath fold geometries. Toward the east, in lower strain zones, linear structural elements have steep SE plunges (domain 2) that give way to earlier moderately southeast plunges, indicated by overprinting relationships seen in Figure 2a, b. It has been proposed by Caddey et al. (1991) that the complex folds seen on the eastern limb (City Creek structures) represent regional D1 structure. The youngest ductile structural feature that can be seen locally across the anticlinorium is a shallowly dipping crenulation cleavage that Caddey et al. (1991) have correlated with the emplacement of the Crook Mountain granite.

Metamorphism

Metamorphic grade in the northern Black Hills increases from biotite zone west of the Homestake Mine to sillimanite+K-feldspar zone under Paleozoic and younger cover rocks to the northeast of the mine (Figure 1). Temperature estimates using garnet-biotite geothermometry range from approximately 350° to 630°C (Kath, 1990; Terry et al., 2003). Pressure estimates for metamorphism range from 3.5 to 5.0 kb (Kath, 1990). The timing of metamorphism overlaps with D2 deformation folding and continues through D3.

The largest part of the ore ledges (centroids) are located in domain 1. The deposit is located on the western limb of a major anticlinorium that coincides with a vertical N-S-striking garnet isograd, and garnet-biotite geothermometry of metapelites sampled across the anticlinorium indicates a steep metamorphic field gradient of 150°C/km (east side warmer) (Terry et al. 2003, 2007). This gradient is coincident with a pronounced increase from west to east in vein quartz $\delta^{18}O$ ranging from 10 to 18 per mil (Rye and Rye, 1974).

In the high strain or shear zone on the west side of the anticlinorium, kinematic indicators are left-lateral and east-side-up indicating sinistral-oblique motion. These results agree with previous structural studies in the Homestake mine ~2.5 km vertically below this study area. The shear zone is coincident with the garnet isograd.

Geochronology

The timing of Paleoproterozoic events associated with metamorphism, deformation, mineralization, and Crook Mountain Granite magmatism have been of great interest due to the amount of gold production associated with Homestake gold mine. In the DUSEL site, successful attempts to date these events have been made by Frei et al. (2009), Morelli et al. (2010, in press), and Chasten (2009). Frei et al. (2009) separated garnet from a sub-surface sample of the Homestake Formation collected from the nose of the so-called "main ledge" syncline, and subjected to Pb stepwise leaching (PbSL) to determine the age of garnet growth and thus metamorphism. PbSL analysis revealed a $^{207}Pb/^{206}Pb$ age of 1746 ± 10 Ma (± 2σ). Frei et al. (2009) also determined a $^{207}Pb/^{206}Pb$ age for arsenopyrite of 1719 $^{+38}_{-45}$ Ma and interpreted this to be the age of mineralization. A more precise age Re-Os age of 1736 ± 8 for arsenopyrite is reported by Morelli et al. (2010, in press). The Crook Mountain Granite and associated pegmatite from Whitewood Peak yield ages of 1718 ± 22 Ma (Gosh et al., 2009) and 1713 ± 10 Ma (Hark et al., 2008), similar in timing to emplacement of the Harney Peak granite (1715 ± 3 Ma) in the southern Black Hills Precambrian core.

Chasten et al. (2009) and Chasten (2009) focused on total lead dating of low Th monazite in the Homestake Formation. In this work several growth episodes were identified by chemical and textural differences in samples from gold mineralized and unmineralized rocks and from different metamorphic grades across the mine. A core domain of ~1848 ± 16 Ma supports previously seen subordinate ages as an indication of growth during the early Trans-Hudson orogeny (THO) in the Black Hills, where terminal Wyoming-Superior collision did not occur until ~1750 Ma (Black Hills orogeny) (Dahl et al. 2005a, b). A monazite to allanite reaction texture included in garnet (Fig. 3) preserves the age of this reaction as 1757 ± 30 Ma, and monazite included in garnet clusters around D1 at ~1775 Ma. Within the matrix, ~1750 Ma monazite ages correspond to regional D2. A matrix monazite grain with concentric zonation contains D1- and D2-age domains as well as a younger ~1670 Ma domain and later reaction texture, corresponding to accretion of the Mazatzal terrane and related mineral growth after the terminal Black Hills orogeny and Harney Peak/Crook Mountain granite magmatism. The timing of monazite growth event is consistent with those reported by Dahl et al. (2005a, b), however no monazite age associated with the Crook Mountain Granite has been recognized in the DUSEL site.

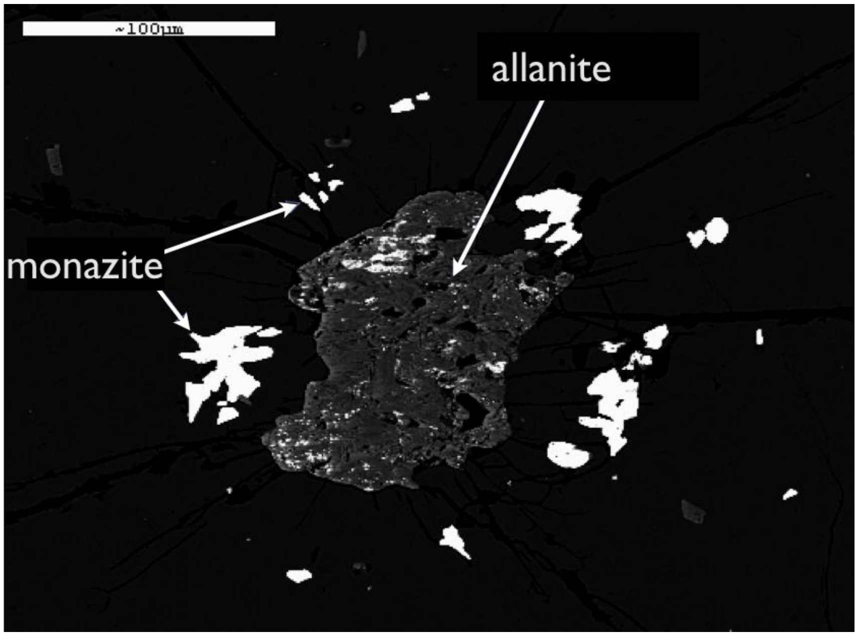

Figure 3. Allanite to monazite reaction texture on the core of a garnet (17760-325)

Deep Underground Science and Engineering Lab at Homestake (source http://dusel.org/)

The Deep Underground Science and Engineering Lab (DUSEL) at Homestake will address the underground needs of all of the major scientific fields included in the NSF solicitation process: particle and nuclear physics, geology, hydrology, geo-engineering, biology, and biochemistry (Fig. 4). The former Homestake Mine was the deepest mine in North America with rooms at 8000 ft., well-suited for experiments that require extremely low cosmogenic backgrounds: in particular, the search for neutrino-less double beta decay and relic dark matter. The Yates unit of the Poorman Formation has well characterized strong rock that can support deep large cavities for very large multipurpose detectors for proton decay and neutrinos from many different natural sources. These large detectors can be used for long baseline neutrino experiments using beams from US accelerator laboratories located at appropriate distances from Homestake. The large number of tunnels, shafts, boreholes, dedicated access and well known patterns of water flow will allow studies of the dynamics of the earth's crust and critical issues of carbon sequestration and rock mechanics over long time scales and many length scales. The dedicated access and the diverse geology at Homestake are well-suited for studies of microbiology and life at extreme depth.

Summary of Homestake DUSEL Geoscience Research Projects:

Larry D. Stetler (SDSM&T) has several projects in progress:
Microclimate Monitoring: Recording stations located on the 800, 1250, 2000, 2600, and 4850-ft levels that include air temperature, relative humidity, and barometric pressure. A surface station contains additional instrumentation including wind speed and direction, precipitation, and is online at http://204.114.27.11/.
Water Reduction Measurements: Instruments deployed in 6 winze from the 4850-ft level include temperature, specific conductance, and a pressure transducer.
Slow Ground Motion: 18 tiltmeters installed on the 2000-ft level in three arrays.
Hydraulic Assessment of Large Cavities: Pressure and flow testing of drill-holes on the 4850-ft level to determine aquifer and hydraulic properties of the area to be excavated for large physics experiments.

Michael Terry and Alvis Lisenbee (SDSM&T) are currently working with Golder Associates preparing a geologic model of the 4850 Level between the Ross and Yates shafts. The purpose of the model is to assist in locating sites for three chambers, the largest ever constructed at this depth, which will house enormous water tanks used in determination of neutrinos fired from the Fermi Laboratories in Chicago. The first chamber is currently sited within

Tertiary rhyolite dikes and amphibolite of the Yates Member. The study synthesizes information from several thousand feet of detailed drift maps and oriented cores.

Michael Terry (SDSM&T) and his students are working on the structural and metamorphic evolution of the Paleoproterozoic rocks in the area of the DUSEL site. Studies include U-Th-total Pb dating of monazite, deformation mechanisms in quartz across a steep metamorphic field gradient using SEM-EBSD and rock fabric anisotropy and rheologic properties using microstructural analysis and SEM-EBSD.

Colin Paterson and Michael Terry (SDSM&T) and their students and Kelli McCormick (SDGS) (I don't know if you need to include me – I've hardly done anything with this, though I hope to in the future) are using drill core and data from the Homestake document archive to investigate controls on ore deposition in the Homestake deposit. The projects include analysis of mineral chemistry of chlorites from alteration zones, petrography and chemistry of alteration adjacent to mineralization, and assessment of controls on localization of mineralization in synclinal structures (ledges) in preference to anticlinal structures. Colin is also collaborating with Ross Large and Jeff Steadman (University of Tasmania, Australia) on sulfur isotope and trace metal studies of mineralization and testing the epigenetic model of formation.

Maribeth Price and her students at SDSM&T, in collaboration with Mary Kopco and Carolyn Weber at the Homestake Adams Research and Cultural Center (HARCC), are working to assemble a GIS-hosted spatial map index for thousands of original hand-drawn geology maps that are now archived at HARCC. The database will include geologic maps from each level, the drifts and other infrastructure, and extents of the available maps to allow users to search for maps available for various areas. Eventually all of the maps will be scanned, allowing users to search and select maps for viewing remotely without needing to visit the center. The maps contain a wealth of information not otherwise available, including lithology, mineralogy, attitudes of bedding and foliations. A pilot project to design the database is in progress in Spring 2010. Completion of the database will likely take years and will require us to apply for significant funding to complete the task.

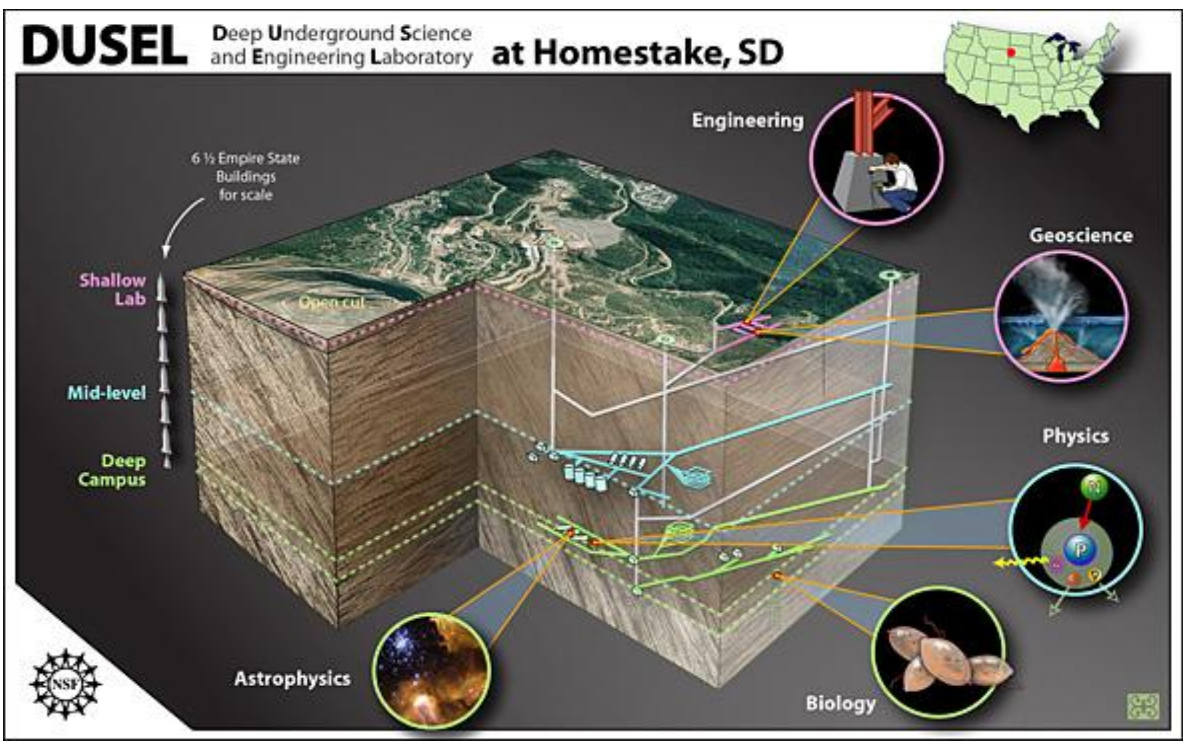

Figure 4. Proposed layout of Homestake DUSEL.

Nuri Uzunlar (SDSM&T) is collaborating with Eric Sonnenthal (UC Berkeley and Lawrence Berkeley National Lab), Derek Elsworth (Pennsylvania State Univ.), Barry Freifeld (Lawrence Berkeley National Lab), Robert Lowell (Virginia Tech), Kate Maher (Stanford University), Brian Mailloux (Barnard College) on a Coupled Thermal-Hydrological-Mechanical-Chemical-Biological (THMCB) Experimental Facility. This involves developing a preliminary design for a large-scale subsurface experimental facility to investigate coupled processes in fractured rock at depth. Fundamental geochemical, isotopic, and microbiological laboratory experiments, and numerical modeling would guide the experimental design and evaluation of the time and spatial scales of the coupled THMCB processes. The only way to fully understand such processes is to carry out well-controlled experiments at a range of scales (grain/pore-scale to decimeter-scale) that can be interrogated and modeled. The THMCB experimental facility is also intended to be a unique laboratory for testing hypotheses regarding effects of heat and chemical reactions on microbial communities. Will microbial communities and gene assemblages evolve rapidly in response to changes in heat-flow and stimulate changes in subsurface geochemistry? Does hydrothermal circulation alter the availability of nutrients, trace metals, and control observed microbial responses? Will microbial species and gene diversity decrease in the hottest zones but increase in zones of moderate temperatures with altered nutrient fluxes?

Road Log:
The route begins outside the lobby of the Rushmore Plaza Holiday Inn, east of the Civic Center, 5th Street, Rapid City.

0.0 miles: Turn right on to 5th Street, and head south, crossing Rapid Creek.

0.25 0.25: Turn right on Omaha Street, and drive westward, following the floodplain of Rapid Creek. During the day of June 9, 1972, a torrential rain (12"-15") fell along the eastern flank of the Black Hills, and especially in the Rapid Creek drainage between Rapid City and Pactola dam. This water produced a catastrophic flood through Rapid City, destroying homes, businesses, and resulting in about 240 deaths. A one hundred million dollar reconstruction plan, aided by several Federal programs, set aside much of the land along the flood plain as a recreational greenbelt through the city. Average stream discharge here is 60 cfs. Peak discharge during the flood was estimated to have been 50,000 cfs (Lisenbee et al., 1996).

0.75 0.50: Turn right on I-190, and head north. A ridge of upper Cretaceous Newcastle Sandstone is on the left (west). The highway follows an overpass over I-90. Merge on to I-90 west.

2.8 2.05: The hogback comprises mostly quartz arenites of the Lower Cretaceous formations (Fall River and Lakota), and Jurassic-aged Unkpapa and Morrison formations. West of the hogback, I-90 follows the red shales, siltstones, fine sandstones and gypsum of the Spearfish Formation (Triassic), northward to Sturgis.

6.0 3.2: Straight ahead to the north, a large sand and gravel operation occupies a gently eastward-sloping terrace of White River Group rocks. This Oligocene formation comprises alluvium that discharged in river systems off the Black Hills uplift that began its rise about 62 Ma. The alluvial deposits preserved as east-sloping ridges, both north and south of Rapid City, probably represent the locations of the paleostream channels. They overlie with slight angular unconformity the older rocks ranging from Precambrian metamorphic in the hills to the west to upper Cretaceous sedimentary formations in the east. Finer-grained equivalents of these sediments occupy the White River badlands southeast of Rapid City.

6.9 0.9: Partially obscured on the right (east) is a small open pit that is the site of gypsum mining, providing material for the cement plant in west Rapid City.

11.7 4.8: Exit 48, Stagebarn Canyon

12.6 0.9: Stagebarn Canyon on the left is rimmed by cliffs of Minnekahta Limestone (Permian).

13.8 1.2: At Exit 46, there is a view of Little Elk Monocline at 10 o'clock.

30.4 16.6: Take Exit 30 at Sturgis, and turn left on to Boulder Canyon road (Highway 14A), and drive west under I-90.

31.2 0.8: Trailer house park on right on the flood plain was threatened during heavy rains and flooding in May 1995.

31.8 0.6: The road enters Boulder Canyon, beginning the traverse of the Permian to Cambrian sedimentary section with low cliffs of the Minnekahta Limestone (Permian). This is the same limestone that is mined in several places around the Black Hills for road aggregate and feedstock for the cement plant.

32.5 0.7: The high cliffs rising to the west (straight ahead) comprise the Minnelusa Formation (Mississippian to Pennslyvanian). Bear Butte Creek is usually dry, the water having already entered the Madison aquifer through loss zones.

32.8 0.3: Pahasapa Limestone (Mississippian) is well exposed on the right. Bedding is mostly preserved, and dips eastwards. Locally, the formation is chaotic, consisting of reddish iron-stained brecciated carbonate rocks, with calcite-lined cavities and small caves. The breccia zones are likely the result of cave collapse. In the subsurface, this formation is the Madison aquifer.

33.8 1.0: The road turns left to follow the southerly-trending axis of the Whitewood Anticline. The high cliffs consist of the Minnelusa Formation, and the underlying Pahasapa Limestone is exposed at road level by the bridge over Bear Butte Creek.

34.4 0.6: Opeche Shale (Permian) behind the house underlies the cliff of Minnekahta Limestone. Along this straight section of road the open area of the golf course Spearfish Formation (Triassic to Permian) forms the core of an open, northerly-trending Boulder Park syncline.

36.2 1.8: Road rises on dip slope of Minnekahta Limestone.

36.6 0.4: Camp 5 road on left. From here to mile 38.1, prominent roadcuts on right (north) display Pahasapa Limestone characterized by iron-stained breccias.

38.2 1.6: Englewood Formation (Mississippian to Devonian) on right.

39.6 1.4: Gravels on road cuts on right and at open area at top of hill are of the White River Group (Oligocene).

39.9 0.3: Roo Ranch on right – kangaroos from Australia reside here.

41.0 1.1: Road descends hill to cross Whitewood Creek – cliffs to left and right are the type locality of the Whitewood Formation (Ordovician), with underlying Winnipeg Shale (Ordovician).

41.7 0.6: Immediately past the junction with Hwy 85 is a small outcrop of Winnipeg Shale (green) overlying glauconitic sandstone of the Deadwood Formation (Ordovician to Cambrian) whose type locality is in high cliffs on right (north) behind the AmericInn Hotel.

42.5 0.8: The Great Unconformity between the Deadwood Formation (Ordovician to Cambrian) and the early Proterozoic metamorphic basement (> 1.8 Ga) is exposed along the gravel track at the base of cliffs across Whitewood Creek to the south. Large boulders of vein quartz were probably derived from Precambrian erosion of Homestake-type gold-quartz veins.

Entering historic city of Deadwood, the site of the old mining town where Wild Bill Hickok was shot in the No. 10 Saloon holding the "Dead Man's Hand" (aces and eights). Deadwood is the site of legalized gambling which has resulted in historic restoration.

Continue through town on Highway 14A/85.
43.8 1.3: The Broken Boot "gold" mine, a tourist mine, was originally mined for pyrite. The exposed rocks through the canyon of Deadwood Creek are Precambrian metamorphics.

44.6 0.8: Sign for "Second Deadwood Gold Discovery" on right.

44.7 0.1: Pass through Central City – county road 195 Maitland Road and Blacktail Gulch on right. The route is traversing around the north end of the Homestake Open Cut.

45.9 1.2: Cutting Mine Rd on right. Route continues up Poorman Gulch to the Golden Hills Resort hotel.

46.8 0.9: Continue straight at the hotel.

47.6 0.8: Turn right in to parking area by Lewies Pub – walk back to road cut (This stop and others are shown on Fig. 5).

Stop 1: Ellison Formation, Hwy14A/85, SW of Lead [following section is modified from Bachman and Caddey, 1990]

Approximately 300 m of Ellison Formation is exposed in the roadcut. The formation is composed of intensely sheared, sericitic phyllite interbedded with thin quartzite units and tuffaceous metasediments, metamorphosed to biotite zone. The rocks here are uniformly steeply dipping; minor folds are rare. Differential zones of high strain appear throughout the outcrop with preservation of mylonitic fabric. Shearing is generally partitioned along margins of the more competent quartzite units where interbedded with phyllite. Massive quartzites on the western side of the outcrop are intensely sheared internally. This exposure lies in the widest part of structural domain 1 which is dominated by steeply plunging lineations, including aligned mineral aggregates and minor fold axes, and a NNW striking foliation.

Retrace route toward Lead.

48.0 0.4: Stop 2: Poorman, Homestake and Ellison Formations in anticline, right (south) side of Hwy14A/85, SW of Lead [following section is modified from Bachman and Caddey, 1990]

Exposed in the roadcut from east to west are Ellison, Homestake, Poorman, Homestake, and Ellison formations in a gently southeasterly-plunging anticline. The orientation of the fold is characteristic of domain 3 and contains quartzite rods parallel to its axis. There is also a weakly developed steeply plunging lineation that has an orientation parallel to that seen in domain 1 at stop 1 (Fig. 6). The Ellison Formation, largely a sericitic phyllite, is interlayered with quartzite, thus distinguishing it from Poorman Formation, which characteristically is finely banded, with alternating graphite-rich and graphite-poor layers. The Homestake Formation, originally siderite-bearing, weathers rusty brown and is typically veined by quartz. Caddey et al. (1991) defined three stages of veins; the second stage associated with gold mineralization. No economic gold mineralization was discovered on this structure. The 21 ledge synclinal structure is located just east of here up the ridge. Down plunge, the first ore body on this structure is 2600 m below surface.

Continue in to Lead on Hwy 14A/85;
48.3 0.3: Continue straight at traffic lights by the Golden Hills Resort.
49.1 0.8: Turn left into Cutting Mine Rd, and park. Walk to the northeast.

Stop 3: 9 Ledge exposure on old haul road north of Open Cut
Exposed on the reclaimed haul road on the eastern limb of the 9 Ledge syncline (Fig. 7) is a stratigraphic sequence that from west to east includes Poorman, Homestake and Ellison Formations which have similar composition characteristics to those seen at stop 2 though the Homestake Formation does not have the abundant veining seen previously. The fold plunges here are steep to the southeast and typically very uniform (Figure 1d). These are very characteristic of Domain 2 (Fig. 1b). There is spectacular rodding and minor folds that are cut by a shallowly dipping crenulation cleavage (S4). A notable exception to the steep plunges seen in most of the outcrop is the moderately plunging fold in the Ellison Formation at the east end of the exposure. The 9 Ledge structure is mineralized down plunge from our present location. Approximately 11 million ounces were removed from this structure over the life of the mine.
Continue toward Central City on Highway 14A/85.

49.7 0.6: Take road on right – this is mine property and not accessible to the public.

Stop 4: North end of Homestake Open Cut.
Located southeast of a metal pump house at the north end of the open cut, the west wall is composed of a pyrrhotite- bearing graphitic phyllite. The exposure contains steeply plunging fold axes and mineral aggregate lineation that are characteristic of domain 1 (Figs 1 b, c, 2a, b). East of this exposure (~50 m) is an outcrop of Homestake Formation containing shallowly plunging folds and lineations that are characteristic of structural domain 3 (Figs 1e and 2c, d, e). This domain 1 region is interpreted as a discrete shear zone and is representative of partitioning of strain that takes place across the anticlinorium.

Return to Highway 14A/85 (49.6 miles), and turn left. Retrace route to Lead.

51.1 1.4: Turn left at Golden Hills Resort hotel.

51.6 0.5: Lead Mining Museum on right.

51.8 0.2: Turn left in to parking lot for the Homestake Open Cut visitor center.

Stop 5: Lunch and Overview of Homestake Open Cut, Main St, Lead [following section modified from Bachman and Caddey, 1990]

Gold in the Open Cut area was first discovered by two Frenchmen, Moses and Frederick Manuel, on April 9, 1876 (Irving, 1904). A quartz outcrop located somewhere near the center of the current Open Cut was the site of the original Homestake lode discovery in 1876. By the following year the numerous claims filed in the area had been consolidated into four large companies. Irving further stated: 'Not long after the mines opened it was found advisable to work them under a single management, and as time went on the Homestake Company came either into control or into actual possession of the other properties...' The gold ore was free-milling, and by the summer of 1878, 80 stamps were in operation in mills near large open cuts on the steep hillside. By 1880, a total of 740 stamps were crushing 2 to 3 tons of ore each per day. The old headframe of the B & M No. 2 underground mine, one of the early underground operations on the Homestake gold deposit, remains beneath the hill crest. Mining in the Open Cut was renewed as a supplemental surface operation in 1984. Annual gold production from the open cut around 1990 was about 3100 kg (100,000 oz). Annual gold production from surface and underground operations peaked at about 600,000 oz in 1994.

Gold at Homestake can be found both in quartz veins and adjacent wall rock of the Homestake Formation, which is a carbonate-rich iron formation that is recrystallized to garnet-grunerite assemblage above the garnet isograd. Locally within the quartz veins, gold is visible, especially along chlorite selvages. Alteration halos are characterized by chlorite and arsenopyrite, the latter containing micro-crystals of gold (with contained silver) that occur along grain boundaries or microfractures in associated arsenopyrite. There has been considerable debate on the source of the gold – was there a syngenetic source from syn-sedimentary submarine hot springs in the Homestake Formation, with subsequent remobilization during metamorphism or granite emplacement (Rye and Rye, 1974; Sawkins and Rye, 1974; DeWitt, 1996; Redden and DeWitt, 2008), or was the mineralization epigenetic, with gold derived externally from the source rocks outside of the mine formations and emplaced during metamorphism or granite emplacement (Caddey et al., 1991; Frei et al., 2009)? Dahl (2010) concluded that the geochronologic data (see earlier section) and the contrast in Pb isotopic characteristics of barren versus mineralized Homestake Formation "points more to an epigenetic origin rather than to a syngenetic (or syngenetic but remobilized) origin for the massive gold deposit hosted therein."

Within the Open Cut, a series of antiformal and synformal fold structures known as Main Ledge, plunge southeasterly at 35 degrees, roughly between the Ross and Yates Shafts. The Main Ledge ore system has produced more than 75 million tonnes of gold ore at an average grade of 8.15 g/t (0.26 oz/t) gold. The Main Ledge structure extends more than 5000 m down plunge to depths of 2300 m below the surface. A series of light-colored, Tertiary-age dikes of rhyolitic composition are exposed in the northeast highwall of the Open Cut (Fig. 8). The 'dike swarm' was emplaced along the eastern margin of a major Early Proterozoic ductile shear zone, the Main Ledge Deformation Zone (MLDZ). At depth and on the surface, the volume of Tertiary igneous rocks in the 'dike swarm' markedly decreases along strike away from the Homestake Formation. Where the dikes intersect the overlying Cambrian/Precambrian unconformity and flat-lying Deadwood Formation, the Tertiary igneous rocks spread out laterally to form sills within the Deadwood Formation (rusty brown horizons in the open cut).

It is difficult to discriminate the individual Early Proterozoic formations (Ellison, Homestake, and Poorman) from the overlook vantage point (see Fig. 9). In general, however, the hematitic red color in the northeast highwall represents weathered Homestake Formation with rocks of the Ellison Formation lying to the east. The southwest highwall is generally Poorman Formation. The Open Cut floor consists of all units complexly intermixed in southeast plunging, isoclinal folds.

The garnet isograd, as mapped by Noble (1939), occurs slightly west of the southwestern Open Cut highwall. Caddey et al. (1991) postulated a syn-deformational development and control for the isograd. They indicate a near vertical dip on the garnet zone as expressed in the Homestake Formation on multiple underground levels. Homestake Formation west of the garnet zone is generally siderite-dominant (upper greenschist facies) whereas to the east it is grunerite-dominant (lower amphibolite facies).

North of the ridge on the east side of the Open Cut, the old Reno mine penetrated the base of the Deadwood Formation exploiting thick paleoplacer conglomerate for its gold content. The unusual thickness of the conglomerate at that site suggests that this represents a fluvial channel. The conglomerate, which is dominated by quartz pebbles, cobbles and boulders, is locally silicified, presumably by Tertiary hydrothermal fluids. "Also to the east of the Open Cut, the Golden Terra mine took gold from conglomerate ores and a sediment-hosted replacement deposit in stratigraphically higher dolomite of the lower Deadwood Formation. The dolomitic ore carried about 3.1 g/t (0.1 oz/t) Au.

'Intrusive breccias' are common along the margins of the rhyolite dikes and locally extend outward, or upward, from them into the Precambrian country rock or into the overlying Tertiary rhyolite sills and the Deadwood Formation. Their compositions may vary such that one breccia dike is dominated by rhyolite fragments whereas another nearby consists chiefly of fragments of Precambrian schist in a black, rock flour matrix of the same material.

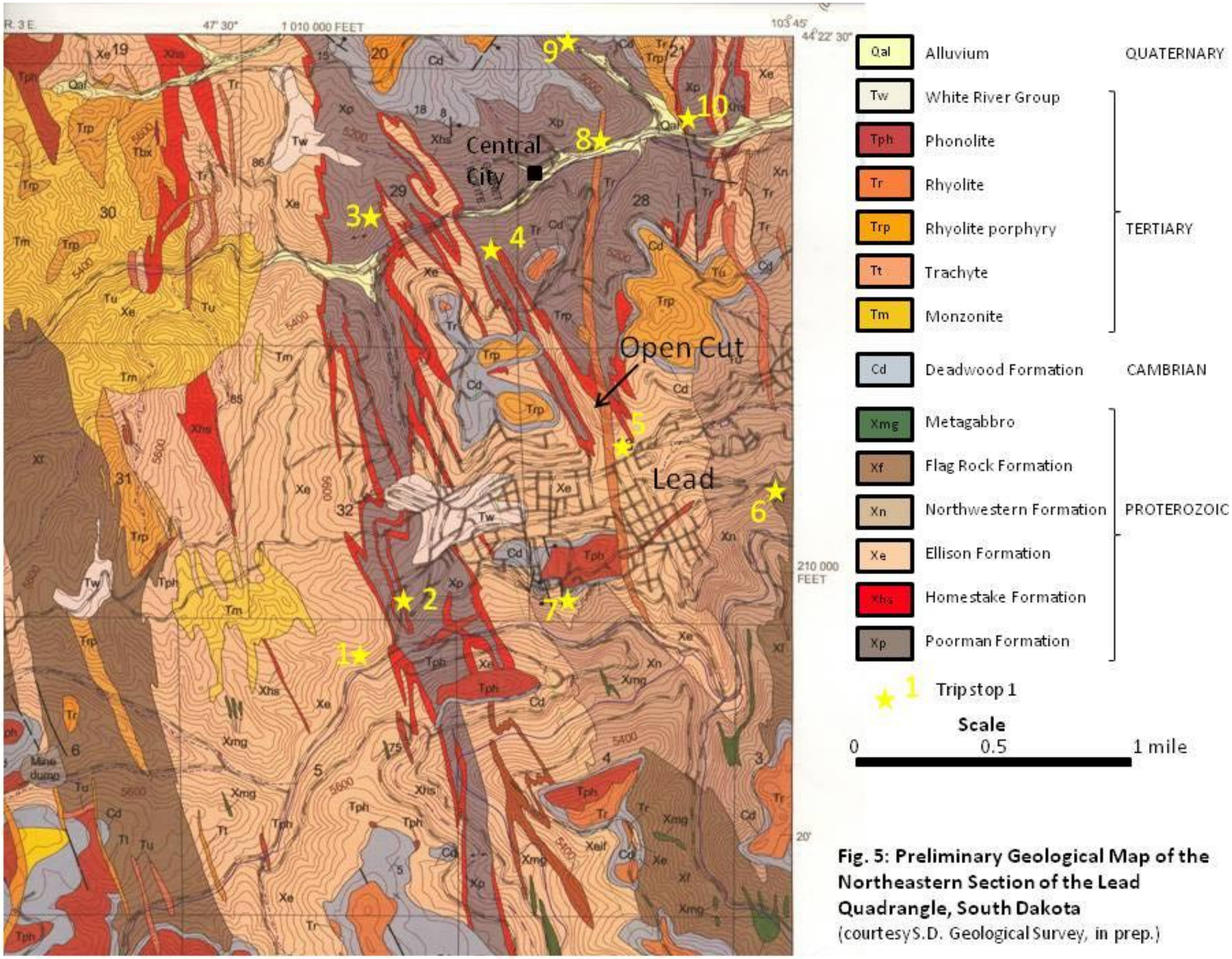

Fig. 5: Preliminary Geological Map of the Northeastern Section of the Lead Quadrangle, South Dakota
(courtesy S.D. Geological Survey, in prep.)

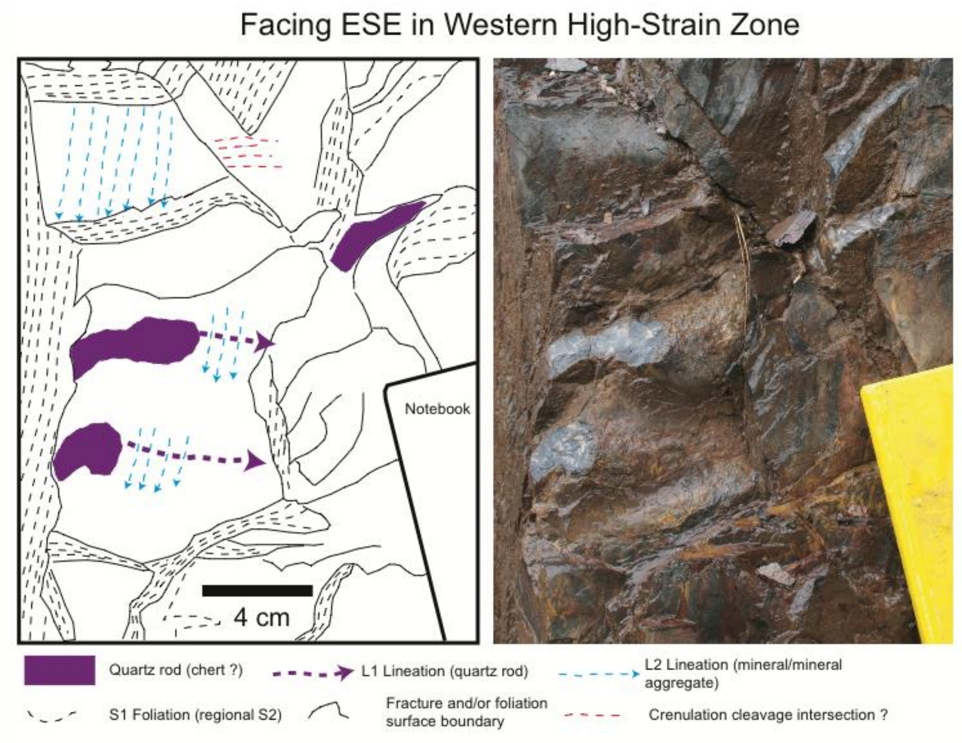

Figure 6. Sketch showing relationships between early and late linear features at stop 2. S1 and S2 correlate with regional D2 and D3 events.

Figure 7. Exposure on old haul road (facing north) that contains Poorman, Homestake and Ellison Formations (Stop 3).

Tertiary precious-base metal veins in Precambrian rocks extend from surface exposures in the Reno mine NE of the Open Cut down to at least the 8000 foot level in the Homestake mine, and are texturally and mineralogically zoned with depth and proximity to the Tertiary dike swarm (Uzunlar et al., 1990). These veins locally cut Tertiary dikes, and contain saline fluid inclusions and stable isotope signatures that suggest a magmatic hydrothermal fluid source. Sediment-hosted Carlin-like mineralization in the Deadwood Formation (e.g. the active Wharf gold mine near Terry Peak) is the distal manifestation of similar Precambrian-hosted, Tertiary-aged veins (Uzunlar, 1993).

Figure 8. Geology of the Homestake open cut, Lead (viewed to northeast). Steeply-dipping rhyolite dikes (light colored) cut the metamorphic section, and flatten out to sills within the Deadwood Formation (dark brown horizontal layers) immediately above the unconformity.

The question of the metallogenic relationship between the Homestake ores and the younger deposits is not completely resolved. Clearly, the spatial association of basal Cambrian paleoplacer deposits with resistant ridges of Homestake Formation on the Precambrian paleosurface suggests that the paleoplacers derived their gold from the Homestake deposits (French, 1986). The Tertiary igneous-hosted and sediment-hosted deposits in the Phanerozoic rocks are generally relatively small and low in gold grade, and it is considered that they did not depend on a rich gold source in underlying Homestake Formation (Paterson et al., 1988), but the ore fluids and the gold were likely associated with the Tertiary alkalic magmatism. In addition, Tertiary veins and intrusions which cut the Homestake Formation have a narrow alteration halo, and have apparently not remobilized significant gold.

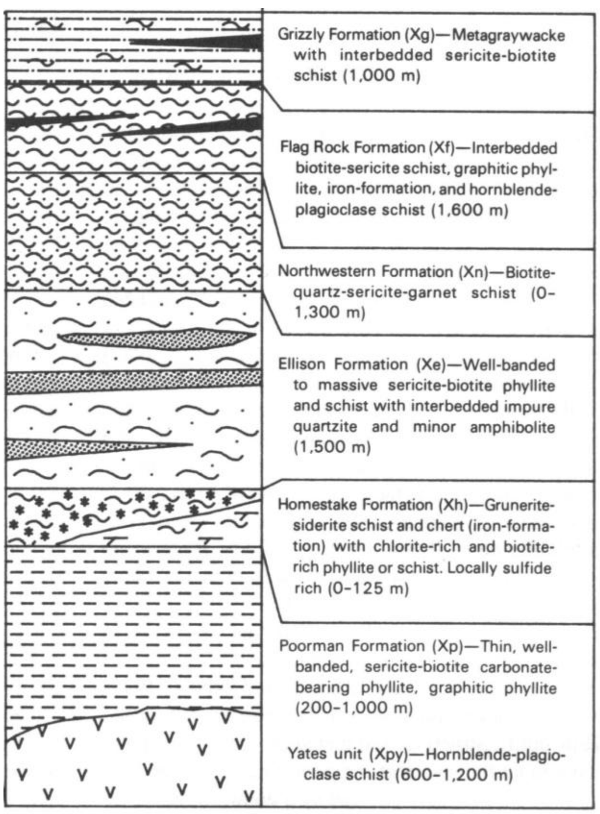

Figure 9. Schematic diagram illustrating Proterozoic stratigraphy of the Homestake mine area, Lead (not to scale). Modified from Caddey et al. (1991).

From the Open Cut, drive south up steep Mill Street, and at mile 52.2, turn left at top, and proceed to the Homestake DUSEL operation.

52.6 0.8: park at DUSEL offices.

Stop 6: Examination of drill core from the Homestake gold mine

Upon exiting the mine, return to Mill Street, and at mile 53.2, veer left down the hill on Mill St, passing cemetery on right.

53.5 0.9: Turn left on to Houston St.

53.7 0.2: Stop 7: Cambrian/Precambrian nonconformity, Houston St, Lead
[following section is from Bachman and Caddey, 1990]

"A nonconformity representing a gap of more than 1.3 billion years separates the steeply-dipping phyllite of the Early Proterozoic Ellison and Northwestern Formations from the overlying flat-lying Ordovician to Cambrian Deadwood Formation (Fig. 10). The basal portion of the Deadwood Formation is exposed in the roadcut and is composed of dolomite, sandstone/quartzite, and conglomerate. The basal quartz-pebble conglomerate is the host for paleoplacer gold deposits in the district. These deposits derived their gold from the Homestake lode (Main Ledge and Caledonia) and occur exclusively near the Homestake open cut and areas to the north (French, 1986)."

Continue on Houston Street to the west.

53.9 0.2: Veer left down hill at Y-intersection on Pavillion St, passing the Lead high school.

54.4 0.5: Turn left at Stop sign.

54.5 0.1: Turn right at T-junction on Hwy 14A/85, and proceed towards Central City.

56.5 2.0: Pasties, traditional miner's lunch, may be purchased at the gas station in Central City.

56.7 0.2: Stop 8: Poorman Formation and Tertiary rhyolite dikes on north side of road, Central City [following section is modified from Bachman and Caddey, 1990]

Phyllite of the Poorman Formation is here intruded by Tertiary-aged rhyolite dikes. These dikes are on the northern extension of the Open Cut dike swarm. Dips of foliation/bedding are unusually shallow to the SW, and folds plunge gently SE. Subsurface geology indicates that a frontal lobe of the Yates Member amphibolite (originally tholeiite) underlies this area. Caddey et al. (1991) postulated that the Yates Member acted as a regionally competent strain buttress during deformation, controlling folding and shearing in the bounding phyllites and schists.

Figure 10. Nonconformity between the Deadwood Formation (Ordovician to Cambrian) and metamorphic rocks (Precambrian, about 1.8 to 1.9 Ga), Houston St., Lead. Basal quartz-pebble conglomerates locally are host to paleoplacer gold in the Lead area.

56.8 0.1: Turn left on to county road 195 Maitland Road up Blacktail Gulch.

57.5 0.7: Stop 9: Yates Member, Poorman Formation.
A small outcrop of Yates Member amphibolites is exposed on the right, and also about a hundred yards back in the creek bottom west of the road. Stockwork calcite veinlets and alteration in the outcrop of amphibolite are probably related to the Tertiary-aged epithermal Au-Ag system.

The protolith is interpreted as an oceanic tholeiitic basalt with pillow structures locally exposed elsewhere. The Yates Member is voluminous at depth forming the central core of the Lead Anticline. The unit plunges to the southeast, and is well exposed in the Yates Shaft and No. 4 Winze the Homestake mine. The major cavities planned for the DUSEL are proposed to be sited in the Yates Member because of its inherent competency and lack of pervasive foliation. This exposure is tentatively interpreted to lie within domain 4 although, this may change as more is learned about the influence of differing rheologic properties on the structural fabrics.

Return to Hwy 14A/85
58.2 0.7: Turn left toward Deadwood.

58.3 0.1: Pull off to left at "Second Deadwood Gold Discovery"

Stop 10: Homestake Formation, north side of road, east of Central City [following section is modified from Bachman and Caddey, 1990]

The chert-grunerite-garnet schist of the Homestake Formation is enclosed entirely within upper Poorman phyllites. Metamorphic grade here is garnet zone, increasing to the NE. The Homestake Formation dips gently eastwards, reflecting the influence of the Yates Member at depth. No significant gold mineralization was discovered in the Homestake Formation northeast of the Caledonia ore system.

Continue east to Deadwood, and retrace route to Sturgis and on I-90 east to Rapid City (end of trip at 102.9 miles).

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REFERENCES CITED

Allsman, P.T., 1940, Reconnaissance of gold-mining districts in the Black Hills, South Dakota: U.S. Bur. Mines Bull. 427, 146 p.

Bachman, R.L., and Caddey, S.W., 1990, The Homestake iron-formation-hosted gold deposit, Lead: Road log for surface tour, in Paterson, C.J., and Lisenbee, A.L., eds., Metallogeny of gold in the Black Hills, South Dakota: Soc. Economic Geologists Guidebook Series, v. 7, p. 129-135.

Caddey, S.W., Bachman, R.L., and Otto, R.P., 1990, 15 ledge ore discovery, Homestake mine, Lead, South Dakota: 4th Western Regional Conference on Precious Metals and the Environment, Black Hills Section, Society for Mining, Metallurgy and Exploration, 1990 Meeting Proceedings Volume, p.405-423.

Caddey, S.W., Bachman, R.L., Campbell, T.J., Reid, R.R., and Otto, R.P., 1991, The Homestake gold mine, an early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota: U.S. Geological Survey Bull. 1857, 67 p.

Chasten, L., 2009, Electron microprobe (Ultrachron) geochronology of monazite from the Homestake iron formation, Lead, Black Hills, South Dakota, USA: Unpub. M.S. thesis, South Dakota School of Mines and Technology, 97 p.

Chasten , L.E., Terry, M.T., and Jercinovic, M.J., 2009, Electron microprobe dating of monazite from the paleoproterozoic homestake iron formation at the deep underground science and engineering laboratory, South Dakota, USA: constraining reactions and episodes of mineral growth within the Homestake mine: Geological Society of America Abstracts with Programs, v.41.

Dahl, P.S., Hamilton, M.A., Jercinovic, M.J., Terry, M.P., Williams, M.L., and Frei, R., 2005a, Comparative isotopic and chemical geochronometry of monazite, with implications for U-Th-Pb dating by electron microprobe: An example from metamorphic rocks of the eastern Wyoming craton (U.S.A.): American Mineralogist, v. 90, p. 619–638.

Dahl, P.S., Terry, M.P., Jercinovic, M.J., Williams, M.L., Hamilton, M.A., Foland, K.A., Clement, S.M., and Friberg, L.M., 2005b, Electron probe (Ultrachron) microchronometry of metamorphic monazite: Unraveling the timing of polyphase deformation in the eastern Wyoming craton (Black Hills, South Dakota): American Mineralogist, v. 90, p.1712–1728.

Dahl, P.S., 2010**,** Precambrian geochronology of the Black Hills, South Dakota: past results and future directions, in Terry, M.T., and Duke, E.F., eds., Guidebook to Geology of the Black Hills (this volume).

DeWitt, E., 1996, Geochemistry of non-mineralized Homestake Formation, Black Hills South Dakota, *in* Paterson, C.J., and Kirchner, J.G., eds., Guidebook to the Geology of the Black Hills, South Dakota: South Dakota School of Mines and Technology Bulletin 19, p. 210-221.

Frei, R., Dahl, P.S., Frandsson, M.M., Jensen, L.A., Hansen, T.R., Terry, M.P., and Frei, K.M., 2009, Lead-isotope and trace-element geochemistry of Paleoproterozoic metasedimentary rocks in the Lead and Rochford basins (Black Hills, South Dakota, USA): implications for genetic models, mineralization ages, and sources of leads in the Homestake gold deposit: Precambrian Research , v. 172, p. 1-24

French, G. M., 1986, Relationships of lithology and ore deposits in the lower Cambrian Deadwood Formation and the Precambrian basement in the Lead-Deadwood dome area, Black Hills, South Dakota: Unpub. M.S. thesis, South Dakota School of Mine and Technology, 69 p.

Ghosh, A. K., 2009, Reconnaissance U-Pb geochronology of Precambrian crystalline rocks from the Northern Black Hills, South Dakota : implications for regional thermotectonic history [M.S. Thesis]: Kent State University, Kent, Ohio, 140p.

Gries, J.P., 1996, Roadside Geology of South Dakota: Missoula, Mountain Press Publishing Co., 358 p.

Hark, J.S., Frei, R., Whitehouse, M.J. and Dahl, P.S., 2008, New evidence for 2.01 Ga rifting in the easternmost Wyoming craton (Black Hills, SD): Implications for break-up of a supercraton (Superia), Geological Society of America Abstracts with Programs, v. 40(6), abstract 145-17.

Irving, J.D., 1904, Economic resources of the northern Black Hills, with contributions by Emmons, S.F., and Jaggar, T.A., Jr.: U. S. Geological Survey Paper 26, 222p.

Kath, R.L., 1990, Petrogenesis of the Homestake iron formation and associated pelitic rocks, Lead, South Dakota: implications for P-T paths, fluid evolution, and gold mineralization: Unpub. Ph.D. dissertation, South Dakota School of Mines and Technology, 228 p.

Lisenbee, A.L., Kirchner, J.G., and Paterson, C.J., 1996, Tertiary igneous intrusions and related gold mineralization, northern Black Hills, South Dakota: Road log, Field Trip 11, *in* Paterson, C.J., and Kirchner, J.G., eds., Guidebook to the Geology of the Black Hills, South Dakota: South Dakota School of Mines and Technology Bulletin 19, p.108-128.

Morelli, R.M., Bell, C.C., Creaser, R.A., and Simonetti, A., 2010, Constraints on the genesis of gold mineralization at the Homestake Gold Deposit, Black Hills, South Dakota, from rhenium-osmium sulfide geochronology: Mineralium Depositum, in press.

Noble, J.A., 1939, Geology of the Homestake gold mine: Ph.D. dissertation, Harvard University, 278 p.

Paterson, C.J., Lisenbee, A.L., and Redden, J.A., 1988, Gold deposits in the Black Hills, South Dakota, *in* Diedrich, R.P., Dyka, M.A.K., and Miller, W.R., eds., Eastern Powder River Basin-Black Hills: Wyoming Geol. Assoc. 39th Field Conference Guidebook, Casper, Wyoming, p. 295-304.

Reid, R.R., 1982, Structural geology of the Homestake mine, South Dakota: Summary Report: Unpub. company report, Homestake Mining Company, 117 p.

Rye, D.M., and Rye, R.O., 1974, Homestake gold mine, South Dakota: I. Stable isotope studies: Econ. Geol., v. 69, p.293-317.

Sawkins, F.J., and Rye, D.M., 1974, Relationship of Homestake-type gold deposits to iron-rich Precambrian sedimentary rocks: Inst. Mining Metallurgy, v.83, p.B56-B59.

Terry, M.P., Dahl, P.S., and Frei, R. 2003, Isotopic and geothermometric constraints on the structural and metamorphic evolution of Homestake gold deposit, Black Hills, South

Dakota (USA) Geophysical Abstracts Volume, 5, EUG05-A-13191.
Terry, M.P., Chasten, L., Dahl, P.S., and Jercinovic, M.J., 2007, Structural analysis of an Early Proterozoic shear zone and its tectonic implications for the Early Proterozoic evolution of the Wyoming province, Homestake Mine area, Black Hills, SD USA: Geol. Soc. America Annual Meeting, Program with Abstracts, v 39.
Uzunlar, N., 1993, Genesis of Tertiary epithermal-mesothermal gold-silver deposits in the Lead-Deadwood dome, northern Black Hills, South Dakota: Unpub. Ph.D. dissertation, South Dakota School of Mines and Technology, 261 p.
Uzunlar, N., Paterson, C.J., and Lisenbee, A.L., 1990, Tertiary epithermal to mesothermal porphyry-related Au-Ag mineralization in the Homestake mine, Lead, South Dakota: mineral and metal zoning, *in* Paterson, C.J., and Lisenbee, A.L., eds., 1990, Metallogeny of Gold in the Black Hills, South Dakota: Society of Econ. Geol. Guidebook Series, v. 7, p. 119-124.

Structural and Tectonic Evolution of the Proterozoic Trans-Hudson-Archean Wyoming Province Boundary.

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Introduction

This trip attempts to give a sampling of various Precambrian lithologies and structural features to provide a general picture of the tectonic evolution of the Precambrian core of the Black Hills uplift. The trip starts with the Nemo area (see Fig. 2 in Dahl, this volume), which differs from the remainder of the Precambrian in that these rocks (excluding small amounts of Archean rocks to the northeast) are largely rift-related clastic rocks in contrast to the deeper-basin sediments (mainly turbidities) and some basaltic flows that are characteristic of the remainder of the Black Hills. The Nemo area is host for some of the oldest metasedimentary rocks that include quartzite and banded iron-formation clasts, and chloritic quartzite. The Box Elder Creek Formation at stop 3 is cut by the Blue Draw metagabbro that has a Pb^{206}/Pb^{208} (titanite) age of 2484 ± 11Ma (Dahl et al. 2004). The stratigraphic and structural development associated with rifting is nicely laid out by Redden and Dewitt (2008) and includes open folding followed by the development of a growth fault related to rifting.

The remainder of the Precambrian core can be broken into two major packages of metamorphosed sediments with lesser amounts of metamorphosed volcanic and related igneous rocks. The older sequence (2484-1900 Ma) contains metamorphosed fanglomerate and quartzite in the Nemo area (refer to Table 1 and Fig. 1 in Dahl, this volume). The most famous group of these rocks are exposed in Lead window and includes the Ellison, Homestake, and Poorman formations, which have a minimum age range of 2012-1974 Ma (Redden and Dewitt, 2008; Frei et al. 2009). Age range equivalents to these formations occur in the area of the Bear Mountain dome and other areas of the Precambrian. The youngest Precambrain sediments (post-1900 Ma) exhibit a very similar sequence and are best exposed in the Rochford area. These rocks again include metamorphosed sediments with lesser amounts of metamorphosed volcanic and related igneous rocks.

The rocks above were deformed by four major Paleoproterozoic deformation events that have affected rocks in the Precambrian core of the Black Hills including folding about ENE-trending axes during north-directed thrusting (D1) (~1780 Ma), folding about shallow to moderately plunging NW-trending axes and development of steeply east-dipping foliation (D2) (~1750 Ma), folding about steeply E- to SE-plunging axes with development of a NNW-striking steeply E-dipping foliation (D3) (~1750-1715), and doming (D4) (~ 1715 Ma). D4 includes the direct effects of emplacement of S-type granite and pegmatite including the Harney Peak granite (1715±3 Ma) in the central Black Hills.

DAY 1

0.0 Depart parking lot at Holiday Inn. Turn South.

0.3 Main Street. Turn right (west) on Main St. at approximately 1.2 miles you pass through the Cretaceous sandstone hogback which more or less divides Rapid City into two parts.

2.6 West Chicago St. (South Canyon Rd., Nemo Rd.). Turn left.

18.6 **Stop 1**. Outcrop along steep slope along west side of road with Steamboat Rock (Pahasapa Fm.) on ridge to east. Stop at the bend in road and walk back to visit outcrop along road. The unit consists of metamorphosed pyritiferous grit, quartzite and pebble conglomerate. This fluvial section, which has radioactivity, is about 100 m thick and was mapped in detail during the original uranium 'boom' in the Nemo area (Redden, 1980). The radioactivity is due to concentrations of various heavy minerals. Detrital uraninite has not been recognized.

21.4 Turn off Nemo Road, turn left past village store on road to Boxelder Creek just before crossing bridge in Nemo, the Boxelder Creek Iron Formation (bif) from the mine crosses the creek but is concealed. Good exposures of the unit occur along the ridge just south of Nemo and on the north side of the town.

22.7 **Stop 2**. (walking) Road crosses creek and pull into parking area on south side adjacent to a prominent cliff of Boxelder Creek quartzite. An old mine drift is barely visible across Boxelder Creek and if one stands on the road and looks south, it is evident that the dip of the quartzite beds differs on both sides of the old drift. The drift is along an E-W trending fault. Park vehicles and follow trail on north side of road (across fence) for approximately 150 m to the north where the trail goes up the west side of a small draw. Walking to the east up slope about 150 m to the left are exposures of the inverted upper contact of the approximately 1000 m thick, gravity differentiated Blue Draw metagabbro sill. Quartz and biotite are readily visible in exposures of the sill top as are outcrops of the Boxelder Creek quartzite unit to the east which was intruded by the sill before later overturning occurred. Return to cars.

23.0 Relatively fresh middle part of sill exposed on right side next to the bridge.

23.2 **Stop 3**. At bend in road bear right and pull onto parking road with large mud hole. About 20 m to the north across the creek bend is a steep slope to the northwest. This slope is approximately the lower 100 m portion of the gravity differentiated Blue Draw sill. If one crosses the creek, the rock on the steep slope consists largely of serpentine containing pseudomorphs of olivine crystals that were as much as 2 cm across. Immediately across the creek at the bend is an outcrop consisting largely of talc. Again this is a product of alteration of the base of differentiated Blue Draw sill. Turn vehicles around and return to Nemo Rd.

24.7 Turn left on Nemo Rd.

26.9 Cross the equivalent of the fluvial section at stop 1which has been displaced by to the NW by listric faults.

28.8 **Stop 4**. Pass steep outcrop and pull off on the right shoulder of the road. Spectacular deformed conglomerate. Clasts including quartzite and iron formation are generally ellipsoidal and define a steeply plunging lineation.

37.7 Nemo road intersects US 385 at Brownsville. Turn left.

49.4 Turn right on Rochford Road.

60.2 **Stop 5**. Road crosses relatively good 'Homestake'-like cummingtonite bearing carbonate facies iron formation with interlayered quartzites that are interpreted to have been chert nodules and/ or layers. The similarities between the stratgraphic sequence here the sequence observed at the DUSEL site (Homestake Mine) are remarkable; however, this sequence is ~100 Myr younger (Redden et al., 1990; Redden and Dewitt, 2008). Return to Rochford.

61.9 Back at Rochford road intersection turn right.

66.5 Mystic Road. Turn right (south).

77.8 Deerfield Road intersection. Turn left.

80.0 **Stop 6**. Newton Pond on right. Pull over to parking area. Walk across road to the north to old railroad track (Mickelson Trail) and turn easterly for about 70 m to where trail is bordered by outcrop. This outcrop has excellent exposures of early folds that are nearly isoclinal folds having NNW trends that have been refolded by later southerly trending folds (Harney Peak age). The rock is part of a widely distributed unit generally referred to as the mica schist unit. It has been traced to the Rochford area where volcanic flows suggest that the aluminous part of the unit in the Hill City areas represents a sea-floor weathered tuff. It also has subunits of biotite-garnet rich rock which can be relatively graphitic and resemble a black shale. Such subunits make it difficult to distinguish this unit from the so-called Oreville black shale unit in the Hill City-Custer areas.

This unit acts as a shear surface bounded by major thrust faults which extend to the South to the Pringle area. These thrusts along the unit possibly were responsible for the original crustal thickening which led to the generation of the Harney Peak granite. Return to vehicles and proceed east toward Hill City.

80.4 Fantastic view of the Harney Peak granite.

83.2 Hill City. Turn left on Hwy 16 and head toward Three Forks.

86.9 Three Forks. Turn left on Hwy 385.

87.0 **Stop 7**. Pull over to right and carefully cross the road. This expose is composed of steeply dipping interlayered metamorphosed greywacke and phyllite.

There is spectacular preservation of primary structures including bedding, crossbedding, and graded bedding. Structural features include steeply plunging folds and boudinage. Return to vehicles and continue north on Hwy 385.

Figure 1. Photo show steeply dipping bedding at the Three Forks exposure.

90.0 Sheridan Lake Rd. Turn right.

94.4 **Stop 8**. Debris flows in the Bluebird Formation. Pull to the right and park, then carefully cross the road to steep south-facing exposures. Return to vehicles and continue along Sheridan Lake Rd.

96.3 **Stop 9**. Pull off to right and park just before the intersection at bend in road. The major structure here has been interpreted as a D1 structure in interlayered metamorphosed greywacke and phyllite. The outcrop is currently the subject of a senior research project. Preliminary data indicate that this fold has been completely overprinted during a later deformation (D2/D3?). The units exposed at the road define a steeply-plunging fold with a well developed WNW-trending axial planar cleavage. The fold axis has a subparallel lineation defined by ellipsoidal shaped spots of biotite and quartz. The spot geometries are currently being used to determine the nature of the strain associated with the youngest deformation. Return to vehicles and continue along Sheridan Lake Rd.

108.0 West Main St. to East St. Joseph St. Turn left.

110.2 Continue to city center and the Radisson Hotel.

DAY 2

0.0 Hotel Parking Lot. Proceed east ~ 0.1 to Mt. Rushmore Rd. Turn right.

0.1 Cross Main St.

2.1 Road climbs hill for 1.6 miles and then have a flat surface for about 2 mi. This flat is underlain by white River Deposits such as in Badlands. Harney Peak is clearly visible to SW.

6.6-9.7 Cross major valley in red beds and following flat is again White River

12.2 Road cut is in Pahasapa Limestone.

12.4 Road now is in Precambrian but no exposure as road splits around the small settlement of Rockerville (named for the rockers used in recovery of placer gold on patches of gravel). Some of which might have been of White River age.

14.9 **Stop 1**. Park on the right side about 150 m before a slight rise and ~200 ft before a power line crosses the road. The outcrop of metagraywacke exposed on the north side of road shows excellent folds that refold as earlier set of folds.

16.1 Stop 2. Shear–fold coupled deformation

The distinguishing components of a coupled shear-fold structure are well exposed along Highway 16 between Rockerville and Hill City S.D. (Figure 3, inset map). Mapping along this portion of Highway 16 and north to Sheridan Lake Road defined four structural domains based on number, style, and intensity of deformation (Figure 1; Portis and Allard, 2006; Allard and Portis 2007; Allard et al., 2009; Allard, 2010, Portis and Allard, in prep). The authors describe a shear-fold couple where strain is partitioned into a NW-striking central mylonite zone (Domain 3; Figures 3 and 4d) bound on either side by zones containing NW-striking F_3 folds oriented parallel to the mylonitic fabric (Domains 2 & 4; Figures 3 and 4b), in turn bound to the west by rocks where only NNW-striking F_2 folds are present (Domain 1; Figures 3 and 6a) and to the east by Paleozoic cover (Domain 5; Figure 3). Subsequent research to the north, predominantly within the Little Elk Terrane, where a window exposes the Proterozoic–Archean contact (Figure 3-inset map; Raymaker and Allard, 2006; Springstead and Allard, 2007; Schoolmeesters and Allard, 2009, Allard et al. 2009; Matzek and Allard, 2010; Schmidt and Allard, 2010), as well as to the west along the Proterozoic–Archean contact in the Bear Mountain Terrane (Figure 3-inset map; Traut and Allard, 2009; Schmidt and Allard. 2009; Allard et al., 2009), identified additional exposures of this coupled structure and interpreted basement-involved, left-lateral, east-side up transpression. Furthermore, the timing of this event is coincident with deformational ages as far west as the central Laramie Mountains in Wyoming, opening the possibility for a regional-scale event (Allard et al, 2009; Allard, 2010; Portis and Allard, in prep.).

This field stop will demonstrate the transition from Domain 2 with an exposure of an F_3 fold (Figure 5), to Domain 3 where a strong shear fabric is present (Figure 6). This stop is on private property and the owners ask we respect their privacy and not publish the location. In order to allow others not on this field trip to view the important exposures related to this structure, provided below are descriptions for locations with open access along Highway 16 and Sheridan Lake Road where similar and associated features are present. The descriptions and interpretations included below will be address at this location during this field trip.

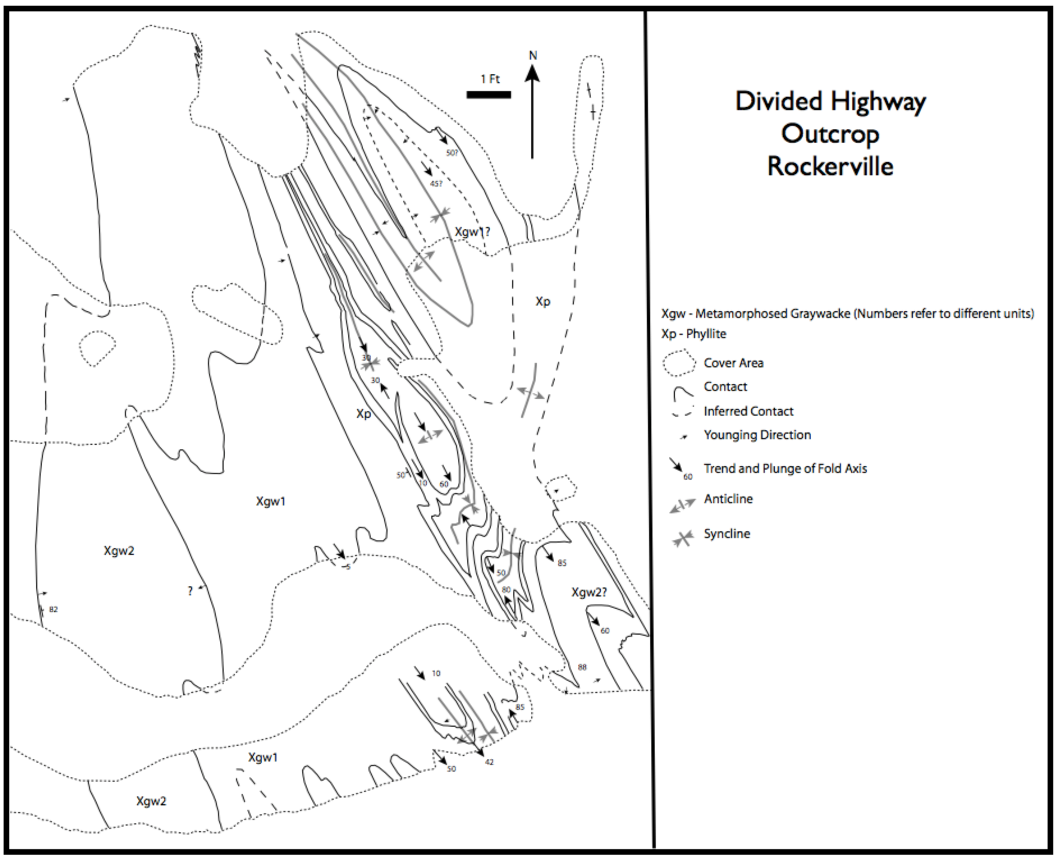

Figure 2. Generalized geologic map of the Divided Hwy outcrop showing folded folds.

O3BH-05, Domain 2: Exposed at this location are metagraywacke and metabasalt deformed by F_3 folding. Near the contact of these two units, the hinge area of a vertical F_3 fold is exposed in the metagraywacke displaying a crenulation of S_2 with overprinting by S_3 cleavage (Figure 7). The amphibolite-grade metabasalt adjacent to and west of this hinge contains both a NW-striking S_3 cleavage and locally is an L-tectonite oriented parallel to the F_3 fold hinge line. Only M_1 metamorphism is present at this location, as is typical of rocks outside Domain 3.

18.6 Turn left toward Keystone. Road follows an irregular valley marked by many mine workings and prospect in what is locally know as the Keystone gold belt. Mostly the gold mineralization is in carbonate facies banded iron formation cut by quartz veins. Small metagubbro bodies are relatively common and the detailed geology is complex. A debris flow unit is also associated with the basalt and metagabbro bodies as well as trickle down quartzites and local unconformities are likely but difficult to recognize due to incomplete outcrop.

21.1 Enter Keystone. Excellent turbidtites with recognizable tops are exposed in outcrops by pullout at signal. Proceed through Keystone toward Mt. Rushmore.

22.0 Stop 3. Pull out at Mt Rushmore Memorial. Stop just beyond to visit outcrop 100' to west. The outcrop in typical turbidities has a relatively large, south plunging syncline (F2) visible form the south side but on the north vertical side careful examination shows a earlier (presumably F1 fold) which has been refolded. On the extreme east side of outcrop, a complete Bouma sequence can be recognized ending with small cross beds. Continue up to Mt Rushmore but go past entrance to what is called the profile pullout.

24.7 Stop 4. Profile pullout. A brief stop to note refolding and deformation of the calc-silicate concretions and some of the oldest metamorphosed black shale unit which lies to the west of the carvings and is exposed in the center part of the granite dome. The geology here is obviously quite complicated due to the emplacement of the Harney Peak granite. Back track to Keystone and up north hill to U.S. 16 then turn to the left (west) on U.S.16.

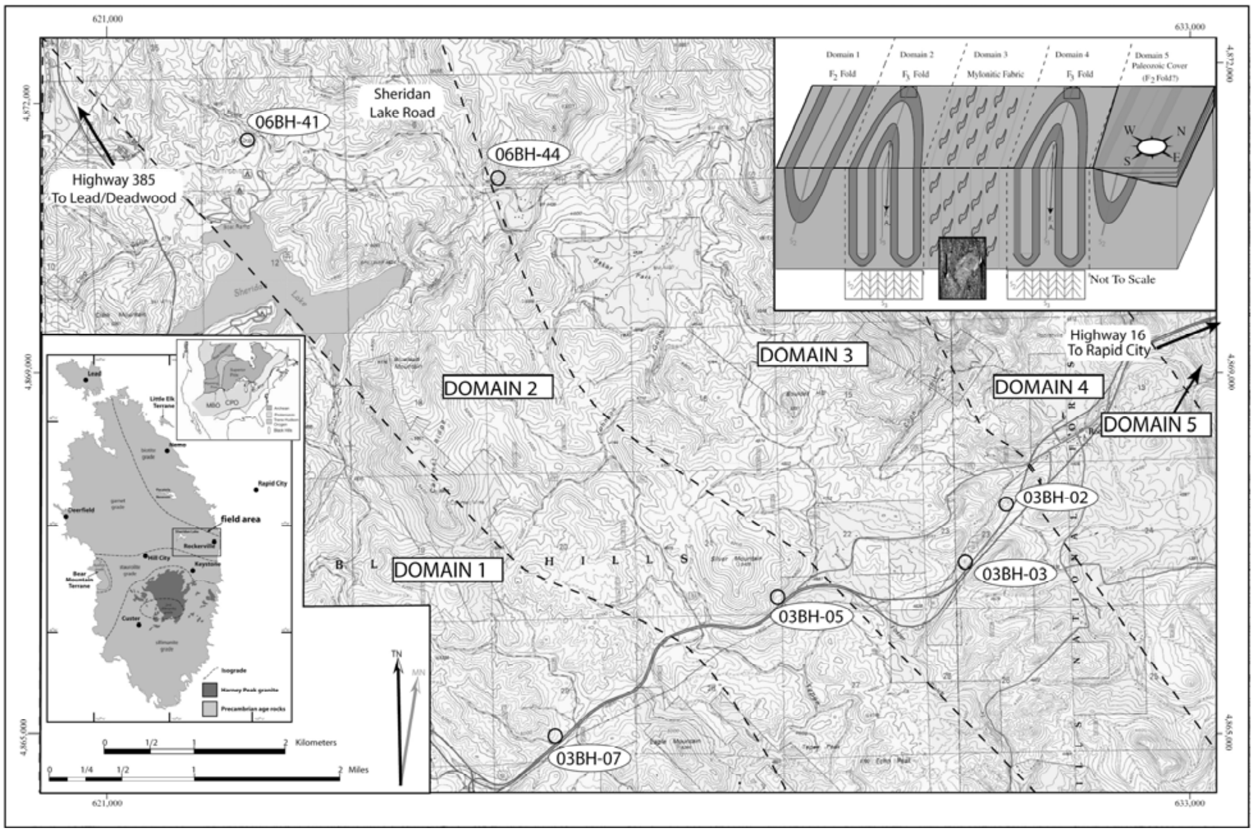

Figure 3. Location map of the Rockerville field area (Portis and Allard, 2006). Structural domains separate structural styles with increasing strain from outer to inner domains. Domain 1 contains F_2 folds only, Domain 2 and 4 contain F_2 and F_3 folds, Domain 3 contains mylonitic fabric and locally F_3 fold hinge areas (inset diagram and Figure 2). Inset map of the Black Hills, South Dakota, after Strobel et al. (1999). Metamorphic isograds from Helms and Labotka (1991) and Nabelek et al. (2006). Box in east-central Black Hills indicates location of Rockerville field area for this study. Location for Little Elk Terrane and Bear Mountain Terrane field areas also shown.

31.3 Stop 5. Pull off on U.S. 16 by the 55 mph sign. Excellent exposures of metagraywacke occur for about 200' to the west. Very fine grained garnet is visible in some dark beds but in general the rocks appear to be relatively low metamorphic grade. However on the west are exposures with relatively euhedral staurolite. On the north side of the main mass of Harney Peak granite and about a mile to the south of U.S. 16 are extensive spotted schists which developed due to alteration of earlier and also later metamorphic minerals. Some of these later alterations clearly required addition of potassium from the HPG.

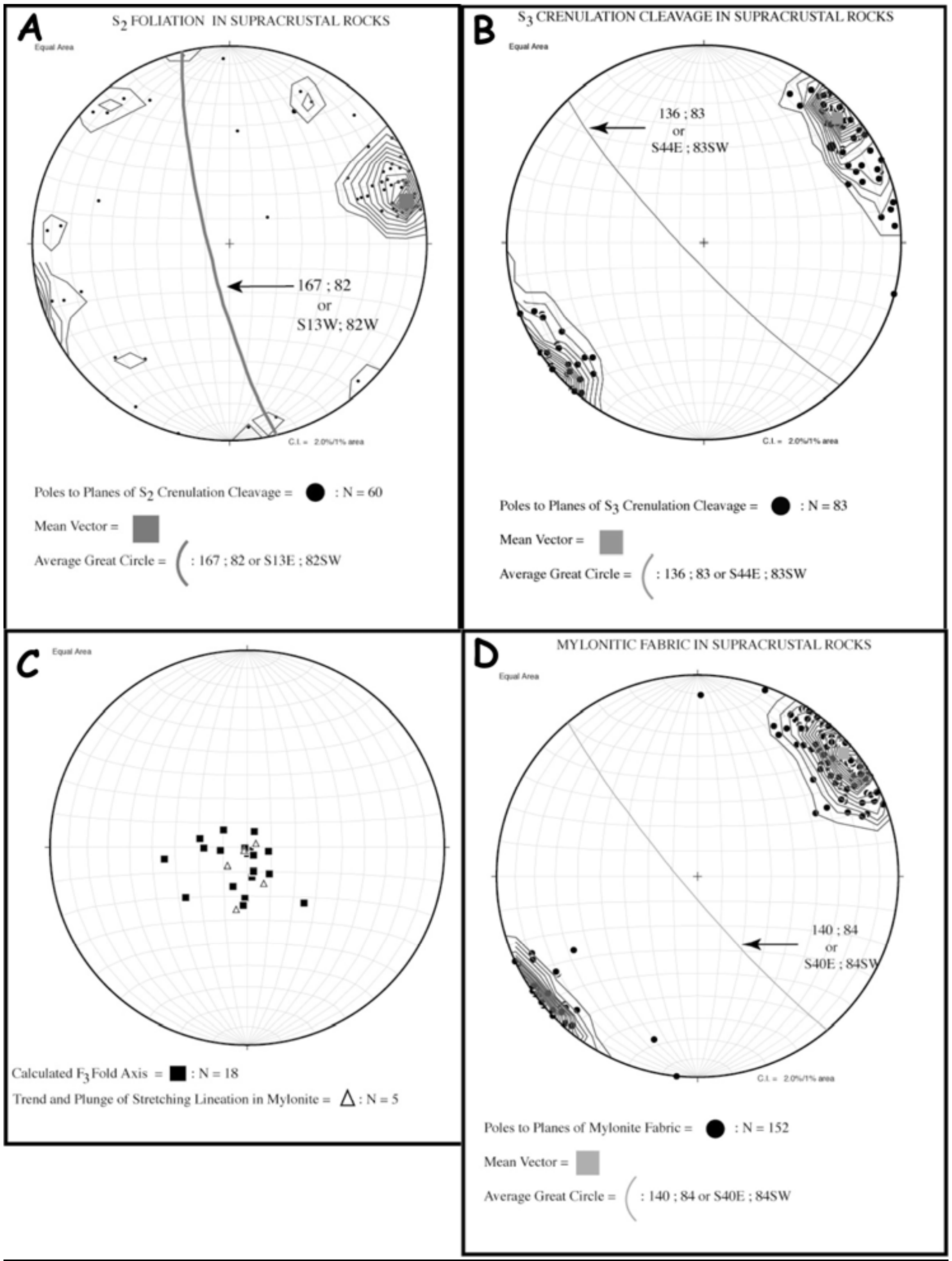

Figure 4. Lower-hemisphere stereoplots for Rockerville field area. A, foliation associated with F_2 folds. B, foliation associated with F_3 folds. C, lineations in mylonitic foliation and fold axis for F_3 folds calculated using Pi-method. D, mylonitic foliation.

33.5 **Stop 6**. Park at approximately 300 ft long outcrop cut along north side of road. A large nearly white structure of unknown origin is visible with outcrop. The outcrop is of interest because it apparently shows extremely complex structures with variable foliations. Again, the metamorphic minerals vary greatly in size, but garnet is generally very fine grained. Large partly altered porphyroblasts are mainly cordierite may include andalusite.

37.6 **Stop 7**. Mitchell Lake. Park on left side of road. Bench on west side of road is parallel to the axial plane of a large recumbent anticline fold in relatively proximal graywacke consisting largely of Bouma A beds (Fig. 8). The main fold plunges about 10° in a northwesterly direction. Calc-silicate ellipsoids plunge gently northeasterly and southeasterly in the two limbs of the fold. The fold plunges at right angles to a major anticlinal structure (Summit Hill anticline) which is at least 5 miles and possibly 7 miles long, in the Hill City 7.5 minute quadrangle. The anticline trends northeast and has a small domed area near its middle. It is believed to be caused by emplacement of HPG at depth even though the anticline is remarkably straight. Several folds apparently similar to the Mitchell Lake fold have been mapped along the major structure and there is some indication they formed by elongation of the major fold. Gravity data in Redden and Dewitt (2008) suggests the possibility of granite below the general area including the Three Forks area. Obviously additional detailed structure work is needed.

Figure 5. Hinge area of an F_3 fold with folded S_2 at a high angle to axial-planar S_3 within Domain 4. Pencils oriented parallel to S_3, Brunton oriented to north.

On the southwest end of the bench in a relatively inaccessible part about 30' above the road level is a good example of rebar structure formed where a small quartz vein ends a cuts Bouma A bed approximately vertically adjacent to the coarse granite quartz vein. The thickness of the original Bouma A bed is preserved but approximate 15 cm along the strike of the bed, away from the vein, the bed thickness is approximately 10 cm less. This is a classic example of grain size controlling the deformation. The coarse grained quartz vein has acted as a rigid member preserving the original Bouma A bed thickness.

Figure 6. S-C mylonitic fabric in sheared metagraywacke from Domain 3. Inset photomicrograph of σ-grain. Shear sense at this location is east-side up, left-lateral oblique slip.

38.6 Boudinage at bend in road. This exposure approximately 0.5 mi northeast of Hill City is on the west flank of the Summit Hill anticline whereas the small domal part of the anticline is almost due southeast of Hill City on the road to Keystone.

Figure 7. Stop 03BH-05. CM-scale fold parasitic to F_3 with well developed S_3.

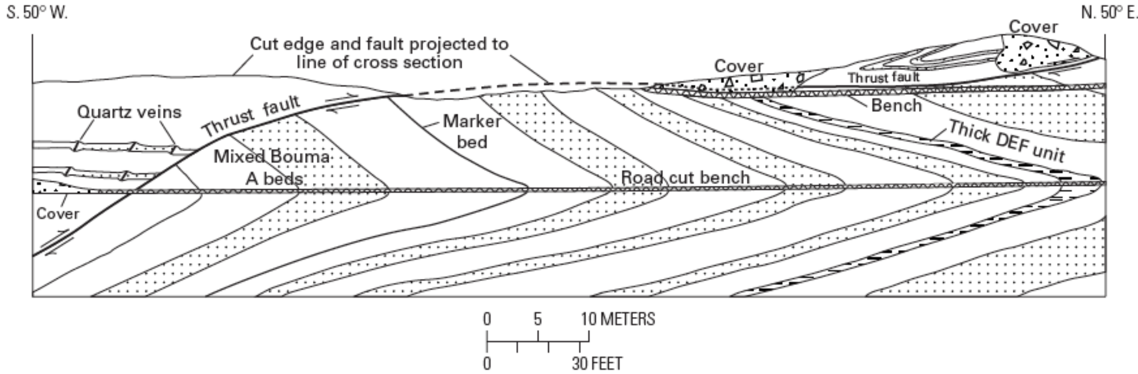

Figure 8. Diagrammatic cross section from Redden and Dewitt (2008) of late (D4) recumbent anticline and small thrust fault exposed in road cut along U.S. Highway 16 at Mitchell Lake (D4), northeast of Hill City. Rock units are all metagraywacke turbidites (unit Xgw3). Approximately 70 partial or individual Bouma sequences are present. The contacts shown represent boundaries of predominantly Bouma A sequences (patterned) versus mixed or predominantly Bouma DEF sequences that could be readily recognized in photographs. The late, chevron-style fold plunges gently to the northwest and has poorly developed axial-plane foliation in the hinge area along the bench. Above the apparent thrust fault, small crenulations and mineral lineations plunge to the southwest parallel to earlier (F2?) folds. Although the road cut is somewhat curved, and the cross section was prepared from photographs, the units shown are approximately true thicknesses because of the low plunge of the fold. The greater apparent thicknesses in units above the road-cut bench are due to slight differences in strike and in cut exposure. Massive quartz veins in the two individual Bouma A beds shown on left above fault zone are rotated and indicate right-lateral shear. They also document extensive thinning of host Bouma A beds away from the rigid quartz veins. The degree of thinningis somewhat exaggerated in the drawing.

39.2-40.2 Town of Hill City

41.2 Reno Gulch road to west.

45.7 Spring Creek Road. Currently impossible to visit but approximately two miles to west is area in a mica schist unit (Tendertooth Formation) derived from sea floor weathered tuff in which and andalusite crystals are nearly a foot in length. Andalusite crystals are aligned along an intersection lineation between early schistosity and crenulation cleavage indicating Harney Peak Granite deformation (D4) was active at the time of growth. Area also has considerable coarse-grained cordierite porphyroblasts.

48.9 Entrance to Crazy Horse monument. The highway for the next mile or so crosses a large treeless domed area underlain by a metamorphosed black shade unit named the Orville Formation. The domal area is undoubtedly cored by a Harney Peak Granite mass which also resulted in potassium metasomatism in the granite-rich schist of the Orville Formation.

50.5 **Stop 8**. Road on left named Village Ave. Turn left onto road for approximately 450 ft where it intersects the Mickelson Trail which follows the original rail road route, stop at parking area and walk approximately 450 ft to the east on an old railroad cut which exposes the Orville Formation. Careful examination permits recognition of isoclinal folds (F1), which have been refolded in association with the emplacement of granite. Return to vehicles and turn left on main road going toward Custer.

53.5 Center of Custer. Turn left.

57.4 Enter Custer State Park and go past Stockade Lake.

78.4 **Stop 9**. Campgrounds (closed) on right. Park and walk east approx. 100 feet east on road to outcrop on north side. Exposure shows “rebar” effect of small granitic intrusion cross crossing bedding (Fig.10). This exposure shows a top-to-the-NNW shear sense with components of pure an simple shear highly partitioned in quartz and mica rich layer respectively during granite emplacement. Knowledge of the original orientation the vein and layer thickness allow two-dimensional modeling associated with simultaneous pure and simple shear. Return to vehicles and proceed east past Custer State Park game lodge.

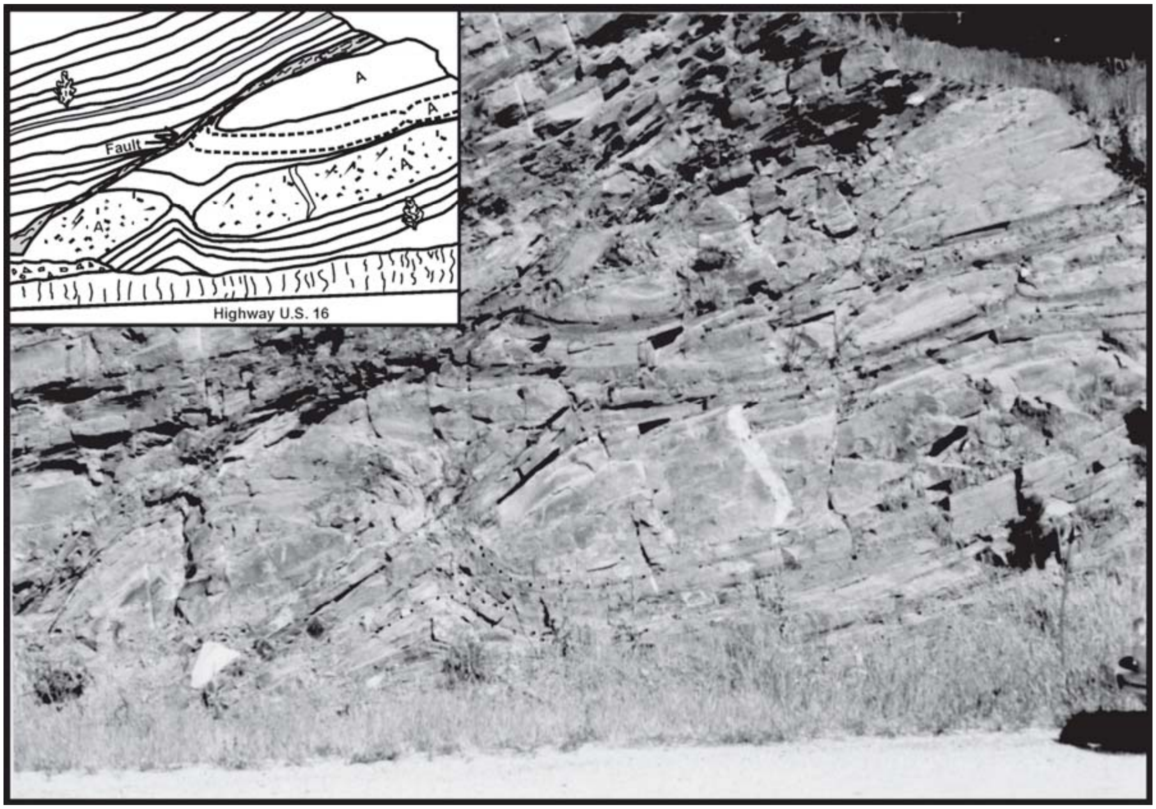

Figure 9. Photgraph from Redden and Dewitt (2008) showing boudinaged Bouma A units in staurolite-grade metamorphic zone turbidites (unit Xgw3). The large boudin in the thickest Bouma A bed also shows right-lateral rotation, which is probably related to the development of the small thrust(?) fault. The fold below the fault is inaccessible for detailed examination and could conceivably be one side of a boudin. Incompetent Bouma DEF beds deform into the tensional break of the Bouma A beds. Plunges of the boudin ends are to the northwest, similar to the large late F4 fold of figure 8. Both fold and boudin development are believed to be related to a buried D4 domal structure underlying the Hill City area. Compare deformation of the competent and incompetent turbidite beds here with those at high metamorphic grade shown in figure 6. Grain size is the major factor in establishing the relative competency in these bedded rocks. Location on U.S. Highway 16 at 0.6 km east of Hill City and 1.3 km west of Mitchell Lake.

81.0 Contact of Precambrian and Phanerozoic Rocks on east side of road.

92.2 Junction of SD 79, Route 36 ends. Turn left to return to Rapid City.

106.8 Rapid City limit

110.2 Turn left on Omaha Street.

112.1 Mt. Rushmore Rd. Turn right and 0.2 mi further is hotel starting point.

REFERENCE CITED

Allard, S.T., Portis, D.H., 2007, Thick-skinned Paleoproterozoic shear-fold coupled deformation along the eastern margin of the Black Hills, South Dakota, Geological Society of America, abstracts with programs, vol.39, no.6, pp.202.

Allard, Stephen, Portis, Douglas, Raymaker, Paul, Schoolmeesters, Nicole, Springstead, Karsten, and Traut, Jolene, 2009, Basement-involved shearing along eastern and western margins of the Black Hills, local or regional Paleoproterozoic event? Geological Society of America, abstracts with programs, vol.41, no.6, pp. 38-39.

Allard, S.T., 2010, Rethinking the Proterozoic Assembling of the North Central US, Geological Society of America, abstracts with programs, this meeting.

Matzek, Carl, and Allard, Stephen, 2010, A Quantitative Study to Differentiate Similar Gneiss from the Archean Little Elk Terrane, Black Hills, South Dakota, Geological Society of America, abstracts with programs, this meeting.

Nabelek, P. I., Labotka, T. C., Helms, T., and Wilke, M, 2006, Fluid-mediated polymetamorphism related to Proterozoic collision of Archean Wyoming and Superior provinces in the Black Hills, South Dakota, American Mineralogist, v. 91, p. 1473–1487.

Portis, D.H., and Allard, S.T., 2006, Evidence for sinistral offset along a shear zone exposed in supracrustal Proterozoic rocks near the eastern margin of the Black Hills, South Dakota, Geological Society of America, abstracts with programs, vol.38, no.6, pp. 37-38.

Portis, D.H., and Allard, S.T., (in prep.) Kinematics and timing of a Proterozoic shear-fold couple event near the eastern margin of the Black Hills, South Dakota; implications for tectonic evolution of Laurentia

Raymaker, P.R., and Allard, S.T., 2006, Sinistral shearing of Archean basement in Little Elk Canyon, Black Hills, SD; an alternative hypothesis, Geological Society of America, abstracts with programs, vol.38, no.6, pp.38.

Schmidt, Christopher, and Allard, Stephen, 2009, Pressure and Temperature Conditions of Proterozoic Metamorphism in Supracrustal Rocks near the Bear Mountain Terrane, Black Hills, S.D. Proceedings of the 3rd annual student-faculty research celebration symposium, unpublished abstracts with program, Winona State University.

Schoolmeesters, Nicole A., and Allard, Stephen T., 2009, Proterozoic shearing and folding in the Archean Little Elk Terrane, Black Hills, South Dakota, Geological Society of America, abstracts with programs, vol.41, no.6, p. 51.

Springstead, Karsten, 2007, Structural mapping of shear fabrics in the Little Elk Terrain; Black Hills, South Dakota, Proceedings of the 1st annual student-faculty research celebration symposium, unpublished abstracts with program, Winona State University.

Strobel, Michael L., Gregory J. Jarrell, J. Foster Sawyer, John R. Schleicher, and Mark D. Fahrenbach, 1999, Distribution of hydrogeologic units in the Black Hills area, South Dakota. USGS Hydrologic Investigations Atlas, Report: HA-0743, 3 sheets

Traut, Jolene T., and Allard, Stephen T., 2009, Shear deformation in the Archean basement in the Bear Mountain Terrane, Black Hills, South Dakota, Geological Society of America, abstracts with programs, vol.41, no.6, p. 51.

Redden, J.A., 1980, Geology and uranium resources in Precambrian conglomerates of the Nemo area, Black Hills, South Dakota: U.S. Department of Energy Open-File Report GJBX–127(80), 147 p.; available from U.S. Geological Survey Information Services, Box 25286, Denver Federal Center, Denver, CO 80225.

Redden, J.A., Peterman, Z.E., Zartman, R.E., and DeWitt, Ed, 1990, U-Th-Pb geochronology and preliminary interpretation of Precambrian tectonic events in the Black Hills, South Dakota, in Lewry, J.F., and Stauffer, M.R., eds., The Trans-Hudson Orogen: Geological Association of Canada Special Paper 37, p. 229–251.

Karst and Fractured Aquifer Hydrogeology in the Rapid City Area, South Dakota: Road Log

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Introduction

This field trip starts in the Surbeck Center parking lot at South Dakota School of Mines & Technology (SDSM&T). The itinerary includes 15 stops along the route following Hwy 44 into the Black Hills, stopping for lunch at Nemo, and returning via Nemo Road (Figure 1). The primary emphasis of the trip is the hydrogeologic character of the Missippian-age Madison Limestone (also locally known as the Pahasapa Limestone), which was exposed to erosion and karstification for millions of years and forms the Madison aquifer. Numerous fractures and solution openings in the Madison Limestone provide extensive secondary porosity in the aquifer. The Madison aquifer receives substantial recharge from streamflow losses and precipitation on the outcrop. The Madison aquifer is confined by low permeability layers in the overlying Pennsylvanian- and Permian-age Minnelusa Formation, although localized leakage can occur between the Madison and Minnelusa aquifers (Driscoll and others, 2002). The Madison and Minnelusa aquifers are the most heavily used aquifers in the Black Hills area (Long and Putnam, 2002).

Additional stops will address groundwater contamination within the Precambrian terrane. The Precambrian rocks generally have low permeability and form the lower confining unit for the series of sedimentary aquifers in the Black Hills area. Localized aquifers occur in Precambrian rocks in many locations in the central core of the Black Hills, where enhanced secondary permeability results from weathering and fracturing (Driscoll and others, 2002). Participants are encouraged to refer to the new geological map by Redden and DeWitt (2008) accessible at http://pubs.usgs.gov/sim/2777.

Itinerary

0.0 Leave Surbeck Center parking lot at South Dakota School of Mines and Technology (SDSM&T). Turn left (west) onto Hwy 79 (East St. Joseph St.).

0.5 Turn right onto East Blvd.

0.6 Turn left (west) on Omaha St. This street marks the approximate boundary of Federal Emergency Management Agency's (FEMA) Rapid Creek "floodway" (right) and the area considered above the 100-year flood stage (left).

1.1 Monument to the 238 people who drowned in the 1972 flood (Carter and others, 2002).

2.0 The concrete fish sculpture on the right was built in the floodway. We pass through the sandstone hogback of the Cretaceous-age Fall River and Lakota Formations. Collectively, these formations contain the Inyan Kara aquifer, which is one of the major aquifers in the Black Hills area. Looking north, note the "**SMD**" on hill. This hill is known locally as "M Hill" because of the big "M" on it, placed there by the SDSM&T.

2.7 Turn left (south) on Hwy 44 (Mt. View Rd.).

3.3 Rapid City Water Treatment Plant (right).

4.3 Cross Rapid Creek.

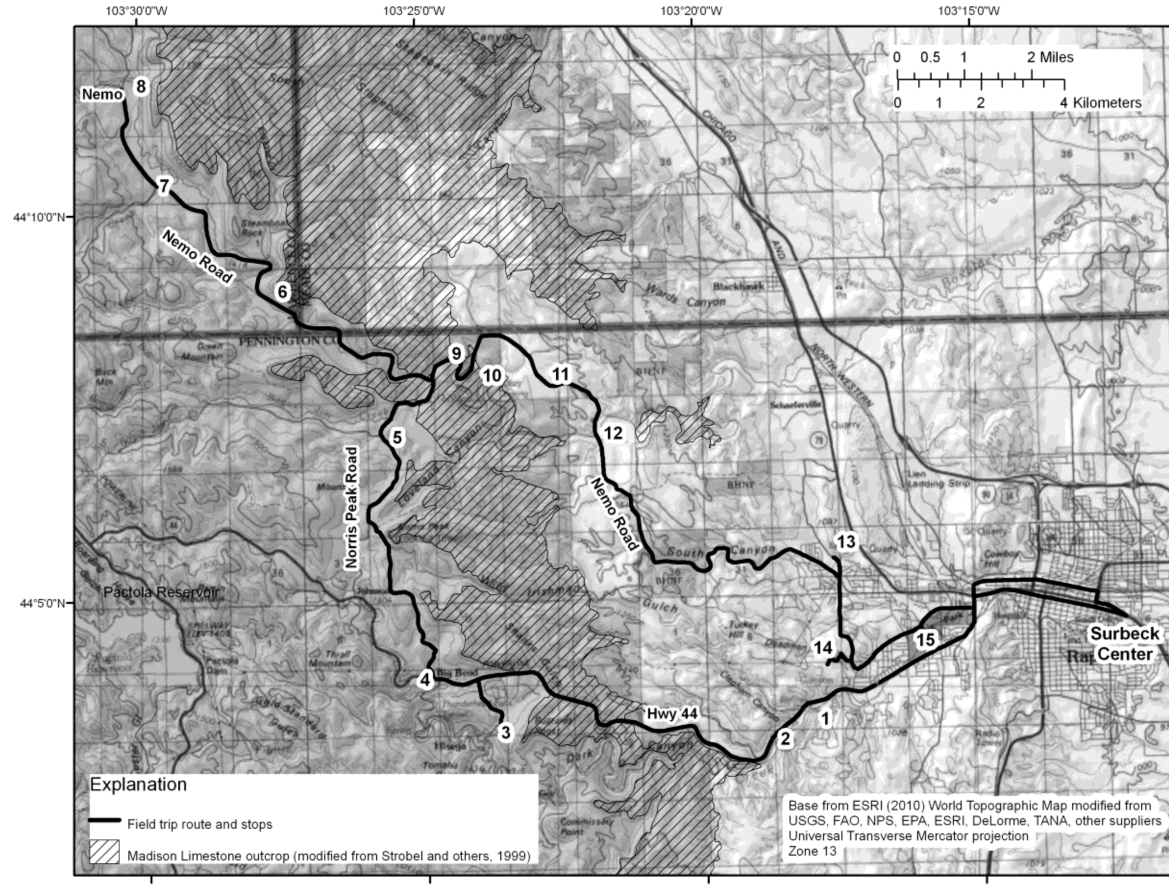

Figure 1. Map of area northwest of Rapid City showing route and itinerary stops.

4.5 Meadowbrook golf course (left). The Meadowbrook water infiltration gallery, supplying water to Rapid City, is in approximately 9 m (30 ft) of alluvium overlying the Triassic-age Spearfish Formation and extends about 500 m (1,600 ft) south of Rapid Creek (Anderson and others, 1999). The Spearfish Formation consists of red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers and is considered a confining unit (Driscoll and others, 2002).

5.5 Canyon Lake (left). This earthen dam failed in 1972 resulting from the large amounts of debris that clogged the spillway (Carter and others, 2002). The dam was subsequently rebuilt with a larger spillway.

6.0 **STOP #1.** Jackson and Cleghorn Springs. Jackson and Cleghorn Springs supply water for the Cleghorn Springs Fish Hatchery (left) and Rapid City. Jackson and Cleghorn Springs are adjacent springs that issue from a similar source, predominantly the Madison aquifer. The only visible flows from the springs are the outfall from the hatchery and seepage into Rapid Creek adjacent to the springs. The combined discharge from the springs is about 0.6 cubic meter per second (m^3/s) (22 cubic feet per second (ft^3/s)) (Anderson and others, 1999). During periods of low streamflow, these bedrock springs provide important base flow to Rapid Creek to sustain cold-water fisheries. An observation well completed in the Madison Limestone is located near Jackson Spring. Hydraulic head measured in this well indicates declines in the Madison aquifer near Jackson Spring of about 9 meters (m) (30 feet (ft)) during the 2000-08 drought (Figure 2). The seasonal change in hydraulic head is related to increases in pumping withdrawals from nearby production wells during the summer time. Model simulations of hypothetical pumping in the Rapid City area indicate that increased pumping could diminish discharge from Jackson and Clehorn Springs (Putnam and Long, 2009).

6.3 A Datsun pickup remains buried to this day under the Hwy 44 bridge, a result of scour in

Cleghorn Canyon during the June 9, 1972, flood (Rahn and others, 1981).

6.8 Cross Rapid Creek. This is the type section of the Pennsylvanian- and Permian-age Minnelusa (Sioux words for fast moving water) Formation. The Minnelusa Formation consists of yellow to red cross-bedded sandstone, limestone, and anhydrite locally at the top; interbedded sandstone, limestone, dolomite, shale and anhydrite; red shale with limestone and sandstone at the base (Driscoll and others, 2002).

6.9 **STOP #2.** U.S. Geological Survey streamflow-gaging station on Rapid Creek (station 06412500). Turn right to parking area. At this location “Knecht’s Cliffside Condominiums” were wiped out by the June 9, 1972, flood. The “Braeburn Addition” was to be built here in 2005, but the idea was abandoned owing to the flood history. Figure 3 shows the view looking downstream the day after the 1972 flood. A peak flow of 890 m^3/s (31,200 ft^3/s) occurred at this gage just before midnight on June 9, 1972 (Carter and others, 2002).

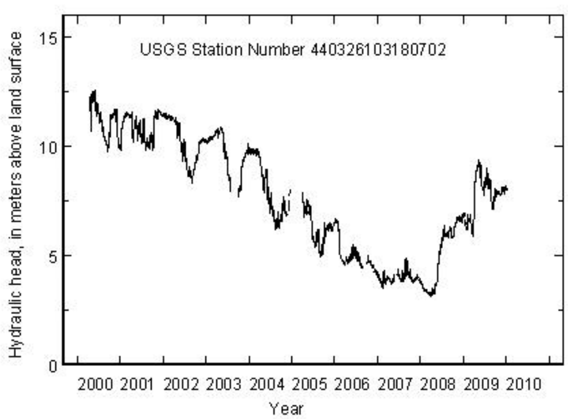

Figure 2. Hydrograph of hydraulic head in observation well completed in Madison aquifer near Jackson Spring.

7.3 Leave Rapid Creek (elevation 1,049 m, 3,440 ft). The Madison (Pahasapa, Sioux words for “hills that are black”) Limestone is barely visible along Rapid Creek. The Madison Limestone is a massive light-colored limestone and dolomite in part (Driscoll and others, 2002).

7.9 Westberry Trails forest fire. In 1988, the Westberry Trails fire started 3.2 kilometers (km) (2 miles (mi)) west of Rapid City and burned 17 houses in 48 hours.

9.3 Entry road to Black Hills Caverns (right).

10.6 Tree thinning in progress by the U.S. Forest Service (USFS).

11.4 Contact of Madison Limestone and the Devonian-age Englewood Formation (right). The Englewood Formation is a pink to buff limestone with shale locally at the base (Driscoll and others, 2002).

Figure 3. Photograph taken on June 10, 1972 after flood looking downstream from Hwy 44 bridge at mile 6.9 (Photograph by Perry Rahn).

11.6 Cambrian-age Deadwood Formation exposed (right). The Deadwood Formation consists of massive thin-bedded buff to purple sandstone (Driscoll and others, 2002).

12.2 Turn left (south) on Hisega Road.

13.1 **STOP #3**. Hisega Spring. A substantial amount of the private land in watersheds upgradient from the Paleozoic outcrops occurs along streams. Potential contamination from accidental spills, road runoff, septic systems, livestock, and lawn fertilizers is a concern in watersheds that contribute recharge to the karstic Madison aquifer and to other highly permeable aquifers such as the Minnelusa and Minnekahta aquifers. Hisega Spring (Figure 4) has a steady discharge of about 50 liters per minute (13 gallons per minute). Two water samples collected from the spring in the summer of 2007 had concentrations of nitrite plus nitrate as nitrogen of about 8 milligrams per liter (mg/L; Putnam and others, 2008). The general direction of groundwater flow in the Precambrian setting is assumed to follow the topography. The developed area adjacent to the south side of Hwy 44 probably is a source-water area for the spring (Putnam and others, 2008). Return to Hwy 44.

13.9 Turn left (west) onto Hwy 44.

14.2 We now continue traversing Precambrian-age rocks. Hwy 44 rejoins Rapid Creek (elevation 1256 m, 4120 ft). The 244-m (800-ft) drop in elevation in Rapid Creek between mile 14.2 and mile 7.3 is accomplished through a series of rapids in Dark

Canyon, south of Hwy 44. Unfortunately, Hwy 44 does not traverse the entrenched meanders of Rapid Creek in Dark Canyon that expose the rocks within the Paleozoic section. Gries (1996) described a 244-m (800-ft) northwest/southeast tunnel built in 1893 as a water diversion for gold placers at Big Bend. The water diversion tunneled through an entrenched meander of Rapid Creek and failed because it was not accurately surveyed resulting in a 9-m (30-ft) underground waterfall.

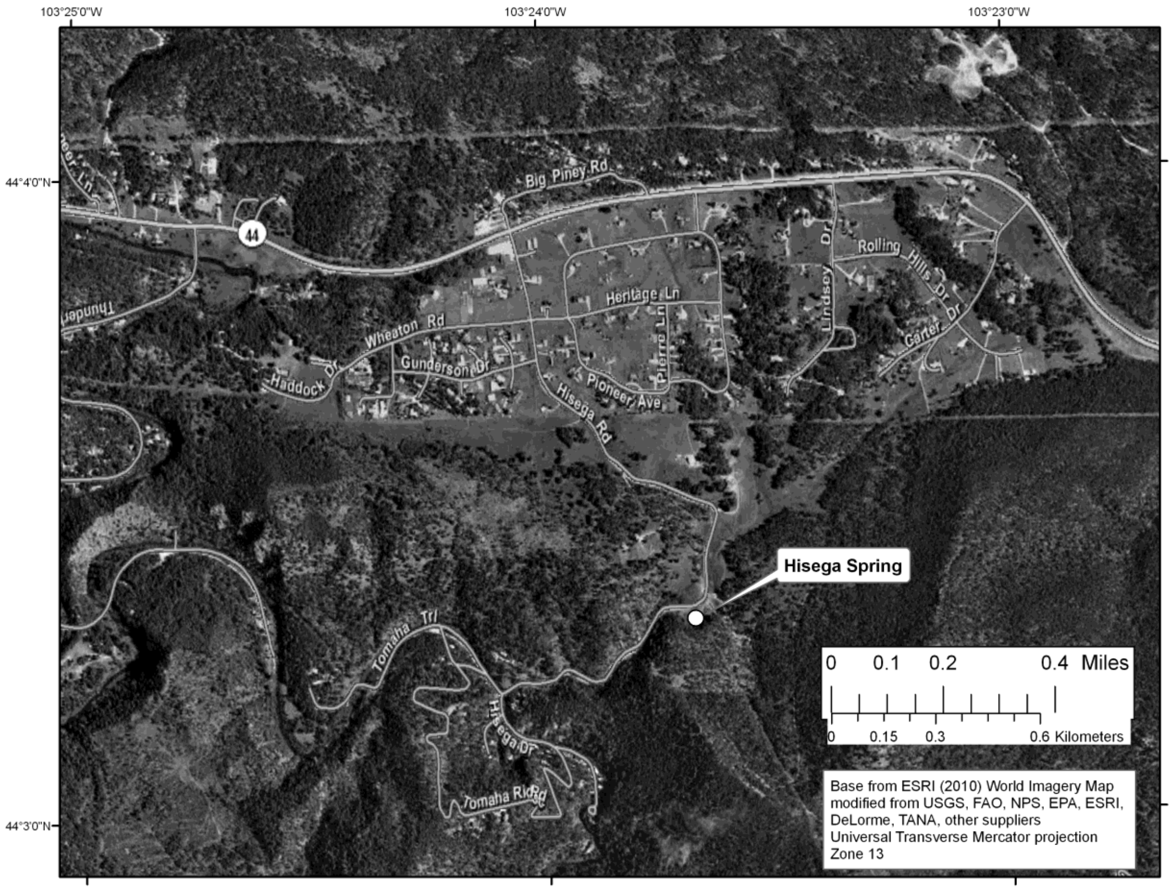

Figure 4. Location of Hisega Spring in relation to suburban development.

17.1 **STOP #4.** Johnson Siding. Conoco Station. Rest stop/coffee and donuts.

17.2 Backtrack about 0.1 mi on Hwy 44 to the intersection with Norris Peak Road and turn left on Norris Peak Road proceeding northerly.

18.2 Large boulders of Precambrian-age brown quartzite (right). Around the bend, the quartzite is exposed on the left side of the road.

20.3 **STOP #5.** Short stop at edge of road. The basal Deadwood Formation is exposed along the road.

20.9 Sandstones of the upper Deadwood Formation are exposed near the road. The Deadwood aquifer is a major aquifer in the Black Hills area but generally is used mainly by domestic and municipal users near its outcrop area (Driscoll and others, 2002).

21.6 Junction of Norris Peak Road and Nemo Road. Note the Madison Limestone bluff across Boxelder Creek. The thin-bedded pink strata below the Madison Limestone is the Englewood Limestone. Turn left on Nemo Road.

22.2 Deadwood Formation, massive red sandstone with calcareous concretions.

22.8 “Forsythe’s Glen” as photographed by Illingsworth of the 1874 Custer expedition (Grafe and Horsted, 2005).

23.9 **STOP #6.** Walk across bridge to see the angular unconformity shown in Figure 5. This unconformity marks the hiatus between the

Precambrian-age (Early Proterozoic-age) Boxelder Creek Formation (>2.48 billion years ago (Ga)) and the Cambrian-age Deadwood Formation (0.52 Ga). Redden and DeWitt (2008) dated a metagabbro sill that intruded the Boxelder Creek Formation at 2.48 Ga.

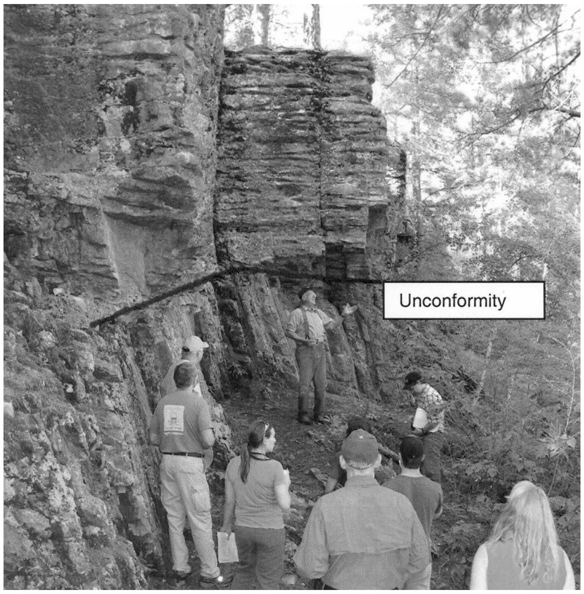

Figure 5. Unconformity between the nearly vertical Precambrian-age Boxelder Creek Formation (>2.48 Ga) and the gently dipping Cambrian-age Deadwood Formation (0.52 Ga) (Photograph by Ingrid E. Arlton).

25.1 Metagabbro exposure (right). Gries (1996) describes this 900-m (3,000-ft) thick gabbro sill. Redden and DeWitt (2008) dated the sill at 2.48 Ga.

26.9 USFS Steamboat Rock Picnic area.

27.5 Precambrian metaconglomerate. This uraniferous metaconglomerate tongue of the Boxelder Creek Formation contains a chromium mica called fuchsite.

27.7 Exposures of Madison Limestone and Deadwood Formation in canyon wall on right along with rock slide.

28.5 Cross Estes Creek. Looking northeast across the flood plain of Boxelder Creek is a taconite mine. Hematite from the banded iron-formation (inferred Archean age by Redden and Dewitt, 2008) is used at the cement plant.

29.5 STOP #7. Estes Creek Road (left). Nemo cemetery. Walk in to see Precambrian-age marble.

30.0 STOP #8. Lunch stop. Drive in to the Nemo Guest Ranch. Walk up hill to south. We will examine the influence of metamorphosed bedrock on an ethylene dibromide (EDB) groundwater contamination plume (Figure 6). In 1996, low concentrations of EDB were found in 13 domestic water wells completed in Precambrian-age metamorphic rocks at Nemo. The source of the contaminant is believed to be the result of pesticides disposed in taconite pits at a USFS Work Station area in the 1970s (Rahn and Johnson, 2002). The EDB plume probably follows the bedding and foliation towards the south-southeast (Figure 7). Return to Nemo Road and proceed southerly.

38.4 STOP #9. Custer Gap. As Custer's 1874 expedition left the Black Hills, they wisely decided to avoid the downstream entrenched meanders along Boxelder Creek. The Madison Limestone exposed here is dove-colored, but weathers gray. Boxelder Creek typically sinks (loses flow) just downstream (Figure 8) and provides recharge to the Madison aquifer.

38.7 Streamflow loss zone. Figure 9 is a map of Boxelder Creek sinkhole and springs complex. Boxelder Creek can lose as much as 1.4 m^3/s (50 ft^3/s) to the Madison, Minnelusa, and Minnekahta aquifers as it crosses their outcrops with most of the losses to the Madison aquifer (Hortness and Driscoll, 1998). The Minnekahta aquifer is one of the five major bedrock aquifers. The Minnekahta Limestone is about 15 m (50 ft) thick and is a thin to medium, fine-grained, purplish gray laminated limestone (Driscoll and others, 2002).

39.3 STOP #10. USFS gate. Walk in to Gravel Spring and Doty Spring (Figure 10). Details of the dye tests performed here are given in Strobel and others (2000). The travel time of dye from major sinkhole #1 (Figure 9) to Gravel Spring is about 1 hour and to Doty Spring is about 3 hours (Rahn and Gries, 1973). In order to visit Doty Spring, we will cross Boxelder Creek twice. Continue driving on Nemo Road towards Rapid City.

40.1 The tombstone (right) marks the grave of a soldier who died on the 1874 Custer expedition.

40.8 STOP #11. "Dream Bar Road." On-site wastewater treatment systems (OWTS) are increasing in number within aquifer recharge areas such as this area west of Rapid City. Putnam and others (2008) collected and analyzed water samples downgradient from areas of dense OWTS in four hydrogeologic settings on the eastern flank of the Black Hills: alluvial deposits, the Triassic-age Spearfish Formation, the Permian-age Minnekahta Limestone, and Precambrian rocks. The mean dissolved nitrite plus nitrate concentration was 8.62 milligrams per liter (mg/L) and the mean chloride concentration was 498 mg/L in samples from the Minnekahta aquifer downgradient from the area of dense OWTS. Of the four settings, the mean nitrate concentrations were highest in samples from the Minnekahta aquifer. Microbiological indicators, including fecal coliforms, *Escherichia coli*, and enterococci, were found in samples from all four settings. Eleven different organic wastewater compounds also were detected at eight sampling locations. Nitrogen and oxygen isotope ratios in nitrate (Figure 11) and concentrations of chloride and boron in groundwater samples indicated a relatively small contribution from synthetic fertilizer and probably a substantial contribution from OWTS.

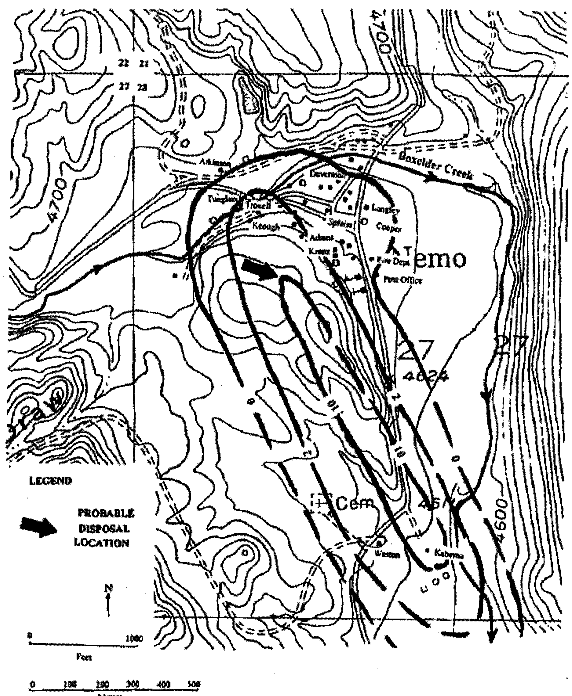

Figure 6. Map showing ethylene dibromide (EDB) plume in the Nemo area (modified from EnviroSearch International, 1998). Lines of equal EDB concentration are in micrograms per liter.

42.2 STOP #12. Schmitz Ranch Road. Walk down Nemo Road 30 m (100 ft). The Madison Limestone is exposed again in an anticline about 1.6 km (1 mi) to the east (Figure 12). The Minnelusa Formation has numerous slumps along the west side of Nemo Road.

42.6 Cross Boxelder Creek.

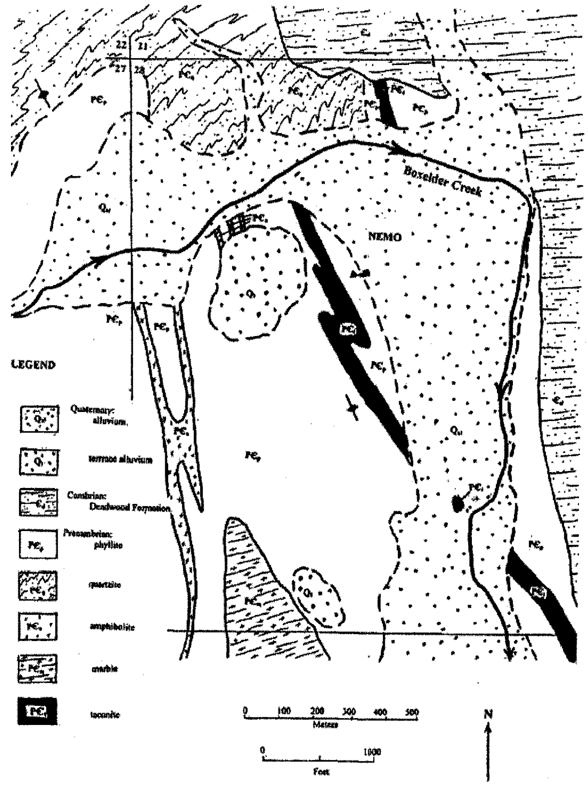

Figure 7. Geologic map of Nemo area (modified from Redden, 1981).

45.0 Rubble layer (left) in Minnelusa Formation due to gypsum solution. We pass through the Westberry Trails 1988 forest fire area.

46.1 Chaotic (sinkhole) collapse structure (left) in the Minnelusa Formation (Rahn and Hayes, 1996).

47.2 Cross outcrop of Minnekahta Limestone.

48.2 Turn left (north) onto 44th St.

48.6 STOP #13. Wilderness Park. Rest stop. A dye test in 1968 showed that City Springs derives much of its water from Boxelder Creek (Rahn and Gries, 1973). A Boxelder Creek dye test was repeated by the U.S. Geological Survey in 1993 (Greene, 1999). Figure 13 is a map of the western part of Rapid City showing the location of City Springs (CS) and well sites where dye was detected in 1993. Figure 14 shows the breakthrough concentrations of dye in water samples collected from the five sites. A production well completed in the Madison aquifer is located about 30 m (100 ft) from City Springs. Dye was first detected in the production well about 30 days after dye injection in Boxelder Creek about 10 km (6 mi) upgradient (Greene, 1999). Putnam and Long (2007) and Long and others (2008) describe additional tracer tests that characterize Madison aquifer flow paths in the Rapid City area. Return to 44th street and continue south.

Figure 8. Stream injected with Rhodamine dye at Custer Gap disappears a short distance downstream on Boxelder Creek (photo courtesy of Derric Iles, South Dakota Geological Survey).

48.9 Cross West Chicago St.

49.6 Stevens High School is on the left, and the U.S. Army National Guard Camp is on the right. Gypsum is exposed in the Triassic-age Spearfish Formation. Because gypsum is easily dissolved by water, numerous sinkholes in the Spearfish Formation have developed, especially in the northern Black Hills (Epstein, 2000).

50.2 The house on the left is built on a gypsum outcrop.

50.4 Turn right on Saint Patrick street for about 1 block, then continue northwest on Red Dale Drive.

50.6 Turn left on National Guard Road.

50.9 **STOP #14.** Cedar Canyon Dam. Cedar Canyon dam was built in 1959 and is 431 m (1415 ft) in length and 13 m (42 ft) high. The spillway is 15 m (50 ft) wide and 2.7 m (9 ft) deep. The reservoir area would cover 4 hectares (10 acres) if it ever filled up. Of course, it will never get anywhere near filling up because of the underlying permeable Minnekahta Limestone and the small drainage area of 1.2 km^2 (0.47 mi^2). On June 10, 1972, the reservoir had a paltry 2 m (6 ft) of water in it, with 11 m (36 ft) to go before the water would ever reach the spillway. Return to Red Dale Drive.

51.2 Right turn on Red Dale Drive.

51.6 Turn left on Canyon Lake Drive.

52.2 Quaternary-age gravel (Sturgis Terrace) is angularly unconformable on the Spearfish Formation (left).

52.5 On the left is the Sioux Sanitorium on the Sturgis Terrace, and on the right is the "floodway" for Rapid Creek.

52.8 STOP #15. Turn right into Rapid City Parks Division. South Dakota Department of Environment and Natural Resources Water Rights Program observation wells completed in the Madison Limestone and Minnelusa Formation. These wells are located near production wells. The hydrograph for the well completed in the Madison aquifer (Figure 15) shows a decrease in hydraulic head following development of the Madison aquifer in the early 1990s. Return to Canyon Lake Drive and turn right.

53.1 On the left is the Senior Citizens's Center. Behind it is a Madison aquifer production well, which is about 520 m (1700 ft) from the Sioux Park observation wells.

53.3 The hand-built boulder wall on the left surrounds the U.S. Army National Guard headquarters. The wall was built by the Works Progress Administration (WPA) in the 1930s.

53.7 Cross Rapid Creek.

53.8 Turn left on Mt. View Road heading north.

54.0 Turn right on West Main. This road becomes St. Joseph St. that leads to SDSM&T.

54.8 Cross West Blvd.

56.3 Surbeck Center parking lot.

End trip.

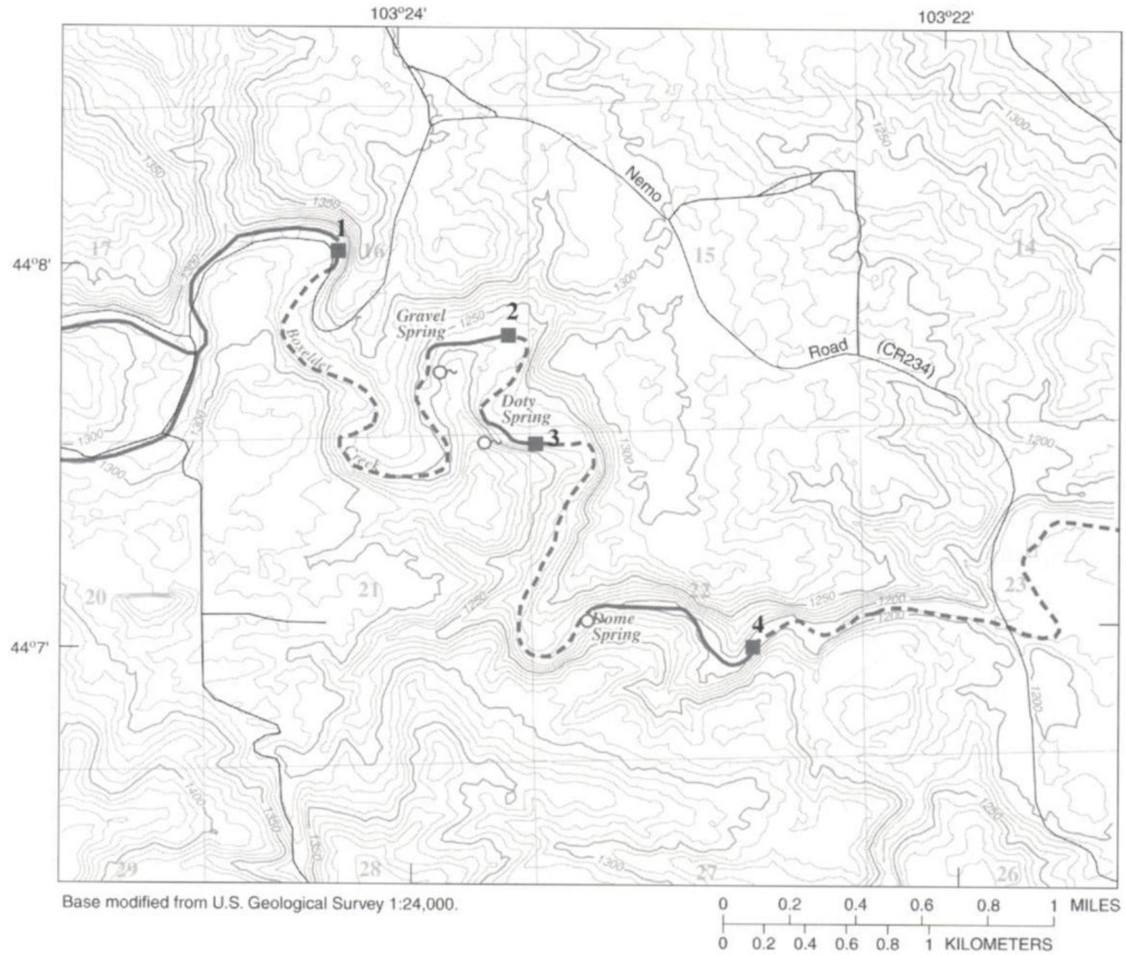

Figure 9. Map of Boxelder Creek sinkholes and springs (from Strobel and others, 2000).

Figure 10. Water emerging from Madison Limestone at Doty Spring (photo by Joanne Noyes, South Dakota Geological Survey).

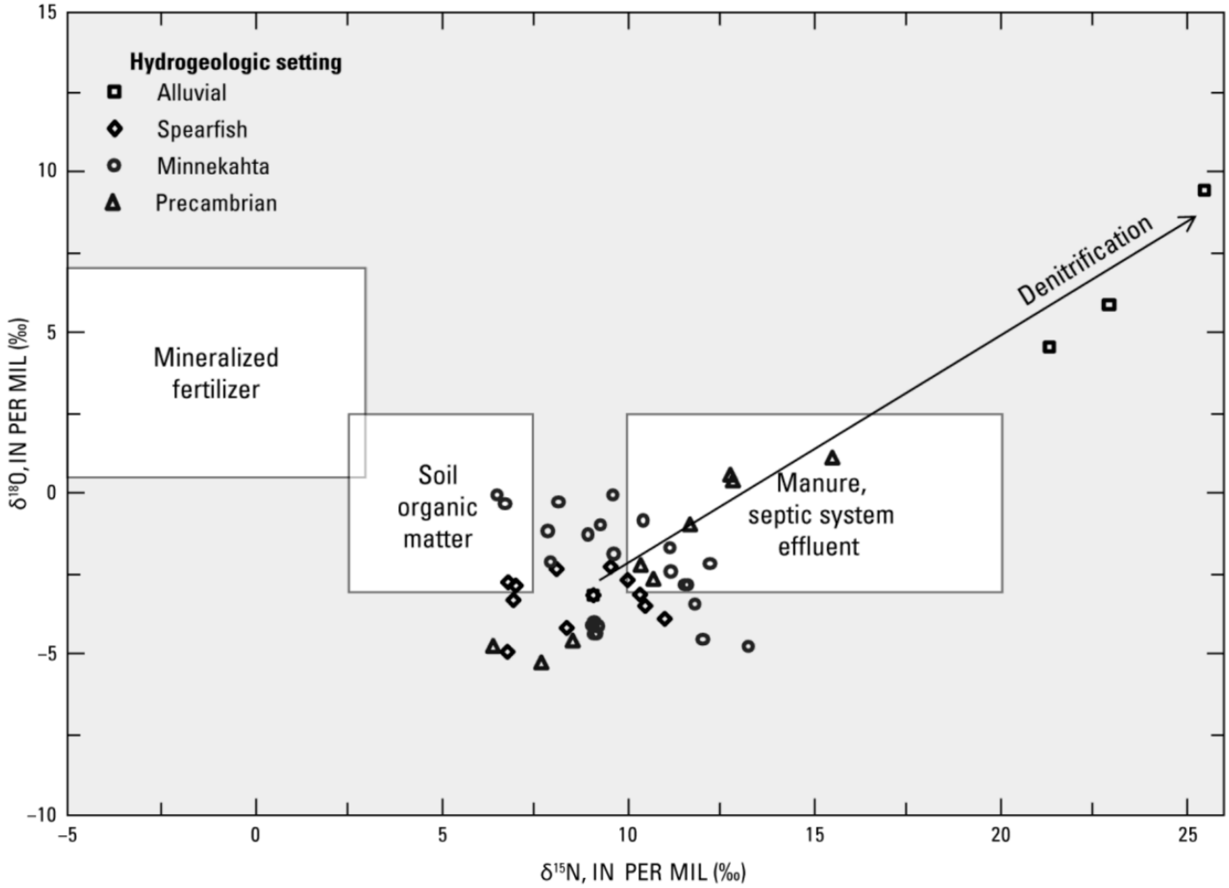

Figure 11. Nitrogen and oxygen isotope ratios for nitrate in groundwater samples in relation to the isotopic composition of nitrate sources (from Putnam and others, 2008).

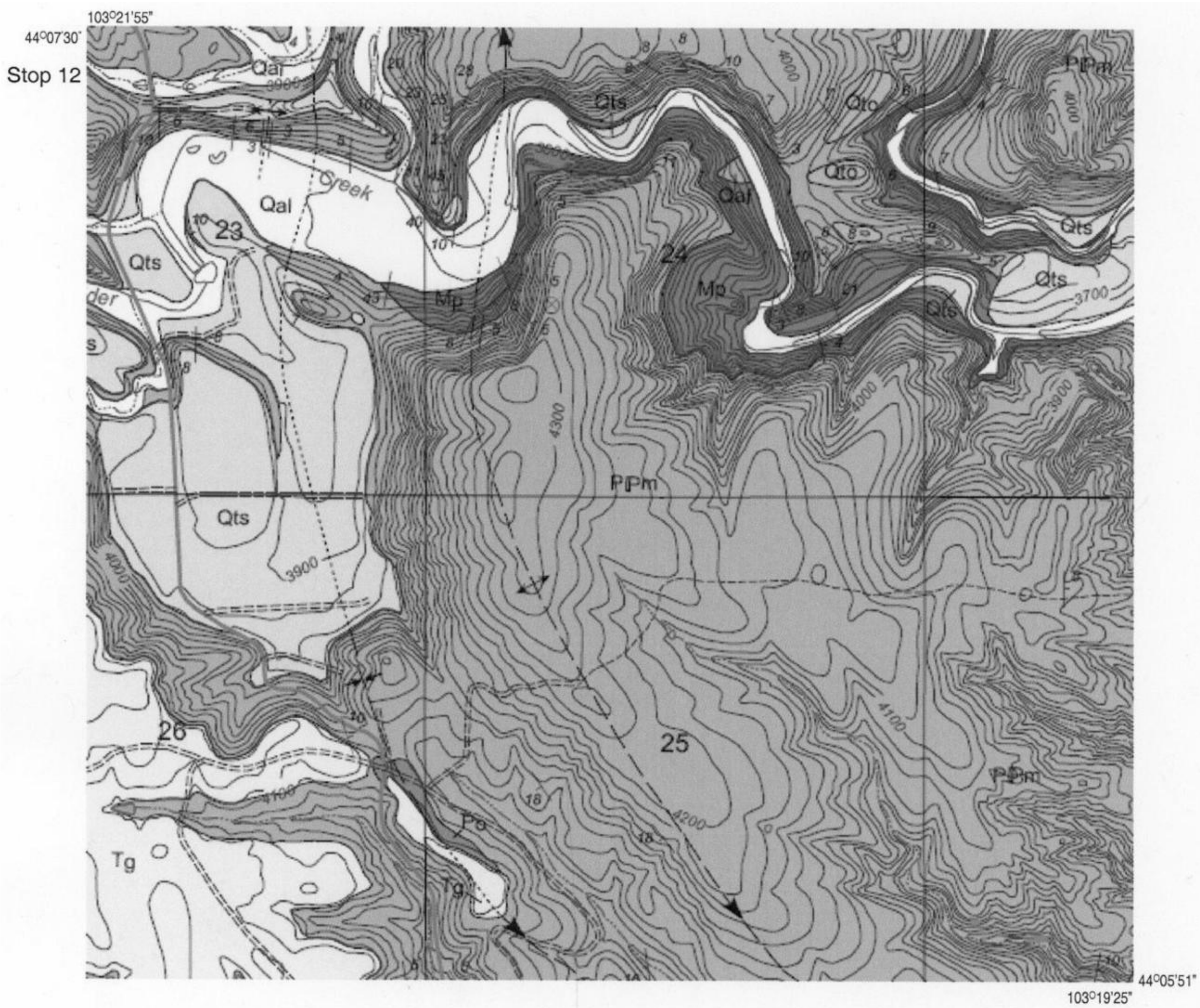

Figure 12. Geologic map showing Madison Limestone (Pahasapa Limestone, Mp) outcrop along Boxelder Creek near anticline east of Nemo Road (modified from Fahrenbach and Sawyer, 2001).

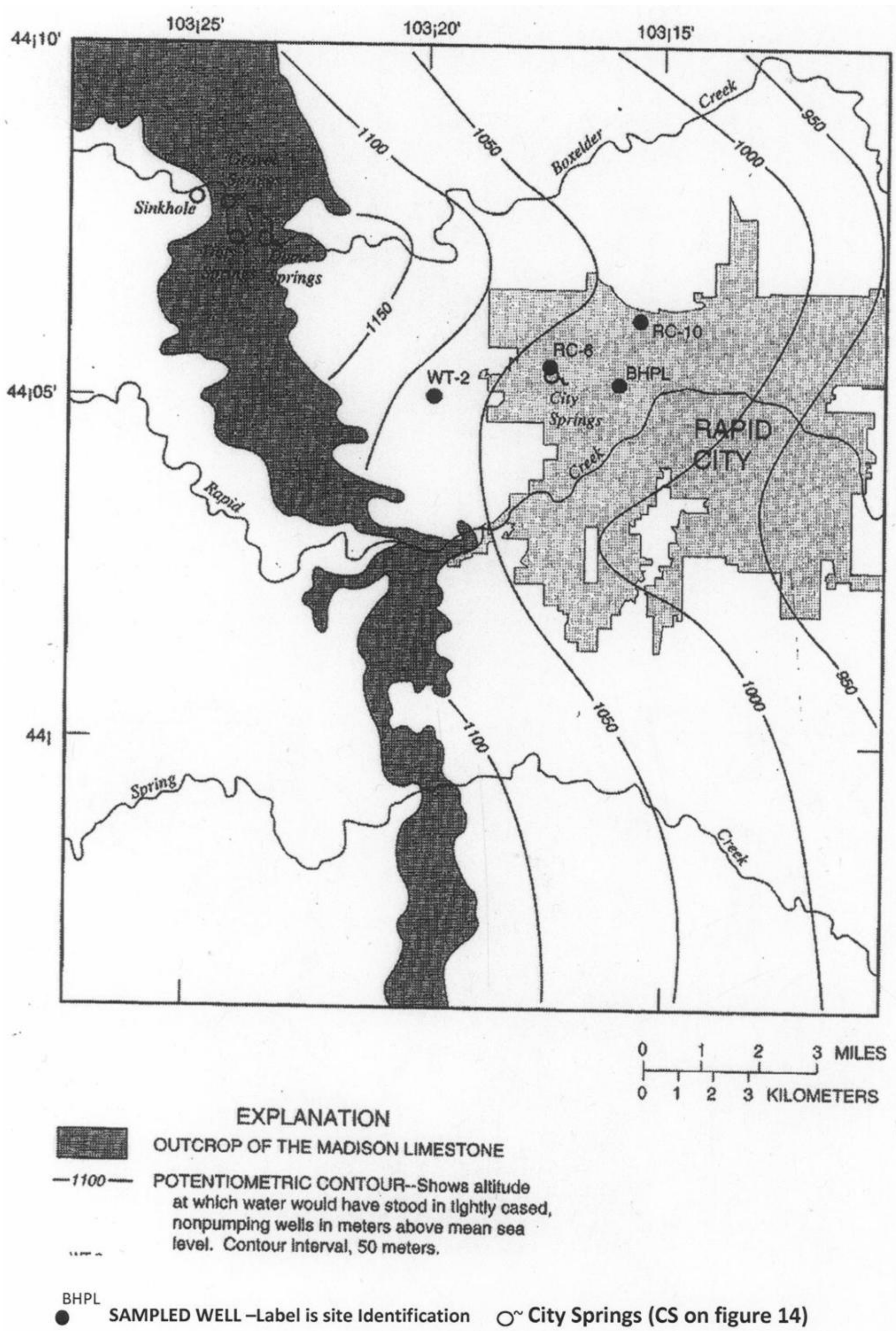

Figure 13. Location of sampled wells and springs where dye was detected during 1993 Boxelder Creek dye test and potentiometric surface of Madison aquifer near Rapid City, South Dakota (Strobel and others, 2000).

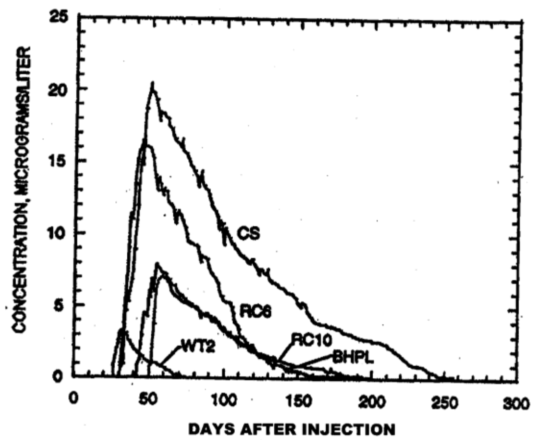

Figure 14. Breakthrough curves of Rhodamine WT sampled from wells and spring near Rapid City following injection in Boxelder Creek in fall of 1993 (Greene, 1999).

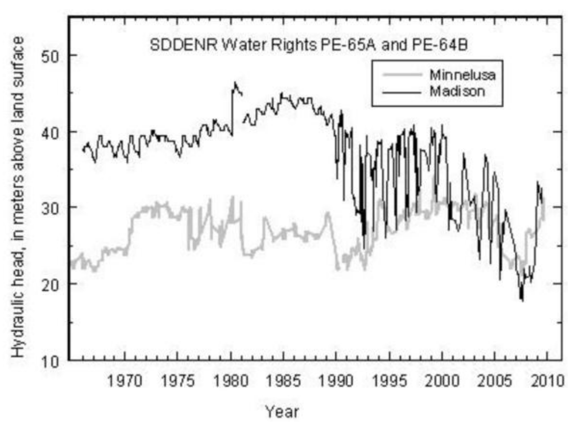

Figure 15. Hydrograph of hydraulic head in the Madison and Minnelusa aquifers at Sioux Park.

REFERENCES CITED

Anderson, M.T., Driscoll, D.G., and Williamson, J.E., 1999, Ground-water and surface-water interactions along Rapid Creek near Rapid City, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4214, 99 p.

Carter, J.M., Teller, R.W., and Williamson, J.E., 2002, The 1972 Black Hills-Rapid City flood revisited: U.S. Geological Survey Fact Sheet FS-037-02, 6 p.

Driscoll, D.G., Carter, J.M., Williamson, J.E., and Putnam, L.D., 2002, Hydrology of the Black Hills area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 02-4094, 150 p.

EnviroSearch International, 1998, Contaminant survey and site characterization report, v. I of III: Nemo, South Dakota, and Salt Lake City, Utah, U.S. Department of Agriculture Forest Service Work Center, October 4, 1998.

Epstein, J.B., 2000, Gypsum karst and hydrologic evolution in the northern Black Hills, South Dakota, *in* Strobel, M.L., and others, eds., Hydrology of the Black Hills—Proceedings of the 1999 Conference on the Hydrology of the Black Hills, Rapid City, South Dakota School of Mines and Technology Bulletin No. 20, p. 73-79.

Fahrenbach, M.D., and Sawyer, J.F., 2001, Geologic map of the Rapid City West Quadrangle, South Dakota: South Dakota Geological Survey 7.5 Minute Series Geologic Map 1, scale 1:24,000.

Grafe, Ernest, and Horsted, Paul, 2005, Exploring with Custer, the 1874 Black Hills Expedition: Custer, South Dakota, Dakota Photographic, 285 p.

Greene, E.A., 1999, Characterizing recharge to wells in carbonate aquifers using environmental and artificially recharged tracers, *in* Morganwalp, D.W.,OK and Buxton, H.T., eds., Proceedings of the Technical Meeting, Charleston, S.C., March 8-12, 1999, Toxic Substances Hydrology Program: U.S. Geological Survey Water-Resources Investigations Report 99-4018-C, p. 803-808.

Gries, J.P., 1996, Roadside geology of South Dakota: Missoula, Montana, Mountain Press Publishing Company, 358 p.

Hortness. J.E., and Driscoll, D.G., 1998, Streamflow losses in the Black Hills of western South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4116, 99 p.

Long, A.J., and Putnam, L.D., 2002, Flow-system analysis of the Madison and Minnelusa aquifers in the Rapid City area, South Dakota--Conceptual Model: U.S. Geological Survey Water-Resources Investigations Report 02-4185, 100 p., 2 pl.

Long, A.J., Sawyer, J.F., and Putnam, L.D., 2008, Environmental tracers as indicators of karst conduits in groundwater in South Dakota, USA: Hydrogeology Journal, v. 16, no. 2, p. 263-280.

Putnam, L.D., and Long, A.J., 2007, Analysis of ground-water flow in the Madison aquifer using fluorescent dyes injected in Spring Creek and Rapid Creek near Rapid City, South Dakota, 2003-04: U.S. Geological

Survey Scientific Investigations Report 2007-5137, 27 p.
Putnam, L.D., Hoogestraat, G.K., and Sawyer, J.F., 2008, Water-quality effects and characterization of onsite wastewater disposal systems in the east-central Black Hills area: U.S. Geological Survey Scientific Investigations Report 2008-5232, 115 p.
Putnam, L.D., and Long, A.J., 2009, Numerical groundwater-flow model of the Minnelusa and Madison hydrogeologic units in the Rapid City area, South Dakota: U.S Geological Survey Scientific Investigations Report 2009–5205, 81 p.
Rahn, P.H., and Gries, J.P., 1973, Large springs in the Black Hills, South Dakota and Wyoming: South Dakota Geological Survey, Report of Investigations No. 107, 46 p.
Rahn, P.H., Bump, V.L., and Steece, F.V., 1981, Engineering geology of the central Black Hills, South Dakota, *in* Rich, F.J., ed., Geology of the Black Hills, South Dakota and Wyoming: Alexandria, Virginia, American Geological Institute, Field Trip Guidebook for the Geological Society of America, Rocky Mountain Section, 1981 Annual Meeting, p. 135-146.
Rahn, P.H., and Hayes, T.S., 1996, Hydrogeology of the central Black Hills—Road log, Field Trip 3, *in* Paterson, C.J., and J.G. Kirchner, eds., Guidebook to the geology of the Black Hills, South Dakota: South Dakota School of Mines and Technology Bulletin No. 19, p. 19-29.
Rahn, P.H., and Johnson, C.S., 2002, Effects of anisotropic transmissivity on a contaminant plume at Nemo, South Dakota: Environmental and Engineering Geoscience, v. 8, no. 1, p. 11-18.
Redden, J.A., 1981, Summary of the geology of the Nemo area, *in* Rich, F.J., ed., Geology of the Black Hills, South Dakota and Wyoming: Alexandria, Virginia, American Geological Institute, Field Trip Guidebook, Geological Society of America, Rocky Mountain Section, 1981 Annual Meeting, p. 193-209.
Redden, J.A., and DeWitt, Ed, 2008, Maps showing geology, structure, and geophysics of the central Black Hills, South Dakota: U.S. Geological Survey Scientific Investigations Map 2777, 44 p. pamphlet, 2 sheets.
Strobel, M.L., Jarrell, G.J., Sawyer, J.F., Schleicher, J.R., and Fahrenbach, M.D., 1999, Distribution of hydrogeologic units in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-743.
Strobel, M.L., Sawyer, J.F., and Rahn, P.H., 2000, Field trip road log—Hydrogeolgy of the central Black Hills of South Dakota, *in* Strobel, M.L., Davis, A.D., Sawyer, J.F., Rahn, P.H., Webb, C.J., and Naus, C.A. eds., Proceedings of the 1999 Conference of the Hydrology of the Black Hills: Rapid City, South Dakota School of Mines and Technology Bulletin No. 20, p. 239-245.

Field trip 4: The Black Hills and I-90/Hwy 79 Development Corridor.

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JACK EPSTEIN *U.S. Geological Survey, 12201 Sunrise Valley Drive, MS926A, Reston VA 20192*

1 day – Tuesday April 20, 2010

Itinerary

This is a one-day field trip that will explore geological hazards and landuse development issues in the rapidly growing regions of the eastern and northern Black Hills. Bedrock geology in these developing areas consists primarily of Triassic to Tertiary sedimentary rocks overlain by mainly fluvially-derived alluvium. Underlying Mississippian to Permian rocks (most of which we will drive across) constitute major groundwater aquifers that require special consideration for protection. Much of the recent development has occurred on or very near the recharge areas of these regional aquifers raising concerns for protecting clean groundwater sources. In addition, many other geologically-based issues are present including dissolution and subsidence, landslides, rock falls, and flooding. Recent work by the Department of Geology and Geological Engineering (in cooperation with funding partners, West Dakota Water Development District, US Geological Survey, SD DENR—Geological Survey, Pennington County Commissioners, and RESPEC, Inc.) has been directed toward defining the geology and potential development hazards within the I-90/Hwy 79 development corridor. These projects have been successful in producing several 1:24,000 scale geologic quadrangle maps, depth to groundwater maps, structural contour maps, aquifer susceptibility and vulnerability maps, and factor-of-safety maps for slope failures. These various products have been used to create a digitally-based landuse development risk model for one quadrangle as part of a pilot study. The intent of this large project is to provide city and county planners and water managers with the tools required to make responsible decisions regarding future development in the Black Hills and surrounding areas.

The field trip will entail a rolling history of the geological and development issues that occur along the route. At key locations, mapping and modeling products will be displayed and discussed in terms of their usefulness to the area's geology.

The field trip is limited to the first 20 registered people. Transportation will be in two vans, 10 participants and one driver per van. Most of the stops will be in areas where discussions will take place within the vicinity of the vehicles. No strenuous walking will be required, however, sturdy walking boots/shoes are encouraged. Lunch and snacks will be provided during the day.

Schedule: Tuesday, April 20, 2010
Meet in the Holiday Inn Lobby by 7:45 AM
(breakfast on your own)
Load into the vans and depart the hotel at 8:00

The Black Hills and I-90/Hwy 79 Development Corridor Field Trip Stop Summary

0.0 Depart Holiday Inn (Civic Center) parking lot at 8:00 AM: Exit to right onto 5th Street

0.2 Cross Rapid Creek at Memorial Park, established in tribute to the 237 persons lost in the June 9, 1972 flood.

0.3 Turn right onto Omaha Street.

0.7 Turn left onto West Boulevard. Cross railroad tracks and pass two stop lights.

1.1 Turn right onto Quincy Street.

1.5 Cretaceous Fall Formation sandstone beds in road cut on right. Note the low dip, thinly bedded sandstone near the upper surface that is broken showing evidence of rotation and colluvial activity (Fig. 1).

2.0 **STOP No. 1** Dinosaur Hill Parking Lot: Walk up steps to hill top.

The bright green dinosaurs were constructed by workers of the WPA (Works Projects Administration—part of the New Deal agencies to employ Americans during the 1930's depression era) in the 1930's. They include Stegosaurus (blades on the back), a stegosaurid armored dinosaur; Camaraosaurus (duck-bill), a quadrupedal, herbivorous dinosaur; *Tyrannosaurus rex* (more upright and bulky than now known), a theropod dinosaur; Diplodocus (Brontosaurus of old and with a too-droopy tail), a sauropod dinosaur; and Triceratops, a ceratopsid, herbivorous dinosaur.
View to north along "Cretaceous hogback". Geological items of interest include:
a. East-dipping panel of strata
b. Landsliding along bedding planes
c. Rotational failures on steep west slope
c. Water gap on Rapid Creek

View west from hill top (Fig. 2). Geological items of interest include:
a. Flood plain
b. East dip of Phanerozoic strata
c. Cement plant anticline
d. South facing monocline gap
e. Red valley
f. Q terraces along creek
g. Jurassic strata on west hill slope (engineering problems)
h. Topographic front is not equal to structural front
i. Harney Peak range in the Black Hills core

Figure 1. Cretaceous Fall River sandstone outcrop on eastern hogback in Rapid City. Note the thin-bedded and fractured sandstone and the down slope nappe-like structure evidence of active colluvial processes. From Rahn (1996), Fig. 6.7.

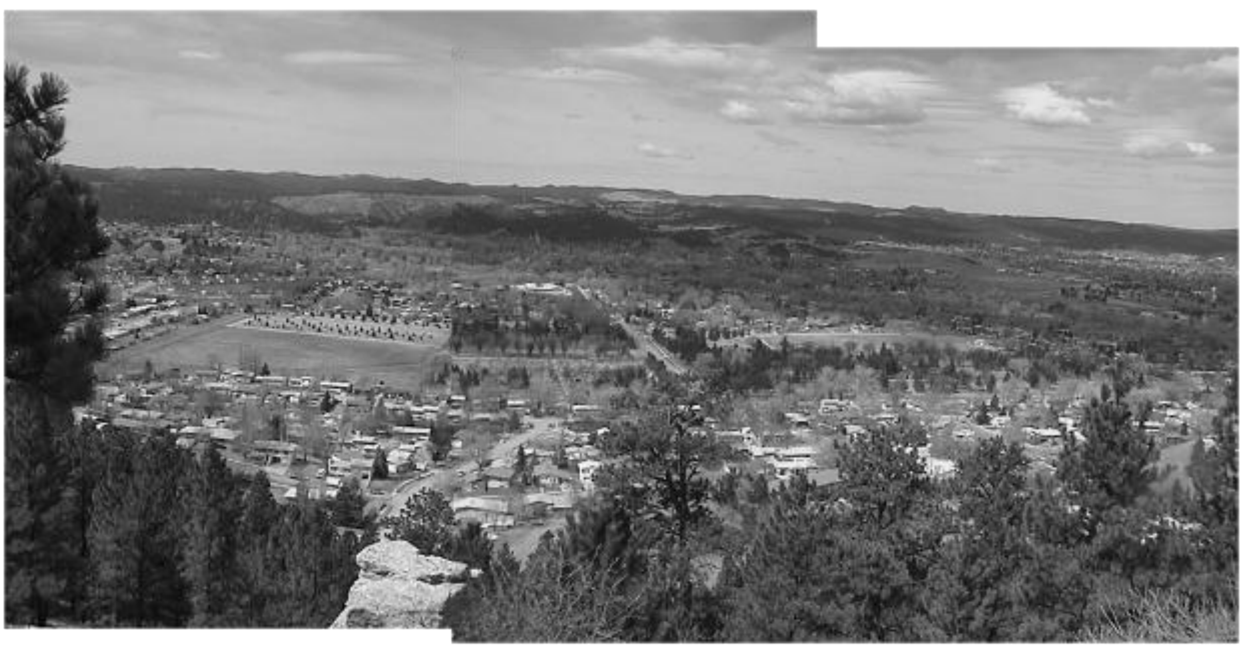

Figure 2. View looking westward from the top of Cretaceous hogback in Rapid City. The urbanized area is mostly on the Triassic Spearfish Formation. First ridge is tree-covered Permian Minnekahta Formation. The far ridge is Precambrian metasedimentary rocks.

View east to plains (Fig. 3). Geological items of interest include:

a. Flood plain
b. Terrace plateaus and eastward extensions
c. Cretaceous prairie

Figure 3. View looking eastward from the top of the Cretaceous hogback ridge in Rapid City. The base of the tree-covered slope begins a thick sequence of middle to upper Cretaceous shale units that extend far eastward on the prairie.

Return to vans.

Continue south along ridge crest. Road cuts reveal sandstone and mudstone units of the Upper Cretaceous Fall River Formation formed in streams flowing northwestward to the advancing northern arm of the Western Interior Cretaceous Seaway. Isolated and thin coal units are also visible. When US Highway 16 was constructed below the ridge top adjacent to Stop No. 3, many small landslides began to develop along exposures of these coal seams (Fig. 4).

4.2 Rock retaining wall on west (right) side of road showing rotational slumping and numerous road re-pavements. Note the number of new home constructions and their positions along the ridge.

4.6 <u>**STOP No. 2:**</u> Intersection with Tower Road. This is the approximate northern limit of the Tertiary gravel deposits which we will be driving on for the next few miles south. These Oligocene gravels rest on top of an erosional surface formed during late Eocene, early Oligocene time (Gries, 1994). Locally, this terrace is referred to as the Mountain Meadows Terrace. In many places, a well developed organic soil is exposed (Fig. 5) that shows good soil stratigraphy including the leaching (elluviation) and mineral enrichment zones (illuviation). Much of the leached zone is represented by a caliche (calcium carbonate coating) horizon.

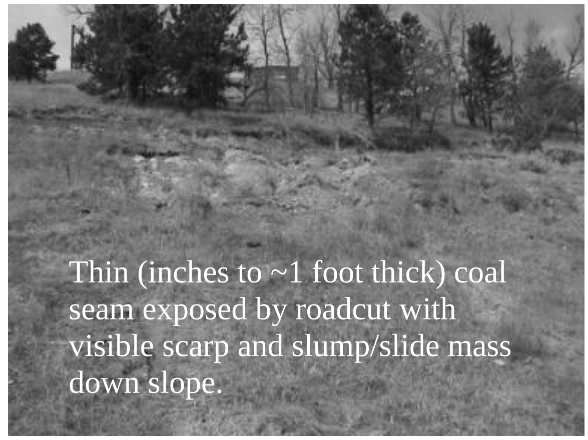

Figure 4. Thin coal seems exposed during road construction were the source areas of many small landslides that still are active along US Highway 16, south of Rapid City and on the eastern slope of the Cretaceous hogback ridge.

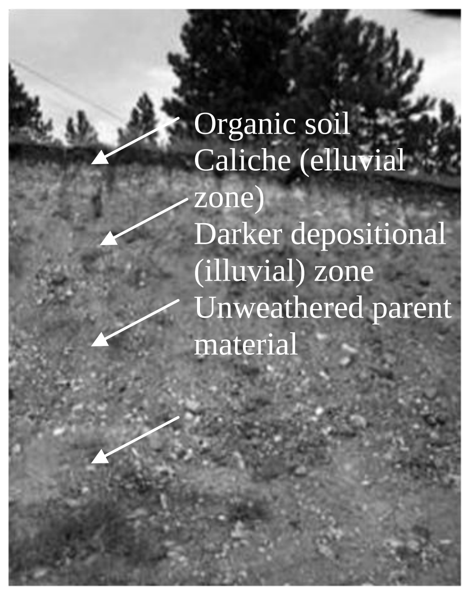

Figure 5. Soil profile developed on top of Tertiary terrace gravels.

Initial construction on the terrace proved difficult. Early development bids planned on using front-end loaders to excavate the gravels but in reality, many of these gravel units have been indurated and required drilling and chiseling to excavate. Recent development of homes on the edge of the gravels near the steep slopes has resulted in many landslides. A proposed new Wal-Mart Superstore on the terrace was rejected by the City three years ago citing potential for aquifer contamination to the sandstone units which lie immediately below the gravel.

The 1 million gallon water tower (Fig. 6) was constructed in the early 2000s to service the development on the terrace and to provide adequate fire protection. This is part of the Rapid City water distribution system and is referred to as the 'Ultra-High System'. The water is pumped from city wells in the underlying Pahasapa Limestone (Madison aquifer).

Figure 6. Rapid City's 'Ultra-High' 1 million gallon storage tank located across US Highway 16 from Stop No. 2.

Return to vans.

Turn right on Tower Rd.

4.7 Turn left then right onto Highway 16.

6.2 Stop Lights at Catron Boulevard. Turn left onto Catron Boulevard. Proceed east to Highway 79 south. This portion of road begins in the Tertiary terrace gravels and descends through Fall River sandstone units along the upper hill slope and onto the lower to middle Cretaceous Graneros Group rocks toward the bottom of the slope ending in the Belle Fourche shale at Highway 79 (Fig. 7). In the north-south direction along the eastern base of the ridge, numerous slides and slumps have occurred throughout the history of Rapid City. Some homes along the flank of the ridge have up to three visible stages of slope stability mechanisms in place (Fig. 8), an original retaining wall, asecondary extension of the retaining wall, and finally a buttress system along the base of the retaining wall. The fine-bedding in the upper-most part of the Fall River sandstone promotes a colluvial march of material downslope through time (Fig. 1).

9.7 Turn right onto Highway 79 South.

14.5 West (right) side on ridge top are silicified conglomerate formed in White River Group channels that drained the paleo-Black Hills. The cementing silica was derived from the enclosing tuffaceous flood plain deposits. These units can be traced in a southeast direction for many miles. East (left) side is the Ranch at Black Gap, a housing community about 10 years old. These homes were built on top of the Belle Fourche shale and are on individual on-site wastewater treatment systems (septic tanks).
The high ridge is the watershed divide between Rapid and Spring Creeks.

Figure 7. View looking westward from US Highway 79. The eastern slope of the hogback has experience rapid development in recent years as shown in this photo.

15.7 Turn right onto Hart Ranch Rd.

STOP No. 3: Spring Creek drainage.
Spring Creek is an ephemeral stream due to its crossing over loss zones in the Pahasapa Limestone ~5 miles west of here. Live water will flow here only during wet years. Alluvium along the creek serves as shallow water supplies for many ranches to the east.

Beginning in about 2002, the South Dakota School of Mines and Technology began a long-term project, funded by the West Dakota Water Development District, to develop tools to assist city and county governments to make informed development-planning decisions regarding development and has been described by Davis et al. (2003). The study involved several phases, the first of which was the preparation of 1:24,000 scale *geologic maps* of the eastern portion of the Hills in Pennington County. Such maps defined the outcrop areas through which recharge of the aquifers occurred as well as the areas of overlying deposits of gravel and alluvium which may affect recharge. Four derivative maps were then be prepared. A *structure contour map* was developed using the elevations of contacts and the penetration points from the water wells. Through the use of a GIS a *depth-to-aquifer map* was developed by subtracting the structure contour elevations from that of the topographic contour map. Simultaneously the physical characteristics of these formations were determined in order to prepare *aquifer susceptibility* (the ability of a material to absorb fluids) *maps*. The locations of potential sources of pollution within the recharge areas (on-site waste water systems, roads, streams, etc.) were defined from aerial photographs and other sources. These features were then combined with the susceptibility maps in order to prepare maps showing the relative potential risk *(aquifer vulnerability*) for the aquifer within the quadrangle.

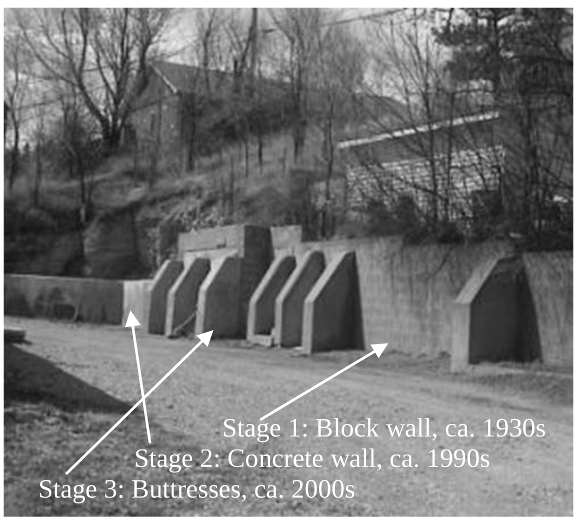

Figure 8. Three-tier retaining wall system in east Rapid City built to stop the continual colluvial movement of material down the eastern slope of the Black Hills.

In June 2006, a pilot project was funded by the Pennington County Commissioners and the SD Department of Environment and Natural resources to develop a landuse and hazard risk model for the Hermosa NW 7.5 minute quadrangle. The model relied upon the previously produced maps described above with the addition of development of a factor-of-safety map for slope stability. The research was conducted in a partnership with RESPEC, Inc of Rapid City. The area in question has been proposed to have several multi-dwelling housing tracts constructed and county officials had no scientific information upon which to base landuse decisions. The pilot project had two objectives (Stetler and Minnick, 2007):

Goal 1: Create a geodatabase of available data for the project area.

Goal 2: Create a land use classification map ranking locations within the study area as being low, moderate, or high risk to geological and/or environmental impacts from development.

Goal 1 was accomplished by constructing a geodatabase using ESRI's ArcMap to collect and store spatial data as input layers in the form of ESRI GIS shapefiles and rasters. Goal 2 landuse classification maps were developed from the construction of a multivariate analysis model. Ten basic input utility layers were used: **1)** Aquifer Vulnerability—areas that represented sensitivity to contamination of the ground water. The relative vulnerability ratings used were developed by Miller (2005) and Hargrave (2005) at SDSMT. The data layer was created from a modified version of aquifer vulnerability for the Hermosa NW 7.5 minute quadrangle map complied by Francisco (2007) at SDSM&T; **2)** Cobble Fraction—derived from the National Resources Conservation Service (NRCS) **SSURGO** database (Natural Resource Conservation Service, 2004); **3)** Depth to Bedrock—derived from NRCS **SSURGO** database (Natural Resource Conservation Service, 2004) and represented the depth, in inches, to bedrock or a similar restrictive layer; **4)** Flood Potential—derived from NRCS **SSURGO** database (Natural Resource Conservation Service, 2004) and modified by the modeler. Values for the model were derived from a pairwise comparison method (Stetler and Minnick, 2007); **5)** Permeability—derived from NRCS **SSURGO** database (Natural Resource Conservation Service, 2004) and modified by the modeler. The data layer represented the loading rate, in gallons per day per square foot, and was calculated from **SSURGO** values of hydraulic conductivity; **6)** Road Subgrade—derived from NRCS **SSURGO** database (Natural Resource Conservation Service, 2004). The road subgrade suitability was derived from a Department of Transportation table of American Association of State Highway and Transportation Officials (AASHTO) soil classifications [South Dakota Department of Transportation, 2006]. The AASHTO soil classifications were related to soil-bearing capacity; **7)** Road Grade Slope—derived from the National Elevation Dataset 10-meter Digital Elevation Model (DEM) (United States Geological Survey, 1999); **8)** Septic Drainfield Slope—derived from the National Elevation Dataset 10-meter Digital Elevation Model (DEM) (United States Geological Survey, 1999). The septic drainfield slope percentages were obtained from the NRCS soil limitation table for septic tank and soil absorption fields (Natural Resource Conservation Service, 2004); **9)** Slope Stability—derived from slope factor-of-safety maps (Minnick, 2007) at SDSM&T. The factory-of-safety values used to derive the slope stability data layer were given for a saturated condition; and **10)** Soil Shrink/Swell—derived from NRCS **SSURGO** database (Natural Resource Conservation Service, 2004).

The basic input layers were then used to construct three major development components:

1. On-Site Sewage Treatment Suitability
2. Roads Suitability
3. Structures Suitability.

A weighting system was developed to determine contributing factors by each of the basic layers. These were adjusted, using professional judgment and knowledge of the study area, to meet expected impact rankings based on recent and past development problems. The final development risk model (Fig. 9) was a simple visual tool, constructed in ArcMap, to display the development risk associated with a spatial analysis of the three major input layers. A unique aspect of the model was the ability of the user to drill down inside the data set to determine which factor(s) was responsible for the ranking of low, moderate, or high risk.

Return to Vans
Proceed west on Hart Ranch Road

17.1 Crossing back into the upper Fall River sandstone units. Note the blocky nature of the jointing pattern. Small areas of rock fall potential also exists in these units.

We are now driving up-dip (down section) along Hart Ranch Rd. The Fall River sandstone attains higher elevations to the west and underlies the tree-covered ridges ahead on the sky line.

Also note that Spring Creek is dry along this road. Three developments have occurred along this road, Hart Ranch Resort, a club camping facility; Hart Ranch Development, a residential housing community; and Hart Ranch Golf Course, an 18 hole golfing experience through the valley. All sewage from Hart Ranch Resort is gathered into one central processing station as the Resort is not unlike a small community for ~4-5 months per year.

21 Jurassic Sundance and Gypsum Spring Formations appear to the north (right) side of the road. Gypsum bands are ubiquitous at the base of the yellow sandstone in the Sundance. Below the Gypsum Springs is the Triassic Spearfish Formation consisting of gypsum units intercalated throughout sand and silt beds. The Spearfish is oxidized and appears bright red, earning the name 'Red Valley'. It generally is highly erosive and forms low valley topography between the overlying Sundance and the underlying Permian Minnekahta Limestone. Most high elevation areas inside the Red Valley are more resistant bands or knobs of gypsum that are more erosion resistant and stand out in relief (Fig. 10).

21.8 Turn right onto Neck Yolk Rd.

22.2 Turn right onto Highway 16 heading north. The road progresses up a hill that transects the Spearfish, Gypsum Springs, Sundance and tops out on the Tertiary terrace deposits on top of the ridge. To the west (left) side, many small slumps and shallow slips are evident in the Spearfish Formation.

24.1 Turn left onto Moon Meadows Rd. This road roughly follows the watershed divide between Spring (to the south) and Rapid (to the north) Creeks.

24.8 **<u>STOP No. 4:</u>** Terrace gravels are generally flat areas that are favorable for development. As such, many homes have been recently constructed on these gravels (Fig. 11). In this area, the Minnelusa Formation is immediately below the gravel and is an aquifer for many homes in west Rapid City. Development using on-site wastewater treatment systems is causing controversy regarding potential degradation to the water supply (Rahn, 2008). Pennington County is discussing the adoption of instituting an inspection fee for all county residents using on-site systems.

26.8 Turn right onto Whispering Pine Rd.

26.9 Turn right onto Sheridan Lake Rd. Immediately north of this intersection is one of the newest housing development. This development, and the one immediately to the west, are on city water and sewage systems. There are over 600 additional home within 1 mile to the west that are using on-site wastewater treatment systems. The majority of these homes sit atop the Minnelusa Formation or are on terrace gravels above the Minnelusa. Many other homes immediately down dip rely on the Minnelusa for their drinking water supply. The fate of this aquifer has yet to be decided.

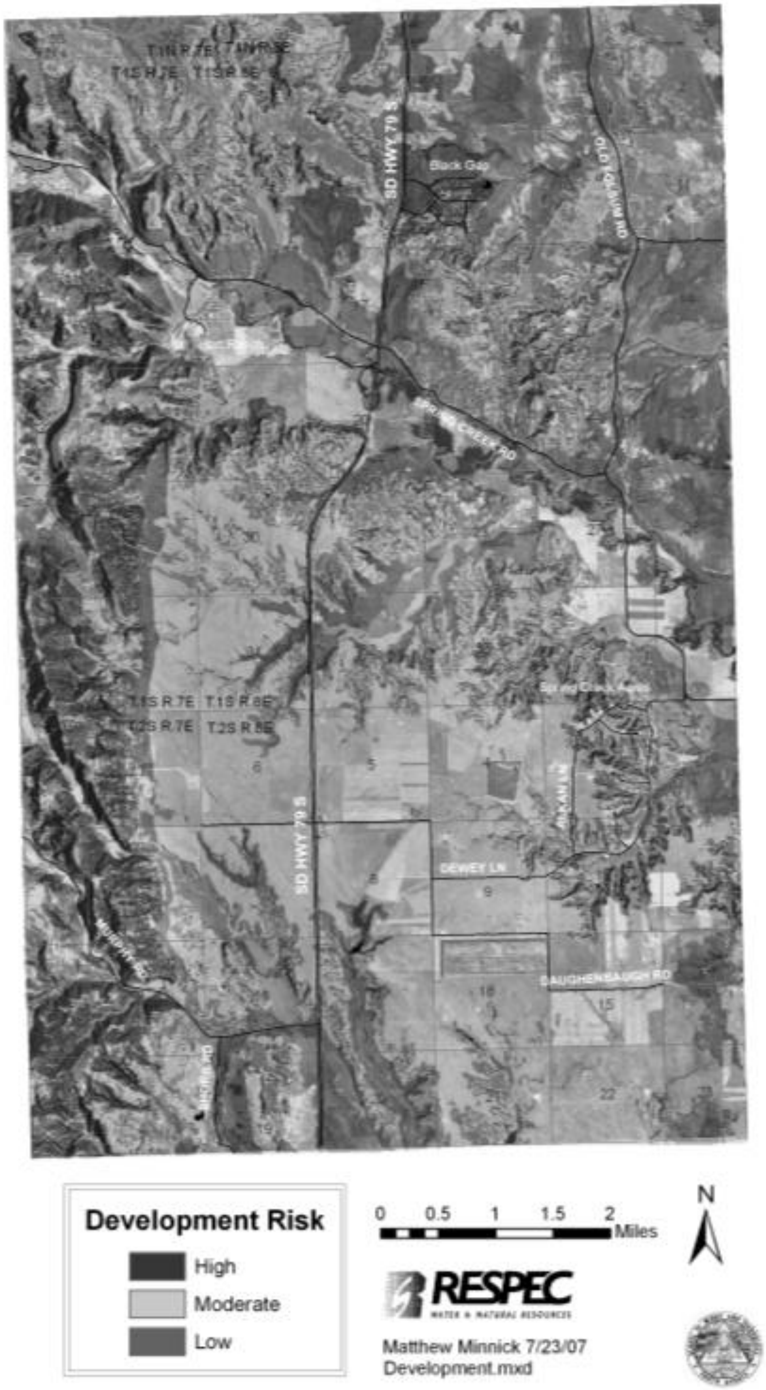

Figure 9. Final Development Suitability Impact Map developed by Minnick (Stetler and Minnick, 2007) for the Hermosa NW 7.5 minute quadrangle. A full-color copy will be made available to the field trip participants at this stop.

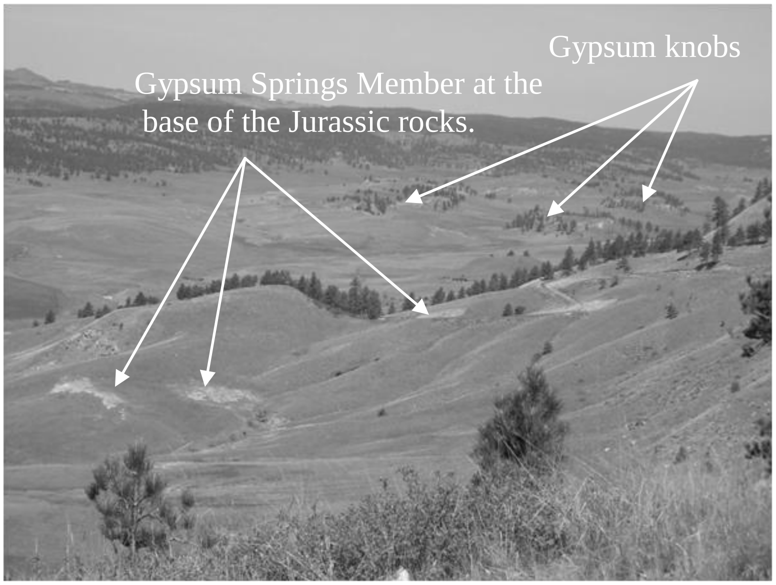

Figure 10. View from the top of the Fall River Formation looking northwest down the Red Valley (Spearfish Formation). The high knobs that host trees in the valley are erosional highs of gypsum.

Figure 11. Home development (in picture middle) on ~flat terrace gravel deposits in the Black Hills. Potential exists for aquifer contamination from these developments.

30.1 West (left) side is the upper Spearfish Formation. At this bend in the road, there are purple lime-rich units. East (right) side in the bottom of the stream drainage is the Permian Minnekahta Limestone. This unit is normally 40 feet thick, but is much reduced here due to karstic weathering below the early Tertiary erosional surface. The pure $CaCO_{3,}$ cryptocrystalline character of this thinly bedded limestone make it ideal for cement production and road meterial and it is extensively quarried within the Rapid City limits and around the Black Hills.

31.3 **<u>STOP No. 5:</u>** Intersection of Sheridan Lake Rd and Catron Blvd. This location is in the Red Valley and has seen rapid development since the 1990s. Gypsum stringers and knobs are ubiquitous and their locations are unpredictable. Many homes on these slopes are sited on top of gypsum and over the years, weathering of the hard gypsum has resulted in swelling that has lifted portions of foundations, roads, and other structures. Many of these homes have windows and doors that won't close properly, broken foundations and basement floors and some foundations have pulled apart from the basement floor. All of the evidence of land mobility (shallow slips and slumps, see figure 12) is removed by site preparation and construction appears solid. Routing of runoff is critical to maintaining integrity in the structure.

The native un-weathered gypsum is very hard and durable. It has the appearance of making a solid foundation, which, unfortunately, un-aware homeowners find out some years down the road that it does not. Settlement issues in the Red Valley are very irregular given the scattered appearance of the gypsum beds in the Spearfish, therefore, foundation problems must be addressed on a site-by-site basis. Deeper drilling during construction would be required to know for certain how far below and excavation the gypsum might be. These data would allow for proactive mitigation as needed.

Return to Vans

Figure 12. Upper Spearfish Formation slope at the base of the Jurassic units in western Rapid City. Ubiquitous shallow slips are evident on the slope. Pre-development land preparations remove these tale-tell signs of instability rendering many homes in danger of foundation movement.

31.9 Turn left onto Corral Drive. Massive gypsum immediately on left around corner.

32.3 Turn right onto Park Drive. Massive gypsum is seen to the east (right) along the top of the ridge. Small, shallow slips are covering the surface of this slope.

32.5 On the ridge top to the east (right) side a house built on top of the massive gypsum (Fig. 13).

33.9 Turn right onto Jackson Blvd. To the left is the dam of Canyon Lake. This portion of the Rapid Creek flood plain was swept clean of houses as failure of the dam added a temporary surge to the flooding waters on June 9, 1972. Currently, water is pumped from galleries within gravel deposits under the flood plain by Rapid City to meet the summer water needs for lawns, etc.

34.8 Turn left onto Soo San Drive.

35.2 West (left) side in Canyon Lake School yard is a swampy area with cattails and other riparian vegetation. This is an area of active springs and several small streams flow eastward from this source into Rapid Creek. It is likely this is an area of groundwater upwelling through the Spearfish Formation via fractures and/or collapse zones in underlying formations propagating upward through the shale. These features are ubiquitous in the Spearfish Formation around the Black Hills and will be discussed in detail at Mirror Lakes.

Figure 13. Several homes are built on top of massive gypsum beds in this area. Many additional areas of gypsum outcrop are evident. Homes at base of hill encountered scattered gypsum boulders while being built. Once the foundation has been constructed, it is imperative that water routing is maintained away from the foundation so as not to weather potential underlying gypsum stringers.

35.3 Turn right onto Canyon Lake Drive.

36 Turn left onto Sheridan Lake Road. Proceed up this small hill, which is another terrace deposit. The South Dakota National Guard Camp is located on this feature.

36.3 Turn right onto West Main Street.

36.8 Turn left onto Mountain View Road.

37 Turn left onto Omaha Street.

37.1 Turn right onto Deadwood Avenue.

39.8 Turn left onto I-90 West

45 During the past 10 years much of this area has experienced rapid development (Fig. 14) in the Red Valley and adjacent slope areas. All homes utilize onsite wastewater treatment systems. Several of the development districts are based on traditional home spacings but some of the newer developments have gone to ~2 acre (and larger) plot sizes. This will serve to reduce concentration loading into underlying units through fractures. However, the need still exists to produce development risk models for the entire I-90 development corridor before all of the areas has been developed without any scientific data to base landuse decisions upon. Unfortunately, the recent economic downturn has stopped the modeling work. Geologic mapping and preparation of the supportive product maps is continuing.

Figure 14. View looking NW along the I-90 development corridor. The trees on the left side of the valley are on the dip slope of the Minnekahta Limestone. The highest ridges are underlain by the Minnelusa Formation although the upper portion of the Pahasapa Limestone (Madison aquifer) is seen as curve in the canyon wall in the upper left. This is the anticlinal hinge of the White Gates monocline. The unit at the right by the gravel road is the lower Fall River Formation. Development has occurred mostly on the Spearfish Formation, above two groundwater aquifers.

51.6 Exit right opposite of Summerset (Exit 48), into housing development east (right) side. Drive to south end of development.

STOP No. 6: This is an active research area for studying the geomorphology and fluvial history of debris flows from small watersheds. USGS stream gage records for the past ~50 years have been used to determine flood peak and flow recurrence intervals, yet, many of these small watersheds around the periphery of the Black Hills have a depositional record that cannot be reconciled with the current fluvial regime. As development continues along the corridor, one question is directed toward determination of flood events of the magnitude required to move these debris deposits and to determine their potential impact on future development. The railroad is also interested since they are proposing new tracks in this area and have a need for this information to design sufficient track and overpass structures.

On the north side of the freeway is the Cretaceous hogback ridge capped by the Fall River Formation. This area was burned about 4 summers ago by a wildfire that denuded the slopes. No reported debris flows or slides have occurred as a result.

Return to Vans

Turn right back onto I-90 West.

69.2 Exit I-90 at Sturgis. Continue north on Junction Street to Highway 34.

70.7 Turn right onto Highway 34 East. Proceed to the Sturgis City Park

70.8 Turn left into Sturgis City Park

STOP No. 7: Lunch at the City Park.

The slope directly south of Sly Hill Road above City Park in Sturgis, SD has shown signs of instability during the past decade. Following what was one of the wettest years in over a decade, this instability accelerated in mid May 2009 to the point where Sly Hill Road had to be closed to traffic (Fig. 15). In addition several other slides have occurred in this area during the past 8-10 years.

The portion of Sly Hill Road where the failure occurred is within city limits and is maintained by the City of Sturgis. Due to the costs required to appropriately repair the road, the City discussed whether to pay for an engineered solution since alternative access could be gained from US Highway 79 (although the trip was lengthened by approximately 10 miles). During several public meetings, the numerous county residents that utilize this road daily for access to Sturgis and the interstate formally requested that the Sly Hill Road be repaired and reopened, and the City of Sturgis applied for and received a federal emergency grant to finance the construction of a soldier pile wall to mitigate the failure. The design and construction process were overseen by the South Dakota Department of Transportation and the wall was constructed by Corr Construction Inc. at a cost of approximately $500,000.

In June 2009, the Geological Engineering Field Camp of the South Dakota School of Mines and Technology visited the slide areas and measured and mapped the slide. Modeling was then performed using Rocscience software.

Return to vans.

Continue back on Highway 34 west to I-90 entrance ramp on the west side of town.

72.7 Turn right onto I-90 West.

92.5 Crow Peak at 11 o'clock position. Crow Peak is a Tertiary laccolithic intrusive consisting of a stock-like body of quartz latite.

Figure 15. (a) The Sly Hill Road failure on May 11, 2009 (Photo Courtesy of the City of Sturgis, SD). (b) The Sly Hill Road failure on May 18, 2009 (Photo courtesy of the City of Sturgis, SD). (c) The Sly Hill Road failure on May 31, 2009. (d) The Sly Hill Road failure with students obtaining measurements on June 8, 2009.

94.6 Lookout Mountain north (right) side capped by sandstone of the Lakota Formation (Cretaceous). Housing development to right makes use of a terrace in gypsum of the Gypsum Spring Formation (Fig. 16).

95.3 Exit 12. City of Spearfish. To north (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. This presents an interesting speculation about the age of erosion.

95.8 Lookout Mountain on north (right) side 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).

97.0 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. 17), 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. The plan to develop a recreation area was abandoned.

Figure 16. Looking west from the top of Lookout Peak. Crow Peak, a Tertiary laccolith, is the highest peak in the left center. The timbered slope beyond the town is the dipslope of the Minnekahta Limestone.

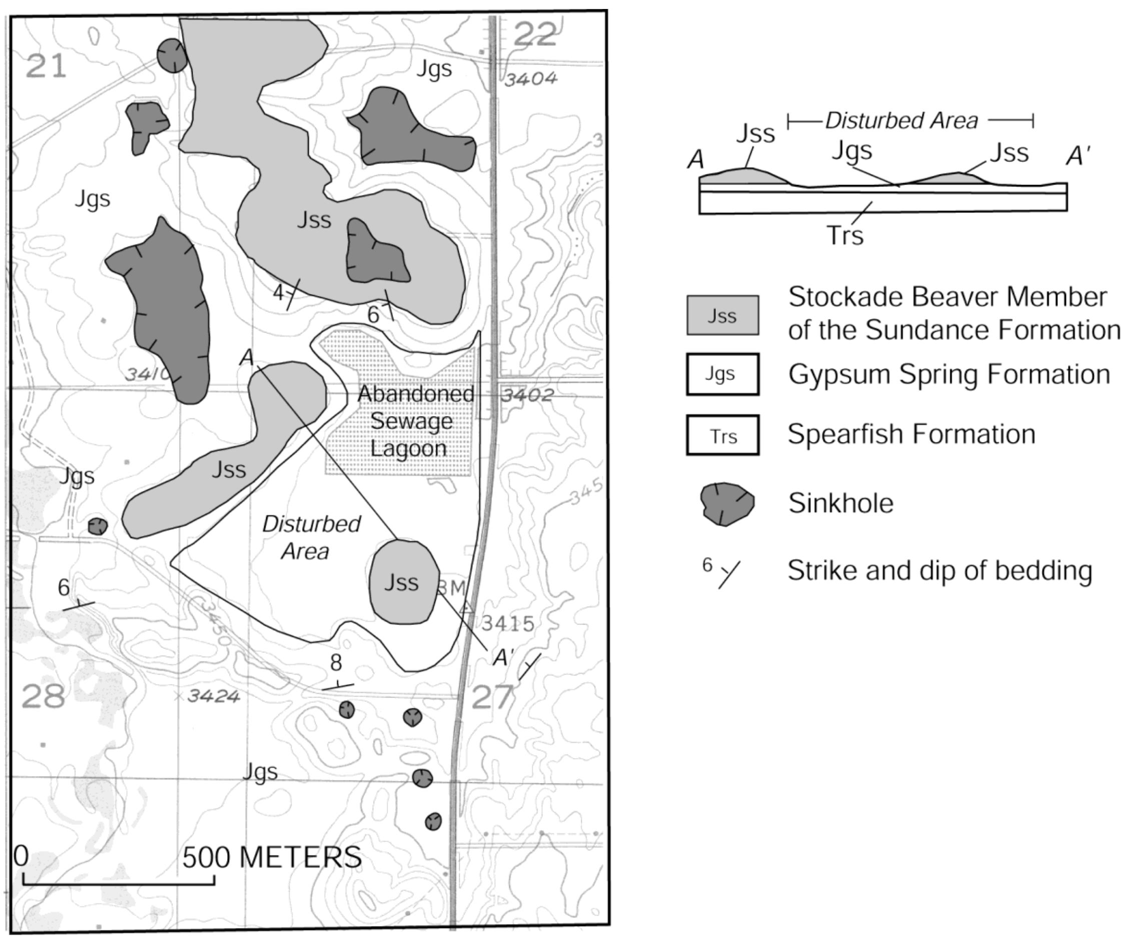

Figure 17. Geologic map of the abandoned sewage lagoon area west of US 85, 2 miles north of I-90, Spearfish, SD. From Epstein, 2003.

99.5 Crow Peak to the south (left) comprises an laccolithic intrusion into the core of the LaFlamme anticline. Dip slope in the Minnekahta Limestone ahead.

100.9 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 the north (right).

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

104.5 Minnekahta outcrop trends southward on the west limb of the LaFlamme anticline. Interbedded gypsum in the Spearfish Formation to right.

105.2 Exit 2. Turn right towards McNenny State Fish Hatchery.

105.5 Stop sign. Turn right on US 15.

107.7 McNenny Road, turn left. Many residual silicified sandstone boulders to right were 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.

107.8 Flowing well on left and two small sinkholes on right.

108.5 Scarps and very shallow depressions in Spearfish due to solution-collapse in gypsum.

108.6 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 (figure 18).

109 McNenny Fish Hatchery, Test Well No. 3 on right. The Minnekahta Limestone lies 267 feet below the surface here. The lithologic log for this well is shown as figure 19.
Continue straight across wooden bridge over Crow Creek.

109.05 Take first right at triple fork in road. Low outcrops of calcareous tufa--spring deposits on left (Fig. 20).

109.2 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 (Fig. 21).

109.4 Turn right at fork in road; 60-foot-long sinkhole to right.

109.5 Park in turnaround. Climb the embankment on the north side of Mirror Lake.

STOP No. 8: Mirror Lake at McNenny Fish Hatchery: Spearfish/Minnelusa karst; sinkholes, gypsum dissolution front, resurgent springs. Jack Epstein, USGS.

Figure 18. Many small sinkholes are present in the McNenny Fish Hatchery area, including circular depressions in red beds with some remaining gypsum (left) and solution widening of joint in gypsum resulting in soil collapse in residential parking area (right).

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

Figure 19. Lithologic log for test well No. 3 at McNenny Hatchery.

The following discussion is modified slightly from Epstein and others (2005). Karst features in the area around Mirror Lake at the McNenny National Fish Hatchery are found within red shale, siltstone, and fine-grained sandstone of the Spearfish Formation. The Spearfish is about 615 feet thick at this locality, although the total thickness varies by one hundred feet or more in wells nearby. Sinkholes, springs, and spring deposits are located at or on the surface 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. Where the gypsum beds are not exposed it is because they are either covered by surficial debris or because they have 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 20 shows the location of these features. Figure 21 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 (marl), and scattered gypsum exposures. Figure 22 is a map and cross section of the area useful in interpreting the karst development at Mirror Lake and environs.

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. These 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. 22). 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's. 21-23**)**. These are part of the slope-retreat process in this area. The sinkholes are characteristically rimmed by a low shrub, western snowberry (*Symphoricarpos occidentalis*).

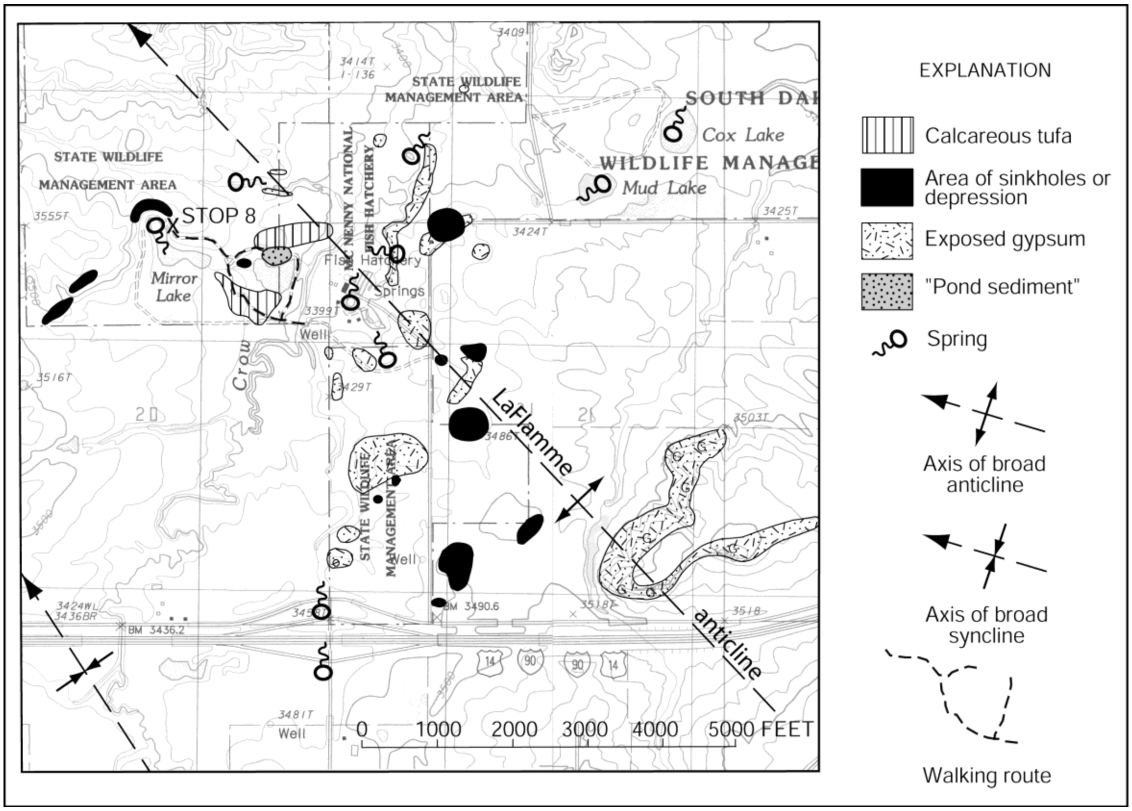

Figure 20. Karst features in the McNenny National Fish Hatchery area at Stop No. 8. The abundance of sinkholes suggests that there is a labyrinth of open conduits near the base of the Spearfish Formation. Base from Beulah, WY.-S.D. and Chicken Creek, WY. 7.5' topographic maps, 1984. If the field vehicle cannot cross the bridge over Creek, disembark and follow walking route.

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 (available at http://dive.scubadiving.com/members/tripreports.php?s=1051 in 2006). 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. 22), indicating a history of pond lowering after the deposition of the tufa.

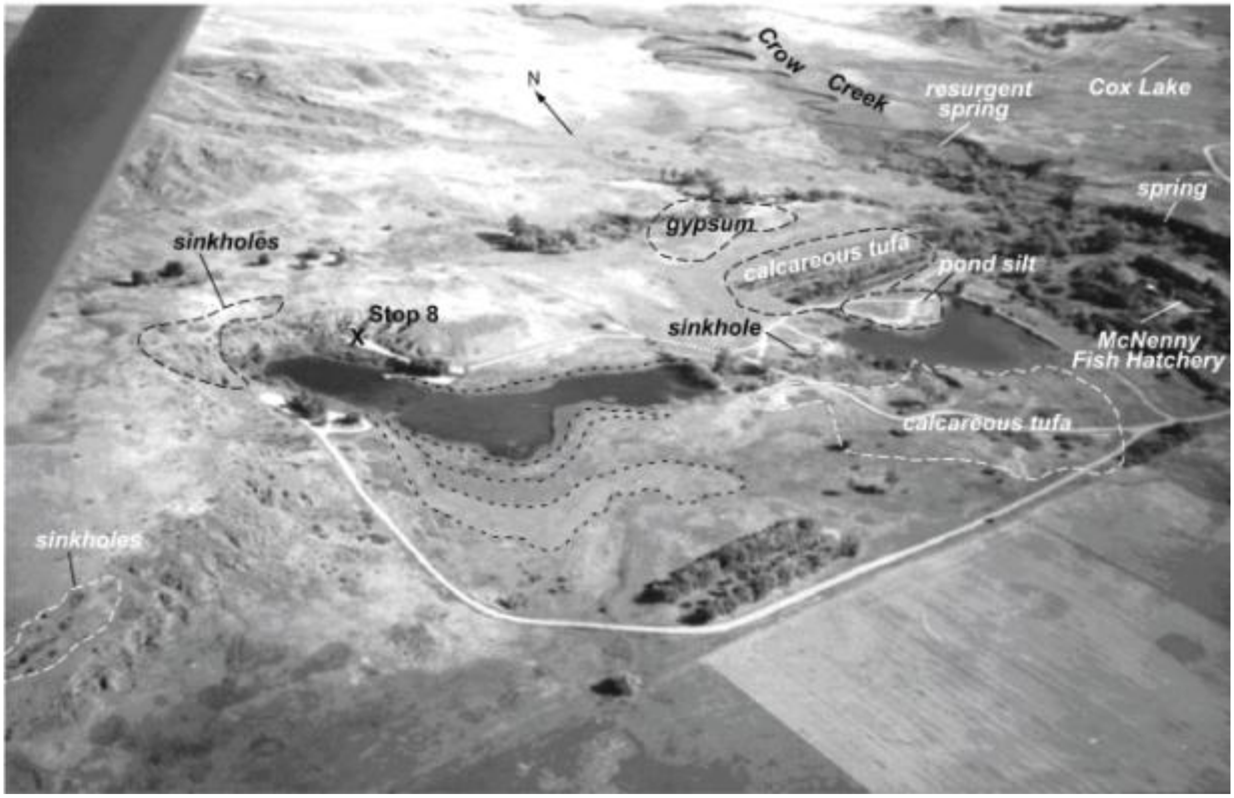

Figure 21. Air photograph showing karst features in the McNenny fish hatchery area.

*The Pahasapa is also termed the Madison Limestone, but let's use the Madison for the aquifer within the Pahasapa in the Black Hills in this discussion.

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 secondary fracture porosity. This part of the formation has supplied water to wells, many sinkholes have developed in it, and there are several springs in the McNenny fish hatchery area (Fig. 24). 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.
Epstein (2003) erroneously 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 Stop 8 and westward into Wyoming, and their stratigraphic confinement to the lower part of the Spearfish Formation indicates that there is a labyrinth of open conduits within the lowest Spearfish created by gypsum removal.

Two observations suggest a complicated pattern of subsurface dissolution affecting several stratigraphic horizons and that the Minnelusa is not the only source of subsidence affected rocks upwards into the Spearfish Formation. First, 3.7 miles southwest of Mirror Lake, at the junction of Sand Creek and South Redwater Creek south of Beulah, WY, the upper part of the Minnelusa is exposed and the topmost 50 feet or so is brecciated. Three miles south in the Sand Creek canyon the beds in the lower Minnelusa are not brecciated and anhydrite is present in outcrop. This locality is only one of two known in the Black Hills where anhydrite is exposed and brecciation is minimal or reportedly non-existent (Brady, 1931, 1958; Martin and others, 1988; Braddock, 1963). No sinkholes are seen in the Minnekahta Limestone above, confirming that here sinkhole development has not extended above the Minnelusa. Second, at another locality six miles southwest of Mirror Lake , the Minnekahta is exposed along South Redwater Creek where numerous sinkholes are present in a 2,000-foot-long low cliff and the unit is extensively brecciated (Fig. 25), and the underlying Opeche Shale is disrupted. These observations suggest that dissolution has occurred in the Minnelusa, affecting collapse in the Opeche and Minnekahta above at this locality.

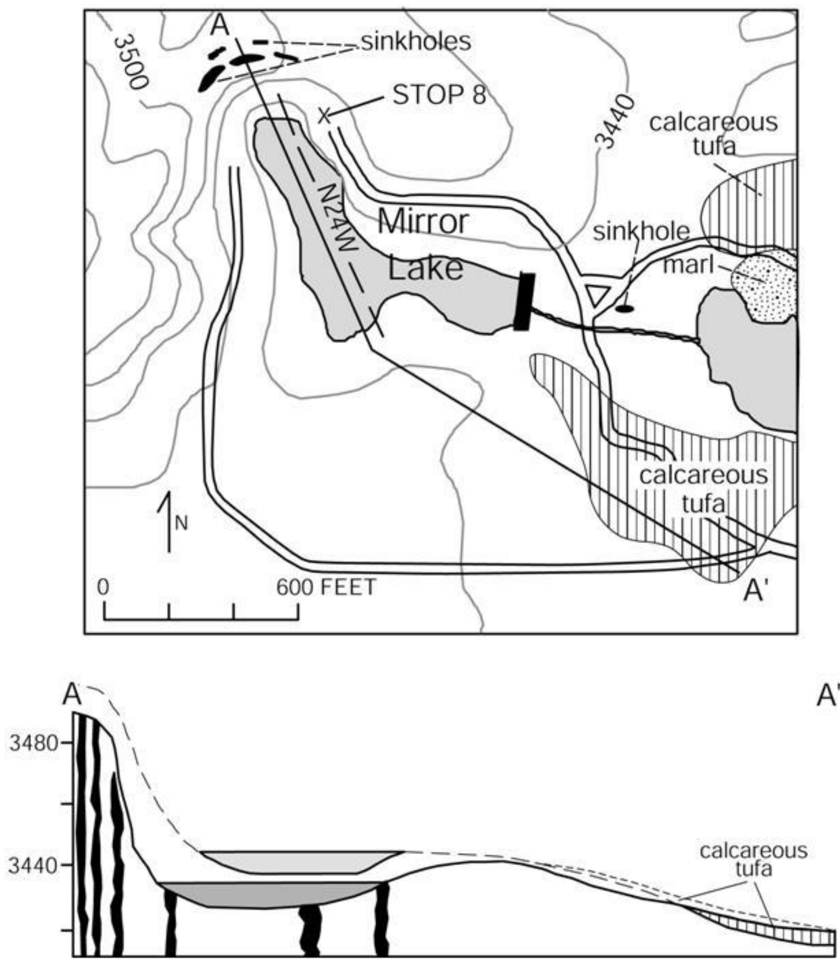

Figure 22. Map and cross section (vertical exaggeration 10x) showing sinkholes at the north end of Mirror Lake (black outlines) and inferred earlier topography (dashed line) in which calcareous tufa was deposited. Contour interval 20 feet.

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 26 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.

Figure 23. Elongate sinkholes, rimmed with western snowberry, paralleling the slope southwest of Mirror Lake.

Figure 24. 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.

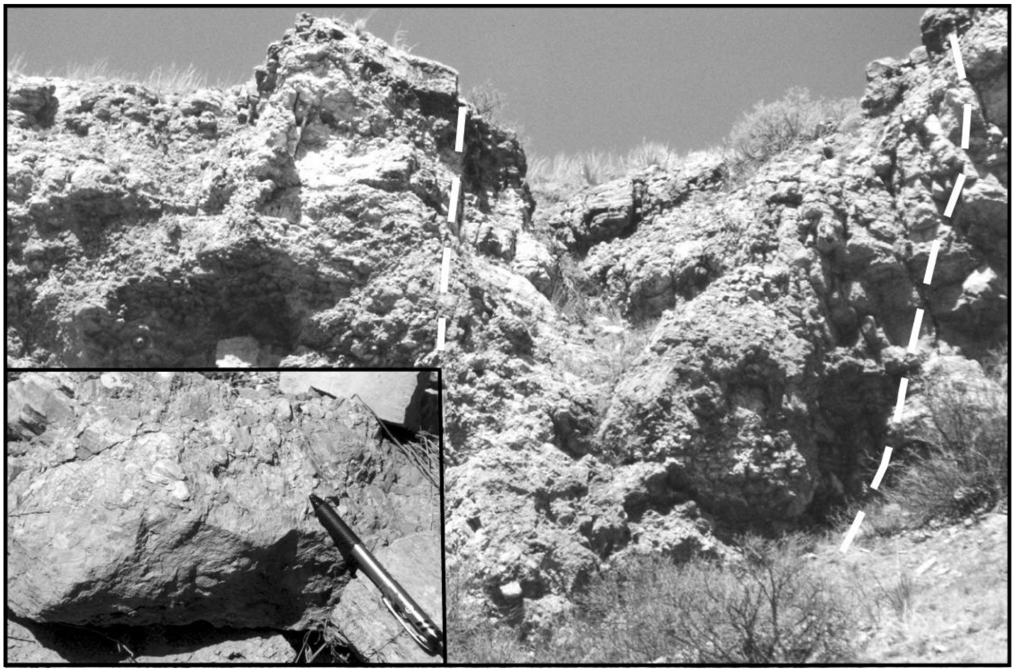

Figure 25. Collapse sinkhole (dashed line) in a zone of brecciated Minnekahta Limestone along Redwater Creek, one six miles southwest of strop 8. Inset shows details of breccia.

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.

DISSOLUTION FRONT IN THE MINNELUSA FORMATION

The upper half of the Minnelusa Formation contains abundant anhydrite in the subsurface, and except for a few areas near Beulah and Sundance, Wyoming (Brady, 1931, 1958; Martin and others, 1988), and in Hell Canyon in the southwestern Black Hills (Braddock, 1963), no anhydrite or gypsum crops out. A log of the upper part of the Minnelusa from Hell Canyon contains 235 ft (72 m) of anhydrite and gypsum (Brobst and Epstein, 1963). Where anhydrite is present in the Minnelusa, its Minnelusa Formation and upwards through the Gypsum Spring formation. Where the potentiometric surface is below ground level, sinkholes are dry; where it is above ground level, sinkholes contain rocks are not brecciated. Where the rocks are brecciated in outcrop, anhydrite is absent. Clearly, the brecciation is the result of collapse following subsurface dissolution of anhydrite.

The Madison and Minnelusa are the major aquifers in the Black Hills. They are recharged by rainfall on and by streams flowing across their up-dip outcrop area. In the Minnelusa, removal of anhydrite progresses downdip with continued dissolution of the anhydrite (Fig. 27), collapse breccia is formed, breccia pipes extend upwards, and resurgent springs develop at the sites of sinkholes. Cox and Mud Lakes (Fig. 28), and Mirror Lake, and McNenny springs, are near the position of the dissolution front (Fig. 27). As the Black Hills is slowly lowered by erosion, the anhydrite dissolution front in the subsurface Minnelusa moves downdip and radially away from the center of the uplift. The resurgent springs will dry up and new ones will form down dip as the geomorphology of the Black Hills evolves. Abandoned sinkholes on canyon walls (fig. 25) attest to the former position of the dissolution front.

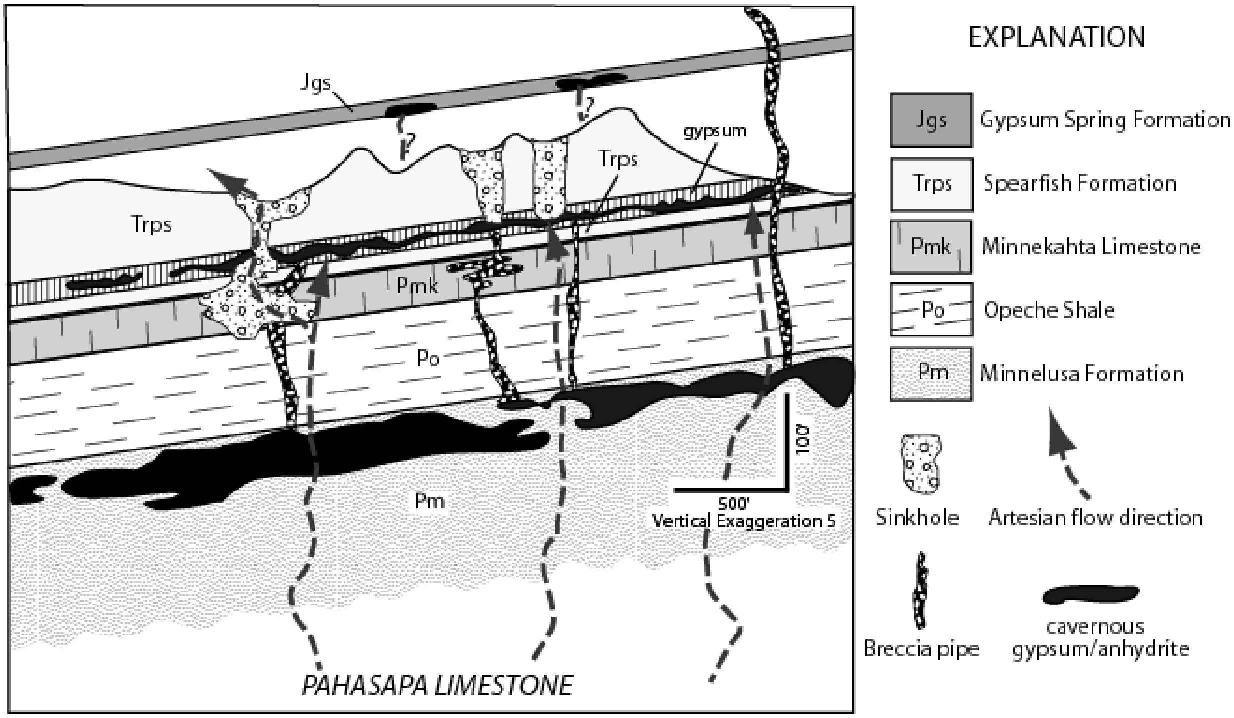

Figure 26. Interpretive cross section based on field mapping between Spearfish, SD, and Sundance, WY, showing dissolution flow paths and development of karst in the dissolution zone in the emergent springs, such as Mirror and Cox lakes seen at Stop No. 8.

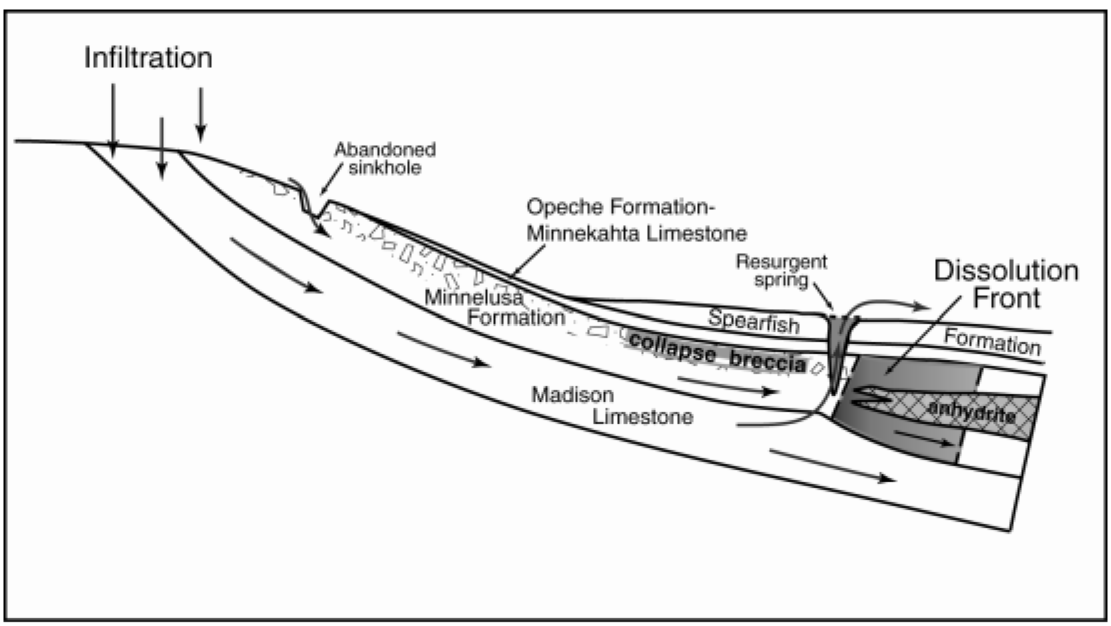

Figure 27. Dissolution of anhydrite in the Minnelusa Formation and down-dip migration of the dissolution front.

Because ground water has dissolved the anhydrite in the Minnelusa in most areas of exposure, and because anhydrite is present in the subsurface, a transition zone should be present where dissolution of anhydrite is currently taking place. A model of this zone has been presented by Brobst and Epstein (1963, p. 335) and Gott and others (1974, p. 45) and is shown here in figure 26. Consequences of this model include (1) the updip part of the Minnelusa is thinner than the downdip part because of removal of significant thickness of anhydrite, (2) the upper part of the Minnelusa should be continually collapsing, even today, and (3) the properties of the water in this transition zone may be different than elsewhere.

If this process is correct, then present resurgent springs should be eventually abandoned and new springs should develop down the regional hydraulic gradient of the Black Hills. One example might be along Crow Creek where a cloud of sediment from an upwelling spring lies 1,000 ft (300 m) north of McNenny Springs (Fig. 29). This circular area, about 200 ft (60 m) across, might eventually replace McNenny Springs.

Solution of anhydrite in the Minnelusa probably began soon after the Black Hills was uplifted in the early Tertiary and continues today. Recent subsidence is evidenced by sinkholes more than 60 ft (18 m) deep opening up within the last 20 years (Epstein, 2003), collapse in water wells and natural springs resulting in sediment disruption and contamination (Hayes, 1996), and fresh circular scarps surrounding shallow depressions.

Figure 28. Resurgent (artesian) springs in the Spearfish Formation about 4,000 feet northeast of McNenny Fish Hatchery (view to southeast). Cox Lake, with a flow of nearly 5 cubic feet (0.5 cu m) per second, occupies a sinkhole that is more than 60 ft (18 m) deep (outlined by the darker water just beyond the edge of the dock). The chemical signature of the water indicates that the Minnelusa Formation and underlying Madison Limestone are the contributing aquifers (Klemp, 1995). The lake is near the anhydrite dissolution front shown in figure 26.

Return to vans.
Retrace route to McNenny Road and back to I-90 East

111.8 Turn left onto I-90 East

186 Exit I-90 at Mount Rushmore Rd

189 Civic Center Parking lot.

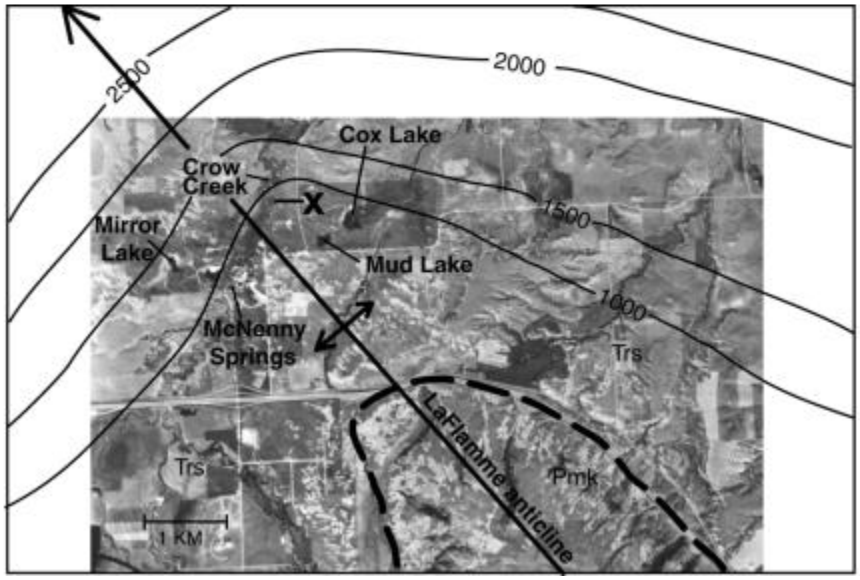

Figure 29. Air photograph showing location of resurgent springs in the Spearfish Formation adjacent to the LaFlamme anticline. X marks site of new resurgent spring along Crow Creek. Pmk, Minnekahta Limestone; Trs, Spearfish Formation. Specific conductance in the Minnelusa aquifer (contours in microseimens per second) from Klemp (1995).

End Road Log

REFERENCES CITED

Braddock, W.A., 1963, Geology of the Jewel Cave SW Quadrangle, Custer County, South Dakota: U.S. Geological Survey Bulletin 1063-G, p. 217-268.

Brady, F. H., 1931, Minnelusa formation of Beulah district, northwestern Black Hills, Wyoming: Am. Assoc. Petroleum Geologists Bull., v. 15, p. 183-188.

Brady, F.H., 1958, Evaporite deposits in the Minnelusa Formation in the Sundance-Beulah area, Crook County, Wyoming: Wyoming Geological Association Guidebook, p. 45-47.

Brobst, D.A., and Epstein, J.B., 1963, Geology of the Fanny Peak quadrangle, Wyoming-South Dakota: U.S. Geological Survey Bulletin 1063-I, p. 323-377.

Cox, E.J., 1962, Preliminary Report on the artesian water, Minnelusa and Pahasapa Formations, Spearfish-Belle Fourche area: South Dakota Geological Survey, Special Report 19, 23 p.

Davis, A.D., 1979, Hydrogeology of the Belle Fourche, South Dakota water infiltration gallery area: Proceedings of the South Dakota Academy of Science, v. 58, p. 122-153.

Davis, A. D., F. W. Beaver, and L. D. Stetler, 2003. “Engineering Problems of Gypsum Karst Along the Interstate 90 Development Corridor in the Black Hills, South Dakota, Johnson,” K. S. and J. T. Neal (eds.), *Evaporite Karst and Engineering/Environmental Problems in the United States, Oklahoma Geological Survey Circular 109*, p.255-261.

Epstein, J.B., 2003, Gypsum Karst in the Black Hills, South Dakota-Wyoming: Geomorphic Development, Hazards, and Hydrology: *in*, Johnson, K.S., and Neal, J.T., eds., Evaporite Karst and Engineering/Environmental Problems in the United States: Oklahoma Geological Survey Circular 109, p. 241-254.

Epstein, J.B., Davis, A.D., Long, A.J., Putnam, L.D., and Sawyer, J.F., 2005, Field Trip 2, Karst Field Trip to the Northern Black Hills: in, Kuniansky, E.L., editor, U.S. Geological Survey, Karst Interest Group Proceedings, Rapid City, South Dakota, September 12-15, 2005: U.S. Geological Survey Water-Resources Investigations Report 2005-5160, p. 232-282. Available January 2010 at *http://pubs.usgs.gov/sir/2005/5160/PDF/FTPart3.pdf*

Francisco, E., 2007. Unpublished Masters Thesis, South Dakota School of Mines and Technology, Rapid City, SD.

Gott, G.B., Wolcott, D.E., and Bowles, C.G., 1974, Stratigraphy of the Inyan Kara Group and localitzation of uranium deposits, southern Black

Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 763, 57 p.
Gries, J.P, 1996, Roadside Geology of South Dakota: Mountain Press Pub. Co., Missoula, MT, 358 p.
Hargrave, R. G., 2005. *Vulnerability of the Minnelusa aquifer to contamination in the Rapid City West Quadrangle, Pennington County, South Dakota*, Masters Thesis, South Dakota School of Mines and Technology, Rapid City, SD.
Hayes, T.S., 1996, Suspended-sediment "reddening" in Cascade Springs, southern Black Hills, South Dakota: Geological Society of America, Abstracts with Programs, Rocky Mountain Section, April 18-19, Rapid City, South Dakota, p. 11.
Jenning, J.N., 1971, Karst, The M.I.T. Press, Cambridge, Mass., 252 p.
Klemp, J.A., 1995, Source aquifers for large springs in northwestern Lawrence County, South Dakota: Rapid City, South Dakota, South Dakota School of Mines and Technology, unpublished M.S. Thesis, 175 p.
Martin., J.E., Motes, A.G., III, and Fox, J.E., 1988, Geology of the northern portion of the Simons' Ranch Anticline, Crook County, Wyoming, with special reference to the depositional history of the upper Minnelusa Formation (Permian, Wolfcampian): Wyoming Geological Association, Guidebook, Thirty-ninth field conference; eastern Powder River Basin-Black Hills, Casper, WY, p. 191-215.
Miller, S. L., 2005. Influences of Geologic Structures and Stratigraphy on Ground-Water Flow Paths in the Karstic Madison Aquifer in the Rapid City Area, South Dakota., Unpublished Ph.D. thesis, South Dakota School of Mines and Technology, Rapid City, SD.
Minnick, M. D., 2007. Unpublished Masters Thesis, South Dakota School of Mines and Technology, Rapid City, SD.
Natural Resource Conservation Service, 2004. *Soil Survey Geographic (SSURGO) Database for Hermosa, South Dakota*, retrieved June 27, 2007, from the World Wide Web: http://soildatamart.nrcs.usda.gov
Rahn, P.H. 2007, Future water supplies for Rapid City: SD Academy Sci, Vol. 86, p. 99-114.
Rahn, P.H. 1996, Engineering Geology: An Environmental Approach, 2nd Ed.: Prentice Hall, Upper Saddle River, NJ, 657 p.
Rahn, P.H., Bump, V.L., and Steece, F.W., 1977, Engineering Geology of Central and Northern Black Hills, South Dakota: South Dakota School of Mines and Technology, Rapid City, S.D., 34p.
Rahn, P.H., and Davis, A.D., 1996, Gypsum foundation problems in the Black Hills area, South Dakota: Environmental and Engineering Geoscience, v. II, p. 213-223.
Shearman, D.J., Mossop, G, Dunsmore, H., and Martin, M., 1972, Origin of gypsum veins by hydraulic fracture: Transaction of the Institution of Mining and Metallurgy, vol. 81, p. B159-B155.
South Dakota Department of Transportation, 2006. *South Dakota Department of Transportation Materials Manual*, retrieved April 20, 2007, from the World Wide Web: http://www.sddot.com/pe/materials/materials_manual.asp
Stetler, L.D., and M.D. Minnick, 2007, Black hills Suitability Risk Model: Topical Report RSI-1953 to Pennington County Planning Department, 35 p, App A.
United States Geological Survey, 1999. *National elevation dataset. Fact Sheet 148-99 (September 1999)*, retrieved June 27, 2007, from the World Wide Web: http://ned.usgs.gov/

Contrasting styles of Laramide Deformation: East and West Flanks of the Black Hills Uplift, South Dakota and Wyoming

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Introduction

The west and east flanks of the 104 km (65 mi) wide Black Hills Uplift (Figs.1and 2) differ in structural styles. Along the western margin large monoclines separate planar blocks of the Powder River basin and the uplift whereas the eastern flank is a broad half-dome.

Day one: Examine the eastern flank of the uplift where monoclinal flexures act as a group to divide the broad arch into small segments having minor changes in strike relative to the adjoining blocks: the sum of these minor changes results in the broad curvature of strata on the half dome. Structural relief across individual folds is less than 370 m (1,200 ft). The best exposures of the structures are seen in Paleozoic strata or the Cretaceous Inyan Kara Group although the folds continue into the Cretaceous shale units underlying the prairies. The axial traces of these folds are generally parallel to regional strike and also parallel the "grain" of the Precambrian basement exposed in the core of the uplift to the west.

Day two: Examine monoclines near Newcastle, Wyoming. There the Black Hills Uplift is separated from the Powder River Basin by the Fanny Peak and Black Hills monoclines which display structural relief to 1,060 m (3,500 ft). West vergence is a characteristic of almost all folds on both flanks of the uplift.

Laramide development in the Black Hills region includes both tectonic and igneous phases. Uplift and monocline development were initiated in the earliest Tertiary at about 64 Ma (Lisenbee and DeWitt, 1995) and the igneous phase followed at about 58 Ma, continuing to roughly </=46 Ma (Duke, 2009). Dikes, sills, stocks, laccoliths, ring complexes, and diatremes of rhyolite, trachyte, monzonite and phonolite are abundant along a N.70^{o}W-trending belt across the northern Black Hills and the Bear Lodge Mountains of Wyoming.

Sedimentation was continuous across the Cretaceous-Tertiary boundary along the uplift-Powder River Basin west flank of the uplift. Along the eastern flank, the White River Group of late Eocene and Oligocene age was deposited across eroded strata and crystalline rocks. Therefore, the Laramide represents an interval of less than 20 m.y. for this uplift.

DAY 1 Excursion Part 1: Rapid City to Piedmont

0.0 Depart Holiday Inn (Civic Center) parking lot: Exit to right onto 5th Street

0.1 Cross Rapid Creek

0.3 Turn right onto Omaha Street.

0.7 Turn left onto West Boulevard. Cross railroad tracks and pass two stop lights.

1.1 Turn right onto Quincy Street.

1.3 Cretaceous Fall River Formation sandstone beds in road cut on right.

1.9 <u>**STOP No. 1**</u> **Dinosaur Hill Parking Lot:** Walk up steps to hill top.

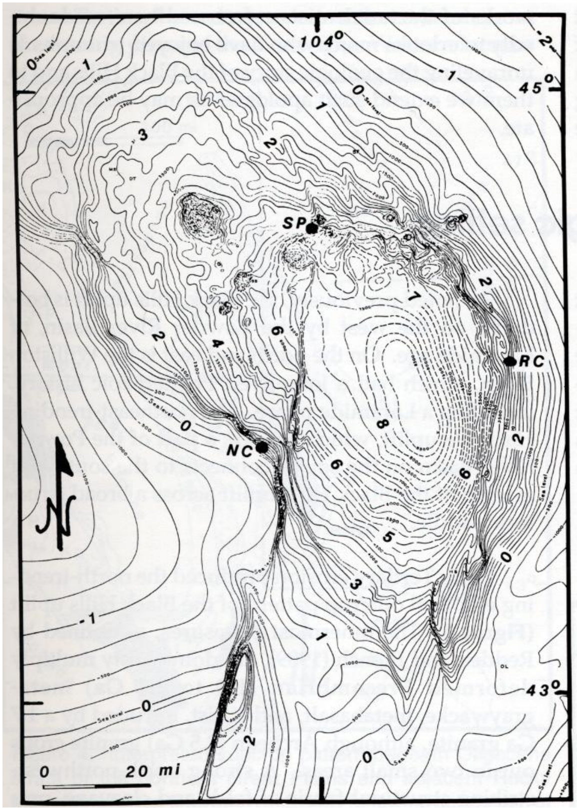

Figure 1. Structure contour map of the Black Hills Uplift by N. H. Darton (1904). The contour interval is 250 feet and the contoured surface is the top of the Minnekahta Limestone, projected over the crestal area. See also Lisenbee (this volume).

The bright green dinosaurs were constructed by workers of the WPA (Works Progress Administration—part of the New Deal agencies to employ Americans) during the 1930's depression era). They include Stegosaurus (blades on the back), a stegosaurid armored dinosaur; Camaraosaurus (duck-bill), a quadrupedal, herbivorous dinosaur; *Tyrannosaurus rex* (more upright and bulky than now known), a theropod dinosaur; Diplodocus (Brontosaurus of old and with a too-droopy tail), a sauropod dinosaur; and Triceratops, a ceratopsid, herbivorous dinosaur.

Phanerozoic strata along the eastern flank of the Black Hills Uplift (Fig. 3) consist of a panel of east-dipping sandstone, limestone, and shale of Cambrian to Cretaceous age. Portions of these strata are well exposed along the "red valley" from Rapid City to Spearfish. The tree-covered ridge west of the valley, and seen here across the flood plain of Rapid Creek, is a dip slope on the Minnekahta Limestone. The valley floor is underlain by red beds of the Spearfish Formation. East of Interstate 90, the margin of the valley contains poor exposures of the Sundance Formation overlain by the Jurassic Unkpapa Sandstone in the midslope above. The Morrison Formation is absent here. Ledges of Cretaceous sandstone of the Lakota Formation and the Fall River Formation of the Inyan Kara Group cap the ridge. The footings for the dinosaur statues on the ridge crest here are in Lakota Formation. The prairie to the east of the "Cretaceous hogback" is underlain by black shale units deposited in the Western Interior Cretaceous Seaway.

Interpretations of Laramide folds generally involve a faulted basement and folded or faulted overlying strata, depending upon the amount of offset along the faults A common usage for the term monocline is that of Kelley (1955) who defined it as "…a double bend involving local steepening of otherwise less steeply dipping strata."
As shown in Figures 3 and 4, three types of folds are present, based upon their orientations within the regional easterly dip.

- Classic monoclines, e.g., the White Gates monocline, (monoclines with regional dip, i.e., the increased dip of the fold limb is in the same direction as the regional dip),
- Asymmetric anticlines, e.g., the Cement Plant-Piedmont and Hudson Ranch anticlines (monoclines opposed to regional dip),
- South-facing monoclines (monoclines whose axial traces parallel regional dip).

West vergence is typical of almost all folds on the Black Hills Uplift. On the western flank of the uplift monoclines (with regional dip) have 1,000 m (3,300 ft) to 1,515 m (5,000 ft) of throw. On the east flank structural relief across the folds is less than 370 m (1200 ft) and only in the mid-segment of the Rapid City monocline is there a fault exposed at the present erosional level.

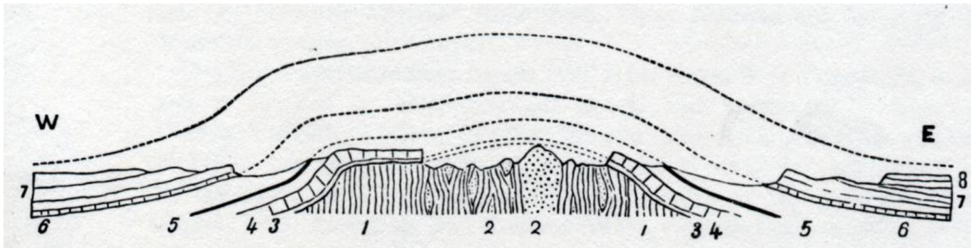

Figure 2. Diagrammatic cross section of the Black Hills Uplift by Newton and Jenney (1880). Note the asymmetry of the uplift with a monocline on the west and broad arch on the east.

Of note is the fact that the topographic limit of the Black Hills seen in the “Cretaceous hogback” does not represent the eastern limit of the Black Hills Uplift. The open synclinal hinge which marks the eastern structural margin of the uplift lies beneath the prairies at least 10 miles east of Rapid City.

Prior to June 9, 1972, much housing was present along the flood plain of Rapid Creek. During the late afternoon and early evening of that day, more than 13 inches of rain fell in the Rapid Creek drainage basin above Rapid City in a period of only a few hours. During the night the creek rose into flood stage, overtopped and destroyed the small dam at Canyon Lake on the west side of town and brought great devastation to this community. Over $100 million in flood damages resulted and 238 people lost their lives. The area beneath Dinosaur Hill on the west was flooded, including the city hospital, which was evacuated.

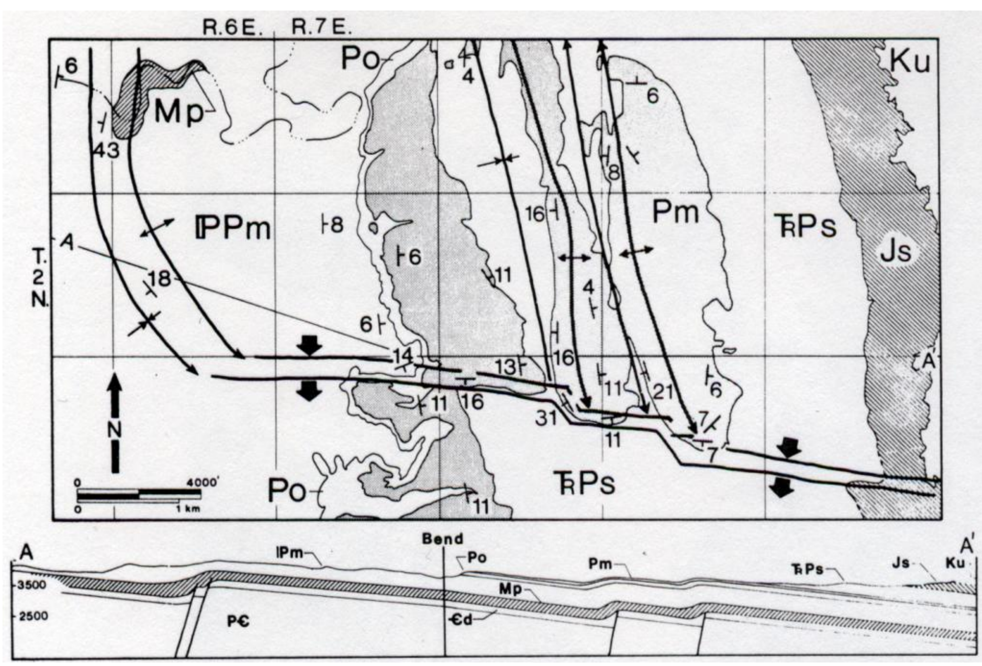

Figure 3. Geologic map and cross section of the Cement Plant anticline area in western Rapid City (Lisenbee, 1978). Three west-vergent anticlines abut against the east-trending, south-facing Rapid City monocline. Strata are: Mp = Pahasapa Limestone; IPPm = Minnelusa Formation; Po = Opeche Shale; Pm = Minnekahta Limestone; TrPs = Spearfish Formation; Js = Sundance Formation and Unkpapa Sandstone (undivided); Ku = Inyan Kara Group. Vertically dipping or reverse faults are more likely to underlie the folds than those shown.

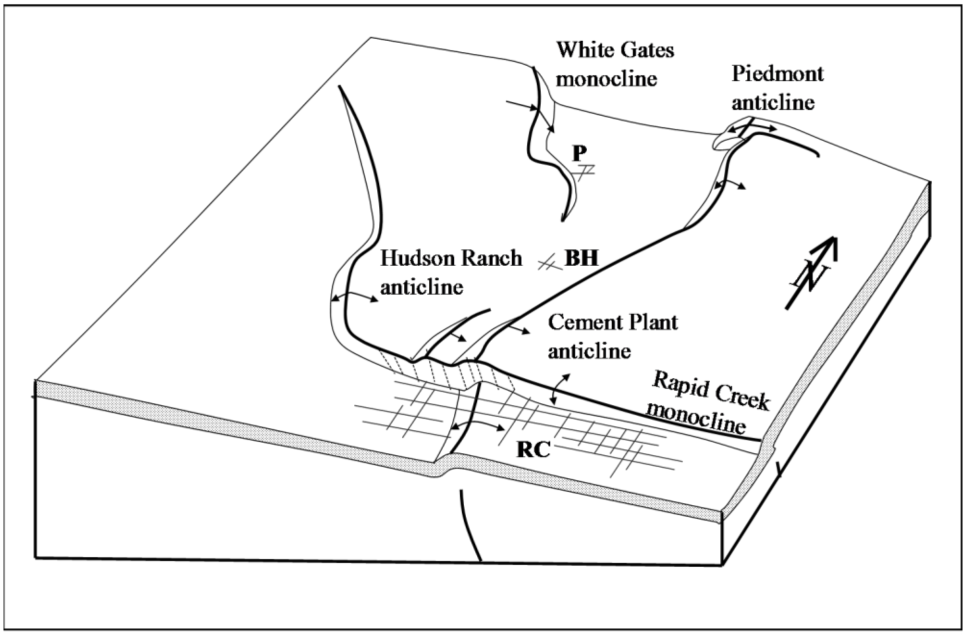

Figure 4. Block diagram illustrating the Laramide fold types of the east flank of the Black Hills Uplift. BH = Blackhawk; P = Piedmont; RC = Rapid City. The surface approximates the reconstructed Minnekahta Limestone. The edges of the block are approximately 16 km (10 mi) long.

A major recovery effort, lead by the mayor and city council and funded by federal grants, led the city to re-zone the flood plain for use as playing fields, bike paths, etc. Alas, subsequent city leaders have forgotten the lesson bought at such expense. A new expansion of one of the city high schools, the Journey Museum, the Civic Center and even condominiums now occupy this danger zone.

Return to vans. Retrace route to West Blvd. and Omaha Street.

3.4 Turn left onto Omaha Street. Drive along Rapid Creek flood plain. The hogback at 3:00 o'clock is Cretaceous Newcastle Sandstone underlain by Skull Creek Shale in the valley. At 1:00 o'clock the dip slope is on sandstone of the Fall River Formation.

Continue west through the "Gap". Rapid Creek follows the trend of the south-facing Rapid City "monocline parallel to regional dip". The termination of the Newcastle Sandstone body at the younger monocline suggests possible reactivations of an older structural weakness here.

4.0 The Lakota Formation-Jurassic Unkpapa Sandstone contact is present in the east-dipping panel of strata across the creek.

4.2 Intersection with Mountain View Road. Wind-blown deposits of Unkpapa Sandstone at 3:00 o'clock.

4.3 Cross Rapid Creek.

4.5 Intersection with Deadwood Avenue. Continue ahead across the "red valley" eroded on the Triassic Spearfish Formation along the southern, down-dropped margin of the Rapid City monocline.

4.7 Terrace gravel deposits on red Spearfish Formation.

5.1 Entrance to the GCC-Dakotah Cement Plant which utilizes the pure $CaCO_3$ deposits of the Permian Minnekahta Limestone, a unit of tidal flat origin, exposed along the anticline crest north of the Rapid City monocline.

5.6 Intersection with Sturgis Road. Turn right.

5.8 Cross Rapid City monocline. View to left along faulted monocline with uplifted Minnekahta Limestone on north against Spearfish Formation on south. A spring producing water chemically correlated with the underlying Pahasapa Limestone (Madison aquifer) issues from the fault zone.

5.9 **STOP 2.** **"Cement Plant" quarry** to east of highway strips Minnekahta Limestone from the crest of a north-trending, west-vergent anticline (Fig. 5). The road ahead (to north) follows the axis of a parallel syncline. This anticline-syncline couple form a "monocline opposed to regional dip", which is the typical form for the eastern flank of the uplift, and continues for more than 15 miles to the north. The pine tree-covered ridge to the west of the road is underlain by Minnekahta Limestone in a second, parallel-trending anticline. The combined production of this quarry and a second, commercial gravel quarry to the north would be greater than $1,000,000,000 at today's market value (C. Paterson, personal communication, 2006).

Figure 5. West limb of Cement Plant anticline and adjacent syncline axis (view north, 2006) exposed in quarry wall. The tree-covered dip slope is on Minnekahta Limestone overlain in the syncline core by Spearfish Formation. Note sharp synclinal flexure.

7.5 Road continues along syncline axial trace. Berm on right is the western limit of limestone quarry and west limb of Cement Plant anticline. Low ridge on west is the crest of the parallel anticline.

8.2 Enter red bed deposits of Spearfish Formation. Limestone quarry on west side of road.

8.8 Cross Box Elder Creek bordered by flood plain deposits and terrace gravel, e.g. that capping the hill to north.

10.4 Intersection with Peaceful Pines Road (stop light). Turn right and cross over I-90. Cross Spearfish Formation-Sundance Formation contact.

10.9 Turn left onto I-90 access ramp. Saddle in tree-covered ridge of Cretaceous Lakota Formation ahead marks the continuation of the syncline that parallels the Cement Plant anticline (called the Piedmont anticline here). This is a "monocline with regional dip".

Urban development has been extensive in this area in the past 15 year providing a number of water wells across the valley, the logs of which are useful in resolving the geology of the grass-covered lowlands.

15.8 Crossing alluvial fan at the mouth of Stage Barn Canyon. Many of these large boulders (to 4 feet) were carried here by the 1907 flood in which four people were swept down the canyon and drowned. Note urban development to east of railroad track surrounded by the alluvial fan boulders.

16.5 Pahasapa Limestone and Minnelusa Formation in anticlinal hinge of the White Gates monocline at 11:00 o'clock. The ridge on the sky line ahead is underlain by ~60 Ma diorite laccoliths, a part of Laramide igneous development in the northern Black Hills.

16.9 Exit 46. South end of Piedmont.

18.4 Exit 44. Exit interstate highway.

18.5 Stop sign. Turn left and cross under I-90.

18.6 Turn right onto Sturgis Road.

18.9 Turn left onto Little Elk Creek Road.

19.2 Note boulders of Deadwood Formation on alluvial fan along Little Elk Creek to right.

19.5 Cross Minnekahta Limestone and begin descent into valley of Little Elk Creek.

19.8 Cross Little Elk Creek. Canyon walls are sandstone, shale and limestone of the Pennsylvanian Minnelusa Formation.

20.4 **<u>STOP 3.</u> White Gates monocline.**

Park vehicles at entrance to U.S Forest Service land. Hike along former White Gates road (partially to completely destroyed by the 1972 flood) for approximately 1.8 km (1.1 miles) with canyon walls of gently west-dipping Minnelusa Formation. The White Gates monocline begins with vertical beams of Pahasapa Limestone in the "White Gates". The synclinal flexure which limits the monocline on the east is exposed in the south canyon wall as an approximately 90^o bend at this stratigraphic level. The sharpness of this synclinal bend decreases in the overlying Minnelusa Formation (Fig. 6). Continue upstream. Note the contrasting character of the broadly curved anticlinal flexure in the north canyon wall ahead. The Pahasapa is strongly fractured and contains karstic cavities lined with dog-tooth spar. Bedding surfaces of the vertically dipping Pahasapa contain abundant stylolites with horizontal axes of the teeth. The timing of their growth relative to formation of the monocline is undetermined.

The "Red Gates" are formed of steeply east-dipping, massive beds of hematite-stained sandstone of the Deadwood Formation. The color is due to tropical weathering during the ~40 Ma period preceding deposition of the overlying Winnipeg Shale. The anticlinal flexure at the level of the Deadwood Formation is a few hundred feet to the west.

Return to parking lot and retrace route to I-90.

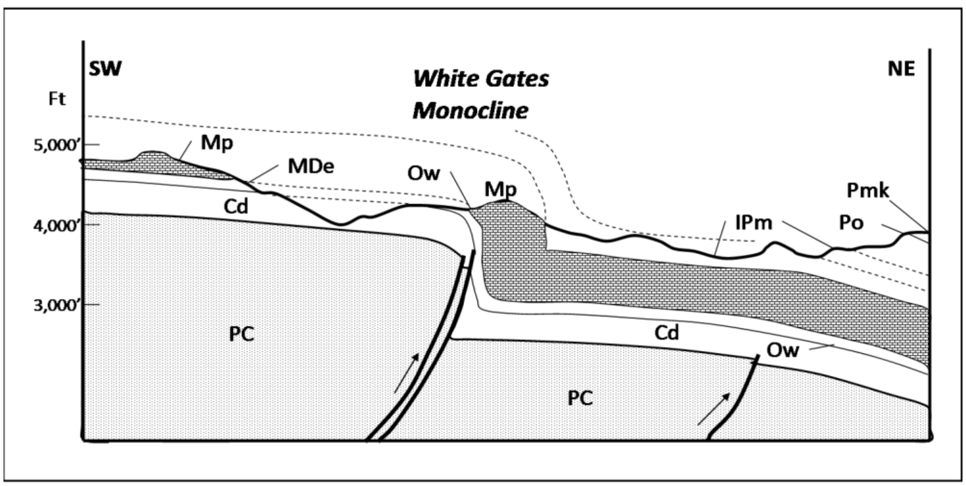

Figure 6. Cross section of White Gates monocline. PC = Precambrian basement; Cd = Deadwood Formation; Ow = Whitewood Formation; Mp = Pahasapa Limestone; IPm = Minnelusa Formation; Po = Opeche Shale; Pmk = Minnekahta Limestone.

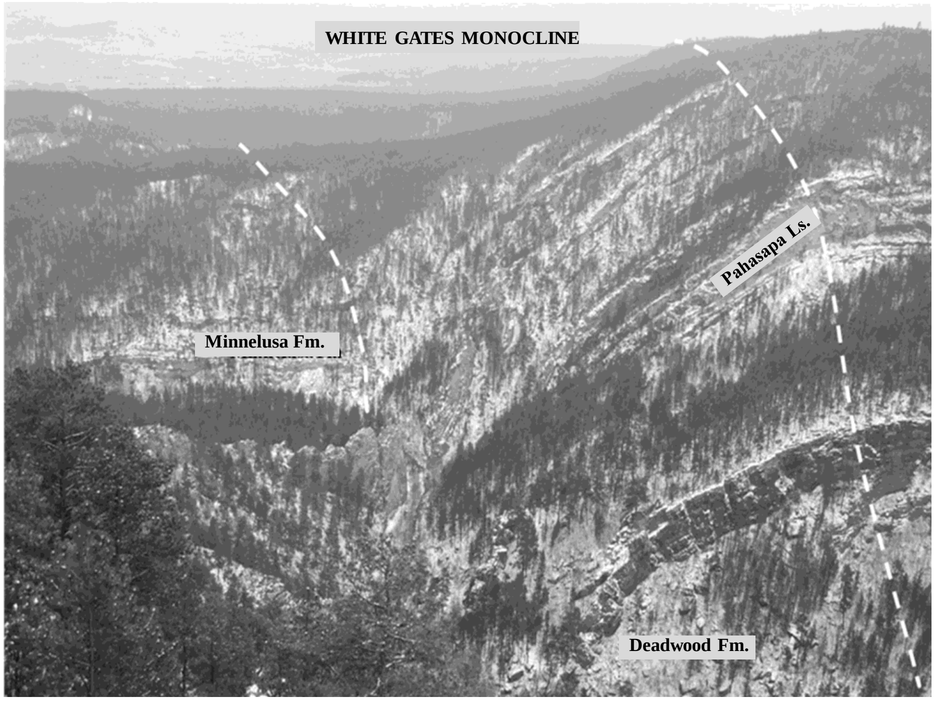

Figure 7. Oblique winter view to the southeast across the White Gates monocline (between dashed white lines). The anticlinal flexure is seen in the massive beams of Pahasapa Limestone and the darker, upper sandstone of the underlying Deadwood Formation.

21.7 Stop sign at Chimney Canyon Road. Turn left and cross under I-90 overpass.

22.3 Cross railroad tracks. Continue ahead on Deerview Road (gravel).

22.7 Gypsum here at top of Spearfish Formation was mined underground in the early 1900's for production of wall board.

23.2 Cross Little Elk Creek. Piedmont Butte at 2:00 o'clock is capped by sandstone of the Lakota Formation: The hill slopes below are underlain by the Unkpapa Sandstone and the upper portions of the Sundance Formation.

23.8 East-dipping sandstone beds of the basal Lakota in hillside.

24.7 Ninety degree turn in road.

STOP 4. Syncline

Quaternary gravel deposits here are underlain by Cretaceous Skull Creek Shale. To the south is a tree-covered dip slope on Fall River Formation in the west limb of the syncline. The ridge along the east side of the valley is the steeply west-dipping common limb of the syncline and the Piedmont anticline. This is the same anticline seen in the Permian limestone quarry in Rapid City, with greater structural relief here. In cases such as this on the eastern flank of the uplift, such asymmetrical anticline-syncline pairs are actually monoclines opposed to regional dip. The axial trace of the syncline extends northward from the saddle on the ridge at the south end of this valley and passes just to the west of the exposures of Fall River Formation east of this stop.

A C-shaped curve in the axial trace of the Piedmont anticline south of Little Elk Creek results in closure on the structure in the area at the east edge of this view. In cases in which the axial trace is nearly parallel to regional strike, such changes in trend result in slightly down-dip plunges away from a central point and a culmination (approximately 60 m (200 ft)) of structural relief in this case). Petroleum test wells on this structure found only fresh water in the Minnelusa, Pahasapa and Deadwood strata. In cases having the opposite pattern of axial trace curvature (a reverse-C in this case), there is a resulting structural depression along the anticlinal crest.

25.5 Intersection with Elk Creek Road. Turn to left.

26.6 Intersection with Edgewood Place.

STOP 5. Piedmont anticline.

The crest of the Piedmont anticline is well exposed in the north wall of this canyon across the flood plain of Little Elk Creek. The upper sandstone units exposed here (Fig. 8) are the lower Fall River Formation: Those in the lower slope are Unkpapa Sandstone. West vergence is revealed in the steep (west) and gentle (east) dips of the fold limbs.

Greater topographic relief in the hill on the south side of the valley is matched by greater structural relief on the anticline there. In addition, the trace of the fold does not project directly across the valley; rather there is 1,500 feet of left separation. Due to the Quaternary cover along the creek (Fig. 8) it is unclear whether this separation results from a strike-slip fault or an abrupt curvature in the axial trace.

Figure 8. Axial trace of Piedmont anticline viewed to north across the flood plain of Little Elk Creek. The axial trace displays left separation across the valley.

27.7 Elk Creek Spur on right. This is the approximate contact of the Fall River Formation and the Skull Creek Shale in the east limb of the Piedmont anticline. Note the landslide mass in the Skull Creek Shale ahead on the right.
The Skull Creek Shale is the basal unit in a thick section of Cretaceous shale deposited in the Western Interior Cretaceous Seaway. With the exception of small hog backs in the Greenhorn Limestone and a few sandstone layers, these Cretaceous units weather without the topographic relief characteristic of the underlying Cretaceous sandstone units and the Paleozoic section. As a consequence, defining Laramide structures in the prairies east of the Black hills requires careful geologic mapping of formation contacts and rare bedding attitudes at 1:24,000 scale.

28.4 Intersection with Erickson Ranch Road. Turn to right (south).

For the next two and one-half miles the road crosses gravel deposits on Skull Creek Shale. The dip slope at 1:00 o'clock is on the Fall River Formation: The pine-tree-covered slopes at 11:00 o'clock are on the siliceous Mowry Shale.

30.7 Road curves to right (west) and passes exposures of the Fall River Formation.

31.2-31.5 Extensive road cut on east side of road in pyritiferous, coal-bearing, estuarine deposits of the Lakota Formation.

32.5 Road crosses the Lakota Formation/Unkpapa Sandstone contact. The broad width of the "red valley" here results from the diagonal crossing of the Triassic and Jurassic units by the Cement Plant-Piedmont anticline and adjacent syncline. Definition of these folds within the valley required mapping of the four members of the Sundance Formation rather than only the Sundance-Spearfish contact (Lisenbee and Hargrave, 2002).

33.6 Turn left at intersection. Grassy slopes to the left (east) are on the friable Unkpapa Sandstone. The higher ledges are the basal Lakota Formation. Artesian water wells in this area produce from the Pennsylvanian Minnelusa Formation.

34.5 Cross Box Elder Creek, bordered by broad flood plain.

35 Red beds of the LAK Member of the Sundance Formation in road cut.

36.4 Overpass on I-90. Continue ahead on Deadwood Avenue.

38.6 Stop light at West Omaha Street. Turn left.

40.0 5th Street. Turn left.

40.3 Holiday Inn Parking lot on left.

<u>*End of Day 1: Part 1*</u>

Day 1: Excursion Part 2. Rapid City to Newcastle, Wyoming

0.0 Depart Holiday Inn (Civic Center) parking lot: Exit to right onto 5th Street

0.2 Cross Rapid Creek

.

0.3 Omaha Street. Continue straight ahead.

0.5 Turn left onto St. Joseph Street.

0.6 Pennington Court House on right.

1.3-1.6 Campus of the South Dakota School of Mines and Technology on right. During the 1972 flood, the buildings nearest the highway were damaged by flood waters, including loss of the geology collection in the basement of the library.

1.8 Hill slope on right on the Belle Fourche Shale. Wind turbines on hill top are part of a SDSMT alternative energy research project.

2.3 Cross St. Patrick Street.

2.8 Merge with U.S. Hwy 79S.

4.2 Cross under Catron Boulevard.

6.8 Road cuts in dark, Cretaceous Belle Fourche Shale. The skyline ahead is capped by White River orthoconglomerite, a channel deposit cemented by silica derived from the enclosing tuffaceous flood plain deposits. Although there is no geomorphic evidence, geologic mapping of the Greenhorn Limestone—Belle Fourche Shale contact reveals a north-trending anticline whose axial trace parallels the highway (Lisenbee et al., in press), as well as a syncline axis to the west (Fig. 9). The Late Eocene-Oligocene White River Group deposits lie with angular unconformity across the folds, indicating that both structural development and erosional stripping of the uplift had ceased by the time of White River deposition. The large blocks lying on the slopes on both sides of the highway are landslides composed of the orthoconglomerite.

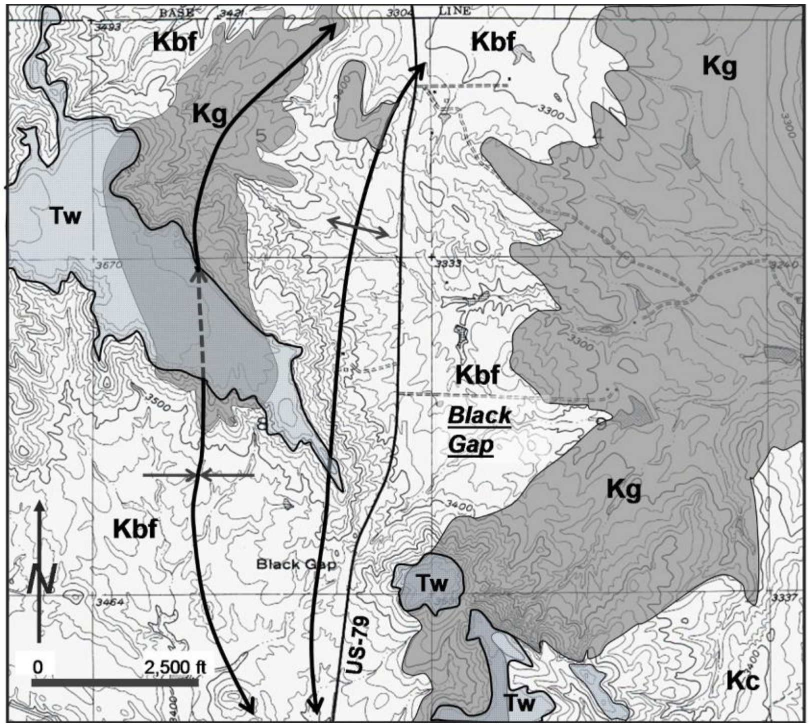

Figure 9. Geologic map of the Black Gap area showing the location of a Laramide anticline in the Cretaceous shale units unconformably overlain by channel deposits of the Oligocene White River Group. Kc = Carlisle Shale; Kbf = Belle Fourche Shale; Kg = Greenhorn Limestone; Tw = White River Group. (Lisenbee et al., in prep.)

8.4 Road to left to Black Gap development. Construction on the Belle Fourche Shale encountered numerous engineering problems including swelling clay, resulting in buckled roads, cracked foundations and septic systems without proper drainage.

8.8 **<u>STOP 1. Black Gap.</u>**

Exposures of gently east-dipping Belle Fourche Shale on both sides of the road. The hillside east of the highway contains the unconformable contact between tuffaceous mudstone of the White River Group and the underlying Belle Fourche Shale. Continue along U.S. Highway 79 and descend hill across Belle Fourche Shale to the flood plain of Spring Creek.

9.8 Intersection with Spring Creek Road. Turn to right. For the next four miles Quaternary terraces are present to the left along Spring Creek.

10.8 Mowry Shale in road cut.

11.2 Road cuts in Skull Creek Formation overlain by terrace gravel.

11.4 Strongly jointed channel sandstone layer of Fall River Formation in hill side to north (left).

11.9 Strongly jointed channel sandstone of Fall River Formation in road cut.

12.3 Landslide blocks of Cretaceous Fall River Formation on the left (north). The tree-covered bluffs along the canyon walls are generally sandstone channel deposits of the Fall River and Lakota formations.

13.7 Sandstone of the LAK Member of the Sundance Formation in road cut on right.

13.8 Sandstone of the Hulett Member of the Sundance Formation in road cut on the right.

14.1 Spearfish/Sundance contact in bluff to north. Enter “red valley”.

14.2 Cross Spring Creek.

14.6 Turn right (north) onto Neck Yoke Road.

14.8 Cross Spring Creek.

14.9 Intersection of Neck Yoke Road with U.S. Hwy 16. Cross highway into Reptile Gardens' parking lot.

STOP 2. Anticline.

The view to the north is across a poorly defined, anticline-syncline couple. The core of the anticline is Triassic Spearfish Formation composed of red sandstone, mudstone and white gypsum (Fig. 10). The basal unit of the Jurassic Sundance Formation is exposed in the hills along the highway to the east and at the crest of the hill directly to the north, in the west limb of the anticline. The south-plunging axis of the fold crosses the highway between the road cuts to the east. White River deposits lie unconformably across the fold along the skyline to the north, showing that folding preceded Late Eocene-Oligocene deposition. Return to the highway and turn to right.

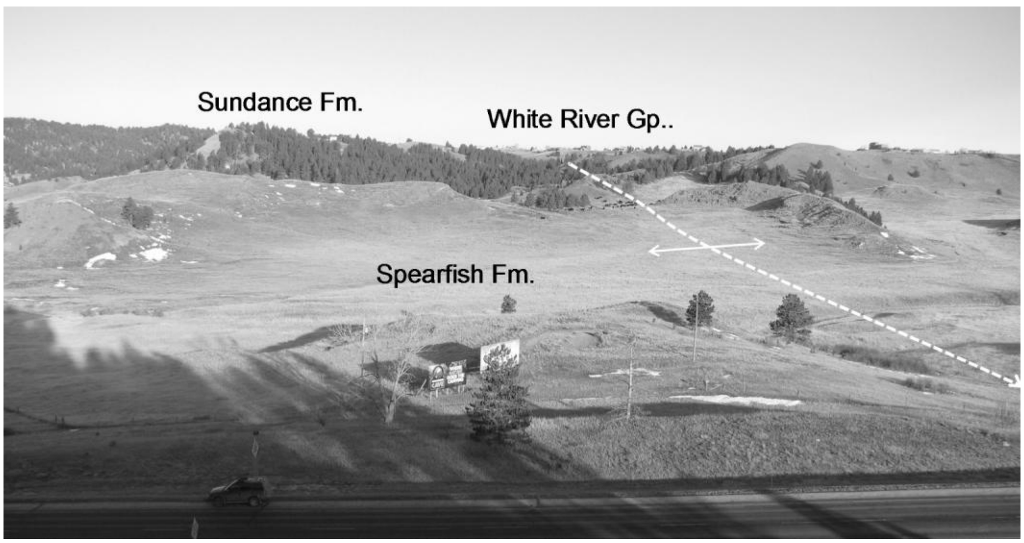

Figure 10. View north-northwest across U.S. Hwy 16 of the Spearfish Formation exposed along the crest of the Reptile Gardens anticline. The Sundance Formation is in the west limb of the fold.

15.2 Cross Spring Creek.

15.9 Contact of red beds of the Permo-Triassic Spearfish Formation and the underlying Permian Minnekahta Limestone. For the next 1.3 miles the thin-bedded Minnekahta is exposed in road cuts. Note the intra-formational box folds.

16.2 Contact of the Minnekahta Limestone and the red Permian Opeche Shale.

16.6 Contact of the Opeche Shale and the upper sandstone of the Minnelusa Formation in small canyon to left. Exposures of the Minnelusa are present in road cuts and in the area of the Bear Mountain animal exhibits ahead.

18-19 Cross grass-covered flat underlain by White River Group. The channel deposits found here connect to the southeast with fresh-water carbonate layers deposited in a large, spring-fed lake. Rowe (2000) found a few three-toed horses and abundant sub-hyracodon (rhino) fossils – some young, but mostly old -- in the layers there. The disarticulated bones showed some evidence of flow orientation as well as radial fractures indicative of breakage by tromping such as is seen in East African watering holes today.

19.4 **<u>STOP 3.</u>** **Stratobowl fault.** The unexposed fault at the west end of this outcrop separates the Pahasapa Limestone (Madison aquifer) and the basal Deadwood Formation (on the west). Note the increased dip of the limestone beds and the west-dipping small faults at the west end of the outcrop. Although this fault is of probable Laramide age, no units younger than the Minnelusa Formation are affected by the fault and associated folding at the present erosional level (Fig. 11). The rubble-filled caves along the north side of the highway are part of an extensive karst (this portion of probable Paleogene age) which helps make the Pahasapa Limestone a major aquifer in the area. The basal sandstone of the Deadwood Formation is exposed in the ridge a few hundred feet to the west.

Figure 11. View north to road cut of Pahasapa Limestone. The left end of the outcrop is only a few feet from the Stratobowl fault. Small reverse faults and an increase in dip in the Pahasapa are present there. Dashed line parallels bedding.

23 **<u>STOP 4.</u>** **Precambrian fault**. This north-northwest trending fault in the vertical cut (Fig. 12) separates metagabbro on the west from quartz-mica schist and parallels the overall "grain" (faults and subvertical strata and schistosity) of the Precambrian basement. Many of the Laramide folds affecting the Phanerozoic section along the east flank of the Black Hills Uplift parallel this trend, suggesting that some reactivation may have occurred along older features during Laramide growth of the uplift.

24.7 Road cut on north side of highway in garnet-staurolite schist.

25.4 Intersection with U.S. Hwy 16A to Keystone and Mt. Rushmore National Monument.

26.4 View to southwest to Harney Peak, the highest point in South Dakota (elev. 7,242 ft) and the bold topography associated with the Proterozoic (1.715 Ga) Harney Peak Granite.

29.6 Exposures of andalusite-bearing metagreywacke in road cuts.

31.1 Three Forks junction with U.S. Hwy 385. Continue on U.S. Hwy 16 to Hill City. For the next three miles road cuts contain north-dipping, metagraywacke turbidite units.

32.3 Mitchell Lake recumbent fold in steep road cut on north side of road. This is a D4 fold related to doming during emplacement of the Harney Peak batholith to the south (M. Terry, personal communication, 2010).

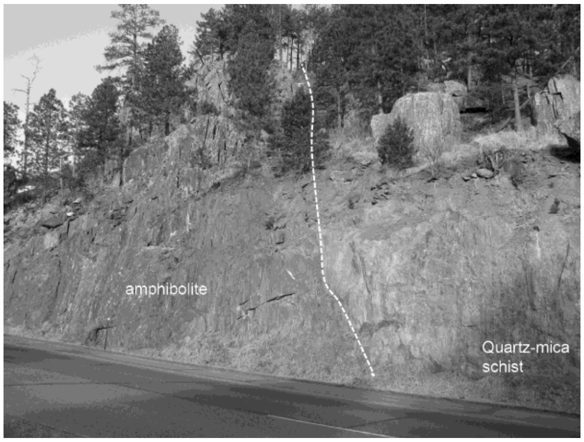

Figure 12. Precambrian fault in road cut along U.S. Hwy 16 juxtaposing amphibolite against quartz-mica schist. The fault follows the approximate structural "grain" of the Proterozoic basement in the eastern Black Hills.

32.8 Cross Spring Creek.

33.6 Mega-boudins in road cuts on north side of highway probably result from stretching in the carapace of the large dome associated with emplacement of the Harney Peak batholith.

33.8 North-dipping, turbiditic metagraywacke layers in road cut.

34.2 Turn left onto Railroad Avenue and bypass down town Hill City. Historic railroad yard of the "1880 Train" on left.

34.7 Stop light at south end of Hill City. Turn left toward Custer on U.S. Hwy 16/385. The road cuts and surrounding hills from Hill City to Custer consist of west-dipping layers of staurolite- (near Hill City) and sillimanite-grade schist and coarse-grained plutons of two-mica Harney Peak Granite. Abundant pegmatites have been commercially exploited for mica, potassium feldspar, Nb-Ta, and spodumene (Li). The road parallels the western margin of the Harney Peak batholith.

37.2 Overpass of Mickelson Trail, the former Burlington Northern Railroad grade.

37.5 Intersection on left with SD Hwy 244 and road to Mt. Rushmore National Monument.

37.7 Intersection on left with SD Hwy 87 and road to Sylvan Lake and the "Spires" in the Harney Peak Granite batholiths.

41.5 Large masses of erosionally stripped Harney Peak Granite to east of highway.

43.5 Entrance to Crazy Horse Monument on east side of highway. The face of Crazy Horse is emerging from the granite bluff (Fig. 13) after years of blasting of the fractured granite. The project began on June 3, 1948 through the inspiration of artist and sculpture Korczak Zilkowski. Work continues under the direction of the Zilkowski family following his death in 1982.

Figure 13. Crazy Horse monument carved in 1.715 Ga Harney Peak Granite. Note diagonal, iron-stained, systematic fracture set from upper right to lower left.

44.9 Grass-covered area is the center of a dome in the schist which is probably underlain by intrusions of Harney Peak Granite, e.g., as those exposed in the massive bluffs east of the highway ahead.

47.9 CUSTER, SD.

In 1874, a military expedition to the Black Hills lead by George Armstong Custer discovered gold on French Creek east of the present town. When word reached the United States, an illegal gold rush into the treaty-protected lands of the Sioux nation ensued and on August 10, 1975, miners formally established a town site at Custer. The town was abandoned by all but 14 residents upon the discovery of major gold deposits along Deadwood Creek in the northern Black Hills in late 1875. Later the population was rebuilt as the potential for pegmatite mining, agriculture and forestry of the surrounding area was established.

Intersection of 5th Street and Mt. Rushmore Road. Turn right on U.S. Hwy 16/89 to Newcastle.

48.3 Intersection with U.S. Hwy 89 on left. Continue ahead to Newcastle.

48.6 For the next six miles the road crosses west-dipping sillimanite-grade, quartz-mica schist, metagabbro and dikes and sills of coarse-grained two mica granite and granite pegmatites (with quartz, muscovite, potassium feldspar and black tourmaline).

50.1 Granite sill in road cut on left.

50.7 Multiple granite sills in road cut on right.

55 Metagabbro in road cut on right.

55.6 Ridges on skyline ahead and to the right are underlain by Mississippian Pahasapa Limestone and Cambrian Deadwood Formation.

56.2 The road for the next five miles follows the Jewel Cave fault system which consists of one to five strands (Fagnan, 2002) across a width of 2,500 feet. Minnelusa Formation on the south is down-dropped against Pahasapa Limestone on the north with an offset of as much as 450 feet. Slickenlines on faults exposed in road cuts before the rebuilding of the highway indicated a normal sense for fault movement. Throughout the length of the fault, the Pahasapa is strongly affected by karstic weathering resulting in collapse breccia, such as that exposed with manganese staining in this outcrop, and hematitic staining. As this fault cuts no strata higher than the Pennsylvanian Minnelusa Formation, the age is poorly constrained, although a Laramide origin is probable.

58.5 This area of good geologic exposures (Minnelusa Formation to the south, Pahasapa Limestone to the north) is recovering from the effects of the "Jasper fire", which began on August 28, 2000 and ultimately burned 83,508 acres of forest. It was the most extensive forest fire in the recorded history of the Black Hills. Suppression of this product of arson cost $8,200,000 (National Park Service).

59 .2 Hematite-stained karst in road cut of Pahasapa Limestone.

60.1 Road to left to Jewel Cave Visitor Center. Over 140 miles of fracture-controlled passages have been mapped to date and an average of three miles are added each year. It is currently recognized as the second longest cave in the world (National Park Service). The passages are stratigraphically and structurally controlled. They result from solution along fracture sets with average trends of N75^{o}E and N25^{o}W in the upper portion of the Pahasapa Limestone. As shown in Figure 14, joint trends from both the surface (A. Minnelusa Formation) and from cave passages (B. Pahasapa Limestone) are strongly grouped, but the averages differ by about 10 degrees. The origin of this disparity is unknown, but may be related to refraction of stresses in the dissimilar rock packages. The Mississippian Pahasapa Limestone is noted for the karst developed in the upper 250 feet of the section (the area of cave passages). This karst appears to have a Mississippian-Pennsylvanian initiation, but to have been reactivated during the early Tertiary associated with the Laramide uplift and, perhaps, again in the late Miocene or Pliocene during the latest erosional unroofing of the uplift.

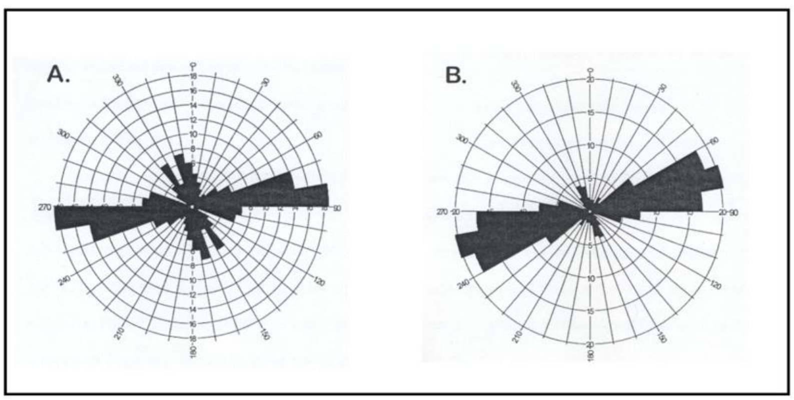

Figure 14. Rose diagram illustrating trends of joints in the Jewel Cave area. A. Surface joints in the Minnelusa Formation. B. Cave joints in the Pahasapa Limestone.

60.6 Minnelusa Formation in road cut: Pahasapa Limestone in hill to north. The road lies along a fault.

61.3 Cross Jewel Cave fault. The road ahead for the next nine miles is on the Minnelusa Formation. From the canyon rim ahead the road descends at about the same angle as the dip of the Minnelusa strata in the western limb of the Black Hills Uplift.

67.9 The ridge line ahead on skyline is capped by sandstone of the Cretaceous Inyan Kara Group along the Black Hills monocline. The slopes beneath the ridge crest are underlain by Jurassic units.

70.5 Permian Minnekahta Limestone in road cuts.

71.3 Gillette Canyon Road on the right. The Minnekahta Limestone forms a cliff and the rim of the canyons on the right (north) side of highway for the next three miles. Beneath the cliff the Permian Opeche Shale forms a slope and the upper sandstone of the Minnelusa Formation may be exposed in the deeper canyon bottoms. Red beds of the Permo-

Triassic Spearfish Formation underlie the broad, grass-covered flats to the south of the highway for the same distance.

72.7 Cross Minnekahta Limestone. Begin descent into valley.

73.5 The upper sandstone of the Minnelusa Formation, the Opeche Shale and the Minnekahta Limestone are exposed on the north canyon wall.

73.8 Cross Wyoming-South Dakota state boundary line into Wyoming.

74.6 The highway crosses the west-dipping Minnekahta Limestone in the rotated limb of the **Black Hills monocline.** This fold limb, evidenced by dip slopes of the Minnekahta Limestone, forms a broad curve northward for two miles from this point to an intersection with the Fanny Peak monocline. At this location, the structural relief across the Black Hills monocline is approximately 800 feet (Brobst and Epstein, 1963). The Fanny Peak monocline is present in the ridge of west-dipping Inyan Kara Group sandstone across the flat west of the highway. Structural relief on this structure is about 3,000 feet.

75.5 Quarries in Minnekahta Limestone at 1:00. Red sandstone of the Minnelusa Formation underlies Frannie Peak on the skyline above the quarries.

77.4 Highway crosses the **Fanny Peak monocline.** Sub-vertical beds of Inyan Kara Group sandstone on both sides of the highway.

78.2 Beaver Creek Road on right.

78.9 Note oil field in the Powder River basin on left.

79.7 Note earlier generations of oil field equipment on right. In 19676, Mr. Al Smith reportedly dug a 21 foot deep, producing oil well here, using a shovel to cut through for the Skull Creek Shale and dynamite for the Newcastle Sandstone. A tree-covered ridge of Mowry Shale is across the valley to the west.

82.8 Intersection with U.S. Hwy 85. Turn right.

83.0 Turn right into parking lot of Fountain Inn. *End of Trip. Part II. Day 1.*

DAY 2. INTRODUCTION

The Newcastle area lies at both the topographic and structural margins of the Black Hills Uplift and near a sharp change in trend of the boundary between the uplift and the adjoining Powder River basin. The trend change results from the intersection of the southeast-trending Black Hills monocline and the north-trending Fanny Peak monocline a few miles east of town. Structural relief of as much as 3,500 ft across the monoclines greatly exceeds the topographic expression of 300 to 800 feet seen in resistant-weathering sandstones of Pennsylvanian through Cretaceous age. Both monoclines extend across the intersection and into the uplift, although with greatly reduced structural relief.

Today’s excursion is directed to observing individual characteristics of several monoclines as well as the nature of their mutual interactions.

0.0 Intersection of U.S Hwy 85 and U.S. Hwy 16. Turn right on U.S. 16 to Newcastle.

0.6 Take left fork at Y.

NEWCASTLE, WYOMING

Newcastle was incorporated as a city on October 25, 1889 and served initially as a railroad and supply center for large eastern Wyoming ranches. A spur line of the railroad extended northward to the coal-mining town of Cambria (the coal was actually of Cretaceous and not Cambrian age) where production for use by the railroad continued until the coal seams were exhausted in 1928 – at which time Cambria almost immediately became a ghost town. Discovery of oil in the Powder River basin began the long association of Newcastle with petroleum development. In the 1970s, the “coal rush” to the extensive Powder River basin coal fields to the west added to the local economy. Although the nearest mines are approximately 60 miles to the west, many miners live in Newcastle and commute on a daily basis.

0.9 Overpass on railroad.

1.3 The Wyoming Refining Co. facility to the right has a production rate of 12,500 barrels of oil per day. First production from the refinery was in the 1930s.

2.2 Intersection with West Main Street. Turn left.

3.3 **<u>STOP 1</u>. Black Hills monocline**

From its crossing point with the Fanny Peak monocline just east of Newcastle, the Black Hills monocline extends for 80 km (50 mi) northwest to Moorcroft where it curves to the north and continues for another 100 km (60 mi) to the Montana-Wyoming state boundary. Along this entire distance it represents the western margin of the Black Hills Uplift. For much of this length there is little topographic expression due to the recessive weathering character of the Cretaceous and Tertiary units exposed at this erosional level. In the most extreme example, along Interstate Highway 90 at Moorcroft, there is almost no topographic distinction between the uplift and basin although the structural relief there is 1,515 m (5,000 ft). The Black Hills monocline continues onto the uplift east of the Fanny Peak monocline, but with much less structural relief.

Numerous structural terraces (Fig. 15 and 16) are present along the trend of the major monoclines. This suggests that the underlying basement faults bifurcate and that structural relief is divided across two monoclines bounding the terrace.

The road cuts at this stop are in fossiliferous sandstone of the Turner Sandy Member of the Carlisle Shale. At this erosional level, these strata, and the monocline, dip ~55^{o}SW in the rotated limb of the Black Hills monocline. The geologic map of the Newcastle Quadrangle by Maple and Pillmore (1963) shows the synclinal flexure of the monocline to lie approximately one-half mile to the southwest within the Pierre Shale, just within the topographic Powder River Basin. The anticlinal hinge is about one mile to the north of the stop in the Fall River Formation. Structure contours of the upper contact of the Fall River show a structural relief of 3,400 feet in this area.

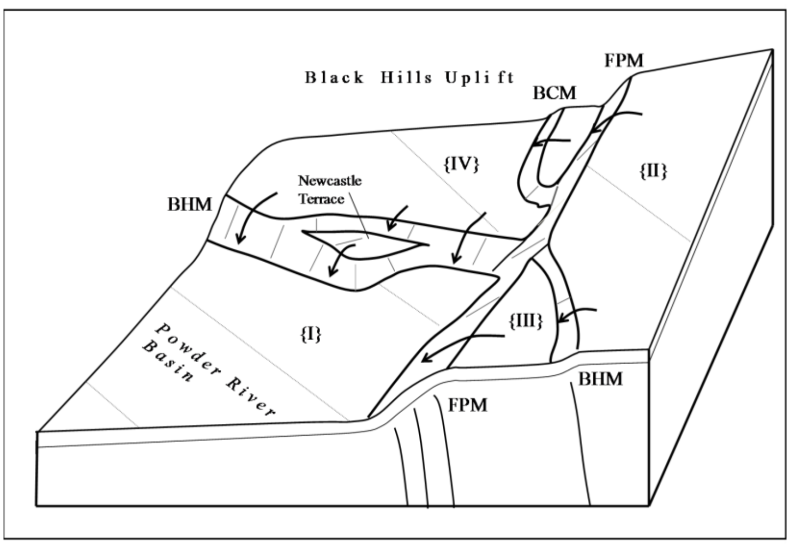

Figure 15. Block diagram illustrating Laramide folds along the west flank of the Black Hills Uplift. BCM = Beaver Creek monocline; BHM = Black Hills monocline; FPM = Fanny Peak monocline; LAKM = LAK monocline. Interaction of blocks I, II, III and IV result in the crossing of the Fanny Peak and Black Hills monoclines.

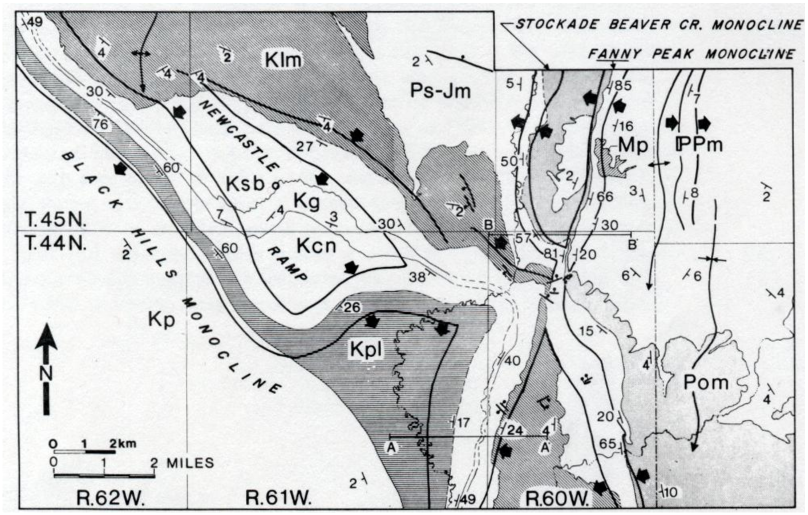

Figure 16. Geologic map of the Newcastle area showing the intersection of the Black Hills and Fanny Peak monoclines (Lisenbee, 1978). Strata are: IPPm = Minnelusa Formation; Ps-Jm = Spearfish Formation, Sundance Formation and Morrison Formation; Klm = Lakota Formation and Fall River Formation; Ksb = Skull Creek Shale, Newcastle Sandstone and Mowry Shale: Kg = Greenhorn Limestone; Kcn = Carlisle Shale and Niobrara Formation; Kpl and Kp = Pierre Shale.

The valley paralleling this ridge on the northeast is underlain by the Greenhorn Limestone, Belle Fourche Shale, and the Mowry Shale. The tree-covered slopes to the right of the valley are underlain by the Newcastle Sandstone, Skull Creek Shale and the Fall River Formation.

As shown in Figure 16, a second strand of the Black Hills monocline begins to the north here although the dominant strand (seen in the sandstone hogbacks of the Turner) continues southeast with about 1,800 feet of structural relief: The northern monocline turns to the east and continues along the north side of Newcastle with approximately 800 feet of structural relief. The result is a gently tilted structural terrace within the monocline which is about three kilometers (two miles) wide by five kilometers (three miles) long. Such terraces are common along the Black Hills and Fanny Peak monoclines.

Retrace route to intersection with U.S Hwy 85.

6.0 Exposure of Belle Fourche Shale in cut on north side of road.

6.6 Trees near highway are on siliceous Mowry Shale.

9.1 Ridge to south of highway is the Turner Sandstone Member. The two strands of the Black Hills monocline have joined in this area to form a single monoclonal limb with 3,300 feet of structural relief (Maple and Pillmore, 1963).

10.3 Site of “Camp Jenny”. The Newton-Jenny geological expedition from Ft. Laramie stopped here before entering the Black Hills along Beaver Creek. The purpose of the 1875 expedition was to establish a value for the Black Hills which could be used when the U.S. Government subsequently “bought” them from the Sioux nation.

11.1 Intersection with Beaver Creek Road.

STOP 2. Crossing of the Fanny Peak and Black Hills Monoclines.

The sharp curve in the hogback of the Fall River Formation to the east of this location represents the crossing point of the two monoclines at this stratigraphic level. This intersection results in a syncline (Figs. 15 and 16), which plunges southwest into the Powder River Basin. Northwest from this point the hogback is part of the Black Hills monocline; to the south it is in the Fanny Peak monocline.

In the limb of the Black Hills monocline to the west, the impressive LAK ranch house is constructed on the Fall River Formation. This ranch was originally developed using British investments in the late 1800s.
West of Stockade Beaver Creek, the highway parallels the Cretaceous strata including hogbacks of Newcastle Sandstone (at the road immediately west of the creek), Mowry Shale and the Turner Sandstone Member of the Carlisle Shale. At this location structural relief on the Black Hills monocline is about 3,000 feet (Maple and Pillmore, 1963**)**.

Continuation of both monoclines onto the uplift to the east results in a southwest-plunging anticlinal nose at the crossing point. At the current erosional level, this fold is present in the Minnekahta Limestone.

Turn left and proceed north through Cretaceous and Jurassic strata in the Black Hills monocline.

11.9 LAK Reservoir on the left. Take road to the right through quarry site. Use normal caution and obtain permission from the LAK ranch and the Fisher Sand and Gravel Company of Spearfish, SD (605-642-5760) before entry.

Note: Minnekahta Limestone in the north-trending Beaver Creek monocline east of the reservoir curves to the east across the quarry area and extends to an abutment against the Fanny Peak monocline.

12 Gently west-dipping sandstone of the Hulett Sandstone Member of the Jurassic Sundance Formation on left.

Continue through quarry site, remain in the valley and head toward cliffs of Minnelusa Formation directly ahead.

12.7 <u>STOP 3.</u> Fanny Peak Monocline

General Characteristics
South of the intersection with the Black Hills monocline, the Fanny Peak monocline continues for 65 km (40 mi) and separates the Black Hills Uplift and the Powder River Basin. Along this distance structural relief is 910-1,060 m (3,000-3,500 ft). The structure continues southward, with the Old Woman anticline on the east side, and extends into the Laramide Hartville Uplift. Although the core of the Black Hills is comprised dominantly of Proterozoic metasedimentary and igneous rocks, Archean rocks are present in the Hartville Uplift and in rafted fragments within Tertiary igneous centers near Sundance. Therefore, the Fanny Peak monocline is along, or near to, the eastern margin of the Wyoming Archean province.

Geophyscial studies of the Fanny Peak monocline south of the intersection are interpreted (Black and Roller, 1963) to show a faulted basement, although no faults are mapped at the surface. This interpretation is shown here in Figure 17. Dips on these faults are unconstrained, however.

North of the intersection with the Black Hills monocline the Fanny Peak monocline continues within the Black Hills Uplift as the prominent ridges of near vertically dipping, upper Minnelusa sandstone so evident here (Fig. 18). Structural relief is about 1,000 ft. The smaller Stockade Beaver Creek monocline (Figs. 16 and 19), which is well defined in the exposures of Minnekahta Limestone, parallels the Fanny Peak monocline for much of its length, but curves eastward and joins the Fanny Peak monocline just to the east of this stop.

Detailed Characteristics
The Minnekahta Limestone, Opeche Shale and Minnelusa Formation display different geometries in the excellent exposures in the synclinal flexure of the Fanny Peak monocline. As shown in Figures 20 and 21, two flexures are present in the Minnekahta Limestone, with planar segments between sharp bends. Stearns (1971) noted similar segmentation of the rotated limb in the Rattlesnake Mountain structure at Cody, Wyoming, although on a larger scale. Erslev and Rogers (1993), using deeper exposures in the northern Teton Range of the Forellen Fault and its associated fault-propagation fold, proposed that the dual flexures at Rattlesnake Mountain were underlain by a wedge of basement. This geometry, seen also in experimental analogs,

smoothes the transition between a single fault at depth and a continuous monocline in overlying strata. Exposures of the upper contact of the Minnelusa Formation in the small canyons here appear to be affected by only a single flexure, with ductile flow of red Opeche mudstone having filled the expanded area between the Minnekahta and Minnelusa beds. The Opeche is only 10 feet thick in one location within the rotated limb compared to a regional thickness of about 100 feet.

The massive upper Minnelusa sandstone rotated in the Fanny Peak structure is strongly and ubiquitously fractured and brecciated. Much of the breccia, however, results from dissolution of as much as 270 feet of gypsum beds within the Minnelusa Formation and collapse of the enclosing strata. Nevertheless, systematic fractures sets are strongly developed here.

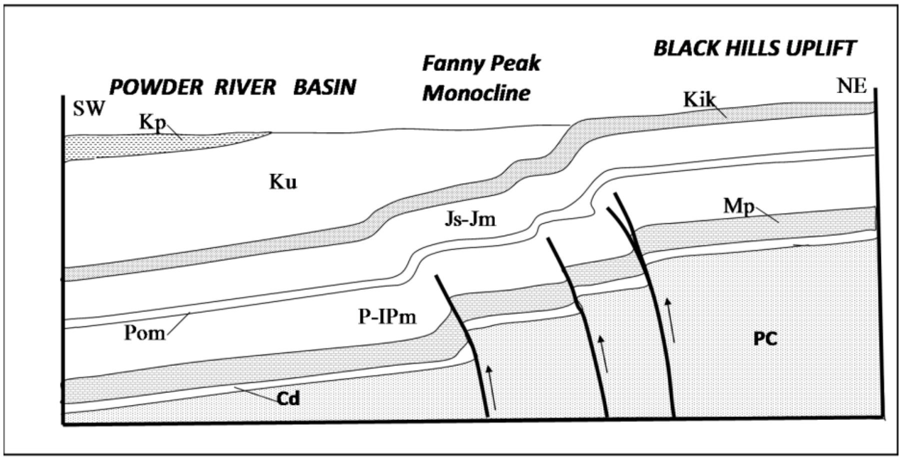

Figure 17. Cross section of the Fanny Peak monocline at the latitude of the southern portion of the Newcastle (Maple and Pillmore, 1963) and Fanny Peak (Brobst and Epstein, 1963) quadrangles (adapted from Lisenbee, 1978).

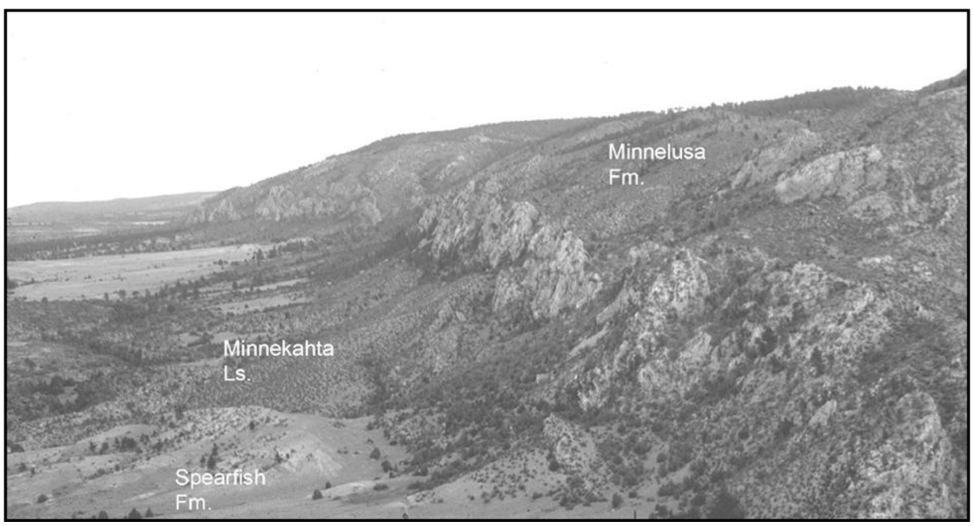

Figure 18. Aerial view of Fanny Peak monocline looking north. This strong topographic front is held up by massive sandstone beds of the upper Minnelusa Formation.

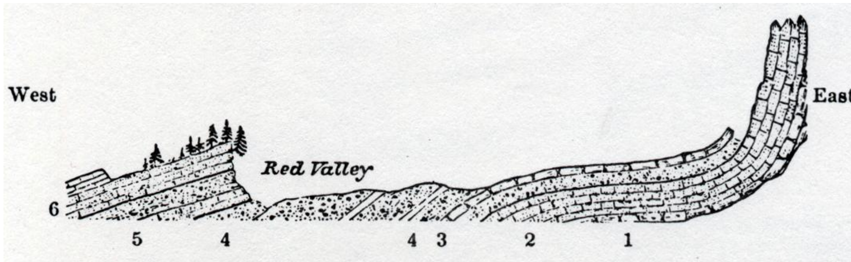

Figure 19. Cross section of the Fanny Peak and Beaver Creek monoclines by Newton and Jenney (1880). In the present stratigraphic usage, units 1 and 2 are Minnelusa Formation, 3 is Minnekahta Limestone, 4 is Spearfish Formation, 5 is Sundance Formation and 6 is Inyan Kara Group.

Joints

Joyce Fry (1982) examined fractures in the Minnekahta Limestone and Minnelusa Formation at 36 stations across the monocline and onto the adjoining uplift, taking 100 measurements at each location. The purpose of the study was to determine the relationship in space and time of fracturing relative to the development of the monocline. Three dominant fracture trends are present in each of the domains shown in the block diagrams (Figs. 21 and 22) summarizing her work.

1. E-W strike
2. NE strike
3. NW strike

Locally, a NNE trend is also present.

The fracture trends do not match all of those expected to have formed during monocline growth during east-west compression (e.g., parallel and perpendicular to the fold axis). If the strata are palinspatically unfolded to the horizontal, the major three fracture sets are similar in all parts of the monocline and adjacent blocks, indicating to Fry (1982) that the fracture sets formed prior to rotation of the monocline. Alternatively, these fractures may have formed during oblique slip similar to oblique Laramide structures to the west (Tetreault and others, 2008). This predicts that fracture set 1 may represent left-lateral Laramide minor faults, fracture set 2 may be right-lateral Laramide minor faults and fracture set 3 may be post-Laramide.

Faults

As shown in the diagrammatic block diagram of Figure 23, three types of faults affect the monocline limb, all of which were active during its development.

1. E-trending, sub-vertical left-slip faults perhaps representing reactivation of existing joint sets during monocline rotation (Fry, 1982) or new Laramide left-lateral faults;

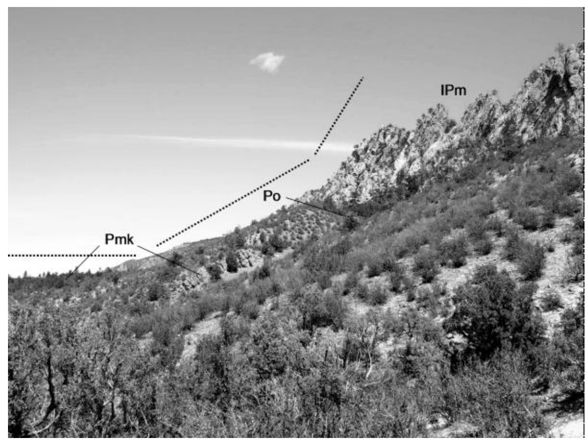

Figure 20. View north along synclinal flexure of Fanny Peak monocline. Note planar segments of rotated Minnekahta Limestone and Minnelusa Formation. The flat-irons of Minnelusa sandstone are strongly broken by cross faulting.

2. Bedding parallel faults due to flexural slip during folding;
3. North-striking (i.e., parallel to the strike of the monocline), east- and west-dipping, reverse faults. This is an unusual case in which the reverse geometry results from extension due to lengthening of the sub-vertical fold limb during folding (Fig. 23).

Cross the valley and walk eastward to the steep exposures of Minnekahta Limestone and Minnelusa Formation sandstone in the vertical limb of the Fanny Peak monocline.

Retrace route to U.S. Hwy 16 and return to Rapid City.

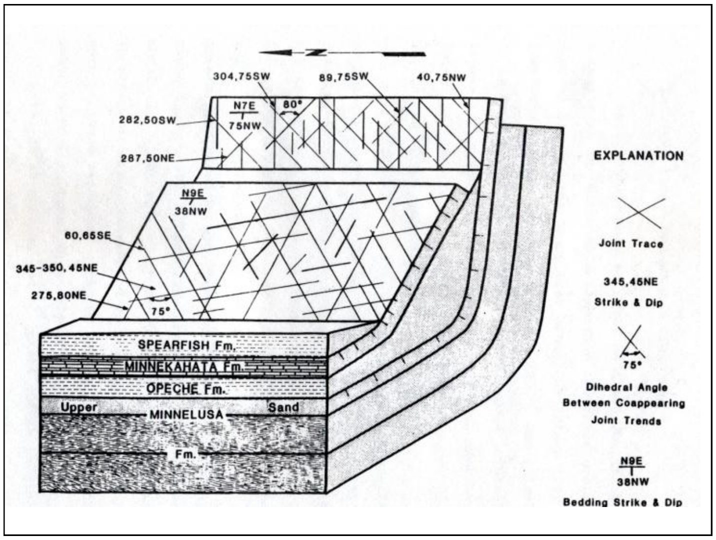

Figure 21. Block diagram illustrating fracture orientations (joints) in the Minnelusa Formation and Minnekahta Formation in the Fanny Peak monocline (Fry, 1982).

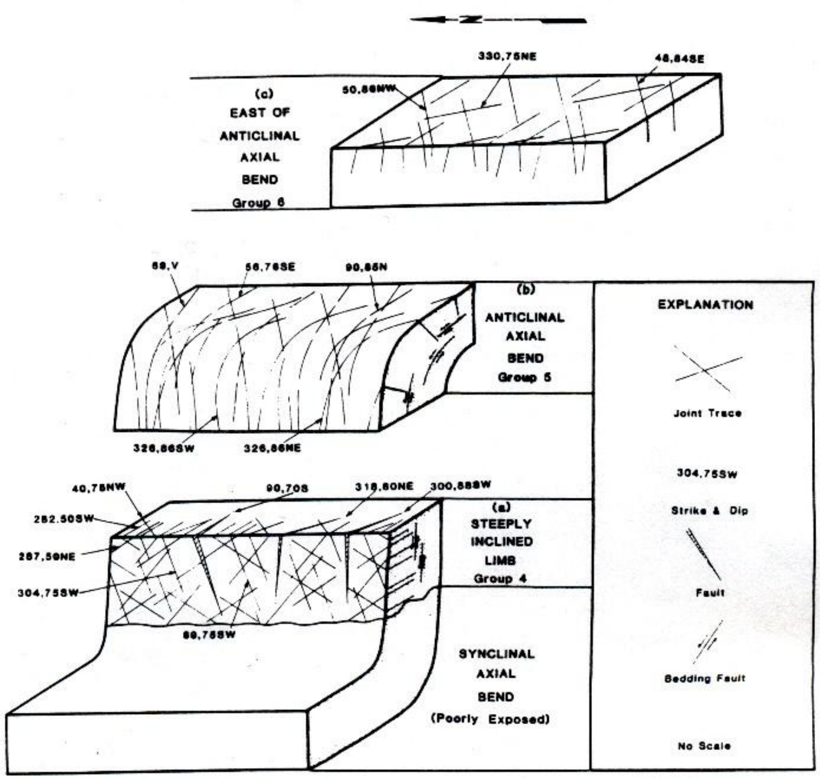

Figure 22. Block diagram illustrating fracture orientations (faults and joints) in the Minnelusa Formation in the of Fanny Peak monocline (Fry, 1982).

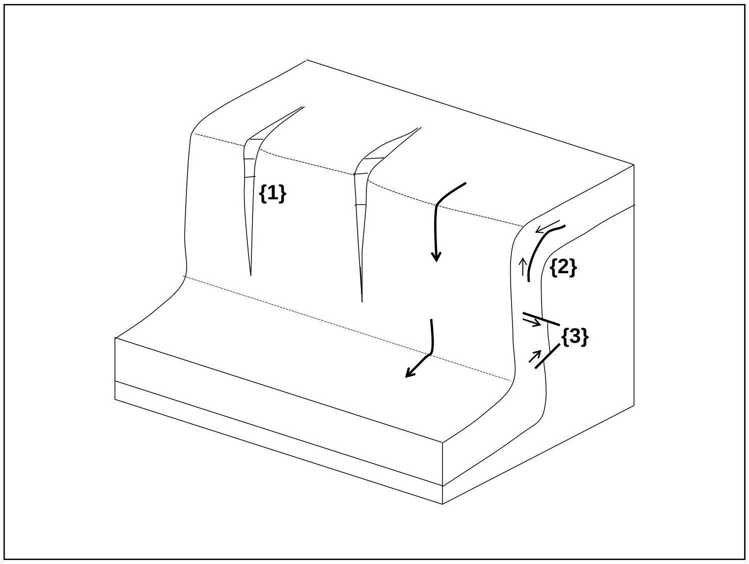

Figure 23. Block diagram illustrating fault orientations in the Fanny Peak monocline. 1. Strike-slip; 2. Flexural slip; 3. Reverse.

REFERENCES CITED

Brobst, D. A. and Epstein, J. B., 1963, Geology of the Fanny Peak Quadrangle Wyoming-South Dakota: U. S. Geological Survey Bulletin 1063-I, p. 323-377.

Black, R. A., and Roller, J. C., 1961: Relationship between gravity and structure of part of the western flank of the Black Hills, South Dakota and Wyoming: U.S. Geological Survey Professional Paper 424-C, p. 260-262.

Erslev, E.A., and Rogers, J.L., 1993, Basement-cover geometry of Laramide fault-propagation folds, in Schmidt, C.J., Chase, R., and Erslev, E.A., (eds.), Laramide basement deformation in the Rocky Mountain foreland of the western United States: G.S.A. Special Paper 280, p. 125-146.

Fagnan, B., 2002, Correlation of surface and subsurface geology and karst development at Jewel Cave National Monument, Custer County, South Dakota: M.S. thesis, South Dakota School of Mines and Technology, Rapid City, SD, 142 p.

Fry, J. A., 1982, Analysis of joints on monoclines in the Fanny Peak Quadrangle—Wyoming and South Dakota: M.S. thesis, South Dakota School of Mines and Technology, Rapid City, SD, 91 p.

Kelley, V. C., 1955, Monoclines of the Colorado Plateau: Geologic Society of America Bulletin, v. 66, p. 789-804.

Lisenbee, A. L., 1978, Laramide structure of the Black Hills uplift, South Dakota-Wyoming-Montana *in* Matthews, V., III, *editor*, Laramide folding associated with basement block faulting: Geological Society of America Memoir 151, p. 165-196.

Lisenbee, A. L. and DeWitt, E., 1995, Laramide evolution of the Black Hills uplift: *in* Snoke, A. W., Steidtmann, J. R., and Roberts, S. M., *editors*, Geology of Wyoming: Geological Survey of Wyoming Memoir NO. 5, p. 374-412.

Lisenbee, A. L. and Hargrave, R., 2005, Black Hawk Quadrangle; South Dakota Geological Survey, 1:24,000 scale map: South Dakota Geological Survey, 7.5 Minute Geological Quadrangle Map 5.

Lisenbee, A. L., Pellowski, C., and Hocking, C. M., (in preparation), Geologic Map of the Hermosa, NW Quadrangle: 1:25,000 scale.

Maple, W. J. and Pillmore, C.J., 1963, Geology of the Newcastle area, Weston County Wyoming: U.S. Geological Survey Bulletin 1141-N, 85 p.

National Park Service: Jasper Fire: http://www.nps.gov/archive/jeca/fire.htm

National Park Service: Jewel Cave: http://visitcuster.com/nationalparksmonuments/jewelcavenationalmonument/?utm_source=MSNPPC&utm_medium=PPC&utm_content=CusterJewelCave&utm_campaign=BHDS2010.

Newton, H. and Jenney, W.P., 1880, Report of the Geology and Resources of the Black Hills of Dakota: U. S. Geographical and Geological Survey, Rocky Mountain Region (Powell), 566 p.

Rowe, B. L., 2000, Lacustrine sedimentation and taphonomy of a fossil assemblage, White River Group (Oligocene), eastern flank of the Black Hills uplift: M.S. thesis, South Dakota School of Mines and Technology, Rapid City, SD, 130 p.

Shapiro, L. H., 1971, Structural geology of the Black Hills region and implications for origins of the uplifts of the Middle Rocky Mountain Province: University of Minnesota (unpub.) Ph.D. dissertation, 213 p.

Stearns, D. W., 1971, Mechanisms of drape folding in the Wyoming province: Wyoming Geological Association, 23rd Annual Field Conference, Guidebook, p. 125-143.

Tetreault, J., Jones, C.H., Erslev, E., Hudson, M., and Larson, S., 2008, Paleomagnetic and structural evidence for oblique slip fold, Grayback Monocline, Colorado: Geological Society of America Bulletin, v. 120, p. 877-892.

Field Guide to Geology of the White River Group in the North Unit of Badlands National Park: A Guide for the Field Trip: Recent Advances in Understanding the Geologic History of the White River Badlands, 24-25 April 2010.

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But it is only to the geologist that this place can have any permanent attractions. He can wind his way through the wonderful cañons among some of the grandest ruins in the world. Indeed, it resembles a gigantic city fallen to decay. Domes, towers, minarets, and spires may be seen on every side, which assume a great variety of shapes when viewed in the distance.

F. V. Hayden on the Badlands, in *The Great West*, 1880, p. 43

Introduction

The Big Badlands of South Dakota is one of the most remarkable areas in North America, noted for its stark beauty, exceptional vertebrate fossils, and unique geologic history. The park includes 243,302 acres (380 square miles; 985 square km) divided into two major areas: the North Unit and the South Unit (Fig. 1). The North Unit is managed solely by the National Park Service, while the South Unit is jointly-administered by the National Park Service and the Pine Ridge Indian Reservation. This guide concerns the White River Group exposed in the North Unit. The name "Badlands" is essentially a translation of the Lakota name for the area, *mako sica*, and the French name *mauvais terre a traverse*. The name does not refer to anything evil about the area, but refers to how hard it is to cross the area by foot. One can hike along the Badlands Wall (the main ridge of badlands in the North Unit) for miles and not be able to find even a game trail that crosses the badlands. However the badlands expose over many miles one of the most complete records of upper Eocene and lower Oligocene terrestrial rocks anywhere in North America, and contains one of the world's most abundant vertebrate fossil records for the late Eocene and early Oligocene. The Quaternary deposits of the North Unit have also been the subject of a Geological Society of America field guide by Burkhart et al. (2008).

The White River Group is composed of abundant volcaniclastic mudstones, siltstones, and fine-grained sandstones, and less abundant claystones, conglomerates, limestones and tuffs (lithified volcanic ash). The White River Group was deposited during the late Eocene and early Oligocene, and represents a depositional pulse in the Great Plains resulting from a great influx of volcanic ash and dust from the west. The White River Group and its equivalents extend from western North Dakota to east-central Colorado and from western Wyoming to east central Nebraska and South Dakota. This huge region was blanketed by volcaniclastic sediment that had an estimated volume of about 25,000 km^3 (Larson and Evanoff, 1998). From regional studies of the distribution, mineralogy, geochemistry, paleomagnetism and numeric ages of the tuffs in the White River sequence, Larson and Evanoff (1998) determined that most of the tuffs were derived from eruptive centers in the Great Basin of Nevada and Utah. However, the vast majority of silt-sized volcanic ash was deposited west of Badlands, and was later blown to the area as dust or was washed into the area by streams. The White River rocks are now very rich in swelling smectitic clay derived from the weathering and diagenesis of small volcanic glass shards.

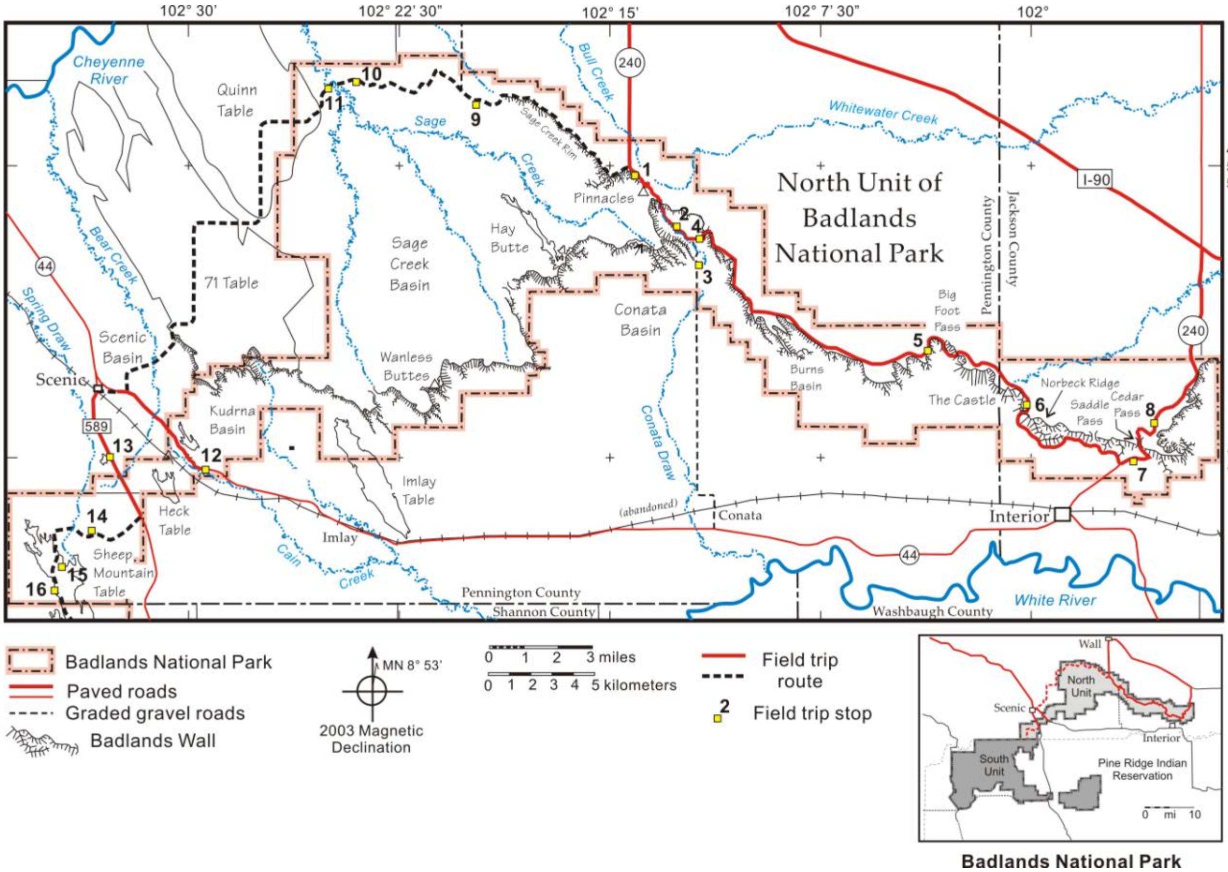

Figure 1. Index map of the North Unit of Badlands National Park showing the trip route, trip stops, and important geographic features discussed in the text.

The prominent banding seen throughout the Badlands is mainly the result of ancient soil formation. Following each depositional event, soil formation modified the sediments through various physical, chemical, and biological processes to produce soil profiles. Particular bands of color, since modified by diagenesis, represent distinct horizons within these ancient profiles (Plate 1-1). The types of horizons that formed represent an archive of paleoclimatic and paleoenvironmental conditions during the deposition of the Badlands. In addition to the vibrant striping, macroscopic evidence of ancient soil formation includes fossil roots, nodules and concretions, mottling, peds, and trace fossils. Based on analyses of paleosols from the bottom to the top of the Badlands, paleoclimates changed from humid to progressively arid conditions from the Eocene to Oligocene (Retallack, 1983).

The White River Group in the North Unit of Badlands National Park is divided into three formations, including the Chamberlan Pass, Chadron, and the Brule formations (Fig. 2). The **Chamberlain Pass Formation** (Evans and Terry, 1994) is the basal unit of the White River Group and includes a series of intense red, highly pedogenically altered overbank deposits called the Interior Paleosol Series of Retallack (1983). Associated with this paleosol are unique silica-rich conglomerates and scattered, very white cross-bedded sandstone channels that are included in the Chamberlain Pass Formation. The few mammal fossils that occur in the Chamberlain Pass rocks (outside of the park) are Duchesnian and early Chadronian in age (LaGarry et al., 1996). Below the Chamberlain Pass is a strong weathering zone developed on Cretaceous rocks and called the Yellow Mounds paleosol. These Upper Cretaceous rocks include the Pierre Shale and Fox Hills Formation. The Pierre Shale is composed primarily of black shales and represents open marine deposition, while the Fox Hills, composed of alternating shale and sandstone beds, was the result of deltaic progradation into the retreating Western Interior Seaway. The **Chadron Formation** in most of the North Unit of the park is composed of a thin sequence (typically 10 to 15 m thick) of gray claystone beds that weather into rounded gray hills. The fauna of the Chadron Formation is characterized by the remains of the huge, rhino-like brontotheres that characterize the Chadronian Land Mammal Age. The **Brule Formation** is divided into the Scenic and Poleslide members. The **Scenic Member** is composed of alternating widespread mudstone layers and silty sandstone layers. The **Poleslide Member** is dominated by widespread thick siltstone layers interbedded with a few widespread silty sandstone intervals. Traditionally the Scenic and Poleslide members have been distinguished by their fauna, with the Scenic Member representing all of the rocks containing a fauna of the Orellan Land Mammal Age, and the Poleslide containing a fauna of the Whitneyan Land Mammal Age (Fig. 3). The Orellan Land Mammal Age is characterized by abundant oreodonts (*Merycoidodon* spp.), tortoises (*Stylemys* spp.) and horses (*Mesohippus* spp.) and the lack of brontotheres. These Orellan taxa also occur in the Whitneyan, but Whitneyan faunas are dominated by the oreodont *Leptauchenia* spp. and the horned artiodactyl *Protoceras* spp. However, the two members are now defined on the lithologic change from mudstone-dominated sequences to siltstone-dominated sequences that occurs high in the Orellan rocks. In the North Unit of the park the Brule Formation is capped by conglomeratic beds at the base of paleovalley fills of the **Sharps Formation**. These “Sharps Channels” are filled by sandy siltstone beds containing a distinct fauna of the Arikareean Land Mammal Age, including the huge entelodont *Daenodon* (Parris and Green, 1969).

The information given in this guidebook is a result of new information gathered over the past decade. Starting in 2000, Dr. Rachel Benton, Paleontologist for Badlands National Park, organized two major research projects to make paleontologic and geologic inventories of parts of the North Unit, first in the Scenic Member (during the years 2000-2002, Benton et al., 2006) and later in the Poleslide Member (2003-2004, Benton et al., 2009). Dr. Benton worked with Carrie Herbel of the South Dakota School of Mines supervising large paleontologic survey crews documenting thousands of fossil sites in the North Unit. These paleontologic studies were made in conjunction with detailed paleosol analyses of the bone beds by Dr. Dennis Terry of Temple University in Philadelphia, Pennsylvania, and detailed regional stratigraphic studies of the Brule Formation by Dr. Emmett Evanoff, now at the University of Northern Colorado in Greeley, Colorado. Several new stratigraphic units are described in these studies, but currently remain as informal stratigraphic units. These unit names (such as the *Hay Butte marker*, *Saddle Pass marker*, and *disappointment limestone interval*) are *italicized* in the following discussion.

The new information on the White River Group given in this guidebook updates the previous geologic and paleontologic studies that have been made in the area since the 1850’s.

The route includes two days of travel. The first day starts in Rapid City, continues to Wall at the 110 exit of Interstate 90, and then loops around South Dakota Highway 240 to the Ben Reifel Visitor Center and then to the Northeast Entrance of the Park. After staying overnight in Wall, the second day travels on the Sage Creek road, a well-graded gravel road, to South Dakota Highway 44 just east of the town of Scenic. After making a stop southeast of Scenic, the route continues to the southwest onto Sheep Mountain Table on the west side of the North Unit of the park. The second day ends in Rapid City. Figure 1 shows the locations of all the roads, geographic features, and stops along this trip. GPS coordinates in WGS84 Datum units are given for stops that are not at official overlooks.

DAY 1, STATE HIGHWAY 240 FROM WALL, THROUGH CEDAR PASS, TO THE NORTHEAST ENTRANCE OF BADLANDS NATIONAL PARK

From the intersection of Interstate 90 and South Dakota State Highway 240 in Wall, turn south on State Highway 240 and drive 7.2 miles to the Pinnacles Entrance Station in Badlands National Park. As you enter the park, State Highway 240 becomes the Badlands Loop Road. Pay the entrance fee at the station and then continue on the highway 0.9 mile southward to the Pinnacles Overlook. Retain you entrance receipt for day two of this trip.

Stop 1 – Pinnacles Overlook. The first overlook on Badlands Loop Road south of Wall has one of the most spectacular views in Badlands National Park. The overlook is on one of the highest places in the North Unit of the Park and the Pinnacles are the high spires due south of the overlook. To the west and southwest are many square miles of badlands that extend toward the horizon. The drainage basin directly below you is the headwaters of the east fork of Sage Creek that flows toward the northwest into the Cheyenne River. Below you is a wilderness area that contains the Park’s *Bison* herd. The grassy flats in the bottomland are the favorite resting and grazing spots for isolated buffalo bulls. The west edge of this drainage basin is the long table capped by two grassy flats called Hay Butte. To give you an idea of the size of this area, the butte is 3.4 miles (5.5 km) to the southwest of the overlook and the southeast end of the butte to the northwest end of the northern grassy top of the butte is 2.7 miles (4.3 km) long. To the left of the butte is the north side of the Badlands Wall, a series of badlands ridges that separate the low prairies of the White River drainage to the south from the higher flats of the northern streams, such as Sage Creek. The Sage Creek valley is about 50 m higher than are the prairies on the south side of the Wall. To the right (northwest) of the overlook is the high grassy prairie that ends in badlands along the Sage Creek Rim. Drainages on the upper prairie flow toward the north-northwest along Bull Creek to the Cheyenne River. A well graded dirt road runs along the Sage Creek Rim that offers the best viewing places for *Bison* in the park.

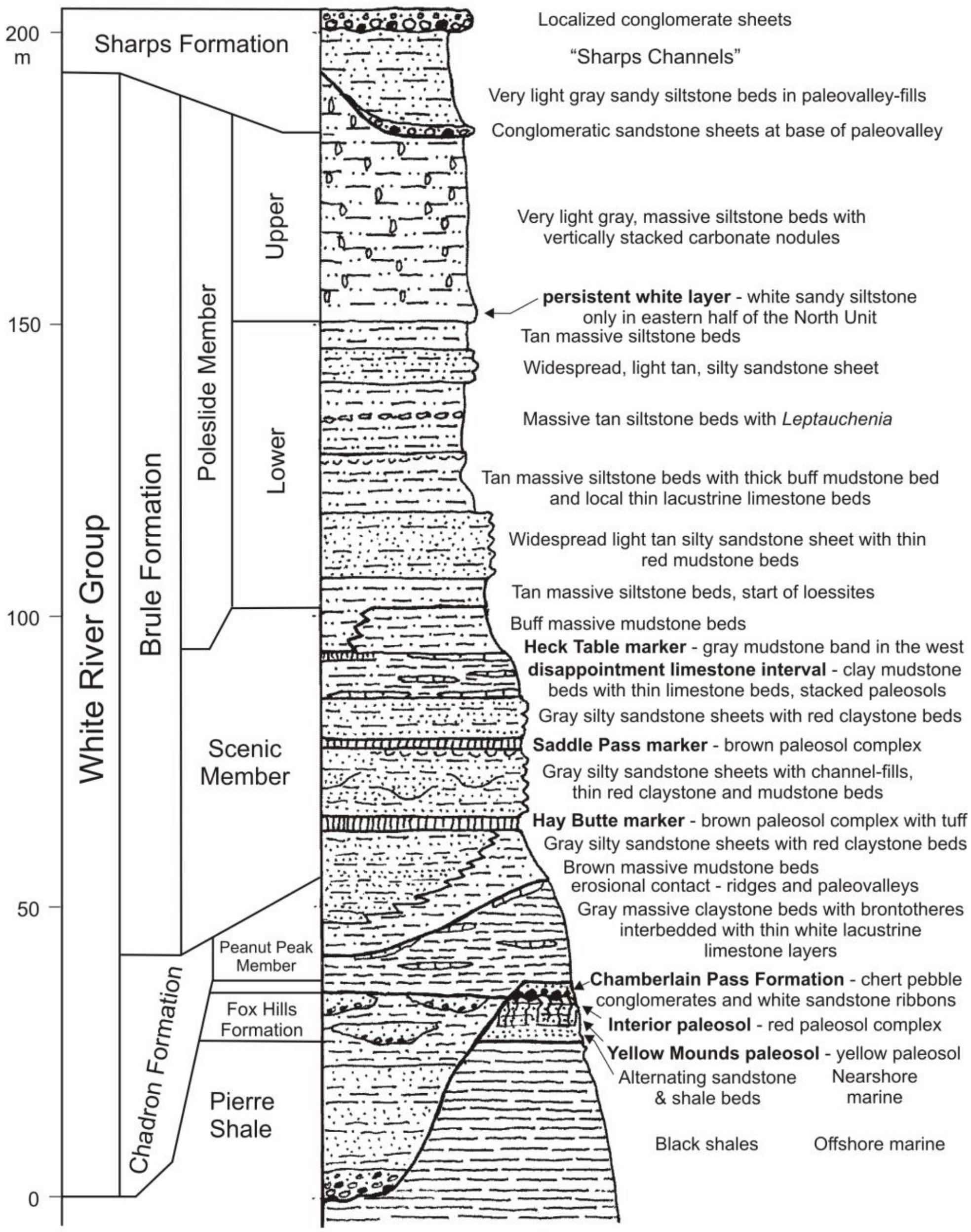

Figure 2. A generalized stratigraphic column of the White River Group exposed in the North Unit of Badlands National Park. Most of the units and thicknesses reflect the eastern half of the North Unit. However, Chadron paleovalleys are found in the west side of the Park.

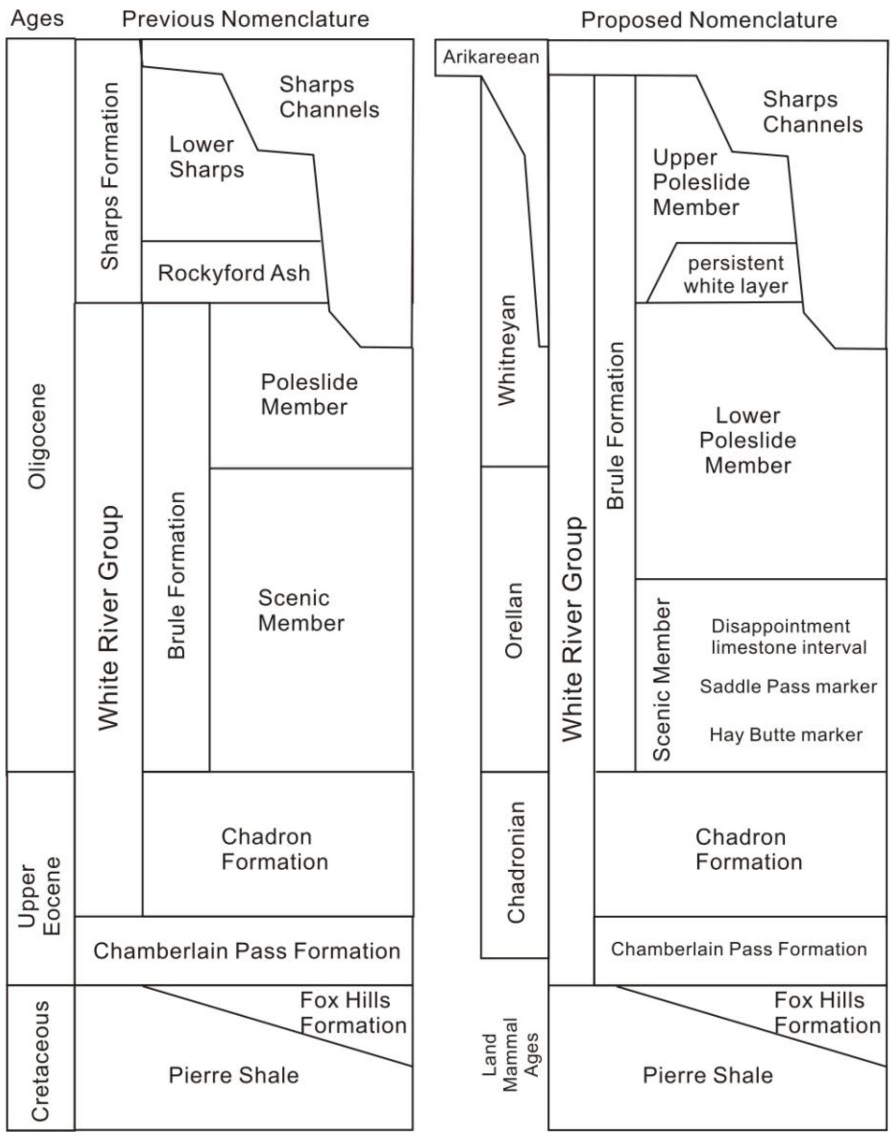

Figure 3. Ages, existing stratigraphic nomenclature and proposed nomenclature for the rocks in the east side of the North Unit of Badlands National Park. The proposed nomenclature of the Brule Formation is based on lithologic changes (not biostratigraphic changes), and correlation with the type sections in the western part of the North Unit.

All of the badlands below you are cut in the middle portion of the White River Group. You do not see the entire sequence of the White River Group at this site because of post-Oligocene deformation. The Sage Creek Rim and the Pinnacles are along the axis of an anticline called the Sage Creek Arch (Fig. 4). The anticline axis is expressed by the high elevation at this overlook. The rocks before you are inclined (dip) to the southwest as much as 4° toward the axis of the adjacent syncline that is along the main channel of Sage Creek. The syncline is expressed by the low elevation of regional marker beds near the center of the Sage Creek drainage. One such marker bed is the prominent white layer just below the western overlook at this stop. You can see its low position in buttes in the Sage Creek valley and can be seen near the top of Hay Butte on the other side of the syncline. The *prominent white layer* that occurs here and many places to the east has traditionally been correlated to the Rockyford Ash, a prominent white tuff at the base of the Sharps Formation on top of the White River Group (Nicknish and Macdonald, 1962). However, even though the prominent white layer in this region superficially looks like a tuff, it does not contain the criteria of an ash-fall tuff as discussed by Larson and Evanoff (1998). This white bed contains highly abraded and weathered heavy mineral grains with few euhedral heavy mineral crystals and the bed disappears within the same stratigraphic level in buttes 8.7 miles (14 km) to the southwest of this overlook. Since White River ash deposits were derived from sources far to the west and southwest, a tuff with a thickness of the *persistent white layer* would not disappear in the direction of the volcanic source. Even farther to the west, the *persistent white layer* is not present at the type section of the Poleslide Member on Sheep Mountain Table. There is a distinct tuff at the top of the White River Group on Sheep Mountain Table that is thought to be the Rockyford Ash. However, this tuff is 40 m higher than the stratigraphic level of the *persistent white layer*. Furthermore, the mineralogy of heavy minerals in this white layer is different from that of the tuff on Sheep Mountain Table.

Continue driving on the Badlands Loop Road toward the southeast. You will pass the **Ancient Hunters overlook** that is situated on a large landslide that has rotated and down-dropped blocks of the Poleslide Member. The upper parts of the larger landslides have rotated blocks and hummocky topography that catches water and allows junipers to grow. Such juniper groves are prime habitat for deer and bighorn sheep. The overlook views over a basin in the headwaters of Whitewater Creek that flows northeast into the Bad River drainage with a ridge of the Badlands Wall on its south side. The road crosses this ridge and enters the headwaters of the Conata Basin that drains south into the White River. Retallack (1983) described and measured a detailed sequence of paleosols through the White River Group along a single transect starting in the drainages on the right side of the highway and ending in the Pinnacles. Stop 2 is next to the highway, 2.1 miles past the Pinnacles overlook. Park on the right side of the road and climb up the small hill on the right (east) side of the road.

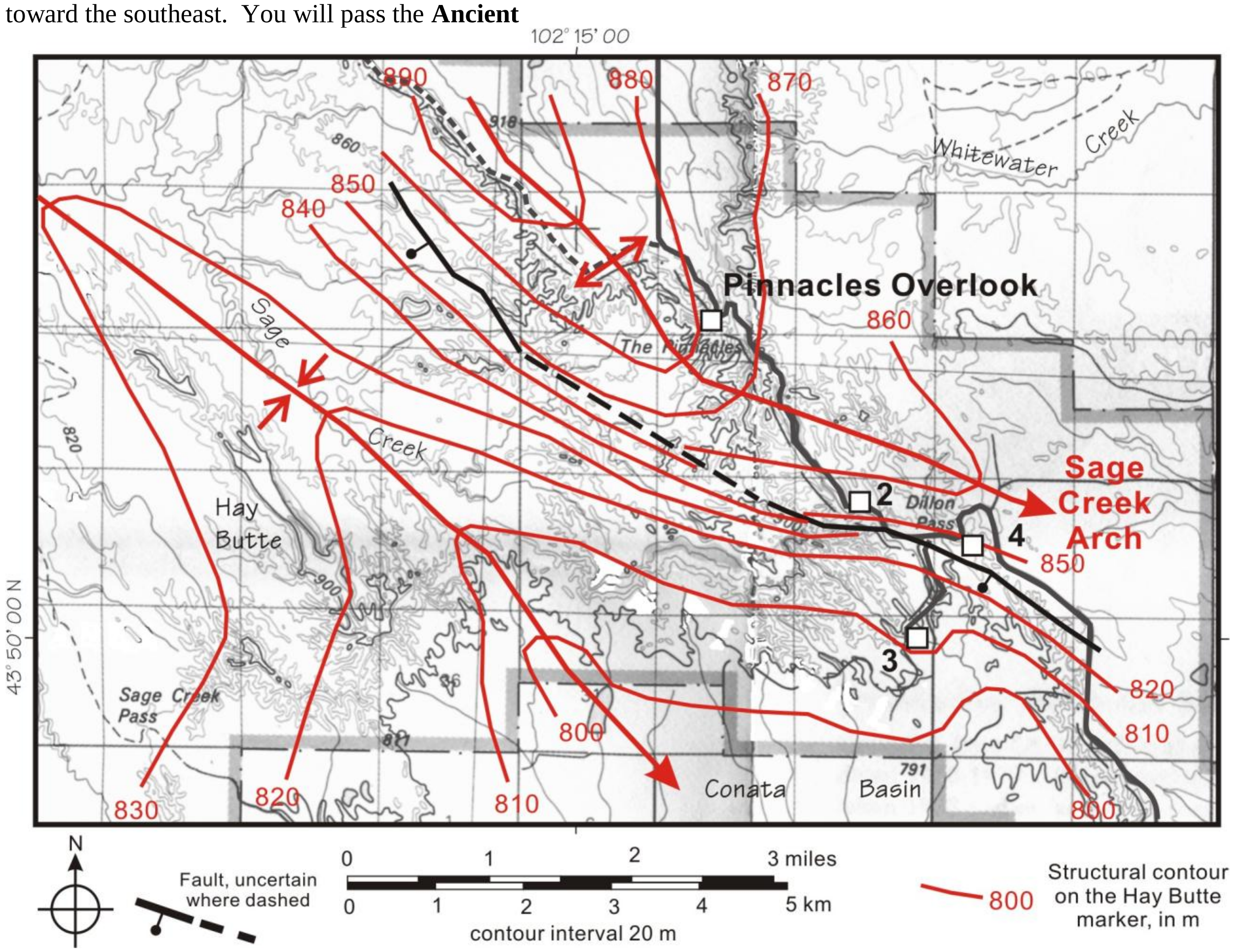

Figure 4. Structures in the Pinnacles, the east fork of Sage Creek and Hay Butte. Structural contours are on the elevation of the *Hay Butte marker*. Numbered points are Field Trip Stops.

Stop 2 – White River Group Stratigraphy. From this undeveloped pull-off at the headwaters of Conata Basin, you can see the entire White River Group in the cliffs to the southwest (Fig. 9). The best view of this sequence is from the top of the hill just to the east of the road. The viewpoint is at latitude 40° 50.832' N and longitude 102° 12.677' W (WGS 84) for a GPS location. Please note that **the collecting of fossils, rocks and any other natural items is not permitted in the Park** – please leave what you find for the enjoyment and education of others.

At this locality the White River Group rests on an unconformity on top of the Cretaceous Fox Hills Formation (Plate 1-2). The Fox Hills is composed of alternating shales and thin sandstones that have been weathered to a yellowish brown color. Marine fossils and strontium isotopes indicate that the Fox Hills in the Park is Maestrictian in age (Chamberlain, et al., 2001). A regionally extensive zone of soft sediment deformation and ejecta is preserved in the uppermost part of the Fox Hills at this locality (Plate 1-2). Based on biostratigraphic data, this impactite is dated to approximately 68 Ma (Jannett and Terry, 2008). A zone of ancient weathering, commonly referred to as the *Interior Zone* for exposures near Interior, overprints the Fox Hills in this area. The lower yellow zone is called the Yellow Mounds Paleosol Series, and is named for the yellow hills in this area (Retallack, 1983). A second paleosol complex overlies the Yellow Mounds, is intense red in color, and is called the Interior paleosol (Ward, 1922; Retallack, 1983). The Interior paleosol formed on the overbank deposits of a widespread nonmarine deposit, up to 11 m thick in places, referred to as the Chamberlain Pass Formation (Evans and Terry, 1994). Based on vertebrate remains preserved in correlative deposits in Nebraska, this unit is Duchesnean to Chadronian in age (LaGarry et al., 1996). Both the Yellow Mounds and the overlying red Interior paleosol can be seen in the drainage directly below you (Plate 1-2).

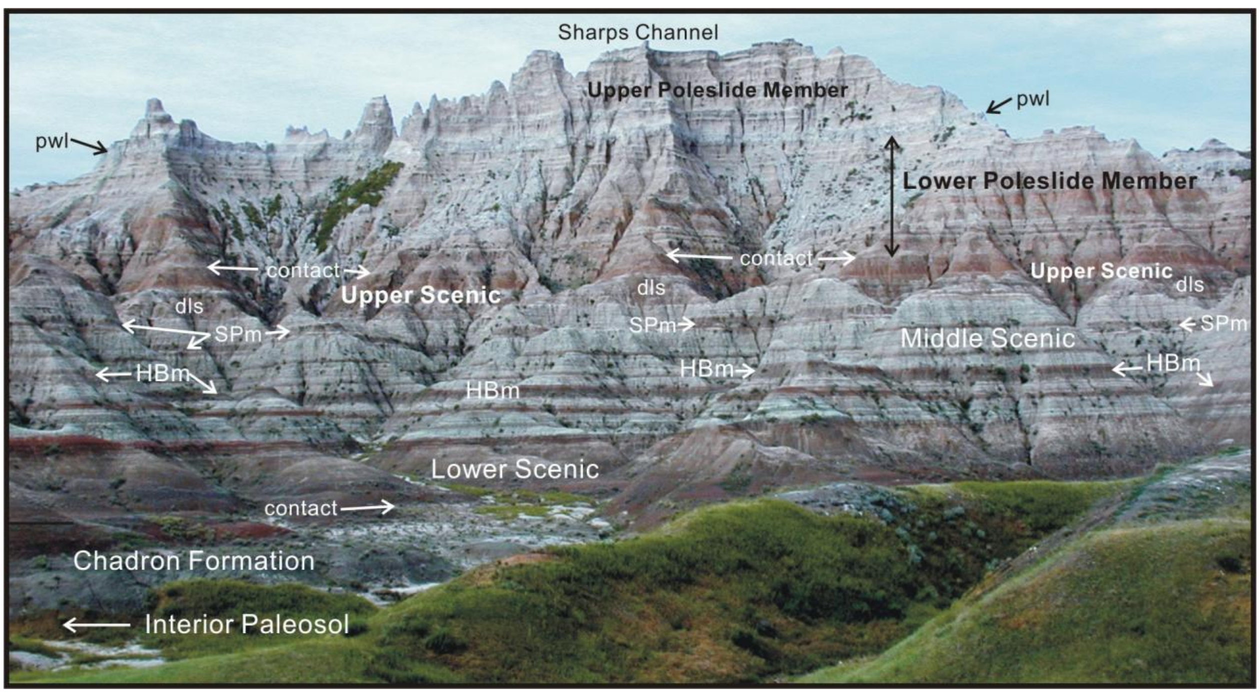

Figure 5. View of the entire White River Group exposed on the ridge south of the Pinnacles at Stop 2. HBm is the *Hay Butte marker*; SPm is the *Saddle Pass marker*; dls is the *disappointment limestone interval*; pwl is the *persistent white layer*. The rocks here dip 4° to the southwest, away from the viewer.

The overlying Chadron Formation at this locality is a relatively thin sequence (about 5-10 m thick) of gray claystones that weather into rounded low hills capped by a strong popcorn surface. This "popcorn" is a result of the drying and contraction of the swelling clays in the Chadron. Vertebrates and radiometric dates of tuffs in the Chadron Formation (but not in the park) indicate a late Eocene age for its deposition. On a regional scale, the Chadron can be divided into four separate members (Terry and LaGarry, 1998), of which the Peanut Peak Member is preserved in this part of the Park.

The upper formation of the White River Group is the Brule Formation that is divided into the Scenic and the Poleslide members. The Scenic Member is a series of alternating widespread, thick brown mudstone beds and light gray sandstone beds interbedded with thin, typically red, mudstone and claystone beds. The Poleslide Member is a series of interbedded tan siltstone and sandstone beds in its lower half and very light gray massive siltstone beds in its upper half. The marker bed between the lower and upper Poleslide member is the prominent white layer midway up the cliff. The shift from the mudstones and sandstones of the Scenic to the thick siltstone beds of the Poleslide reflects a shift in environments from mostly fluvial to mostly aeolian. The shift from river channels and overbank deposits to widespread blankets of silty loess reflects a climatic shift from subhumid to semiarid conditions. Fossil vertebrates tied into radiometric dates indicate an early Oligocene age for Brule deposition, again from stratigraphic studies made outside the park.

In the outcrops before you, the Brule starts with brown mudstones directly above the gray Chadron claystones (near the base of the drainage) and is capped by sandstone ledges at the top of the butte. There are 8 subunits within the Scenic Member that can be correlated throughout the North Unit of the Park. The best marker beds in the Scenic are two widespread, thick, brown mudstone units that are called the *Hay Butte* and *Saddle Pass marker beds*. Figure 9 shows the locations of these marker beds in the high ridge in front of you. The *Hay Butte* and *Saddle Pass beds* are distinct markers that extend for the entire 50 miles (80 km) along the Badland Wall in the North Unit. The prominent white layer at the base of the upper Poleslide Member is another marker bed in the eastern half of the North Unit.

Conglomerate ledges of the Sharps Formation cap the Poleslide Member at the top of the butte. These conglomerate beds were deposited as channels at the base of a paleovalley that was filled with massive silty sandstone beds above the basal conglomerate beds. These paleovalley fills have been traditionally called the "Sharps Channels" (Harksen, 1974). On the basis of faunal evidence, an unconformity separates the upper Poleslide Member from the Sharps Channels. The resistant Sharps Channels preserve the Poleslide Member from erosion, so the entire White River Group is preserved in isolated buttes along the Badlands Wall.

The Brule Formation was deposited on an erosional topography cut into the Chadron Formation throughout the North Unit of the Park. This is well seen in the outcrops at this stop. Locate the *Hay Butte marker* in the outcrops in front of you using Figure 5. Notice also the white sandstones that lie directly below the *Hay Butte marker* and the brown lower Scenic mudstones that underlie the sandstones. Here the total thickness of Scenic rocks below the *Hay Butte marker* is 22.5 m. As you trace the sandstone beds below the *Hay Butte marker* to the right (northwest) along the base of the ridge, the sandstones thin and pinch out into the basal brown mudstones of the Scenic. At the edge of your view, the *Hay Butte marker* rests upon the basal brown mudstones that have a thickness of only 10 m. Figure 6 shows a cross section through the units below the *Hay Butte marker* along the ridge in front of you, showing two filled drainages between two uplands cut into the Chadron Formation. (Section MS 4 is directly in front of you, Section MS 6 is about as far as you can see to the right). An isopach map of the Scenic rocks below the top contact of the *Hay Butte marker* (Fig. 7) shows the geometry of the early Oligocene topography. The isopach map shows two south-flowing drainages cut into the Chadron Formation. The ancient western drainage is directly in front of you at this stop.

Continue driving on the Badlands Loop Road for 0.7 miles where the Conata Road comes in from the right. Turn right onto the Conata Road and drive 0.6 mi to the entrance road of the Conata Picnic Area. Turn right into the picnic area and park near the interpretive sign for the Pig Dig.

Stop 3 – The Conata Picnic Ground Site (the Big Pig Dig). The brown mudstones of the lower Scenic Member are some of the most fossiliferous beds in the Park. Fossil bones of mammals and tortoises are scattered throughout the unit, but locally there are bone beds, or accumulations of skeletal materials along a single stratigraphic horizon, in the lower Scenic. The Conata Picnic Ground Site is one of these bone beds that contains the largest known concentration in the park of remains of the large pig-like entelodont *Archaeotherium*.

Discovered in 1993, the Conata Picnic Ground Site (informally known as the Big Pig Dig in reference to the entelodonts) contained one of the most extensive and best preserved Orellan vertebrate accumulations within the Scenic Member of the Brule Formation. Excavations lasted for 15 years and ended in 2008. The site produced 18 different taxa, including four dominant taxa: *Archaeotherium*, *Subhyracodon*, *Mesohippus*, and *Leptomeryx*. It is estimated that over 15,000 elements have been collected from the site. A final count has not yet been determined due to a backlog in curation of the specimens. The Big Pig Dig has been a joint project between Badlands National Park and the South Dakota School of Mines and Technology. All of the fossils that were collected at the site will be housed in the new South Dakota School of Mines and Technology collections facility.

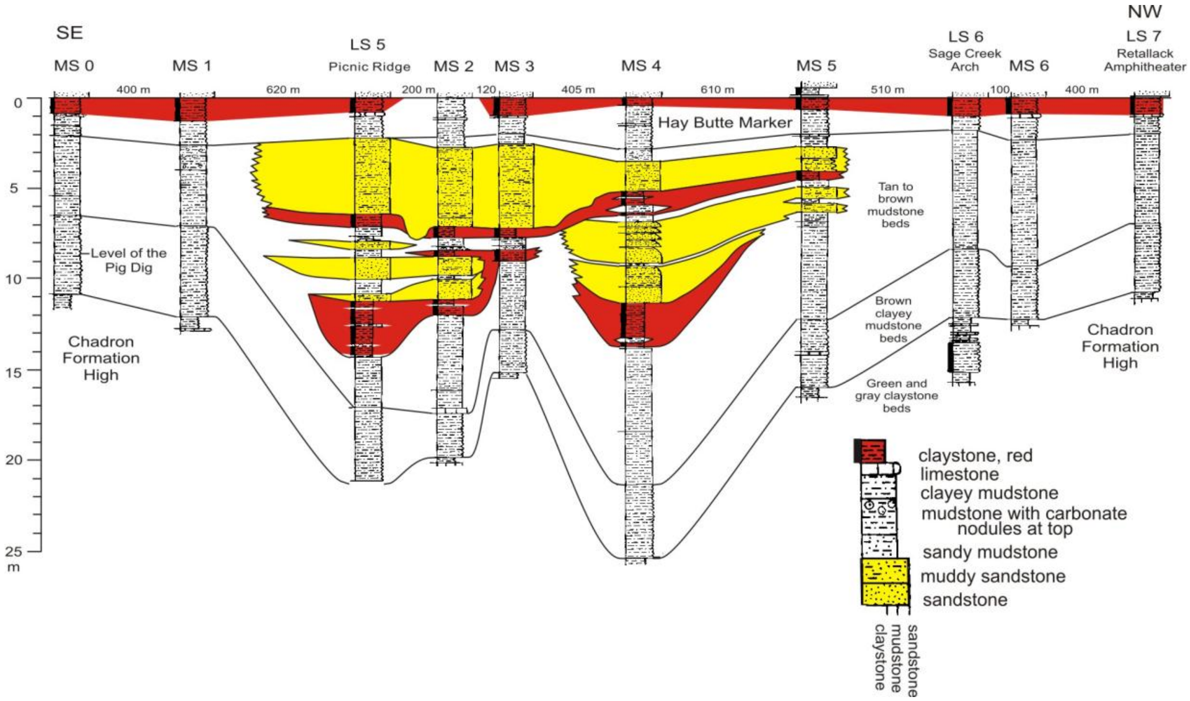

Figure 6. A cross section through the lower Scenic paleovalleys between the Pinnacles (on the north) and the Conata Picnic Ground to the south.

Based on a detailed sedimentological analysis (Terry, 1996a, b), the site may represent an attritional accumulation of animals around a watering hole during drought conditions (Plate 1-3). Animals may have died from thirst, with small weakened animals becoming trapped within a soft substrate of the watering hole while attempting to reach the remaining water. Due to the nature of their preservation, the bone accumulations at the Big Pig Dig are considered unique to the Badlands. Vertebrate fossils from the White River Group most commonly represent either attritional bone accumulation on ancient land surfaces or bones which have been incorporated into channel sandstone deposits. The bones from the Big Pig Dig do not conform to either of these models but instead occur as semi-articulated to disarticulated elements which show no preferred orientation (Stevens, 1996). The bones are most commonly preserved within a light olive gray (Munsell color 5Y 6/2) mudstone layer which can reach a thickness as much as 89 cm (Plate 1-3). The greenish bone bed is bound below by a brown to dark brown (Munsell color 7.5 YR 4/3) mudstone. The bone bed is cross-cut by numerous vertical to sub-vertical fractures which are filled with dark reddish brown (Munsell color 5YR 3/4) mudstone.

During each field season, between 5,000 and 10,000 visitors stopped by the site. The Big Pig Dig provided the opportunity for visitors to speak with scientists and to learn about the protection and study of nonrenewable fossil resources. The National Park Service is presently contracting with an artist to paint a mural which will be a reconstruction of the Big Pig Dig from 33 million years ago. The mural will be included within a series of wayside exhibits to be on display at the site within the next two years.

To accommodate possible future site excavations, three permanent stainless steel monuments were installed at the site in August 2009. The monuments are 18 inches in length and are encased in concrete. Each monument was set below grade and was located at the site origin, back-site, and easting. The monuments were stamped accordingly. Magnets were set in the surrounding concrete so the monuments could be located by a metal detector.

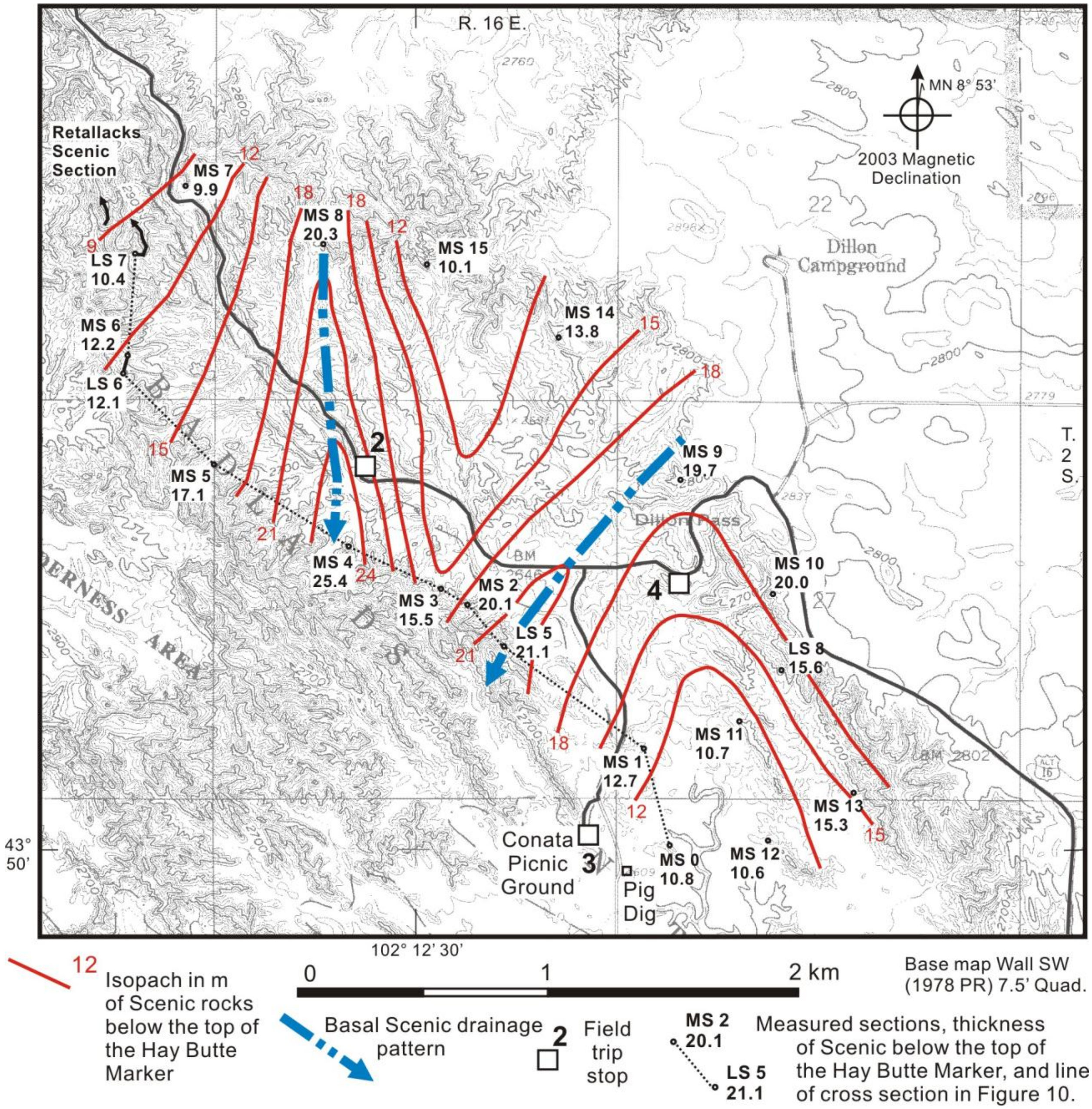

Figure 7. Isopach map of the lower part of the Scenic that the reflect paleovalleys in the upper Conata Basin. The original flow of the drainages was to the south.

When walking back from the Big Pig Dig site to the parking lot at the Conata Picnic Ground, the end of the ridge behind the picnic tables exposes the *Hay Butte marker*, the *Saddle Pass marker*, and a widespread series of clayey mudstones and thin discontinuous limestones, informally called the *disappointment limestone interval*. The interval is named because of their typical lack of fossils. All of these marker units are separated by blankets of thin bedded gray to light brown sandstone beds interbedded with distinct, laterally discontinuous, red mudstone and claystone beds. Sandstone-filled channels occur just above the *Hay Butte marker* in some of the ridges just to the west of the picnic area. Paleosols within the lower to middle part of the Scenic Member in this area range from weak to moderately developed, reflecting their relative positions on and within the paleotopography developed on the underlying Chadron Formation. Paleosols that formed lower on the landscape were influenced by water, whereas those higher on ancient landscapes, and those that formed following the infilling of paleotopography on the Chadron Formation, were better drained and developed (Fig. 8). The widespread marker beds, such as the *Hay Butte marker*, contain a series of stacked paleosols which developed in response to a basinwide period of relative stability, structural control, and rates of sedimentation which were progressively slower to the northeast (McCoy, 2002). In most of Conata Basin, the *Hay Butte marker* is composed of several distinct profiles, but some profiles are extremely well developed (Fig. 9). The degree of development and types of soil features in these profiles are similar to modern grassland soils (mollisols). Horizons are overthickened (cumulic), suggesting slow aggradation and incorporation within the active profile. Based on the fine grain size of these cumulic sediments, an eolian source is most likely. On top of the Chadron hills north of the picnic area near the axis of the Sage Creek Arch, the Hay Butte has a thinner, less developed profile that formed in response to a relatively higher geomorphic position along this paleolandscape. The lateral extent of the *Hay Butte marker bed* and degree of soil development within it suggest a widespread period of geomorphic stability throughout the basin.

Drive back to the Badlands Loop Road where you will turn right. The Yellow Mounds overlook will soon be on your right. Pull into this overlook.

Stop 4 – Faults at the Yellow Mounds. A short walk along the top of the ridge to the west of the parking area provides a spectacular view of a high angle normal fault cutting the Yellow Mounds paleosol and the Chadron Formation. The Yellow Mounds is developed in the upper Cretaceous rocks that been uplifted on the north side of the fault, and abuts the gray claystone of the Chadron Formation on the south side. Sixteen meters of displacement of units along this fault occurs in the Scenic Member in the bluffs to the southeast of this overlook. The fault is exposed along the southern flank of the Sage Creek Anticline for 1.5 km to the east-southeast, and for 2.4 kilometers to the west-northwest where it crosses the west wall of badlands (Fig. 4). On this western side, the displacement of rock layers adjacent to the fault is only 3 m. The movement on this fault is after the deposition of the Scenic Member, because the thicknesses between the individual units on either side of the fault are the same on the upthrown and down-dropped blocks.

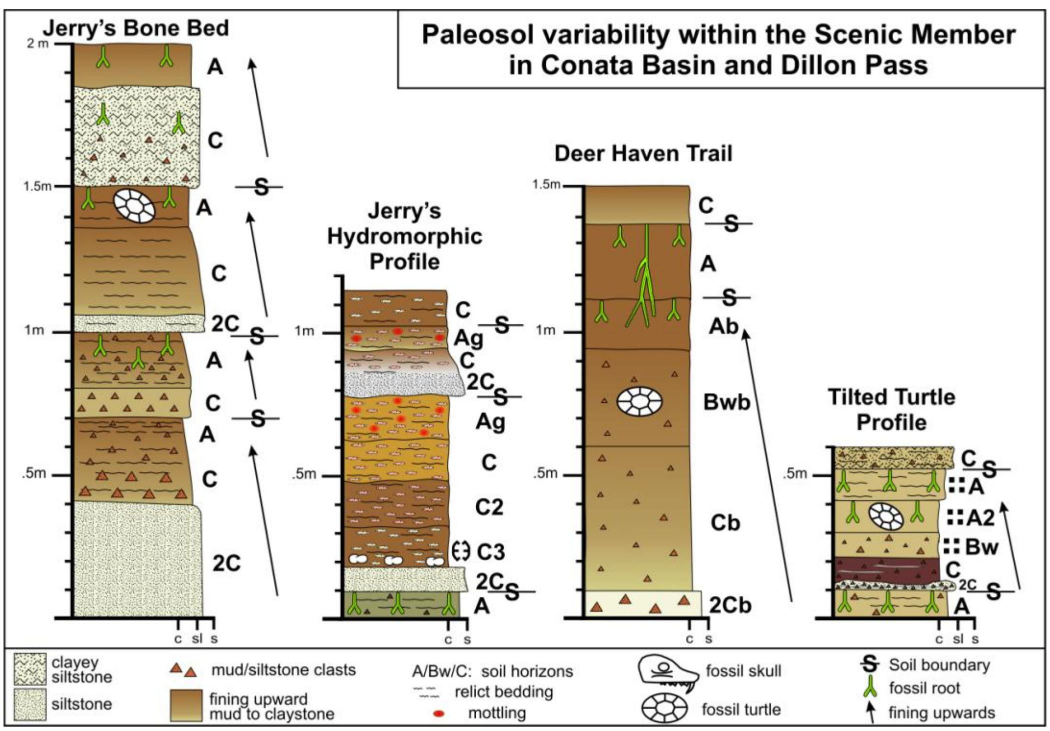

Figure 8. Paleosols of Conata Basin and Dillon Pass. Paleosols reflect changes in paleogeomorphic position during deposition of the Scenic Member.

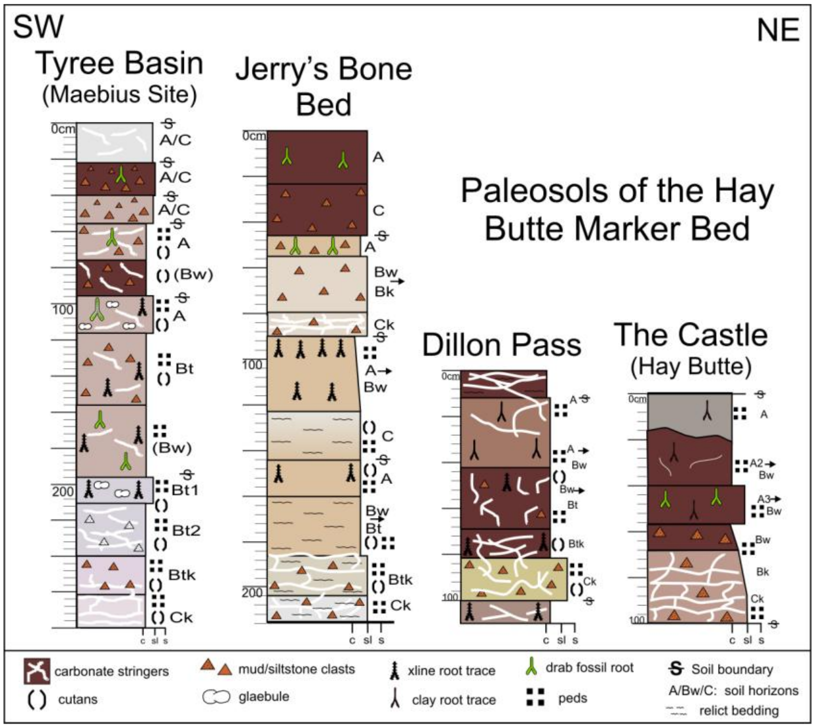

Figure 9. Paleosols of the *Hay Butte marker bed* in and near the Conata Basin of Badlands National Park. Figure modified from McCoy (2002).

Continue driving east on the Badlands Loop Road after this stop. Notice highway survey markers that now are concrete "toadstools" on the left side of the road that were originally set in the ground with concrete. These survey markers have now been exposed by erosion and the shrink-swell action of the Chadron claystone beds.

After passing through Dillon Pass, the **Conata Basin overlook** will be on your right, 0.7 miles past the Yellow Mounds overlook. This overlook provides an excellent view of the inclined layers on southern flank of the Sage Creek anticline. The fault that you see at Yellow Mounds overlook is just to the south of the Conata Basin overlook, and parallels the Badlands Loop Road for the next mile.

The **Homestead overlook** is the next overlook on the Badlands Loop Road, 1.7 miles beyond the Conata Basin overlook. It overlooks the greater Conata drainage basin to the west. The overlook is on rocks of the lower Poleslide Member on a hill that is capped by the Medicine Root gravels. The Medicine Root gravels are lag gravels that cap the higher hills and buttes in the area. The gravels are composed of igneous and metamorphic rocks fragments derived from the Black Hills, and represent post-Oligocene streams that flowed across the region prior to the capture of the east-flowing streams of the Black Hills by the Cheyenne River.

The next overlook is the **Burns Basin overlook** that is on the right side of the road 2.6 miles past the Homestead overlook. The Burns Basin overlook is situated on the basal siltstones of the Poleslide Member. The canyons below you are cut into the Middle and Upper Scenic, characterized by gray sandstones and buff mudstones, respectively. The canyon is also aligned along the axis of a syncline, the Burns Basin syncline that plunges to the southeast parallel to the major drainages below you. Structural contours drawn on the elevations of the *Hay Butte marker* indicate the axis of this syncline (Fig. 10).

The thickness of the lower Scenic rocks below the *Hay Butte marker* in the Burns Basin area vary much in the same way as they do south of the Pinnacles. In places there is a thick sequence of basal Scenic mudstones and sheet sandstones below the *Hay Butte marker*, and in other places the Hay Butte rests only upon the basal Scenic mudstones. This is because the Scenic Member buried a topographic ridge that extended southeast from the Pinnacles through the west side of the Burns Basin area, and through the large, flat-topped butte you can see to the south. This ancient ridge separated two large paleovalley-fills cut into the Chadron Formation, one west of the modern Hay Butte, and the other east of this overlook. Because this ancient ridge occurs on the east side of the modern Conata Basin, it is referred to it as the Conata Ridge. The Burns Basin syncline is located east of the axis of the Conata Ridge.

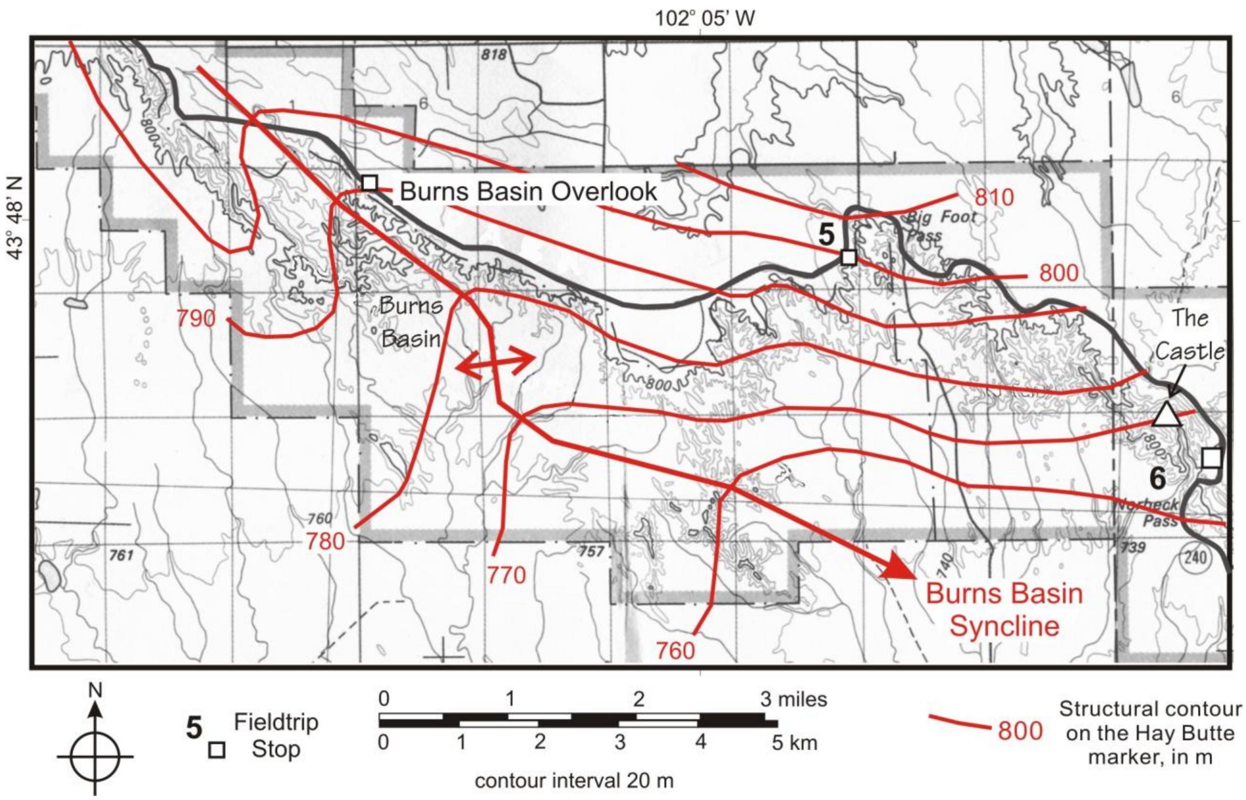

Figure 10. Folds in the area from Burns Basin to Norbeck Pass. Structural contours are on the elevations of the *Hay Butte marker*.

The **Prairie Wind overlook** is on the left side of the Badlands Loop Road, 2.7 miles past the Burns Basin Overlook. The road is on the prairie that is on top of the Badlands Wall. The Wall in this area is capped by thick clayey mudstones laced with thin stringers of limestone of the *disappointment limestone interval* in the upper Scenic.

The highway rises toward Panorama Point, which is Stop 5. Panorama Point is 9.1 miles beyond the Yellow Mounds overlook. Pull off on the right into the parking lot and walk to the overlook.
Stop 5 – Panorama Point. This overlook looks into a drainage that flows south from Big Foot Pass toward the White River. Despite the elevation, the observation deck is built upon middle Scenic rocks, just a few meters above the *Saddle Pass marker*. This position is relatively lower in the stratigraphic sequence from that at the Burns Basin overlook because we are far up the northeast flank of the Burns Basin syncline (Fig. 10) and because the Scenic Member increases its thickness. The total thickness of the Scenic Member below the top of the *Saddle Pass marker* in the basin below you is 49 m thick, as compared to the 25.6 m thickness of the same sequence in the Pinnacles. The reason for the nearly doubling of thicknesses here is because we have entered an early Oligocene paleovalley. The highland that existed in the Pinnacles area extended to the southeast toward the buttes that you see to the southwest (far left) from the observation platform. Presumably the paleovalley at Big Foot Pass also had a southeast trend that was parallel to the ancient ridge. However, the geometry of outcrops along the Badlands Wall exposes only a cross section through this paleovalley. The Scenic Member thicknesses remain high east from here.

This overlook used to be called the Banded Basin overlook, because of the prominent red stripes that occur in the light gray sandstones of the Middle Scenic. Except for the thick brown beds of the *Hay*

Butte and *Saddle Pass markers*, these red bands are typically mudstone or claystone beds that can be traced laterally for typically only a kilometer or less. The red beds represent thin, muddy overbank deposits in a remarkable sequence of sheet sandstone bodies. The color is derived partly from pedogenesis and partly from diagenetic alteration of iron silicate minerals to iron oxide minerals that accumulate in the mudrocks. The Hay Butte and Saddle Pass mudstone beds are unique, for they are very widespread and are not known to be cut by channel sandstones anywhere in the North Unit of the Park.

Turn out of the parking lot to the right and follow the Badlands Loop Road through Big Foot Pass. Big Foot was the leader of a band of 55 Minneconjou Lakota from the Standing Rock Reservation that passed through this gap in the Wall in December of 1890 on their way to Pine Ridge. A few days later, Big Foot and his people were killed in the Wounded Knee Massacre.

At the top of the ridge on the other side of the valley is the **Big Foot Pass Overlook**. This overlook with a picnic area is situated in the middle Scenic a few meters above the *Hay Butte marker*. This picnic area is 1.6 miles past Panorama Point. This picnic area has interpretive signs about Big Foot, his people, and his journey.

The next overlook is on the right side of the road, 0.7 miles past the Big Foot Pass Overlook. This is the **White River Valley Overlook** that is next to an intricate drainage forming maze-like canyons cutting into the Badland Wall. Stratigraphically the overlook is a few meters above the *Saddle Pass marker* in the upper middle Scenic. The high jagged rimmed butte to the east is The Castle. The next stop is 2.1 miles east of this overlook.

The highway approaches The Castle on its north side. This route provides the first good detailed view of the Poleslide Member (Fig. 11). The lower Poleslide Member here includes a basal siltstone (just above the level of the highway), a lower sandstone supporting the low rocky benches at the base of The Castle, a middle sequence composed primarily of buff to tan siltstones, an upper sandstone sequence, and an upper tan siltstone interval directly below the *persistent white layer*. The lower Poleslide rock units in this area are remarkably persistent with 12 stratigraphic intervals that can be traced to the east margin of the park. These 12 units also persist westward to high buttes 17 miles (27 km) to the west of The Castle. The *persistent white layer* lies on top of the tan lower Poleslide beds, and the *white layer* is capped by very light tan, massive siltstone beds of the upper Poleslide. The Castle is capped by the Sharps Channels that has its base marked by basal conglomerate ledges.

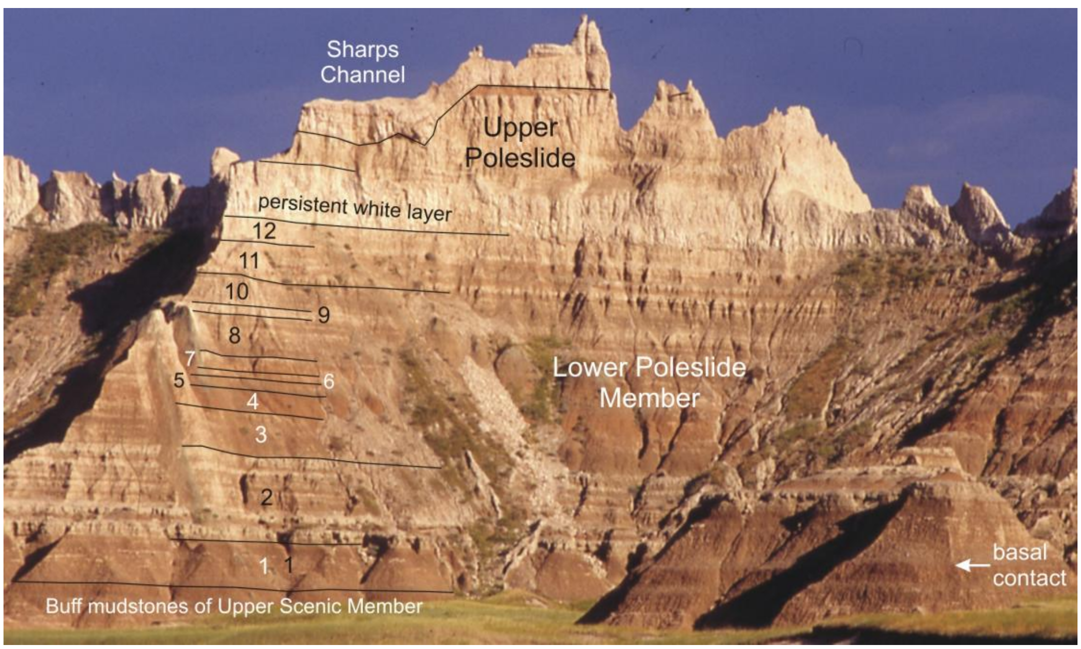

Figure 11. View of the northwest side of The Castle as seen from the Badlands Loop Road, showing the top of the Scenic Member, the units of the Poleslide Member, and the Sharps Formation. The numbered units of the lower Poleslide are described in Figure 21.

The massive siltstones of the Poleslide Member represent the settling of volcaniclastic dust as loess deposits. This is in contrast to the Scenic mudstones in which the volcaniclastic dust was transported by streams or weathered into clays. Such a shift from weathered and fluvially reworked dust to relatively unaltered loess deposits represent a shift from wetter climates (at least subhumid climates) to drier, semiarid climates, using the conditions of modern dryland loess accumulation as a model (Pye and Tsoar, 1987). The fossil vertebrates are also different in the two members. The Scenic vertebrate assemblages are dominated by the horse *Mesohippus* spp., whereas the Poleslide vertebrates are dominated by the extinct oreodonts , ruminant artiodactyls that resemble both pigs and sheep. Overall the Poleslide vertebrate fauna probably reflected the drier conditions during Poleslide deposition.

Stop 6 – Fossil Exhibit Trail. The fossil exhibit trail was developed in the 1960's with the intent to create an outdoor display of original fossil material in-situ. Fossils or replicas were placed in concrete cases that sit on the ground surface of the site. Exhibiting fossils in-situ, whether actual or as reproductions, has been problematic due to the vandalism of the cases, theft of the fossils and exposure of the plaster replicas to the elements. The National Park Service has developed plans to redesign the Fossil Exhibit Trail to expand beyond the casts under domes. Just west of the parking area, the site will include waysides which will explore the historic and contemporary viewpoints of people in the study of paleontology and a discussion on the significance of Badlands National Park to the science of paleontology. At each stop along the boardwalk, the plaster casts will be replaced by bronze sculptures and associated exhibits explaining the significance of the fossils, climate change and adaptation.

Because the Fossil Exhibit Trails lies close to the contact between the Scenic and Poleslide Members of the Brule Formation, it is one of the few areas to gain easy access to the Poleslide Member. In 2005, staff from Badlands National Park and researchers from three academic partners worked in this area documenting the extent and location of the fossil resources contained within the Poleslide Member. The field mapping teams documented the distribution, composition, stratigraphic position, and depositional setting of numerous fossil sites within select areas in the park. Five new paleontological localities were described from this phase of the paleontological survey.

The Fossil Exhibit Trail area is an ideal location to complete the study because it provides an interface between the public and abundant fossil resources. The fossil exhibit trail area is the second most heavily visited trail in the park. Even though the trail is now covered with a board walk, visitors are free to travel throughout the area. The trail itself is constructed on the lowest unit of the Poleslide Member. The area covered by the trail and in close proximity did not produce a lot of fossils. It was not until the survey crew continued about 100 yards to the south that a significant number of micro vertebrate sites were found. However, a paleontological pre-construction survey of the Fossil Exhibit Area, completed in August of 2006 did produce a significant number of micro vertebrate fossils that had been washed under the board walk. It was not until the board walk was physically removed that the fossils were exposed. Presumably, because the specimens were washed under the boardwalk, they were inaccessible to visitors. The following taxa were documented during the 2006 pre-construction survey: *Peltosaurus*, *Eumys*, *Ischyromys*, *Paleolagus*, *Megalagus*, *Hesperocyon*, *Leptomeryx*, and *Merycoidodon*.

The Fossil Trail is situated at the top of Norbeck Pass, and between the Castle and the tall butte to the east called Norbeck Ridge. The base of the Poleslide Member is just below the Fossil Trail, and is marked by the *Cactus Flats bentonite bed* (Stinchcomb et al., 2007). All 12 units of the lower Poleslide occur on The Castle and Norbeck Ridge. The Castle and Norbeck Ridge have small outcrops of the *persistent white layer* near their tops below the Sharps Channels. This white marker bed is cut by a paleovalley filled with Sharps sandstone beds that supports Norbeck Ridge. Just east of the Fossil Trail are Quaternary sod tables that have been described and interpreted by Burkhart et al. (2008).

Clastic dikes are common throughout the Scenic and Poleslide Members of the Brule Formation in the north Unit of Badlands National Park. Some dikes pinch out downward, whereas others preserve evidence of injection and fluid flow (Hamre and Whelan, 1996). The origin of the dikes is unclear, but possibilities include the dewatering of hydrated silica and injection along structurally defined planes, and passive infilling from above (Madison and Fischer, 2007; Shuster and Maher, 2009). Some dikes show evidence of multiple opening and filling, and many of the dikes show imbricated and crenulated fabrics.

Continue east on the Badlands Loop Road, over Norbeck Pass and down the Wall to the lower prairie. Just beyond Norbeck Pass, landslides can be seen on the left side of the road. The base of these landslides tend to move on the clayey mudstones of the *disappointment limestone interval* as groundwater filters down through the overlying siltstones and accumulates on the clay-rich rocks. The landslide debris typically includes buff mudstones of the upper Scenic, siltstones and sandstones of the Poleslide, and coarse sandstones and pebbly conglomerates of the Sharps Channels. This debris then flows over the Middle and Lower Scenic rocks, sometimes ending up at the base of the Badlands Wall.

The base of the Wall in this area is in the beds of the middle Scenic Member, and in this area these beds have been cut by a series of *en echelon* normal faults with the down side to the south. From below Norbeck Pass to the Ben Reifel Visitor Center the road is within rocks of the Scenic Member. Chadron rocks are exposed to the south in the vicinity of the town of Interior.
The first pull-out to the left past the Fossil Exhibits Trail is the bottom of the **Saddle Pass Trail**, 3.0 miles past the Fossil Exhibits Trail parking lot. The Saddle Pass trail is one of the few trails that climbs the Badlands Wall in this area, and though it is a short hike it is quite steep. It also crosses through most of the Scenic Member and ends in the lower 2 units of the lower Poleslide Member. Figure 12 is a stratigraphic column of the rocks seen along the Saddle Pass trail. This section includes the type locality of the *Saddle Pass marker*, situated about half-way up the trail.

The Badlands Loop Road continues east running along the base of the Wall to where it meets with State Highway 377 near the Cedar Pass Lodge, 4.7 miles past the Fossil Exhibit Trail. Keep to the left, continuing on State Highway 240 for an additional 0.3 mile and pull into the Ben Reifel Visitor Center, which is Stop 7.

Stop 7 – Ben Reifel Visitor Center. The spectacular ridge to the north and northeast of the visitor center (across the highway) is called Millard Ridge. It is capped by the sandstones of the Sharps Channels, and the *persistent white layer* is exposed as the ragged white band near the top of many of the spires. The highway climbs up the front of this ridge and reaches the top of the ridge at a gap called Cedar Pass. The *persistent white layer* occurs just above the road at Cedar Pass. This southern side of Millard Ridge also has many large landslides, several of which have caused problems in maintaining the highway.

The Park's visitor center is situated upon the upper Scenic *disappointment limestone interval* that can be seen in detail just to the east of the building. The *disappointment limestone interval* contains thin, light gray, limestone stringers within brown to greenish brown clayey mudstones. The limestone beds contain angular granules of mudstone that weather away on the surface of the limestone, giving the limestone a pitted surface. The carbonate stringers, mottles and abundant fossil roots (rhizoliths) and clay skins in cracks in the mudstones all indicate that the interval is a thick cumulic soil sequence. The intense weathering to form the thick soil complex probably removed all but a few trace fossils from the interval. The limestone beds are not lacustrine because they do not contain fossils of freshwater organisms, such as freshwater snails, ostracodes, or algal structures. The limestone beds are better indurated than are thin carbonate stringers in modern soils, indicating an addition of carbonate from groundwater long after the unit was buried.The Ben Reifel Visitor Center was remodeled in 2005 and has exhibits, a short video tour, a gift shop with maps and literature about the park, picnic tables, and restrooms.

Turn right out of the parking lot of the visitor center. The road rises on the edge of a huge landslide and bends left toward Cedar Pass. On the right side of the highway at 0.6 mile from the visitor center is the parking area for the **Cliff Shelf Nature Trail**. The junipers in this area are growing on the hummocky upper surface of a major landslide involving primarily Poleslide rocks. The side-slope slump at Cedar Pass retains enough moisture to support the growth of trees and shrubs. Rocky Mountain Juniper, (*Juniperus scopulorum*) is the most common evergreen tree in the park. Commonly referred to as "cedars" their abundance here has given Cedar Pass its name. Badlands National Park is within an area of transition between Rocky Mountain Juniper, which is the dominant species of juniper in the western United States and Eastern Red-cedar (*Juniperus virginiana*) the most common juniper species in the eastern part of the county. The two species hybridize and characteristics of both can be found at Cedar Pass (Milton J. Haar, Ecologist, Badlands National Park, written communication, 26 January 2010).

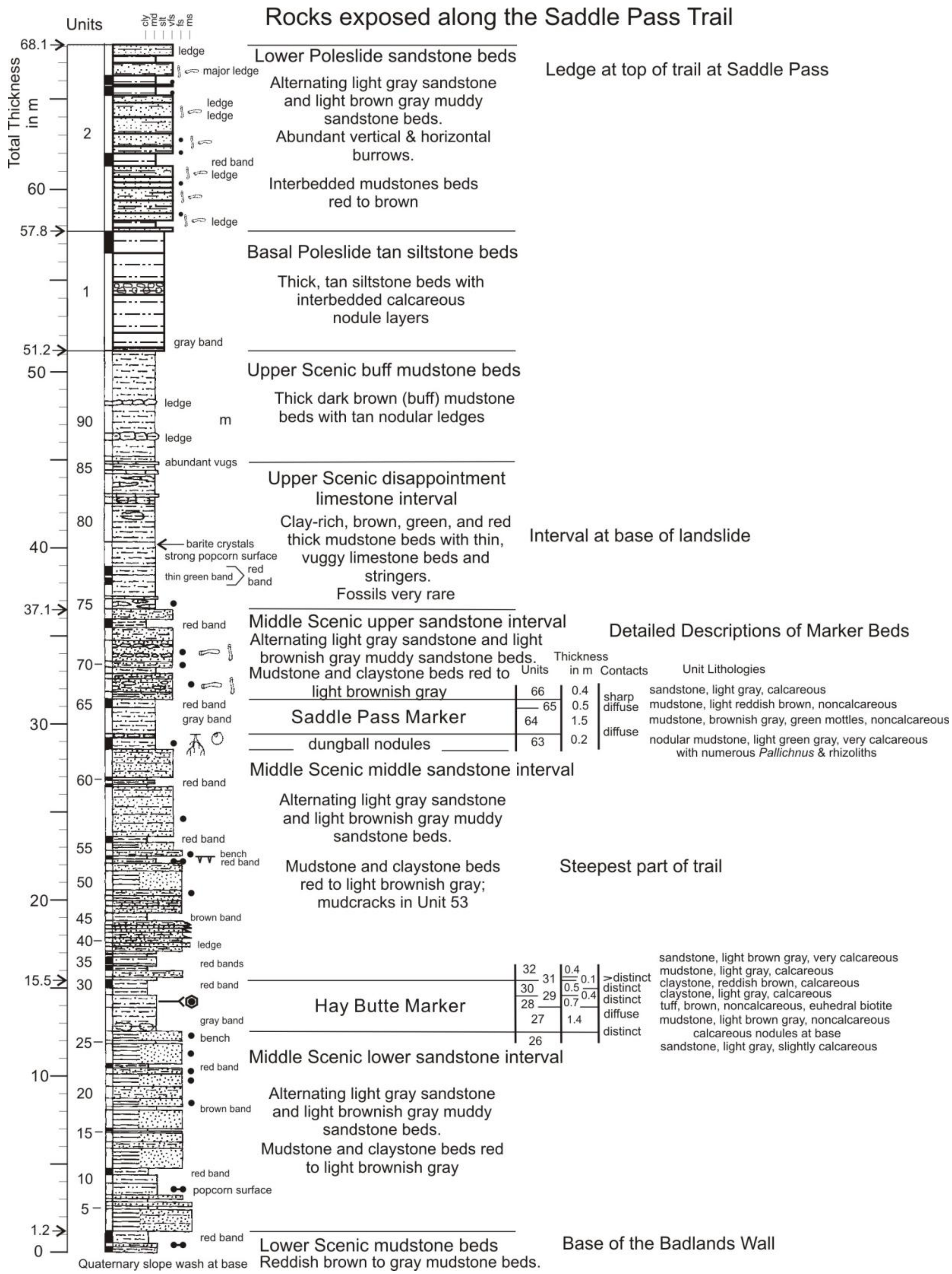

Figure 12. Graphic log of the middle Scenic Member through the lower Poleslide Member section along the Saddle Pass trail.

Continue driving on State Highway 240 for 0.4 miles through **Cedar Pass** across Millard Ridge. The *persistent white layer* in the middle of the Poleslide Member is well exposed just above the road at Cedar Pass. Just beyond Cedar Pass, the Old Northeast Road joins the highway on the left, 1.3 miles past the visitor center. Old Northeast Road is the along the area where Quaternary deposits were studied by Burkhart et al. (2008) and was a major area of focus for the Poleslide Project of Benton et al. (2009). Beyond this road junction, the highway swings to the right (east) through vertical outcrops of the lower Poleslide Member and toward the Door and Window Trailheads, 2.0 miles from the visitor center.

Stop 8 – Door and Window Trailhead. This is one of the best places in the park to see the rocks of the Poleslide Member. The overlook is situated in the middle Poleslide, between the lower and upper sandstone intervals. The wall to the east has numerous small gaps, or "windows" that overlook extensive badlands cut into the Scenic Member by Rake Creek, a tributary of the White River. The north side of the overlook has a walking trail that extends through a large gap, or "Door," onto a bedrock bench supported by the lower Poleslide sandstone interval. To the south the lower Poleslide tan siltstone beds are capped by the white persistent marker at the base of massive light gray massive siltstone beds of the upper Poleslide. The top of Millard Ridge to the south is capped by Sharps Channels. The lower Poleslide sequence along the Door and Window ridge is 49 m thick, the upper Poleslide is 32 m thick, and the Sharps Formation is 22 m thick.

Paleosols and sediments within the Poleslide Member at this locality reflect a combination of soil formation within vertically changing depositional environments (fluvial, lacustrine, and eolian), and relative periods of nondeposition and landscape stability vs. vertical accretion of eolian volcaniclastic sediments (Fig. 13). The thick siltstone unit at the base of the Poleslide was formed by the first widespread accumulation of loess over most of the North Unit. This siltstone unit is capped by a widespread silty sandstone sequence representing fluvial deposits. These in turn were overlain by a period characterized by wetter conditions as manifested by lacustrine deposits and laterally associated soils with hydromorphy and greater degrees of weathering. Loess deposits dominate the majority of the Poleslide above the brown mudstones, and appear as massive siltstone units punctuated with regionally extensive resistant bands which represent former longterm, stable landscapes. Fossils within aggrading eolian deposits appear to be randomly distributed, whereas fossils associated with periods of geomorphic stability are concentrated within resistant paleosol horizons. Paleosols associated with this environment are weak at best and show evidence of hydromorphy. From a facies/environmental perspective, these strata represent a period of landscape stability. Carbonate-dominated lakes form in response to low siliciclastic input, which suggests either that this lake was set far away from an active channel system, and/or that eolian influx was minor. Based on the carbonate rich nature of this lake, it is likely that it was spring-fed, similar to the lacustrine environments and tufas described from the lower part of the section within the Chamberlain Pass Formation and at the Chadron/Brule Formation boundary (Evans and Terry, 1994; Evans and Welzenbach, 1998; Evans, 1998, 1999).

The Door and Window Trailhead is one of the most heavily visited areas in the park. This area was part of a three year study conducted by the National Park Service and three other cooperating institutions to study the Poleslide Member outcrops in the Park. The Door and Window Trailhead provided valuable information on the impact of heavy visitor use area on fossil-rich deposits. The trail system is often the first stop for major tour buses traveling through the park. The development of board walks along the Door and Window trails has channeled visitor traffic to some degree, but due to the lack of signage and abundance of social trails, this area is still heavily impacted. Even though the Middle Poleslide Member outcrops throughout the Door and Window trail system, very few fossils were found in this area. As the survey participants traveled beyond the high traffic areas, fossils were found again in greater accumulations. Once the trail system was created many years ago, fossils were quickly picked clean from the area. This supports the concept that heavily traveled areas are significantly more susceptible to the theft of vertebrate fossils.

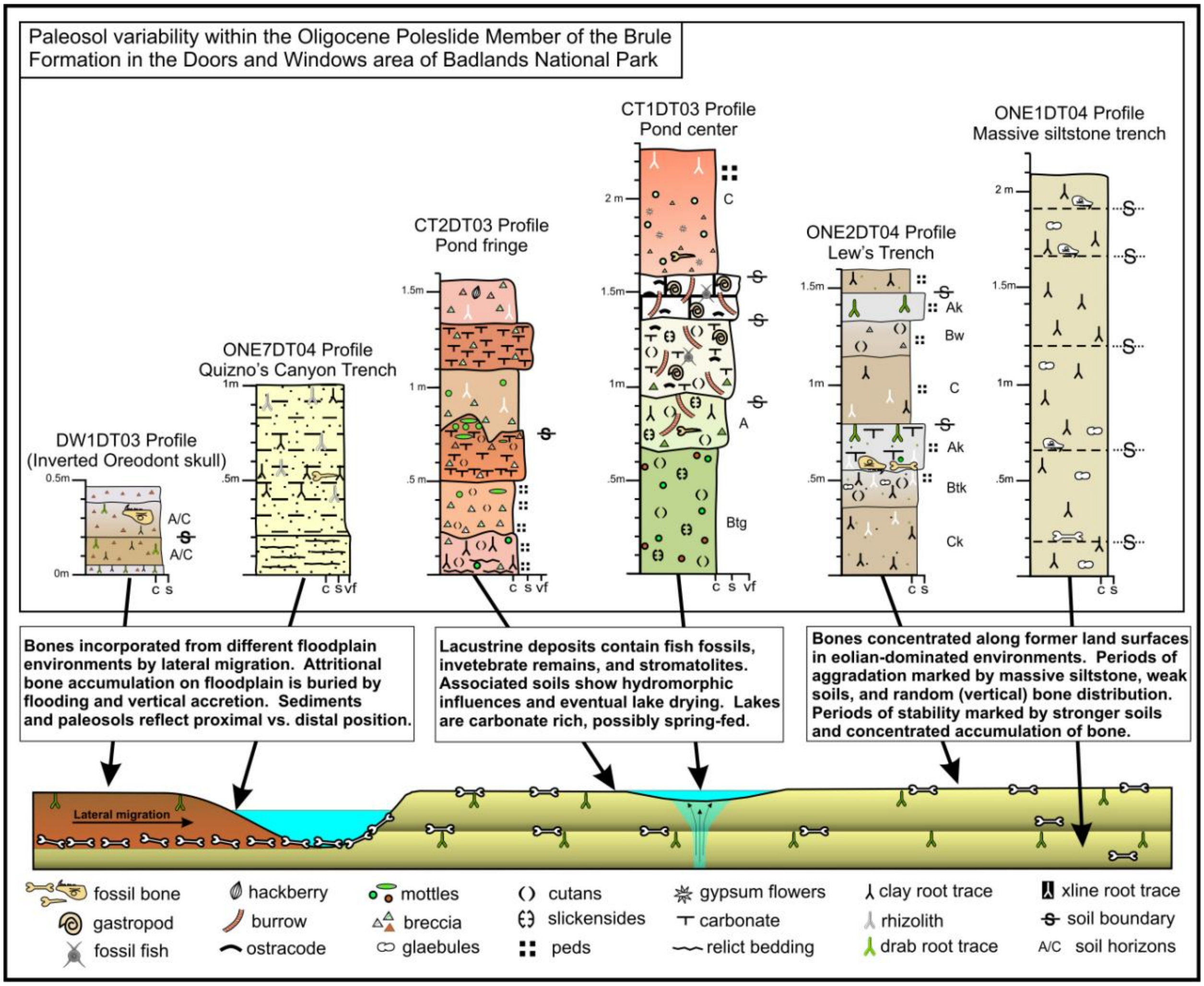

Figure 13. Common depositional environments, paleosols, and associated fossils within the Poleslide Member.

Turn right out of the parking lot and continue north on the highway. The road crosses the upper prairie and comes to the **Big Badlands overlook** 2.2 miles from Doors and Windows. The overlook is just above the *Saddle Pass marker*, and the badlands below the overlook are cut into a very thick sequence of lower to middle Scenic rocks. The Scenic Member in the basin below you has a total thickness of 73 meters, which is the thickest Scenic sequence in the North Unit. The gray claystone hills of the Chadron Formation can be seen in the bottom of the valley. The Northeast Entrance to the park is 0.2 mile past the Big Badlands Overlook, and the highway continues for 3.2 miles past the entrance station to the small community of Cactus Flats that contains the Minuteman Missile National Historic Site headquarters, a gas station, and a restaurant. Interstate 90 is 0.6 miles north of Cactus Flats and Wall is 20.2 miles west of the intersection of State Highway 240 and I-90.

DAY 2, THE SAGE CREEK ROAD, OLD CHAMBERLAIN PASS, SCENIC, AND SHEEP MOUNTAIN TABLE.

Drive south on State Highway 240 from Wall to the Pinnacles Entrance Station in Badlands National Park (Fig. 1). Your park permit that you purchased yesterday should allow you access to the park. Continue on for 0.6 miles to the junction of the Sage Creek Road on the right. Turn right onto the well-graded gravel road that travels on the Sage Creek Rim. The Rim is where the northeastern prairies meet the badlands of the Sage Creek drainage basin. It is a good place to see bighorn sheep and *Bison*. Two overlooks occur upon the Rim. The first is Hay Butte overlook, 1.0 miles from the start of the Sage Creek road, and the second is the Badlands Wilderness overlook, 0.6 miles beyond the Hay Butte overlook. Both overlooks have excellent views of the badlands along the east fork of Sage Creek. Isolated buffalo bulls can often be seen in the grassy areas in the valley of Sage Creek. The Sage Creek Rim is parallel to the axis of the Sage Creek anticline. Since the anticline here plunges to the southeast, the road intersects older and older rocks of the White River. Most of the rim is on the Scenic Member. The road turns to the left (west) and at 4.5 miles from the start of the road is the pull out for the Roberts Prairie Dog town on the right. Please feel free to watch the prairie dogs from the overlook (or better yet your car), but don't approach them for they carry fleas that are known to be infected with bubonic plague. The area around the Roberts Prairie Dog Town has ventifacts, or large gravel clasts that have been cut and polished by sediment transported by the wind. Burkhart et al. (2008) discuss dating techniques used on these ventifacts to determine the age of the upper prairies.

Stop 9 - Sage Creek Basin Overlook. 1.4 miles beyond the Roberts Prairie Town is the Sage Creek Basin overlook on the left side of the road. This is the main trailhead to the Sage Creek Wilderness, and provides a spectacular view of the north sides of Hay Butte and the Badlands Wall. To the left are the Pinnacles along the Sage Creek Arch. In the middle is the north side of Hay Butte. To the left of Hay Butte is a jagged ridge of badlands that represents the Badlands Wall. The four highest buttes along the Wall are capped by Sharps conglomerate beds overlying most of the Poleslide Member. The two largest flat-topped buttes to the southwest are the Wanless Buttes, named for Harold Wanless who first described the White River sequence exposed on them in 1923.

The overlook is situated essentially on the contact between the base of the White River Group and the underlying Fox Hills Sandstone. As you look out toward Hay Butte, notice that it appears to sit lower in the topography than we do at our present stop. We are on the southwest dipping limb of the Sage Creek Anticline. To the southeast (left) the landscape is stair-stepped and marked by repetitive packages of the Chadron, Chamberlain Pass, and Fox Hills Formations bounded by normal faults that are all down-dropped to the southwest. We are also very close to the southernmost edge of the deltaic Fox Hills Formation in this region. The Fox Hills Formation disappears towards Hay Butte, and the Chamberlain Pass Formation rests unconformably on the late Cretaceous Pierre Shale, which was also modified by the Yellow Mounds paleo-weathering event. Approximately 500 m to the southwest, the same zone of severe soft sediment disruption in the Fox Hills Formation that we saw in Dillon Pass is also preserved here, although it is only 1m thick at this location.

Continue driving west on the Sage Creek road, past the road north to Wall, and eventually down the slope toward Sage Creek. The road winds among grass-covered hills near the basal contact of the White River Group. *Bison* like to graze in the hills along this stretch of the road. At 3.8 miles past the Sage Creek Basin overlook, park the cars along the road and walk onto the gravel-capped small hills just southeast (left) of the road. The small hills are located at 43° 54.691' N and 102° 24.067' W (WGS84).

Stop 10 - Basal Gravels of the White River Group. The gravels on these small hills occur at the base of the White River Group, within the Chamberlain Pass Formation. Notice the odd composition of these pebbles. Essentially all of the pebbles are composed of some sort of quartz, such as massive quartz, chert, or quartzite. They are mostly stained orangish-brown, but the cherts can be black or red. They are also well rounded and well polished. The quartz pebbles are derived from pegmatites. Some of the chert pebbles contain Paleozoic fossils derived from such units as the Mississippian Pahasapa Limestone. These gravels also can contain Fairburn Agates, multicolored cherts with intricate thin bands that are derived from nodular chert masses in the limestone beds of the Minnelusa Formation. All three of these lithologies suggest a source in the Black Hills.

The Chamberlain Pass gravels were transported from the Black Hills by east-flowing Eocene streams, but the gravels became so highly weathered that essentially all of the non-quartz-clasts were destroyed. The basal contact of the Chamberlain Pass Formation with the underlying Cretaceous rocks was erosional and is undulatory. These gravels blanket the hill slopes and ridges of this buried topography, suggesting that the gravel is a lag, remaining on the land surface during slow erosion of the soft underlying Cretaceous rocks. Many workers place the base of the White River Group at the base of the Interior paleosol. However, these gravels occur at the top of the paleosol, and represent a gravel lag on the old ground surface. The base of these quartz-rich gravel deposits marks the unconformity at the base of the White River Group. Finally, similar gravels occur throughout the western Great Plains, occurring in northwest Nebraska and northeast Colorado always between the White River sequence and the underlying Cretaceous rocks. The quartz-rich gravels of the basal White River sequence indicate a large area that 1) received gravel from the western mountains, 2) were highly weathered during the warm and wet conditions of the perhaps the early to middle Eocene, and 3) remained as a highly resistant gravel-lag during the slow erosion of the Cretaceous rocks in the region toward the end of the Eocene.

Throughout the Badlands region, these same gravels can be found in association with bright white sandstone channels of the Chamberlain Pass Formation. The white color is due to the intense weathering of these sandstones which resulted in the conversion of a once feldspathic sand into kaolinitic sandstone. This entire assemblage of the Interior Paleosol, white channel sandstones, and basal lags represent different facies of the Chamberlain Pass Formation. Although quite thin as formations go, when put into a regional and geomorphic context, the Chamberlain Pass Formation represents the oldest phase of terrestrial deposition preserved in this region following the retreat of the Western Interior Seaway. Following its deposition, the Chamberlain Pass Formation was subjected to an extreme period weathering when rivers across the region incised (possibly due to tectonic activity in the Black Hills), leaving the Chamberlain Pass Formation preserved only in the uplands (Fig. 14). This upland was cut by large valleys filled with Chadron Formation deposits that are in contact with unweathered Cretaceous rocks.

Continue driving along the Sage Creek Road to where the road crosses Sage Creek, 1.1 miles beyond Stop 10. Park along the road just beyond the bridge (43° 54.615' N, 102° 24.843' N, WGS84). *Bison* are also commonly seen in this area. **Do not get out of the car if *Bison* are standing near this spot!** Buffalo are not the docile animals they appear to be. **Stop 11 - Quaternary Deposits Along Sage Creek.** To the north of the road is an excellent cut in Quaternary deposits showing alluvium derived from the White River Group interbedded with colluvium derived from the Pierre Shale, exposed on the right (northeast) side of the valley. Looking up the ridges to the east, you can see old gullies cut into the Pierre Shale and filled with Pierre debris. Such buried gullies have little or no surface expression. The Pierre Shale is composed of black shales deposited in the Cretaceous Western Interior Seaway prior to deposition of the Fox Hills Formation.

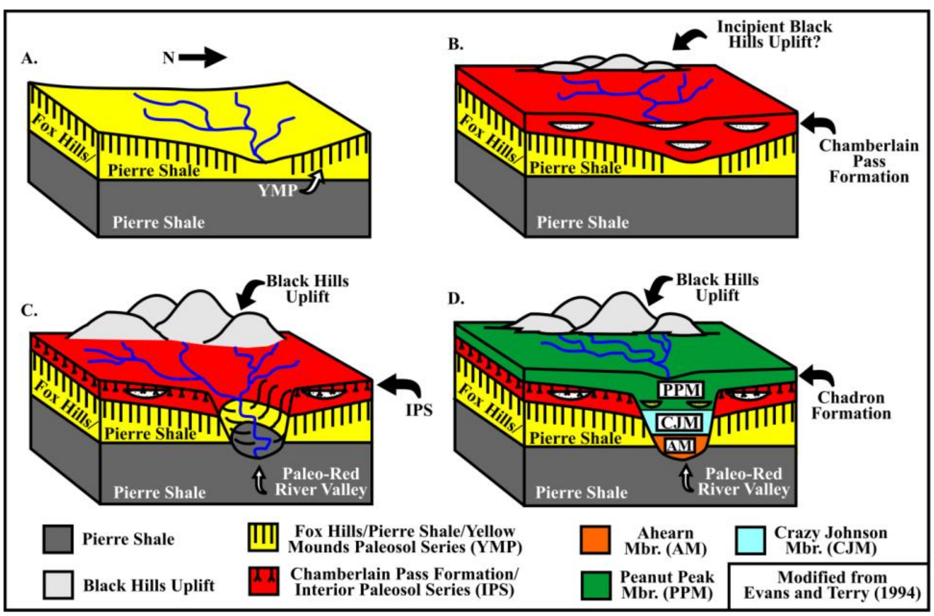

Figure 14. Development of the Yellow Mounds and Interior paleosols and deposition of the Chamberlain Pass and Chadron Formations. A. Retreat of the Western Interior Seaway and pedogenic modification of Late Cretaceous deposits to form the Yellow Mounds Paleosol of Retallack (1983). B. Deposition of the Chamberlain Pass Formation and incipient uplift of the Black Hills. C. Downcutting of river systems flowing east from the rising Black Hills and subsequent intense pedogenesis to form the Interior Paleosol of Retallack (1983). D. Backfilling of paleovalleys with the three members of the Chadron Formation. Figure modified from Evans and Terry (1994).

Continue driving on the Sage Creek Road to where it ends on South Dakota State Highway 44, 14.0 miles beyond the Sage Creek bridge. The road climbs first out of the park on Quinn Table, and then eventually crosses onto 71 Table. There are some spectacular views of the Badlands Wall including the Wanless Buttes from the south end of Quinn Table. The road will drop off into the Scenic Basin at the head of Bear Creek.

By crossing over 71 Table, you enter the Scenic Basin named for the town of Scenic in the center of the valley. The basin is the wide valley formed by the merged headwaters of Bear Creek and Spring Draw. Both Bear Creek and Spring Draw flow northward into the Cheyenne River. The Sage Creek road drops down to the headwaters of Bear Creek off of 71 Table. To the southwest is the large high mesa called Sheep Mountain Table and the Badlands Wall breaks down to a series of isolated buttes on the south side of the valley.

Fur trappers had traveled through the Badlands along the White River starting in the 1820's, and the first described fossil from the Badlands (a brontothere jaw identified by Prout, 1846, as a *Palaeotherium*) was collected by a trapper of the American Fur Company. However, the Scenic Basin was the entrance to the Badlands for the first scientific expeditions to the area. Starting at Fort Pierre, the expeditions traveled up the Teton River (now known as the Bad River), crossed over the divide to the Cheyenne River, came up Bear Creek, and went south to the White River. This is the route of the first expedition led by John Evans in 1849 as a part of the geographic and geologic survey of Wisconsin, Iowa, Minnesota, and a portion of Nebraska Territory. A small but important collection of vertebrate fossils were collected during this survey, and the fossils were sent to Dr. Joseph Leidy of the Philadelphia Academy of Sciences. Leidy eventually published two monographs of the White River fossil vertebrate fauna, the first in 1854 and the second in 1869. This route was also followed by Fielding B. Meek and Ferdinand V. Hayden in 1853. This was the first trip to the west by Hayden, who returned to the area several times in the 1850's and in 1866. Meek and Hayden defined the White River Series in 1857, and the geology of the White River Group was later discussed by Jacob Wortman (1893) and John Bell Hatcher (1893 and 1902) from their work around Sheep Mountain Table. In 1910, the Chicago, Milwaukee, St. Paul and Pacific railroad was built across Chamberlain Pass providing easy access to the towns of Interior and Scenic. Most of the geologic studies of the White River in the early twentieth century were made near these towns, by such workers as William Sinclair (1921), Freeman Ward (1922), and Harold R. Wanless (1922 and 1923), and John Clark (1937).

Turn left onto State Highway 44. Drive 3.8 miles into Badlands National Park, and park on the right side in a small pull-off just to the west of a small hill (43° 44.669' N, 102° 29.291' W, WGS84). Climb this hill to get to Stop 12.

Stop 12 – Old Chamberlain Pass. From the top of this hill you can see a butte to the north and another flat-topped butte to the west. The butte to the west is called Heck Table. The low pass between the two buttes is called Chamberlain Pass on older maps. This pass separates the headwaters of Cain Creek on the south from the Bear Creek drainage to the north. To the east is a long flat-topped table called the Imlay Table for a small abandoned railroad town on its south side. The Kudrna Ranch is between us and Imlay Table, so this large drainage basin to the east and north of us is called the Kudrna Basin. Aeolian dunes occur on top of Imlay Table that have been described by Burkhart et al. (2008).

The Chadron Formation in the Kudrna Basin contains a sequence of gray to brown claystone and sandstone beds that are part of the Crazy Johnson Member of the Chadron Formation. These rocks contain the huge bones of the brontotheres. Brontotheres were related to modern horses and rhinoceros' and were the size of small elephants. All brontotheres became extinct near the Eocene/Oligocene boundary, and are essentially the characteristic mammal fossil of the late Eocene in the White River. Smaller vertebrates are also locally abundant in these rocks. Minkler (2007) described a diverse fauna of vertebrates from the Kudrna Basin outside the park boundary approximately 4 kilometers from this stop and within Peanut Peak claystone beds 16 m below the Chadron/Brule contact. The fauna includes (Table 1) freshwater mollusks, fish, a frog, turtles, lizards, snakes, an alligator, several birds, two marsupials, an insectivore, a dog, a rabbit, rodents, rhinoceros, horses, entelodonts, camels, oreodonts, and a "small deer" (leptomerycid). The fauna included the first documented snake from the Chadron Formation of South Dakota; early occurrences of the lizard *Peltosaurus* sp.; an insectivore (*Micropterodus* sp.) previously known only from Saskatchewan, Montana, and Nebraska; abundant eomyid rodents including *Metanoiamys* previously only known from the middle Eocene Duchesnian faunas; the occurrence of a florentiamid rodent *Ecclesimus* previously known only from Orellan rocks of

Colorado; and the first occurrence of the mouse *Eumys* sp. from the Chadron of South Dakota. Statistical comparisons of the fauna with other Chadronian and Orellan faunas of the Great Plains and Rocky Mountains (Table 2) show affinities with both Chadronian and younger Orellan faunas. The fauna may be late in the Chadronian Land Mammal Age, near the boundary with the Orellan Land Mammal Age. The similarity of this latest Eocene (Chadronian) vertebrate assemblage with those of the earliest Oligocene (Orellan) faunas indicates the Eocene/Oligocene was not a time of major faunal turnover in the Badlands. Minkler's study illustrates that new information can be gained from research of the White River vertebrate fauna in the Badlands, despite 160 years of study on these fossils.

The Scenic Member here has a similar thickness to the Scenic Member at the Bigfoot Pass and Big Badlands overlooks on the east side of the park. Here at Chamberlain Pass the lower part of the Scenic is much thicker because this area was within a broad paleovalley west of the Conata Ridge. Paleosols of the lower Scenic in this area are very weakly to weakly developed and represent minimal soil development on successive overbank deposits that aggraded very quickly (Fig. 15). Vertebrate fossils associated with these deposits are commonly articulated, suggesting that these deposits represent catastrophic flooding events (Fig. 16).

The upper Scenic in the Kudrna Basin is thinner than in the eastern side of the park because of a facies change from the upper Scenic mudstone beds in the east to the tan siltstones of the basal Poleslide here in the west. In this area, the top of the Scenic Member is the distinct gray band found in the upper part of the large flat top buttes to the north and to the west. This band is the *Heck Table marker*, a prominent gray mudstone that is named for the large flat-topped butte to the west. Below the Heck Table marker are mudstones of the Scenic Member. Above this marker are siltstones of the Poleslide Member. The Heck Table marker pinches out on the northeast side of Imlay Table, at the stratigraphic level of the top of the *disappointment limestone interval*. Thus, the basal tan siltstone beds of the Poleslide Member in this area change into the buff mudstones of the upper Scenic farther to the east. The basal Poleslide siltstones are easily seen near the top of the two flat-topped buttes north and west of here, because the drainage density is much higher on these siltstones. Basal Poleslide siltstone beds are intricately gullied unlike the mudstones in the upper Scenic Member. The *Hay Butte marker* is a thick brown band in the middle of the butte to the north. The *Saddle Pass marker* has thinned to the west, so, in this area, it becomes a thin brown persistent band just below the highest light gray sandstone band in the butte to the north.

TABLE 1. UPPER EOCENE FOSSIL TAXA FROM THE PEANUT PEAK MEMBER, CHADRON FORMATION, KUDRNA BASIN, SOUTH DAKOTA (FROM MINKLER, 2007).

- PHYLUM MOLLUSCA
  - Class Gastropoda
  - Class Bivalvia
- PHYLUM CHORDATA
- Class Actinopterygii
  - Amiidae? gen. *et* sp. indet.
  - Ictaluridae gen *et* sp. indet.
- Class Amphibia
  - Pelobatidae? gen. *et* sp. indet.
- Class Reptilia
  - Order Testudines
    - Trionychidae gen. *et* sp. indet.
    - cf. *Echmatemys* sp. indet.
    - *Stylemys nebrascensis*
    - *Chrysemys antiqua*
    - *Pseudograptemys inornata*
  - Order Squamata
    - *Aciprion formosum*
    - *Peltosaurus* sp. indet.
    - cf. *Ogmophis* sp. indet.
    - cf. *Boavus* sp. indet.
  - Order Crocodylia
    - *Alligator prenasalis*
- Class Aves
- Class Mammalia
  - Order Didelphimorphia
    - *Herpetotherium* valens
    - *Nanodelphys* sp. indet.
  - Order Soricomorpha
    - *Micropternodus* sp. indet.
  - Order Carnivora
    - *Hesperocyon* sp. indet.
  - Order Lagomorpha
    - *Megalagus brachyodon*
  - Order Rodentia
    - cf. *Protosciurus* sp. indet.
    - cf. *Metanoiamys* sp. indet.
    - *Adjidaumo minimus*
    - *Paradjidaumo trilophus*
    - cf. *Eumys* sp. indet.
    - *Heliscomys ostranderi*
    - *Ecclesimus tenuiceps*
    - cf. *Agnotocastor* sp. indet.
- Order Perissodactyla
    - *Hyracodon* sp. indet.
    - *Subhyracodon* sp. indet.
    - *Mesohippus bairdi*
    - *Mesohippus exoletus*
  - Order Artiodactyla
    - Leptochoeridae gen. et sp. indet.
    - *Archaeotherium* sp. indet.
    - *Poebrotherium* sp. indet.
    - *Merycoidodon* sp. cf. *M. culbertsoni*
    - *Leptomeryx speciosus*

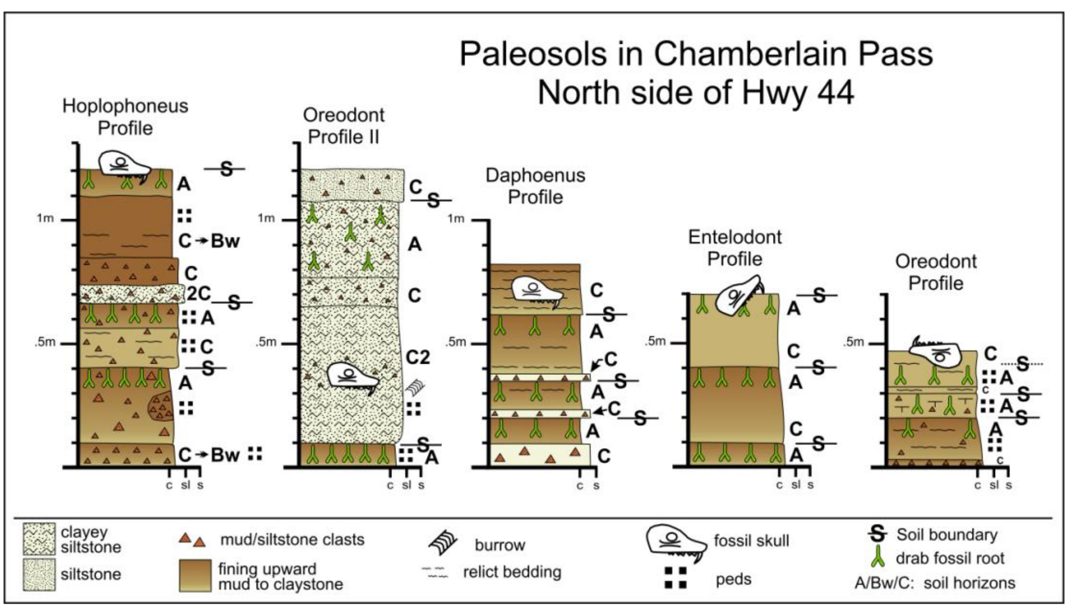

Figure 15. Paleosols of the Scenic Member at Chamberlain Pass. Note the lack of development.

TABLE 2. NUMERIC COMPARISON BETWEEN THE KUDRNA BASIN CHADRON FAUNA WITH OTHER CHADRONIAN AND ORELLAN FAUNAS IN THE WESTERN INTERIOR. AFTER MINKLER, 2007.

	Chadronian Paleofaunas									Orellan Paleofaunas				
							Big Badlands, South Dakota				Nebr.			
							Chadron Formation			Brule Fm.	Brule Fm.		Montana	
	Kudrna Basin	Raben Ranch	Yoder	Flagstaff Rim	Pipestone Springs	Calf Creek	Ahern Member	Crazy Johnson	Peanut Peak	Scenic Member	Orella Member	Fossil Bush	Matador Ranch	Cook Ranch
Total # of Families	30	36	21	48	34	56	25	24	33	37	33	16	13	19
# in common with Kudrna	30	18	12	22	15	24	14	12	19	22	18	10	10	13
100 C/N_1	-	60%	57%	73%	50%	80%	56%	50%	63%	73%	60%	63%	77%	68%
Total # of Genera	29	47	26	65	53	79	26	28	40	47	52	19	16	28
# in common with Kudrna	29	15	8	15	12	15	10	8	17	15	17	9	9	13
100 C/N_1	-	52%	31%	52%	41%	52%	38%	29%	59%	52%	59%	47%	56%	46%
Total # of Species	15	32	24	60	59	66	24	23	30	56	68	13	13	19
# in common with Kudrna	15	3	3	6	6	6	4	4	6	6	6	1	0	1
100 C/N_1	-	20%	20%	40%	40%	40%	27%	27%	40%	40%	40%	8%	0%	7%

During the three year paleontological survey of the Scenic Member (Benton et al. 2006), few fossils were observed and/or recovered near Highway 44, as can be expected. Many tourists stop along this road and examine the sediments flanking both sides of the highway. It is believed that specimens were probably illegally collected from this area. In fact, members of this survey crew caught fossil collectors in the act. The bright yellow coloration of the bones near the Chadron/Brule contact may indicate that some of the mammal fossils are enriched with diagenetic uranium. This could be due to the close proximity to a former channel or a clastic/chalcedony dike. With the exception of the lowermost specimens collected near the Chadron/Brule contact, the remainder of the fossils was found in a typical red/green variegated mudstone beds.

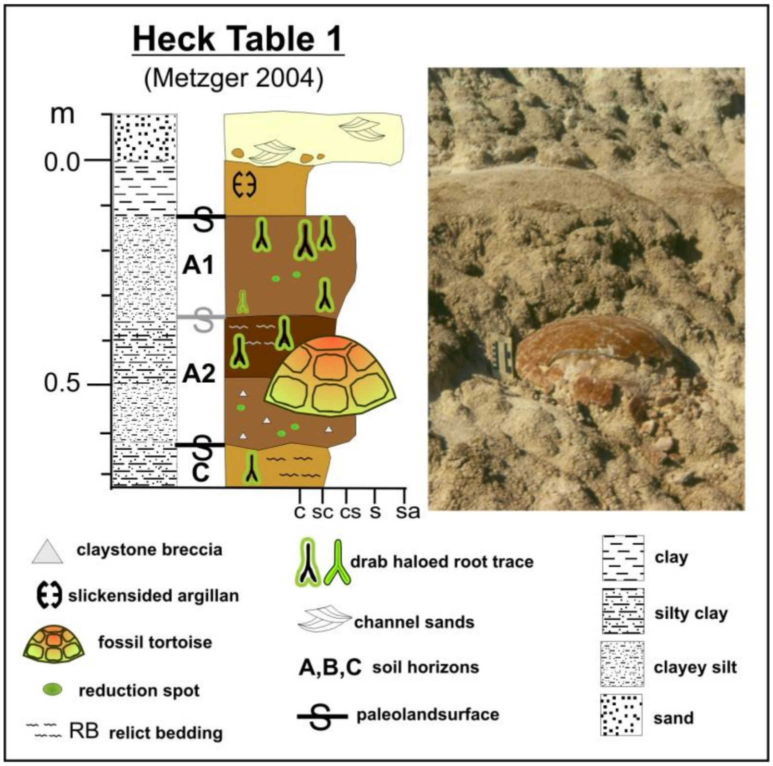

Figure 16. Detailed relationship of vertebrate taphonomy, sedimentology, and paleopedology at Chamberlain Pass. This tortoise was buried by a flooding event which in turn was pedogenically modified. Scale bar in inches and centimeters. Figure modified from Metzger et al.(2004).

Turn left towards Scenic on State Highway 44 and drive to the first road junction to Scenic. This road is a wide gravel road that can be rutted after rains. Drive into the town of Scenic until you join the main paved road near the center of town. Turn left on this paved road (Pennington County Road 589, called Bombing Range Road) and drive 1.9 miles past the left turn in Scenic to a narrow pull-out on the west side of the road (~ 43° 45.064' N, 102° 32.829' W, WGS84).

Stop 13 - The Type Section of the Scenic Member. The Scenic and Poleslide Members of the Brule Formation were named by James D. Bump of the South Dakota School of Mines and Technology in 1956. The type section for the Poleslide Member is on the south side of Sheep Mountain Table. The type section of the Scenic Member is on the butte on the west side of the highway at this stop. The Scenic type section is 45.5 m thick and extends from the top of the gray claystone beds of the Chadron Formation exposed at the base of the butte, to the top of the prominent gray band (the *Heck Table marker*) near the top of the butte. A graphic log of this section is presented as Figure 17. This section is on the Buffalo Gap National Grasslands administered by the National Forest Service. As with the Park Service lands, fossil collecting without a permit on USFS land is prohibited.

Continue south on Pennington County road 589 crossing the boundary of Badlands National Park. Turn right (west) onto the Sheep Mountain Table access road at 2.1 miles past Stop 13. Sheep Mountain Table road is a wide gravel road that can be very slippery when wet - it is not advisable to travel on this road after a rain or snow storm. Drive 1.5 miles on the Sheep Mountain Table road to where the road curves to the left, and park the cars along the side of the road (43° 43.022' N, 102° 33.278' W, WGS84).

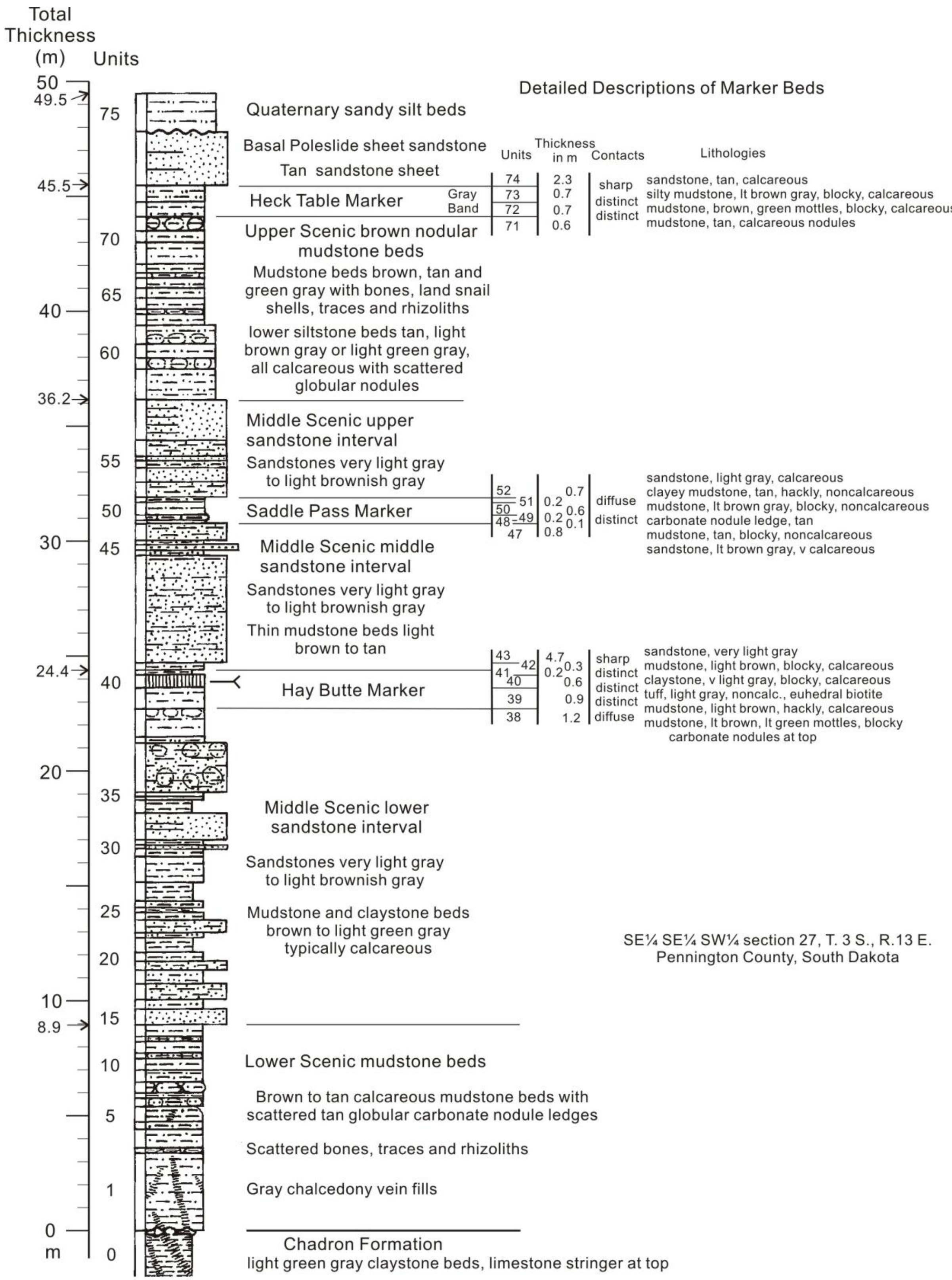

Figure 17. Graphic log of the type section of the Scenic Member.

Stop 14 - The Hay Butte Marker Tuff, the *Metamynodon* Channels, and Chalcedony Veins. The *Hay Butte marker* is well exposed in the badlands just north of the road. The marker bed contains a very distinct tuff averaging 0.6 m thick. The tuff is a gray mudstone that weathers to a light purplish gray with noticeable floating euhedral crystals of biotite, and smaller crystals of zircon, apatite, monazite and rare sphene. Monazite ($(Ce,La,Y,Th)PO_4$) is very rare in tuffs of the White River sequence. The only other two occurrences of this mineral in tuffs are at Douglas in central Wyoming and at Pawnee Buttes in northeastern Colorado. Both of these tuffs are in middle Orellan rocks, suggesting that all three areas contain the same tuff. Additional studies including radiometric dating of the monazite will test this correlation. The tuff in the Hay Butte is near its depositional edge, for the distinct gray bed becomes indistinct east of Chamberlain Pass. The rest of the *Hay Butte marker* is a series of stacked paleosols (see Stop 3, Day 1).

Distinct channel cuts and fills occur below the *Hay Butte marker* in this area. These channel-fills have been called the *Metamynodon* channels (Harksen and Macdonald, 1969) for they are supposed to contain the bones of the huge amynodont rhinoceras *Metamynodon*. However, the paleontologic survey of the Scenic Project in 2002 failed to find any fossil of this rhinoceros in this and other channel-fills in the area. Note the basal coarse bedload deposits and the upper mud-filled channel deposits. Mapping of these channel-fills show they have a sinuous pattern.

In and around this part of the Badlands, numerous chalcedony veins can be seen in erosional relief and armoring slopes. These veins are primarily hosted by the Chadron Formation, but extend slightly upward into the bottom of the Brule Formation. The veins are variable in thickness, ranging from several centimeters to paper-thin sheets and pinch out in all directions. The veins are most commonly dark blue, but varieties of yellowish green, light red, and clear can be found. When viewed over 10's of meters in area, some veins display a roughly polygonal pattern, but with evidence of shear and re-growth. Veins can also be composed of alternating mineralogies of chalcedony and gypsum. In some exposures the veins are ptygmatically folded in cross section. The origin of the veins is unclear, but possibilities include the dewatering of hydrated silica and hydrothermal/geothermal processes (Shuster and Maher, 2009). Chalcedony vein material was exploited by various indigenous cultures for projectile points.

Continue driving west on the Sheep Mountain Table road. The road will bend south and climb to the top of the Table. At the top, turn left on the unimproved dirt road that leads out to a turn-circle at the edge of a large valley. This is Stop 15.

Stop 15 - The Poleslide Member of Sheep Mountain Table. This is an excellent viewpoint to see the features of the Poleslide Member on the north side of Sheep Mountain Table. The Heck Table marker is at the bottom of the valley. The overlying lower Poleslide is a series of thick siltstone and silty sandstone sheets that are tan colored. There are more sandstone sheets on Sheep Mountain Table than in the eastern end of the North Unit, indicating that there were more active stream channels in the southwest. Near the top of the Table are the very light gray massive siltstone beds of the upper Poleslide Member. These siltstones contain numerous scattered carbonate nodules, typically arranged in vertical stacks. They represent groundwater-enhanced carbonate masses around carbonate encased roots of plants. The lower Poleslide sequence in this valley is 50.8 m thick and the upper Poleslide beds are 13.3 m thick. The *persistent white layer* of the eastern part of the Badlands Wall would occur at the transition between the lower and upper Poleslide beds, but is not present on Sheep Mountain Table.

Drive back to the Sheep Mountain Table road and turn left (south). Continue driving 1.1 miles to an overlook on the right side of the road. Turn into this overlook. Note that there are no guardrails at this overlook that is situated above a very high cliff – **take care not to walk too close to the edge of the cliff.**

Stop 16 - The Western Overlook at Sheep MountainTable. You are gazing into the valley of Indian Creek. The hills at the base of the west wall of Sheep Mountain Table are cut into the top of the Scenic Member. The entire west wall of Sheep Mountain Table is in rocks of the Poleslide Member. If the day is clear you can see the Black Hills at the skyline far to the west. High toward the south you can see a white band that is thought to be the Rockyford Ash. Unlike the *persistent white layer* of the east, this tuff contains a distinct minerals preserved as euhedral crystals. This mineral suite includes crystals of biotite, hornblende (abundant), zircon, apatite, and green clinopyroxene (E.E. Larson, written communication, 1997). There is a thin cap of very light gray sandy siltstone beds on top of the Rockyford Ash that are the basal beds of the Sharps Formation.

Looking east from the overlook, the broad grassy flat that caps Sheep Mountain gives an impression of what the Great Plains was like at the end of the Tertiary. This upper surface is not exactly an unaltered depositional surface, for it bevels the Sharps Formation, the Rockyford Ash, and finally the Poleslide Member from south to north. However, the Great Plains must have been remarkably flat prior to the deep erosion of Tertiary deposits forming the modern Badlands. The timing of downcutting of the Tertiary rocks in South Dakota is uncertain, but regional evidence in the Great Plains suggests that most of the erosion has been in the past 5 million years. This down-cutting continues today forming the remarkable Badlands.

Thick brown loess deposits occur on top of the Poleslide rocks at this overlook, and are called eolian-cliff-top deposits. These deposits, their ages and origin are described by Burkhart et al. (2008).

Stop 16 is the last stop in this guide. You can continue on southward on Sheep Mountain Table to the end of the road to see some spectacular scenery. However, you must use a high-clearance vehicle since the road south from the overlook is a single two-track dirt road. **Do not attempt to drive on this road if it is wet.** No tow truck will access this area under wet conditions. You can also turn around and return to Rapid City by retracing your route down the Sheep Mountain Table road, turning left on the paved Pennington County Road 589, and then turning left onto South Dakota State Highway 44 just past Scenic. The center of Rapid City is 51 miles from the Western Sheep Mountain Table overlook, and is approximately 1 hour of driving time if the weather is good and the roads are dry.

REFERENCES CITED

Benton, R.C., E. Evanoff, C.L. Herbel and D.O. Terry Jr., 2006, Baseline mapping of fossil bone beds at Badlands National Park, South Dakota: Natural Resources Preservation Program Grant Final Report, On file at Badlands National Park, 231 p.

Benton, R.C., E. Evanoff, C.L. Herbel and D.O. Terry Jr., 2009, Documentation of significant paleontological localities within the Poleslide Member, Brule Formation, Badlands National Park, South Dakota: Natural Resources Preservation Program Grant Final Report, On file at Badlands National Park, 69 p.

Burkhart, P.A., Rawling, J.E., III, Hanson, P.R., Mahan, S., Benton, R., Heffron, E., Jahn, M., Anderson, T., and Page, B., 2008, Late Pleistocene through Holocene landscape evolution of the White River Badlands, South Dakota, *in* Rayonolds, R.G., ed., Roaming the Rocky Mountains and Environs: Geological Society of America Field Guide 10, p. 235-248.

Bump, J.D., 1956, Geographic names for the members of the Brule Formation of the Big Badlands of South Dakota: American Journal of Science, v. 254, p. 429-432.

Chamberlain, J. A., Jr., Terry, D. O., Jr., Stoffer, P. W., and Becker, M. A., 2001, Fossils of the Cretaceous/Tertiary transition, Badlands region of South Dakota: Geological Society of America Abstracts with Programs, V. 33, no. 6, p. A-69.

Clark, J., 1937, The stratigraphy and paleontology of the Chadron Formation of the Big Badlands of South Dakota: Annals of the Carnegie Museum, v. 25, p. 429-432.

Evans, J., 1852, Incidental observations on the Missouri River and on the Mauvaises Terres (Badlands), *in* Owen, E.E., Report on the Geological Survey of Wisconsin, Iowa, and Minnesota and incidentally of a portion of Nebraska Territory: Philadelphia, Lippincott, Grambo and Co., p. 196-206.

Evans, J.E**.**, 1998. Facies associations of freshwater carbonates in the Eocene-Oligocene Chadron Formation, White River Group, Nebraska and South Dakota, *in* Pittman, J.K., and Carroll, A., eds., Modern and Ancient Lakes: Utah Geological Association, Guidebook 26: p. 209-231.

Evans, J.E., 1999. Recognition and implications of Eocene tufas and travertines in the Chadron Formation, White River Group, Badlands of South Dakota, U.S.A.: Sedimentology, v. 46, p. 771-789.

Evans, J. E. and Terry, D. O., Jr., 1994, The significance of incision and fluvial sedimentation in the basal White River Group (Eocene-Oligocene), Badlands of South Dakota, U.S.A: Sedimentary Geology, v. 90, p. 137-152.

Evans, J.E. and L.C. Welzenbach, 1998. Episodes of carbonate deposition in a siliciclastic-dominated fluvial sequence, Eocene-Oligocene White River Group, South Dakota and Nebraska, U.S.A. *in* Terry, D.O., Jr., LaGarry, H.E., and Hunt, R.M. Jr., eds., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America): Geological Society of America, Special Paper 325, p. 93-116.

Hamre, S. J. and Whelan, P. M., 1996, The origin of clastic dikes; evidence for upward injection of water-saturated sediment in Badlands National Park, South Dakota; Geological Society of America Abstracts with Programs, v. 28, no.6, pp. 42-43.

Harksen, J.C., 1974, Miocene channels in the Cedar Pass area, Jackson County, South Dakota: South Dakota Geological Survey, Report of Investigations no. 11, 10 p.

Harksen, J.C., and Macdonald, J.R., 1969, Guidebook to the major Cenozoic deposits of southwestern South Dakota: South Dakota Geological Survey, Guidebook 2, 103 p.

Hatcher, J.B., 1893, The Titanotherium beds: American Naturalist, v. 27, p. 204-221.

Hatcher, J.B., 1902, Origin of the Oligocene and Miocene deposits of the Great Plains: American Philosophical Society Proceedings, v. 41, p. 113-131.

Hayden, 1880, The Great West: its attractions and resources: Bloomington, Illinois, Charles R. Brodix, 528 p.

Jannett, P. A. and Terry, D. O. Jr., 2008, Stratigraphic expression of a regionally extensive impactite within the Latest Cretaceous Fox Hills Formation of southwest South Dakota, *in* Evans, K., Horton, J.W., Jr., King, D.T., Jr., and Morrow, J.R., The Sedimentary Record of Meteorite Impacts: Geological Society of America Special Paper 437, pp. 199-213.

LaGarry, H. E., LaGarry, L. A., and Terry, D. O., Jr., 1996, New vertebrate fauna from the base of the Chamberlain Pass Fm. (Eocene), Sioux County, Nebraska: Nebraska Academy of Sciences Proceedings, 106th Annual Meeting, Earth Science Section, p. 45.

Larson, E.E., and Evanoff, E., 1998, Tephrostratigraphy and sources of the tuffs of the White River sequence, in Terry, D.O., Jr., LaGarry, H.E., and Hunt, R.M., Jr., eds., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America): Geological Society of America Special Paper 325, p. 1-14.

Leidy, J., 1854, The ancient fauna of Nebraska: A description of remains of extinct Mammalia and Chelonia from the Mauvaises Terres of Nebraska: Smithsonian Contributions to Knowledge, 126 p., 25 plates.

Leidy, J., 1869, On the extinct Mammalian fauna of Dakota and Nebraska: Journal of the Academy of Natural Sciences of Philadelphia, 2nd ser., v. 7, 472 p., 30 plates.

Madison, M. P. and Fischer, M., 2007, The origins of clastic dikes within Badlands National Park, SD: Geological Society of America Abstracts with Programs , v. 39, no.6, pp. 229.

McCoy, M. J., 2002, Controls on paleosol morphology in a basin wide marker bed in the Scenic Member of the Brule Formation, Badlands National Park, South Dakota [M. S. Thesis]: Philadelphia, Pennsylvania, Temple University, 88 p.

Meek, F.B., and Hayden, F.V., 1857, Descriptions of new species and genera of fossils, collected by Dr. F.V. Hayden in Nebraska Territory under the direction of Lieut. G.K. Warren, U.S. Topographical Engineer, with some remarks on the Tertiary and Cretaceous formations of the northwest and the parallelism of the latter with those of other portions of the United States and Territories: Proceedings of the Academy of Natural Sciences, v. 9, p. 117-148.

Metzger, C. A., Terry, D. O., Jr., and Grandstaff, D. E., 2004, The effect of paleosol formation on rare earth element signatures in fossil bone: Geology, v. 32, p. 497-500.

Minkler, H.R., 2007, Paleofauna from the Latest Eocene Chadron Formation, Highway 44 Locality, in southwestern South Dakota, and its implications concerning the Eocene/Oligocne Climatic Shift [M.S. Thesis]: Rapid City, South Dakota, South Dakota School of Mines and Technology, 170 p.

Nicknish, J.M., and Macdonald, J.R., 1962, Basal Miocene ash in White River Badlands, South Dakota: American Association of Petroleum Geologists Bulletin, v. 46, p. 685-690.

Parris, D.C., and Green, M., 1969, *Dinohyus* (Mammalia: Entelodontidae) in the Sharps Formation, South Dakota: Journal of Paleontology, v. 43, p. 1277-1279.

Prout, H.A., 1846, A giganitic *Palaeotherium*: American Journal of Science, series 2, v. 2, p. 288-289.

Pye, K., and Tsoar, H., 1987, The mechanics and geological implications of dust transport and deposition in deserts with particular reference to loess formation and dune sand diagenesis in the northern Negev, Israel, *in* Frostick, L. and Reid, I. eds., Desert sediments: ancient and modern: Geological Society of London Special Publication , no. 35, p. 139-156.

Retallack, G.J., 1983, Late Eocene and Oligocene paleosols from Badlands National Park, South Dakota: Geological Society of America Special Paper 193, 82 p.

Shuster, R. D. and Maher, H., 2009, Are clastic dikes in Badlands National Park a result of structural diagenesis?: Geological Society of America Abstracts with programs, v. 41, no.7, pp. 413.

Sinclair, W.J., 1921, The "turtle-oreodon layer" or "red layer," a contribution to the stratigraphy of the White River Oligocene (Results of the Princeton University 1920 Expedition to South Dakota): Proceedings of the American Philosophical Society, v. 60, p. 457-466.

Stevens, K.K., 1996, Taphonomy of an early Oligocene (Orellan) vertebrate assemblage in the Scenic Member, Brule Formation, White River Group, Badlands National Park, South Dakota [M.S. Thesis]: Rapid City, South Dakota, South Dakota School of Mines and Technology, 103 p.

Stinchcomb, G., Terry, D. O. Jr., and Mintz, J. S., 2007, Paleosols and stratigraphy of the Scenic-Poleslide Member boundary: implications for pedofacies analysis and regional correlation of the early Oligocene Brule Formation, South Dakota, U.S.A.: Geological Society of America Abstracts with Programs, v. 39, n. 6, p. 305.

Terry, D. O., Jr., 1996a, Stratigraphy, paleopedology, and depositional environment of the Conata Picnic Ground Bone Bed (Orellan), Brule Formation, Badlands National Park, South Dakota: Geological Society of America Abstracts with Programs, v. 28, no. 4, p. A-40.

Terry, D. O., Jr., 1996b, Stratigraphic and paleopedologic analysis of depositional sequences within the Pig Wallow Site, Badlands National Park: National Park Service/University of Nebraska-Lincoln Cooperative Agreement #CA-1300-5-9001: Badlands National Park Archives, 164 p.

Terry, D. O., Jr., 1998, Lithostratigraphic revision and correlation of the lower part of the White River Group: South Dakota to Nebraska, ; *in* Terry, D. O., Jr., LaGarry, H. E., and Hunt, R. M., eds., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America): Geological Society of America Special Paper #325, p. 15-37.

Terry, D. O., Jr., and LaGarry, H. E., 1998, The Big Cottonwood Creek Member: A new member of the Chadron Formation in northwestern Nebraska; *in* Terry, D. O., Jr., LaGarry, H. E., and Hunt, R. M., eds., Depositional environments, lithostratigraphy, and biostratigraphy of the White River and Arikaree Groups (Late Eocene to Early Miocene, North America): Geological Society of America Special Paper #325, p. 117-141.

Wanless, H.R., 1922, Lithology of the White River sediments: Proceedings of the American Philosophical Society, v. 61, p. 184-203.

Wanless, H.R., 1923, The stratigraphy of the White River beds of South Dakota: Proceedings of the American Philosophical Society, v. 62, p. 190-269.

Ward, F., 1922, The geology of a portion of the Badlands: South Dakota Geological Natural History Survey, Bulletin 11, 59 p.

Wortman, J.L., 1893, On the divisions of the White River or lower Miocene of Dakota: American Museum of Natural History, Bulletin, v. 5, p. 95-105.

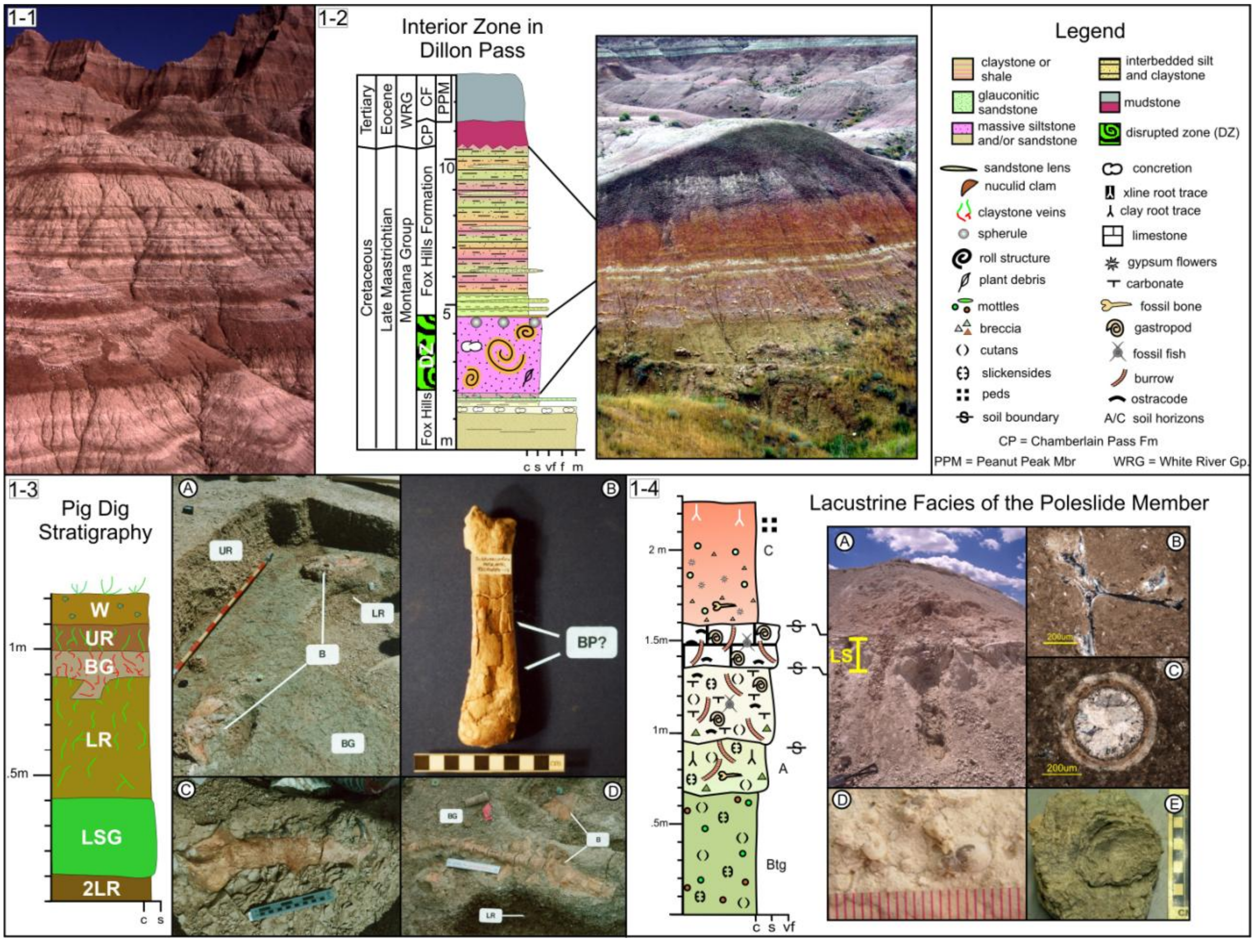

Plate 1. 1-1, Banding in the Badlands represents differing nonmarine lithologies and subsequent pedogenic and diagenetic modification. Darker bands are mudstone and claystone beds
1-2, The Interior Zone at Dillon Pass, composed of the Yellow Mounds Paleosol that forme on Cretaceous deposits and the red Interior Paleosol that formed on the Chamberlain Pass Formation.
1-3, General stratigraphy and fossils of the Big Pig Dig. 1-3A shows the concentration of bones within greenish mudstone of the bone-bearing green layer (BG), 1-3B shows bone processing (BP), 1-3C is the lower jaw of an Enteolodont, and 1-3D shows an articulated vertebral column and pelvis.
1-4, Measured section and photographs of lacustrine deposits within the Poleslide Member 1-4A. Outcrop photograph of lacustrine limestone (LS) interbedded with siliciclastic mudstone. Note shovel for scale (60 cm long) in the bottom left of photograph. 1-4B. Fish vertebra, 1-4C. Oogonia structure, 1-4D. high- and low-spired freshwater gastropods (scale in cm), and E. freshwater stromatolite (scale in cm).

Environmental geology of abandoned uranium mines, Harding County, South Dakota.

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1 day – Saturday April 24, 2010

Itinerary

This is a one-day field trip to abandoned uranium mine sites in Harding County, northwestern South Dakota. Uranium occurrences in South Dakota were first reported in 1929 from pegmatite (granite) sources but it was not until 1948 that commercial-grade uraniferous lignite was discovered in the Williston Basin. The earliest production of uranium ores in South Dakota came from a Cretaceous age sandstone host discovered in 1951 in the Edgemont District. This production was followed in 1954 by the discovery of uraniferous lignite in the North Cave Hills, Harding County (US Forest Service land). Ultimately, uranium exploration and production expanded to include the South Cave Hills and Slim Buttes as well. By 1973, the only mill in the state was closed and uranium production had ceased. A total of 3.2 million pounds of U_3O_8 were produced, 15% of which was from lignite ash (Harding Co.) and the remainder from sandstones in the Edgemont District (southern Black Hills). The abandoned Harding County mines have recently received intense study to determine off-site impacts from the mining period and the past 40-50 years of exposure of the uraniferous lignites to the environment. Environmental concerns associated with the Harding County mines and their relatively isolated location will most likely inhibit any further surface mining activity in this region of the state.

The field trip will entail a history of the uranium production, a visit to three main mined areas, and detailed information about the movement of contaminated materials from the abandoned mine sites onto private land.

This field trip is limited to the first 20 registered people. Transportation will be in two vans, 10 participants and one driver per van. Some walking to and within the sites will be involved. Sturdy walking boots are encouraged. Lunch and snacks will be provided during the day.

Schedule: Saturday, April 24, 2010
Meet in the Holiday Inn Lobby by 7:15 a.m.
(breakfast on your own)
Load into the vans and depart the hotel at 7:30 a.m.

Environmental Geology of Abandoned Uranium Mines, Harding County Field Trip Stop Summary

0.0 Depart Holiday Inn (Civic Center) parking lot at 7:30 AM: Exit to right onto 5th Street

0.2 Cross Rapid Creek at Memorial Park, established in tribute to the 237 persons lost in the June 9, 1972 flood.

0.3 Turn right onto Omaha Street.

0.7 Turn right onto West Boulevard access Rd to I-90.

1.4 To the west (left) is the Cretaceous hogback ridge that is capped by the Fall River Formation. The Skull Creek Shale, Newcastle Sandstone, and Mowry Shale form the slope to the west. We are driving on the Mowry Shale. To the east is the Belle Fourche Shale. All the units between the Skull Creek Shale and the Belle Fourche Shale are members of the Graneros Group.

In the southern Black Hills, the Inyan Kara Group (consisting of the Fall River Sandstone and the underlying Lakota Formation) was a rich producer of uranium from roll-front deposits and in coarse sandstone units cemented by calcium carbonate (Gott, 1956). Gott showed that these calcium carbonate cements exhibited a banded thermoluminescence pattern suggesting that the solutions that deposited the carbonate also transported the uranium. A complete petrographic and structural interpretation of the Inyan Kara Group has been provided by Gott et al. (1974).

2.8 Merge onto I-90 West. This highway passes through the hogback where lighter yellow-colored sedimentary rocks of the Lakota Formation rocks can be observed in the hillsides.

4.3 Deadwood Avenue Exit. At ~3 o'clock position a white band (pit) can be seen on the western flank of the hogback. This is the Jurassic Unkpapa Sandstone, a massively-bedded fine-grained eolian sand unit that lenses and thins to the east. This pit was mined in the 1960s for use in glass-making.

At ~9 o'clock position, large limestone quarry operations are visible. There is also another large quarry located at the 7 o'clock position. These quarries are in the Permian Minnekahta Limestone, a pure $CaCO_3$, cryptocrystalline, thinly bedded limestone that is ideal for cement production and road material. It is extensively quarried within the Rapid City limits and around the Black Hills. This unit is normally 40 feet thick, but in this area an anticline pair doubles the thickness making it a highly desirable mining unit.

The red-colored bedrock we are driving on is the Triassic Spearfish Formation, consisting of sand and silt beds and containing massive gypsum units at both the upper and lower contacts. The Spearfish has been referred to as the 'Red Valley'. It is generally a highly erosive unit that forms low valley topography between the overlying Sundance Formation (right at base of hogback) and the underlying Permian Minnekahta Limestone (tree-covered slope on the left). Most high elevation areas inside the Red Valley are more resistant bands or knobs of gypsum that are more erosion resistant and stand out in relief (Fig. 1). As we continue on I-90 West, note that a variable thickness gypsum unit will be present at many locations at the base of the hogback. This is the Gypsum Spring Member and is the contact between the Spearfish and overlying Jurassic Sundance Formation.

7.3 During the past 10 years much of this area has experienced rapid development (Fig. 2) in the Red Valley and adjacent slope areas. Most homes utilize onsite wastewater treatment systems. Several of the development districts are based on traditional home spacings but some of the newer developments have gone to ~2 acre (and larger) plot sizes. This will serve to reduce concentration loading into underlying aquifers through fractures.

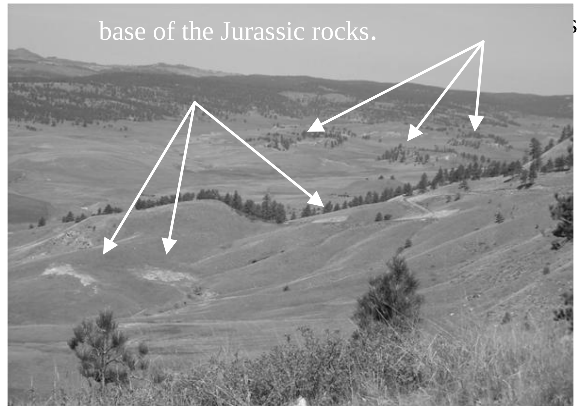

Figure 1. View from the top of the Fall River Formation looking northwest down the Red Valley (Spearfish Formation). The high knobs that host trees in the valley are erosional highs of gypsum.

33.9 Exit I-90 at Sturgis. Continue north on Junction Street to Highway 34.

Figure 2. View looking NW along the I-90 development corridor. The trees on the left side of the valley are on the dip slope of the Minnekahta Limestone. The highest ridges are underlain by the Minnelusa Formation although the upper portion of the Pahasapa Limestone (Madison aquifer in the subsurface) appears in the canyon wall to the upper left. This is the hinge of the White Gates monocline. The unit at the right by the gravel road is the lower Fall River Formation.

35.7 Turn right onto Highway 34 East.

39.7 Turn left onto US Highway 79.

45.1 Bear Butte (Fig. 3), a 1250-ft high Tertiary laccolithic intrusive body, also known as Mato Paha in Lakota Sioux. Mato Paha is a unique geologic feature formed during the Laramide Orogeny 65 to 40 million years ago. The rocks making up the Butte are a porphyritic quartz monzonite and have been dated at 52.1 ±1.5 Ma (DeWitt and Duke, 1996) million years old. The quartz monzonite was much harder than the surrounding sandstone and shale the magma intruded into and has resulted in erosion of the softer rock leaving the laccolith elevated above the plains creating this beautiful landform. Bear Butte is a true mountain at 1250 feet above the surrounding plains and is covered by loose talus (Fig. 4).

Figure 3. Bear Butte, a Tertiary porphyritic quartz monzonite.

Figure 4. Talus slopes on Bear Butte are angle-of-repose and consist of shards of quartz monzonite. An American Indian prayer site is located on the top of the mountain surrounding the viewing platform.

56.9 Cross the Belle Fourche River. This river begins in northwest Wyoming (southeast of Devils Tower) and flows northeast paralleling the general direction of the Little Missouri, Tongue, and Powder Rivers. However, about 55 miles upriver from here, the river makes a sudden 90° bend from the northeast to the southeast direction (Fig. 5). The other three rivers continue flowing northeast. The 90° bend is a classic example of a stream piracy event where the ancestral river in this present valley that flowed southeast of the bend area experienced headward retreat to the northwest until it broke through and captured the upper part of the Belle Fourche into this channel. Prior to being captured, the original upper Belle Fourche had actually flowed into the upper Little Missouri River within 10 miles below the capture point (Darton and O'Harra, 1905).

The Belle Fourche River is an important water source in this region. Waters from the river fill the Belle Fourche Reservoir (143,000 acre-feet) 20 miles northwest of here and are used to irrigate several thousands of acres of hay and cropland.

63.7 Town of Newell. Newell was established in 1910 after the construction of Orman Dam on Belle Fourche Reservoir. This irrigation project began in 1904 and at the time, Orman Dam was the largest earthen dam in the world.

Geologically, Newell is founded on the southern extension of the Cretaceous Pierre Shale north of the Black Hills uplift. The Pierre is a blue-grey to dark-grey fissile shale hosting sandy units and many persistent bentonite beds (Martin et al., 2004) which are mined ~50 miles west of here (Fig. 5). The unit is up 2700 feet thick and is exposed on the surface for thousands of square miles in western South Dakota.

82.7 Turn left onto SD Highway 168.

91.5 Turn right onto US Highway 85.

106 Turn off US Highway 85 at Crow Butte. Rest stop, 20 minutes.

<u>STOP No. 1:</u> Crow Butte rises about 250 feet above the road elevation, reaching to about 3394 feet above sea level. The bedrock is the Cretaceous Hell Creek Formation which lies above the Fox Hills Formation. The contact is less than ¼ to ½ mile southwest of the Butte.

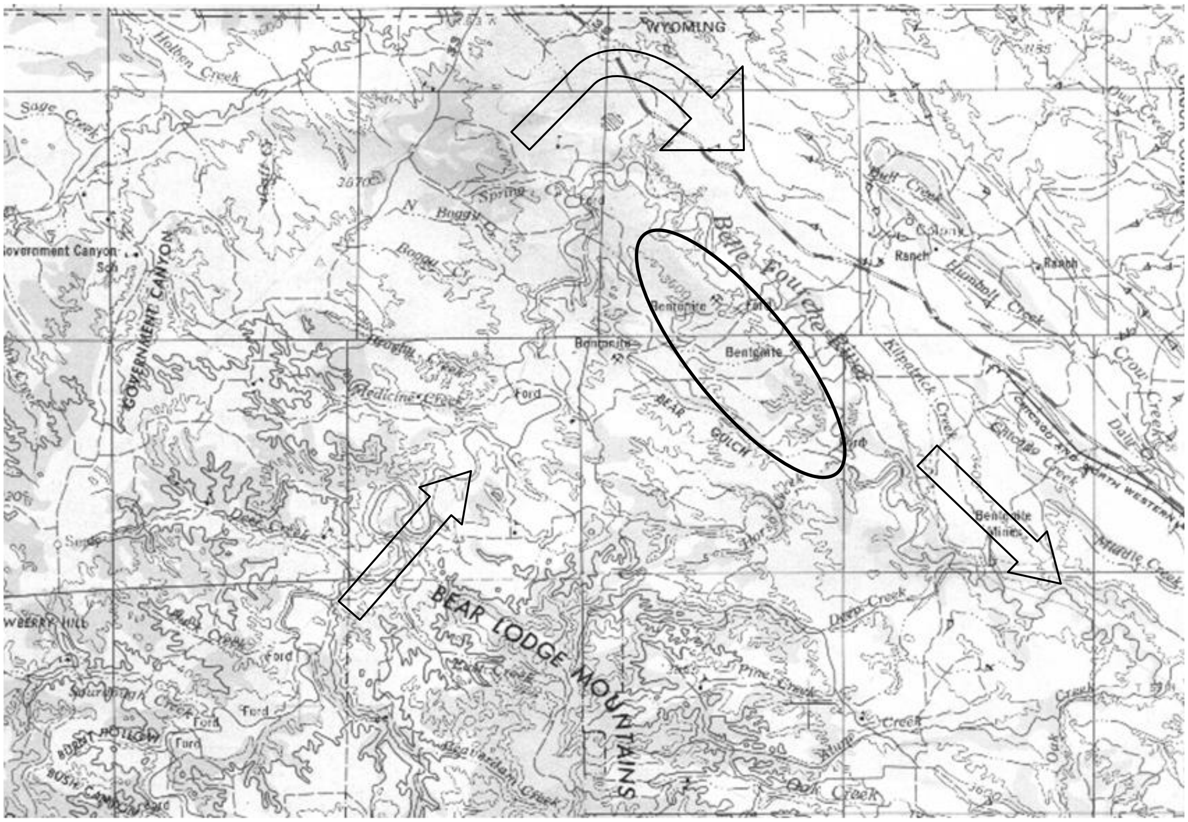

Figure 5. Part of the 1:100,000 Devils Tower 30 x 60 minute Quadrangle showing the 90° bend in river direction from northeast to southeast (Black arrows). The Cretaceous Pierre Shale is exposed along this section of the Belle Fourche River and several bentonite mines are located here (black oval) that feed large mills in nearby Colony, WY. These mines are among the largest producers of bentonite in the United States.

The Butte was also the site of one of the more bizarre battles between American Indian tribes. In 1822, Sioux Indians attacked the Crow tribe whom retreated to the top of the butte to gain a better vantage point. However, they fled without water and the Sioux simply camped below until their enemy died. The canyon nearby was called the 'Canyon of Skulls' after many of the remaining Sioux died there after contracting fever from the Crows.

The Fox Hills Formation is a bluish-green to dark-gray, and yellow to tan, carbonaceous and iron-stained, crossbedded, very fine- to coarse-grained, glauconitic sandstone and siltstone. It has interbeds of gray to brown shale and silty shale with thicknesses between 25-400 feet (Martin et al., 2004). This unit was deposited in a shallow marine and tidal environment during the retreat of the Cretaceous Western Interior Seaway about 70 Ma. The Fox Hills is important regionally as a source of groundwater. North of here in the vicinity of the abandoned uranium mines, many of the ranch wells are completed in the Fox Hills sandstone units. The outcrop area of the Fox Hills around Crow Butte is very thin and structurally is situated on the southern rim of the Williston Basin, which deepens toward the north. East and west of here, the formation surface exposure becomes wider due to low dip angles and serves as the primary recharge zones for the subsurface aquifers in the Basin.

The Fox Hills Formation is famous for is its rich fossil assemblages, including ammonites, plants, reptiles, and dinosaurs, particularly *Tyrannosaurus rex*. Of the approximate 15-18 full *T. rex* skeletons found worldwide, about 12 come from the Fox Hills Formation, mostly from western South Dakota. The most famous *T. rex*, Sue, was excavated about 100 miles east of here.

The overlying Hell Creek Formation is tan to brown and light- to dark-gray, "somber beds" of shale. It is interbedded with carbonaceous shale, bentonitic silty shale, and siltstone, sandstone, and claystone-pebble conglomerate units and has a thickness of 260-600 ft (Martin et al., 2004).

Return to vans.
Continue north on US Highway 85.

133.8 Buffalo, SD. Exit US Highway 85 at truck stop immediately south of town.

STOP No. 2: Uraniferous lignite mining occurred mainly to the north in the Cave Hills and early after production began, the mined lignite was brought to Buffalo where it was incinerated in a burner like the one seen in figure 6. After incineration, the residual ash contained the now enriched uranium ore which was shipped for processing. Burners operated in Buffalo for a number of years before they were dismantled and the lignite shipped elsewhere for processing. Unfortunately, records from the period are mostly non-existent and the exact location of the burning facilities are not known.

Figure 6. Lignite incinerator in Buffalo, SD in the 1950s.

Return to vans.
Continue north on US Highway 85.

136.2 Turn left onto Cave Hills Road. This road is the primary route south and west of the South Cave Hills and then turns northward continuing to the North Dakota border to the west of the North Cave Hills. The Cave Hills complex is comprised of two distinct butte areas, the South Cave Hills, visible in the distant north as tree-covered buttes, and the North Cave Hills, about 15 miles north of here. Uranium exploration and production occurred in both units.

141.7 McKenzie Butte at 4 o'clock position. There are three buttes aligned in a general northwest-southeast orientation, two to the east (right) and one to the west (left). McKenzie Butte is the largest butte to the southeast. At the base of these buttes, as the topography begins to rise above the surrounding prairie, the contact between the Hell Creek Formation and the overlying Tertiary Ludlow Formation of the Fort Union Group is exposed. The highway passes over Ludlow rocks through this line of Buttes then progresses stratigraphically down again into Hell Creek units.

Locally, this is the K-T boundary. Uranium was restricted to the Ludlow Formation and the overlying Tongue River Formation, exposed further north. Generally, remnants of exploration activity on these buttes exist as linear scratches across the sides (Fig. 7) and were made by bull dozers trying to uncover the coal units underlying the talus. No one knows how many of these cuts exist (hundreds at least) but they are ubiquitous below the massive sandstone cap rocks, which marks the Ludlow-Tongue River contact. This zone, immediately below the sandstone cliffs, was one of the higher uranium enrichment zones and often contained uranium grades of 0.1% and higher (Pipiringos et al., 1965). These exploration 'cuts' represent potential sites for uranium products to be leached out of any exposed uraniferous lignite units and transported away from the buttes by water, wind, and gravity.

143.8 Hilton mine at 2 o'clock position. This is one of the many small named prospects located throughout the Cave Hills complex. Uraniferous lignites were discovered here but the records are incomplete as to exactly which of these 'mines' produced lignite ore. As a result, most of these areas were monitored for exposed ore and the possibility of off-site transport of contaminated materials.

147.9 Pull off of Cave Hills Rd.

STOP No. 3: This stop involves a small hike into the Lonesome Peat Mine about ½ mile east of the road.

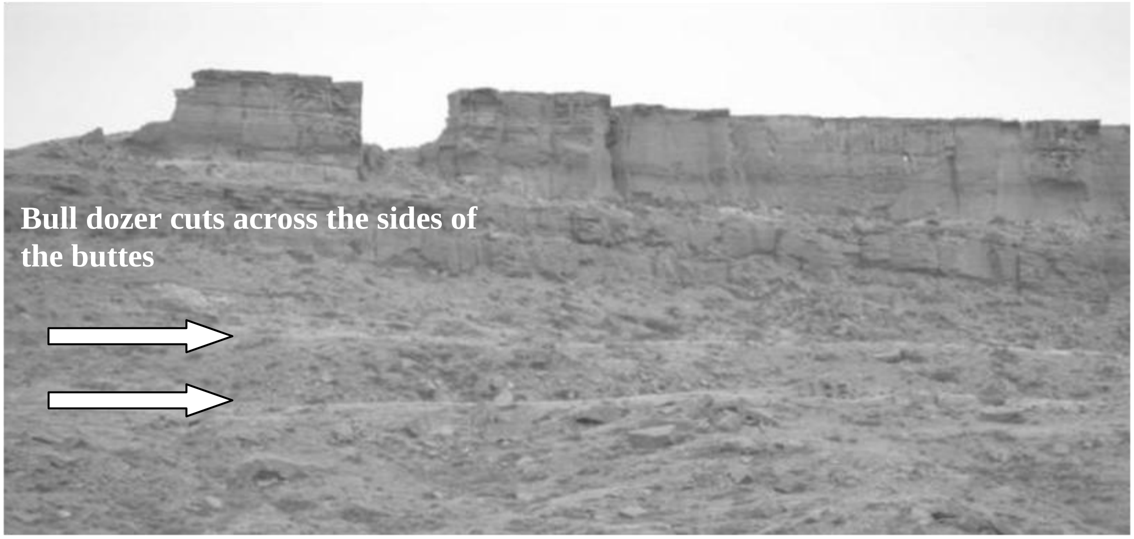

Figure 7. Bull doze cuts across the sides of the buttes below the Ludlow (bottom) and Tongue River (sandstone cliffs at top) contact. These were in an attempt to uncover lignite units that were the host for the uranium.

Uranium ore in the Cave Hills was associated primarily with lignite coal units occurring in the Tertiary Fort Union Group. Locally, two units are exposed in the Fort Union, the lower Ludlow Formation and the overlying Tongue River Formation. Although coal units persists into deeper underlying Cretaceous rocks, the uranium enrichment does not pass the K-T boundary. Pipiringos et al. (1965) defined several lignite/coal units in the Fort Union rocks which have been summarized in figure 8. Typically, the higher up stratigraphically a lignite was positioned, the more abundant the uranium enrichment.

The Lonesome Pete Mine (Fig. 9) consisted of a bed of phosphatic silty claystone less than 5 inches thick, the second host-rock type of uranium in the Cave Hills. This unit occurred a few inches to 1 foot above the Lonesome Pete coal zone which normally can be viewed toward the middle portion of the remaining pit wall. The ore zone here lies about 90 feet below the top of the Ludlow Formation contact. Locally, the phosphatic claystone was given the name “Lonesome Pete ore zone” (Pipiringos et al., 1965). Mineralogically, the Lonesome Pete ore zone contained abundant amorphous carbonate flourapatite grains, analcite spherulites, and nodules and crystals of marcasite. Phosphate in the carbonate flourapatite averaged 1.2 % with an associated uranium average concentration of 0.16 %. The ore zone locally was defined by drilling and was continuous for 2000 feet along the outcrop. For additional information, Pipiringos (1966) provides a robust geochemical analysis of all ore zones in the Cave Hills district.

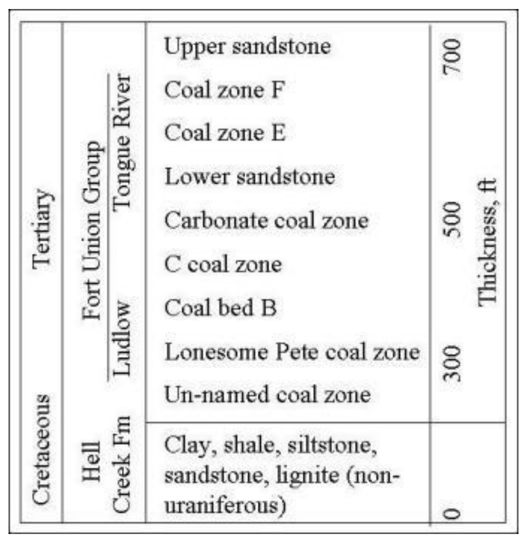

Figure 8. Generalized stratigraphy of the coal units in the Fort Union Group rocks exposed in the Cave Hills. Compiled by Stetler from Pipiringos et al., 1965.

Figure 9. Lonesome Pete mine in the South Cave Hills. The back mine wall is presently exposed and radioactivity can be detected using hand-held Geiger counters. The white dash line is the approximate contact between the Ludlow and the Tongue River Formations.

Environmental monitoring was performed in the Cave Hills and Slim Buttes from 2006-2009 by the South Dakota School of Mines and Technology through the establishment of a Joint Venture Agreement with the USDA-Forest Service Northern Region. The US Environmental Protection Agency (US EPA) Region 8 provided the funding. Transport pathways that were monitored for movement of environmental contaminants included surface water, sediment in water, soil, groundwater, and wind. All sampling was done using a watershed approach. For each pathway, a statistical background concentration value was established by sampling in pristine watersheds, or in areas that were shown to be free from mining influences. Sampling of the various mediums produced concentration values that were then compared to the background value and were used to assess contamination.

Data from the Lonesome Pete mine showed that uranium sediment concentrations in drainages flowing from the mine exceeded background values. Surface water uranium

concentrations did not exceed background for the drainages leaving this area (Tuombe, 2008).

Return to vans.

Continue north on Cave Hills Road.

149.0 Turn right onto SD 121, a gravel road. This road cuts through the northern portion of the South Cave Hills. Many small prospect pits and mined areas exist to the south (right) along the base of the sandstone cap rocks in the Ludlow Formation.

154.3 Turn right onto Brown Johnson Road.

160.1 Turn left onto US Highway 85 north.

170.1 Town of Ludlow on left

172.1 Turn left onto Tufte Road.

178.3 Talus slopes at the 3 o'clock position were derived from mine spoils being piled along the edge of the bluff during mining. Subsequent water erosion and gravity has produced large gullies (Fig. 10) and transport of radioactive materials to these lower and flatter lands where they have been deposited along the many drainages. Surveys in these gullies have located fist-sized pieces of black pitchblende sandstone ore having radiation emissions greater than 22,000 counts per minute.

Also at this location, note the sediment retention pond alongside the north (right) side of the road. Such ponds were built in the 1980s in an attempt to trap radioactive materials before they were distributed further downstream onto the flats.

Figure 10. Gullies developed in the spoils piles on the edge of bluffs that

178.8 Riley Pass, elevation 3275 feet. The sandstone cliffs are the basal Tongue River Formation. The valley to the southwest is Ludlow Formation units. The main floor of the Riley Pass mine can be accessed by following this contact along the ridge for <1/4 mile.

179.2 Turn right onto dirt access road to the Riley Pass mine complex.

180.0 Riley Pass uranium mine complex.

<u>STOP No. 4:</u> We may be forced to park further down the access road depending on road conditions during the field trip. There are a few access points into the mined area and we will utilize the easiest and shortest routes on the day of the trip. Figure 11 is a topographic map of the mine complex along this butte. The designated parking place is noted by the black oval.

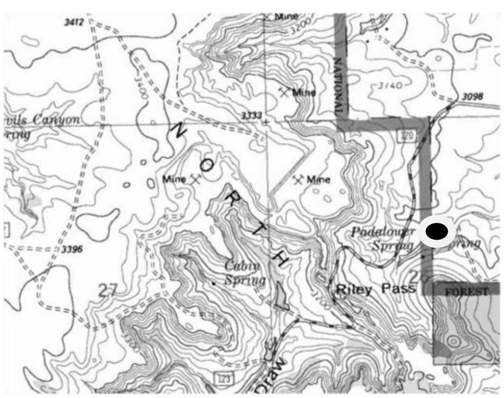

Figure 11. Portion of the 1:24,000 Ludlow, SD 7.5 minute quadrangle map. The van parking spot is near the black oval.

Most of the North Cave Hills mining was from the Riley Pass complex (Bluff B) and as a result, it has the largest disturbed area and has many drainages leading from it. Sampling was conducted around the entire North Cave Hills resulting in background concentration values representing the region (Table 1). Thus, individual concentration values could be assessed. A complete assessment is contained in Stone et al. (2007). A complimentary CD of the Phase I results are contained on the CD provided with your materials.

Commercial uranium ores were first reported in the Cave Hills in 1954 when autunite-bearing lignites were discovered in the Riley Pass district. These ores were in coal bed E and later discoveries were made in the C coal zone (Fig. 8). Mining in the area was accomplished using bull dozers to remove the overburden from above the flat-lying lignite units. The lignite was then removed using belly scrappers and transported to an incinerator for ashing. Overburden was pushed over the side of the butte (Fig. 12) and as a result, the floors of abandoned mines were relatively flat (Fig. 13)

Figure 12. Uranium mining in the Riley Pass district ca. early 1960s. Overburden was pushed over the side of the butte to expose the uranium-bearing lignite units. USFS image.

Table 2. Target analytes for all samples and additional analytes for groundwater*.

Analyte Name	Chemical Symbol	Maximum Contaminant Level (MCL; mg/L)
Arsenic	As	0.01
Copper	Cu	1.3
Molybdenum	Mo	-
Selenium	Se	0.05
Lead	Pb	0.015
Thorium	Th	-
Uranium	U	0.03
Vanadium	V	-
Radium*	Ra	-
Radium-226*	Ra-226	5 pCi/L
Uranium-235*	U-235	-
Gross Alpha*		15 pCi/L

Figure 13. Present floor of an abandoned mine on Bluff H, about 1.5 miles east of the Riley Pass mines. The flat-lying stratigraphy has resulted in broad open floors at the base of the mining.

Based on previous on-site characterization in the 1990s (Pioneer, 2005, 2002), eight analytes were selected for monitoring. These were increased to 12 for the groundwater monitoring (Table 2).

The most impacted site was determined to be the Upper Pete's Creek drainages leading NE away from the base of Bluff B. Elevated uranium concentrations were observed in surface water and soil located within this drainage. During Phase II sampling, elevated concentration values were tracked until they had attenuated to below background values. This occurred about 15 miles NE of Bluff B after the creek flowed in to Crooked Creek and was diluted.

Return to vans after viewing the abandoned mine complex. Lunch.

Retrace route back to gravel road and back to US Highway 85

187.9 Turn right onto US Highway 85 south

189.9 Turn left at Ludlow just past the school.

191.4 Left turn into private drive. Park van ~1/2 mile off pavement. Walk into Flat Top mine.
The Flat Top mine is located on private property and was mined during the same time period as the Riley Pass mines employing the same mining methods. This mine is host to a pit lake (Fig. 14) and has an exposed pit highwall. Uranium was contained in a carbonaceous silt that is exposed near

Table 1. Background concentration values and sample high value as a multiplier of the background (x) for uranium from the North Cave Hills sampling program.

Sample Medium	Backgrnd	High	Location
Surface Water	0.027 mg/L	23x	Upper Pete's Creek
Groundwater	none	0.064 mg/L	4 mi SW of Ludlow
Aerosol Dust	0.74 mg/kg	2.65x	5 mi NW of Bluff B
Soi	l22 mg/kg	1.5x	¼ mi east of Bluff B
Sediment	4 mg/kg	7.45x	¼ mi east of Bluff H

the pit floor. Surface water drainage from this mine is west into Pete's Creek and then NE into Crooked Creek. Although this is a relatively small mine, the environmental impacts were determined to be significant, and analyte concentration values here are the highest of any in the monitored area.

Uranium concentrations within the vicinity of the minesite workings (high wall, pit lake) ranged from 89.6 to 770 mg/kg, or between 29.9 and 259.3 times established background concentrations found within regional non-mining impacted drainages of the North Cave Hills. Sediments collected near the exposed coal seam exhibited the highest concentration of metals and radionuclides. Zones of darkened carbonaceous silt and clay surrounding the pit lake showed consistent radiological background counts, ranging from 1,562 to 6,375 counts per 5 minutes

Figure 14. Pit lake at the Flat Top mine. Pit highwall is visible in the background.

The surface water samples indicated significant on- and off-site impacts within the surface water drainages has occurred. One sample collected from the pit lake was 0.436 mg/L total uranium, or 25 times the established background concentration found within the North Cave Hills. Elevated total metal concentrations within the pit lake were present for As, Cu, Mo, Pb, Th, and V. Further down gradient, a stock pond had been constructed to collect runoff from the mine site, fed from a highly eroded drainage, and occurrence of overland flow over mine spoils was evident. Total uranium in this stock pond was 0.558 mg/L, or 32 times background, and was the highest surface water uranium concentration found during this survey. Further down gradient, a larger stock pond was sampled and contained 0.243 mg/L total uranium, or 14 times background.

Return to vans. Retrace route back to US Highway 85.

193.9 Turn left onto US Highway 85 south.

355 Holiday Inn arrival between 5-6 p.m.

STOP Field Trip Log

REFERENCES CITED

Darton, N. H.; and O'Harra, C. C., 1905, *Description of the Aladdin quadrangle*: U.S. Geological Survey Geologic Atlas, Aladdin Portfolio, No. 128, 13 p.

DeWitt, E.; Duke, G., 1996. *Geochemistry of Tertiary intrusive rocks in the northeastern Black Hills, South Dakota*: Guidebook to the geology of the Black Hills, South Dakota, SD School of Mines Bulletin 19, p. 135-149.

Gott, G.B., 1956, *Inferred relationships of some uranium deposits and calcium carbonate cement in the southern Black Hills, South Dakota*: U.S. Geological Survey Bulletin 1046-A, 16 p.

Gott, G. B.; Wolcott, D. E.; and Bowles, C. G., 1974, *Stratigraphy of the Inyan Kara Group and localization of uranium deposits, Southern Black Hills, South Dakota and Wyoming*: U.S. Geological Survey Professional Paper 763, 63 p.

Martin, J. E.,; Sawyer, J. F.; Fahrenback, M. D.; Tomhave, D. W.; and Schulz, L. D., 2004, *Geologic map of South Dakota*: S.D. Geological Survey, Available online at: http://www.sdgs.usd.edu/pubs/pdf/G-10.pdf

Pipiringos, G. N.; Chisholm, W. A.; and Kepferle, R. C., 1965, *Geology and uranium deposits in the Cave Hills area, Harding County, South Dakota*: U.S. Geological Survey Professional Paper 476-A, 64 p., 4 plates.

Pipiringos, G. N., 1966, Origin of elements associated with uranium in the Cave Hills area Harding County South Dakota: U.S. Geological Survey Professional Paper 476-B, 85 p.

Pioneer Technical Services, 2002, *Final site investigation report for the Riley Pass uranium mines, Harding County, South Dakota*: Report to the USFS, 26 p., Appendix A-C.

Pioneer Technical Services, 2005, *Draft final engineering/cost analysis (EE/CA) for the Riley Pass uranium mines, Harding County, South Dakota*: Electronic document, available at http://www.fs.fed.us/r1/custer/projects/Planning/nepa/Riley_Pass/index.shtml

Tuombe, E., 2008, *Surface water and sediment investigation concerning abandoned uranium mines in the South Cave Hills, North Cave Hills, and Flint Buttes region, Harding County, South Dakota*: M.S. Thesis, SD School of Mines and Technology, 159 p.

Stone, J. J.; Stetler, L. D.; and Schwalm, A., 2007, *Final report: North Cave Hills abandoned uranium mines impact investigation*: Report to USDA-Forest Service Region 1, Missoula, MT, 217 p.

Holocene paleoflood events in the Black Hills: Evidence preserved in alcoves and caves

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Introduction

In the Black Hills of South Dakota, flash floods from large thunderstorms have been lethal. A devastating flood in 1972 near Rapid City resulted in 237 deaths and $160 million dollars (1972 dollars) in damages (Schwarz and others, 1975). Peak streamflows (streamflow is analogous to discharge) were recorded in several drainages in the central Black Hills, and some were an order of magnitude higher than the previous peak of record. The purpose of this trip is to visit several sites where deposits of previously unrecorded floods from the last several thousand years have been preserved in caves and alcoves adjacent to creeks. For example, a site along Boxelder Creek preserves evidence of at least 10 individual floods spanning almost 1,800 years before present, the most recent being the 1972 flood.

Resistant units in the Black Hills that form alcoves and caves that preserve flood deposits typically are Paleozoic-age sandstones and limestones. Such settings provide not only an environment for deposition of flood slack-water deposits, but also a dry and/or dark environment that restricts growth of plants, and reduces bioturbation of flood deposits. Preservation of deposits from bioturbation, erosion, and weathering is essential in order to provide a detailed and lengthy flood history. Elevations of flood deposits at sites in the Boxelder Creek and Rapid Creek drainages indicate that many floods were substantially larger than the devastating 1972 flash flood that affected Rapid City and the surrounding area. Ages and magnitudes of many of these floods are included in this guide.

This field-trip guide describes a one-day loop, starting and ending in Rapid City, SD. From Rapid City, we will travel upstream along Boxelder Creek into the Black Hills, across the drainage divide between Boxelder and Rapid Creeks, and then follow Rapid Creek downstream, back into Rapid City.

Paleozoic Stratigraphy of the Northern Black Hills

A map of selected geologic units in the Black Hills area is shown in figure 1. The stratigraphic column for the Black Hills of South Dakota is shown in figure 2. The Paleozoic stratigraphy summarized herein is taken from descriptions of the regional geology of the Black Hills from Gries (1996), Carter, Driscoll, and Williamson (2002), and Redden and Dewitt (2008).

Paleozoic sedimentary rocks of the Black Hills overlie a "crystalline core" of Precambrian-age igneous and metamorphic rocks that are approximately 1,700 to 2,500 million years old (Ma). An unconformity marks the gap between formation of the crystalline core, uplift and erosion of that core, and deposition of the overlying Paleozoic sediments. During Late Cambrian time (490-500 Ma), seas transgressed across western South Dakota, depositing beach sands and gravels that overlie the crystalline core. As the early Paleozoic shoreline retreated, coastal sands were once again deposited. In the Black Hills, the Cambrian- to Ordovician-age Deadwood Formation is approximately 0-152 meters (m) thick (fig. 2). Resistant units of the Deadwood Formation form alcoves that are suitable environments for the preservation of Quaternary flood deposits. In the northern and central Black Hills, the Deadwood Formation is disconformably overlain by Ordovician rocks, which include the Whitewood and Winnipeg Formations.

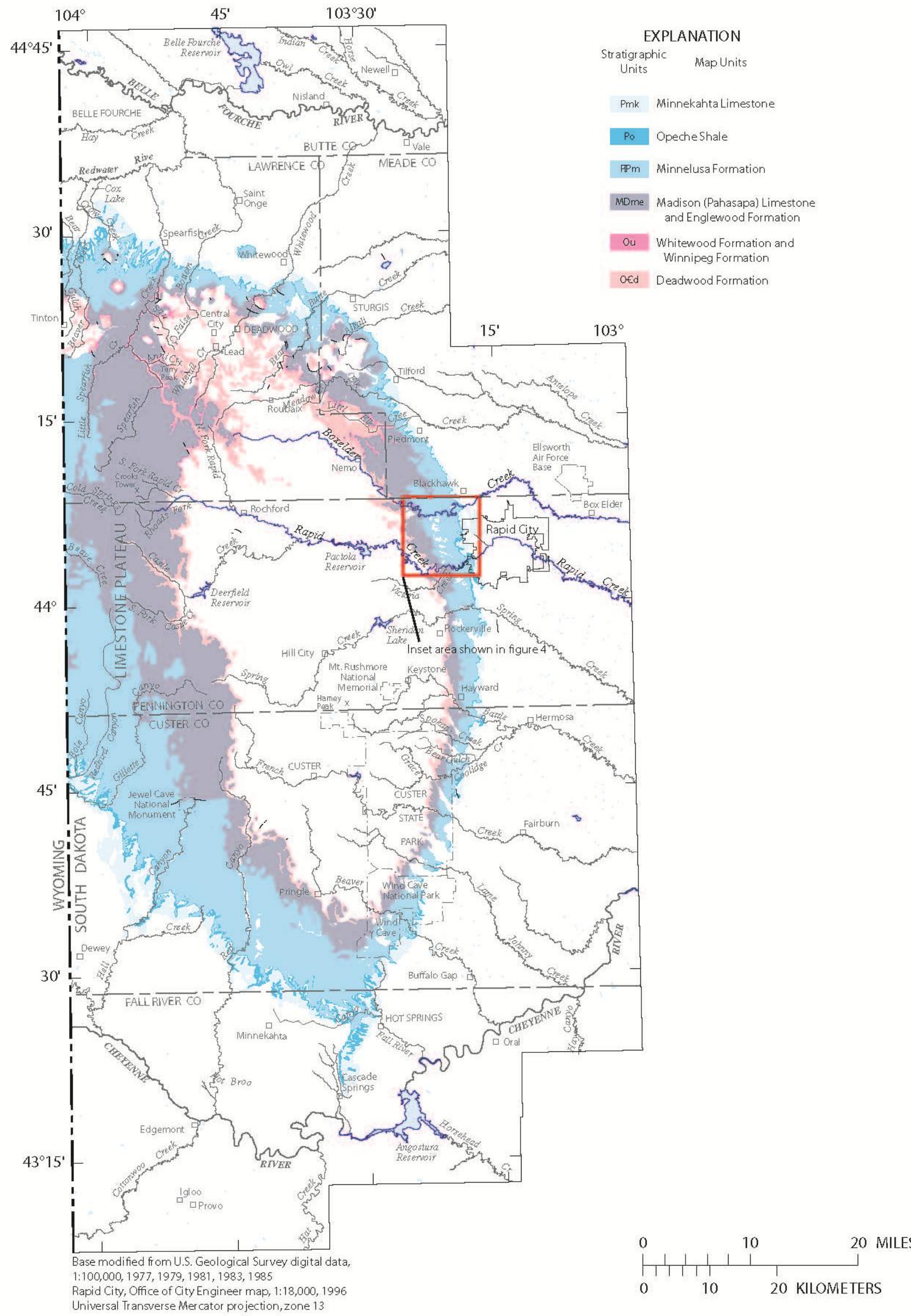

Figure 1. Generalized geologic map of the Black Hills area (modified from Strobel and others, 1999).

ERATHEM	SYSTEM	GEOLOGIC UNIT		THICKNESS IN FEET	DESCRIPTION
CENOZOIC	QUATERNARY & TERTIARY (?)		UNDIFFERENTIATED ALLUVIUM AND COLLUVIUM	0-50	Sand, gravel, boulders, and clay.
			WHITE RIVER GROUP	0-300	Light colored clays with sandstone channel fillings and local limestone lenses.
	TERTIARY		INTRUSIVE IGNEOUS ROCKS	--	Includes rhyolite, latite, trachyte, and phonolite.
MESOZOIC	CRETACEOUS		PIERRE SHALE	1,200-2,700	Principal horizon of limestone lenses giving teepee buttes. Dark-gray shale containing scattered concretions. Widely scattered limestone masses, giving small teepee buttes. Black fissile shale with concretions.
			NIOBRARA FORMATION	[1]80-300	Impure chalk and calcareous shale.
			CARLILE SHALE	[1]350-750	Light-gray shale with numerous large concretions and sandy layers. Dark-gray shale.
			GREENHORN FORMATION	225-380	Impure slabby limestone. Weathers buff. Dark-gray calcareous shale, with thin Orman Lake limestone at base.
		GRANEROS GROUP	BELLE FOURCHE SHALE	150-850	Gray shale with scattered limestone concretions. Clay spur bentonite at base.
			MOWRY SHALE	125-230	Light-gray siliceous shale. Fish scales and thin layers of bentonite.
			MUDDY SANDSTONE NEWCASTLE SANDSTONE	0-150	Brown to light-yellow and white sandstone.
			SKULL CREEK SHALE	150-270	Dark-gray to black siliceous shale.
		INYAN KARA GROUP	FALL RIVER FORMATION	10-200	Massive to thin-bedded, brown to reddish-brown sandstone.
			LAKOTA FORMATION	35-700	Yellow, brown, and reddish-brown massive to thinly bedded sandstone, pebble conglomerate, siltstone, and claystone. Local fine-grained limestone and coal.
	JURASSIC		MORRISON FORMATION	0-220	Green to maroon shale. Thin sandstone.
			UNKPAPA SS	0-225	Massive fine-grained sandstone.
			SUNDANCE FORMATION	250-450	Greenish-gray shale, thin limestone lenses. Glauconitic sandstone; red sandstone near middle.
			GYPSUM SPRING FORMATION	0-45	Red siltstone, gypsum, and limestone.
	TRIASSIC		SPEARFISH FORMATION	375-800	Red silty shale, soft red sandstone and siltstone with gypsum and thin limestone layers. Gypsum locally near the base.
PALEOZOIC	PERMIAN		MINNEKAHTA LIMESTONE	[1]25-65	Thin to medium-bedded, fine grained, purplish-gray laminated limestone.
			OPECHE SHALE	[1]25-150	Red shale and sandstone.
	PERMIAN / PENNSYLVANIAN		MINNELUSA FORMATION	[1]375-1,175	Yellow to red cross-bedded sandstone, limestone, and anhydrite locally at top. Interbedded sandstone, limestone, dolomite, shale, and anhydrite. Red shale with interbedded limestone and sandstone at base.
	MISSISSIPPIAN		MADISON (PAHASAPA) LIMESTONE	[1]<200-1,000	Massive light-colored limestone. Dolomite in part. Cavernous in upper part.
	DEVONIAN		ENGLEWOOD FORMATION	30-60	Pink to buff limestone. Shale locally at base.
	ORDOVICIAN		WHITEWOOD (RED RIVER) FORMATION	[1]0-235	Buff dolomite and limestone.
			WINNIPEG FORMATION	[1]0-150	Green shale with siltstone.
	CAMBRIAN		DEADWOOD FORMATION	[1]0-500	Massive to thin-bedded brown to light-gray sandstone. Greenish glauconitic shale, flaggy dolomite, and flat-pebble limestone conglomerate. Sandstone, with conglomerate locally at the base.
PRECAMBRIAN			UNDIFFERENTIATED IGNEOUS AND METAMORPHIC ROCKS		Schist, slate, quartzite, and arkosic grit. Intruded by diorite, metamorphosed to amphibolite, and by granite and pegmatite.

Figure 2. Stratigraphic column for the Black Hills (adapted from Carter, Driscoll, and Williamson, 2002).

During Mississippian time (359-318 Ma), a large, shallow inland sea formed over much of central North America forming thick units of limestone. The thin Devonian- and Mississippian-age Englewood Formation (9-18 m) is overlain by the much thicker Mississippian-age Madison Limestone, locally know as Pahasapa Limestone. This unit is as much as 305 m thick and is recognized by its pale-gray color and cavernous nature. After the Pahasapa Limestone was deposited, the land rose above sea level, exposing the newly deposited limestone to weathering and erosion. Over time, caverns were formed by the dissolution of limestone by slightly acidic rainwater. Some broke through the surface forming sinkholes. However, many never broke through and remain today as limestone caves. The Madison Limestone is the source of more than 200 caves (Gries, 1996) in the Black Hills including Wind Cave and Jewel Cave National Parks. The abundant caves provide excellent environments to preserve ancient flood deposits from weathering and erosion. Most sites included in this trip guide are located in the Madison Limestone.

A disconfomity marks the upper surface of the Madison Limestone. Overlying the Madison Limestone is the Pennsylvanian-age (318-299 Ma) to Permian-age (299-271 Ma) Minnelusa Formation. The contact between the Pahasapa Limestone and Minnelusa Formation is marked by a reddish soil. The Minnelusa Formation includes sandstone, limestone, and shale (Gries, 1996). Towards the Late Pennsylvanian time, the sea retreated for a period long enough for a red soil to form. This soil was reworked into the formation as the sea transgressed from the south, giving the Minnelusa Formation its distinct reddish-pink hue. The upper Minnelusa Formation contains dune sands that formed in a coastal environment.

The Minnelusa Formation is disconfomably overlain by the Permian-age Opeche Shale, which is marked by maroon shales and siltstones, all in a terrestrial (above sea level) environment. During Middle Permian time (271-260 Ma), the sea level rose and a shallow sea formed over western South Dakota. A thin (8-20 m) bed of pinkish-grey limestone was deposited, and is known as the Permian-age Minnekahta Limestone.

Flood Records and Slackwater Deposits

Existing peak-streamflow records, such as for Rapid Creek (fig. 3), have insufficient length to adequately predict the frequency of occurrence of extreme events. The data record obtained by instruments needs to be supplemented with additional peak-streamflow data, including frequency and magnitude estimations from previously unrecorded floods. One of the most accurate, reliable, and widely used methods to quantify unrecorded flood events is through the analysis of slack-water deposits (Baker, 1987; Kochel and Baker, 1988; Ely and others, 1993; O'Connor and others, 1994; Hosman and others, 2003; Sheffer and others, 2008). Slack-water deposits are sands and silts, carried as suspended load in large, high-velocity flood events, and deposited in channel-margin areas where velocities are reduced and the sediment can fall out of suspension. Typical sites where slack-water deposits are well preserved include tributary mouths, rock shelters, alcoves, and bedrock caves (Kochel and Baker, 1982; Baker, 1987; Kochel and Baker, 1988).

Once a site that contained well-preserved slack-water deposits is identified, a sedimentological study is carried out to differentiate individual flood events. Typically, individual floods are separated by rockfall, organic debris, paleosols, or local colluvium that has a distinctly different mineral composition and grain size. Organic and/or sediment samples are collected for absolute dating analysis. By dating individual flood deposits, the frequency of these extreme flood events can be established. Ages of floods published in this guide were obtained by radiocarbon dating methods (Stuiver and Polach, 1977). Elevations of the individual flood deposits relative to the channel thalweg were surveyed as well as the channel cross-section and cross sections adjacent to the site. Channel geometry data are used in hydraulic models to estimate streamflow associated with given water-surface elevations. Due to differences in preservation potential, flood hydraulics, and depositional environment, one site seldom yields a complete record; thus, multiple sites at various elevations need to be investigated (Baker, 1987).

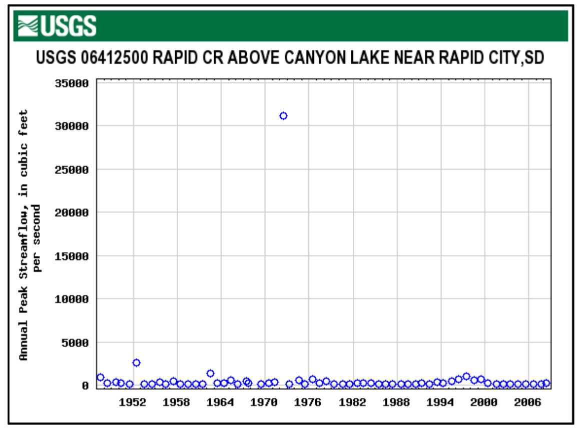

Figure 3. Annual peak streamflow on Rapid Creek just upstream from Canyon Lake in Rapid City from 1947 to 2009. The 1972 peak streamflow is about an order of magnitude larger than any previous peak streamflow at this gaging station.

Field Trip Sites

The field guide starts in Rapid City, from which we will drive west on Nemo Road, heading upstream along Boxelder Creek. Location of field trip stops are shown on figure 4. We will visit three sites before crossing the drainage divide between Boxelder Creek and Rapid Creek on Norris Peak Road. At the small town of Johnson Siding, we will begin traveling east, and follow Rapid Creek downstream into Dark Canyon and eventually to a site just upstream from Canyon Lake to view evidence of the destructive 1972 flood in a former housing development.

Paleoflood information for Rapid Creek and Boxelder Creek included in this guide was completed as part of a more encompassing paleoflood analysis of the Black Hills done in cooperation with the South Dakota Department of Transportation, the Federal Emergency

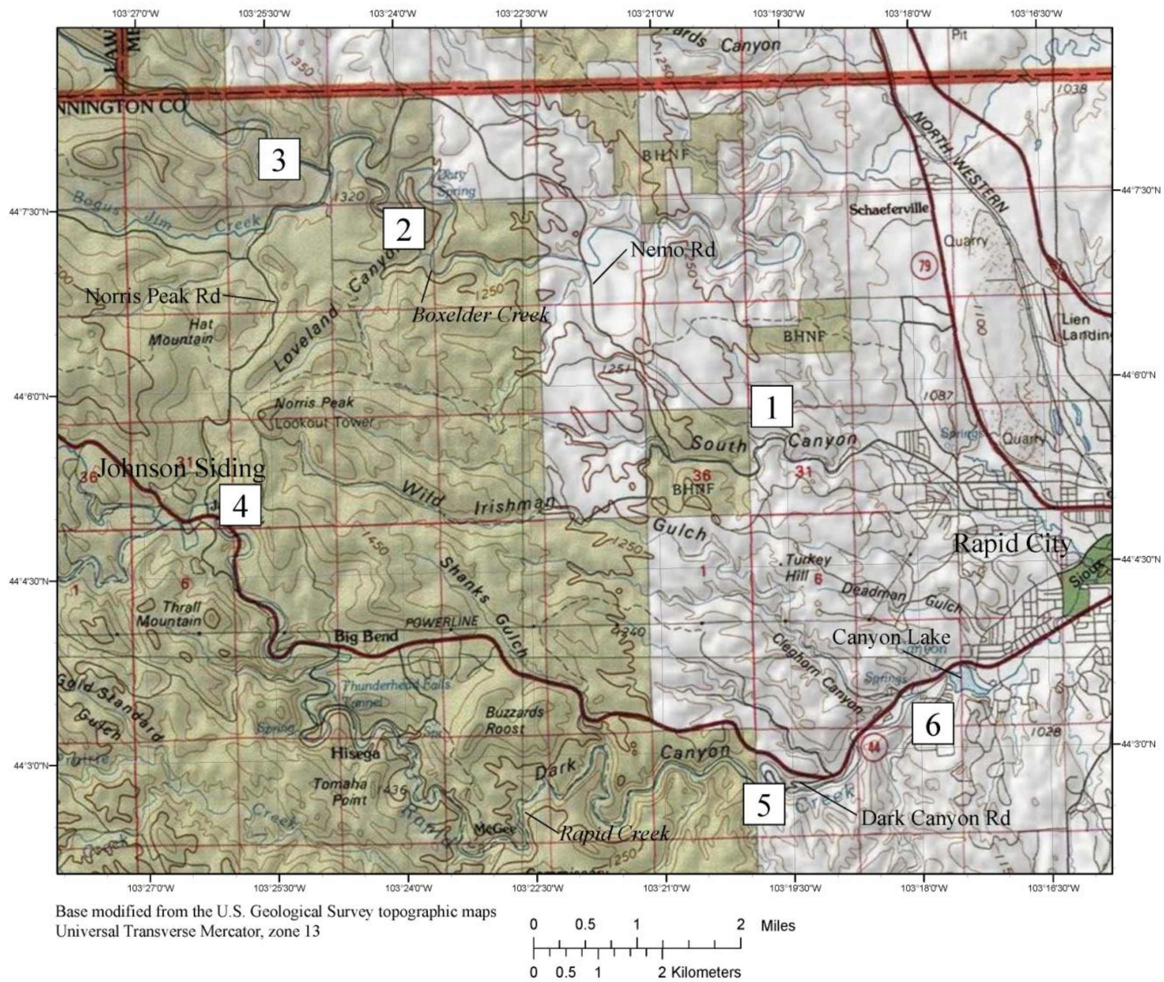

Figure 4. Locations of stops in the trip guide. Site number corresponds to stop number in the text.

Management Agency, the U.S. Geological Survey (USGS), and the City of Rapid City (O'Connor and Driscoll, 2007). Reported streamflow values associated with individual paleoflood sites were calculated using the U.S. Army Corps of Engineers Hydrologic Engineering Center – River Analysis System (HEC-RAS), one-dimensional hydraulic model (Hydrologic Engineering Center, 2008), unless noted otherwise. HEC-RAS results reported herein are preliminary and part of ongoing research efforts. Details of HEC-RAS modeling are planned to be presented in Spring 2010.

The two drainages covered in this field guide, Rapid and Boxelder Creeks, were chosen because the 1972 flood substantially affected both drainages, and because of the extensive paleoflood record contained in the caves and alcoves along the drainages. Rapid and Boxelder Creeks flow through sandstone and limestone outcrops as they drain the central and eastern Black Hills. These sedimentary units are characterized by extensive caves and alcoves that tend to preserve flood deposits from erosional processes. Upstream headwater areas in both drainages include metamorphosed shale and schist that contribute alluvial sediment with a mineralogy (such as mica rich) that is distinct from the mineralogy of local bedrock (carbonates, quartz-sand). Therefore, flood deposits can be distinguished from deposits derived from local processes, such as slopewash.

Road Log: **Many of the stops are located on private property, where permission from the landowner was required to access sites. The landowners of several sites have requested no additional or future site visits (as indicated in the road log).**

0.0 This field trip guide will begin in Founders Park, at the parking lot north of the intersection of West Omaha Street and Canal Street, Rapid City, SD. The park provides a view of the hogback exposing the Early Cretaceous-age Inyan Kara Group.

0.5 Intersection of Omaha Street and Mountain View Road (traffic light). Continue straight on Omaha Street.

0.7 Street name changes to W. Chicago Street.

1.8 Street name changes to South Canyon Road

2.5 Street name changes to Nemo Road.

4.5 **Stop 1: Paleozoic Stratigraphy.** Intersection of Nemo Road and Wide View Drive. This will be a short stop to view the Minnelusa Formation and folds within this unit. Note the well-bedded nature of this unit, which will contrast with the more massive bedding in the underlying Madison (Pahasapa) Limestone.

12.5 Nemo Road crosses Boxelder Creek for the third time at Norris Peak Road. Turn left onto Norris Peak Road.

12.9 Turn left on to Merchen Road. Follow Merchen Road up the hill.

13.2 Turn left onto Louis Drive.

13.4 Louis Drive turns to left.

13.6 Turn right onto Daybreak Ridge Road.

13.8 **Stop 2: Kitty's Corner Cave, Boxelder Creek.** Park in the small gravel lot on the east side of the road. The road dead-ends just past the gravel lot. From here field trip participants will be guided on foot to the field site along Boxelder Creek. **This site is located on private property. The landowner does not desire future visits.**

Kitty's Corner (named for the cave's resemblance to a mountain lion den) is a series of paleoflood sites located at the base of an approximately (~) 45-m vertical outcrop of Madison Limestone on the right bank of Boxelder Creek (fig. 5). The main feature at this location is a large cave, "Kitty's Corner", almost 3-m high and 4-m wide at the mouth, but which narrows to a meter in diameter about 10 m from the entrance. Three different pits have been excavated in the cave. Pit A is located near the mouth of the cave, pit B is located 1-2 m farther back along the left wall, and pit C is on the right wall in the back of the cave. Access to this part of the cave requires crawling on hands and knees a short distance. Flashlights are advisable. Be careful of a low ceiling in the cave.

Figure 5. Multiple slackwater sites in caves and alcoves along Boxelder Creek. Evidence of previously unrecorded floods has been found in each labeled site. Using flood evidence from 2nd Story Cave, the peak streamflow of the largest flood found at this site was approximately 1,700 cubic meters per second (65,000 cubic feet per second) and dates to 740 ± 35 ^{14}C years BP.

The stratigraphy of the flood deposits in the cave is quite complex (fig. 6). There is evidence of at least 10 individual floods spanning almost 1,800 years before present; the most recent being the 1972 flood. Several flood deposits are very charcoal rich (see fig. 6) and may indicate floods after fire events. Most flood layers are separated by angular roof-fall clasts or cave-floor material. Based on the elevation of these flood deposits, in order to inundate this site, peak streamflows of more than 510 m^3/s (18,000 cubic feet per second, ft^3/s) are required. In the last ~100 years, this streamflow has only been exceeded by that of the 1972 flood. The peak-streamflow estimate of the 1972 flood from USGS slope-area calculations from six

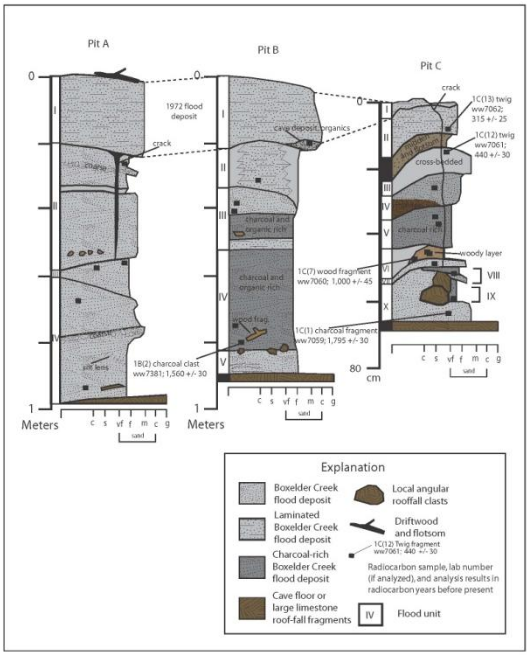

Figure 6. Stratigraphy in the three pits excavated in the large cave at Kitty's Corner. Pit A is located near the mouth of the cave and pit C is located at the back of the cave. Pit C contains evidence of 10 floods spanning almost 1,800 years. Note the grain-size scale below the stratigraphic columns. Horizontal width of each stratigraphic column corresponds to grain size on the scale below. The grain sizes range from clay (c) to gravel (g). Note that in the grain-size scale, clay is labeled 'c', but the 'c' under sand indicates coarse sand.

kilometers downstream from this site is approximately 1,460 m^3/s (51,600 ft^3/s; 303 square kilometers drainage area; Schwarz and others, 1975).

Trail Alcove is a small alcove located outside the cave about 5 m upstream between the base of the outcrop and a talus slope (fig. 5). A large piece of driftwood about 4 centimeters (cm) in diameter can be seen embedded in an old flood deposit. Trail Alcove contains evidence of three large floods on Boxelder Creek. The oldest flood unit is 10-cm thick at about 25 cm below the pit datum (the pit datum is always located on top of the youngest unit) and only exposed on the left side of the deposit (fig. 7). This unit is yellowish tan, silty, very fine sand. Beautiful laminations with thin subhorizontal wavy laminae can be seen near the top few centimeters. This unit likely was fine-grained

Figure 7. Stratigraphy of Trail Alcove. Units A and B are Boxelder Creek flood deposits. Unit A is from the 1972 flood and unit B dates to 630 ± 25 ^{14}C years BP. Unit D is local material that was reworked by a separate flood on Boxelder Creek from 905 ±25 ^{14}C years BP. Units C and E are composed of local roof fall and other colluvium material.

cave floor/ roof material that was reworked by a flood on Boxelder Creek as evidenced by the very fine bedding. The date of this oldest flood is 905 ± 25 carbon-14 (^{14}C) years before present (BP). The second oldest flood (about 3 cm below the pit datum) is a ~7 cm thick, yellowish tan, charcoal-rich, silty, very fine-grained sand that contains abundant limestone chips and includes the driftwood previously mentioned. The lower contact is sharp, but irregular, and appears to infill the rockfall layer below. This flood dates at 630 ± 25 ^{14}C years BP. The most recent flood deposit consists of the first 3 cm of the slack-water deposit. It is gray, very fine-grained sand with tan silty laminae and small lenses of medium-grained sand and is capped by an indurated layer, or silty cap. Some incorporated organic detritus can be seen throughout the unit. Cesium-137 (Cs-137) analysis (Holmes, 1998) done on this unit at the USGS Radioisotope Lab in St. Petersburg, Florida, confirms that the deposit is from the 1972 flood. Notice that the oldest two flood units are separated by a rockfall/colluvium unit, whereas the 1972 flood unit and the next oldest unit are distinguishable by a pronounced color and texture change as well as the placement of the large driftwood piece. A streamflow of approximately 700 m^3/s (25,000 ft^3/s) is required to inundate this site as determined using the HEC-RAS model (Hydrologic Engineering Center, 2008).

The 2nd Story Cave is a small, shallow cave located about 4 m directly above Trail Alcove just above a small ledge in the outcrop (fig. 5). The approximately 1-m diameter cave is visible when standing away from the limestone outcrop a few meters. The cave is best accessed with a ladder and it is not advisable to try to climb to this site. The elevation of the 2nd Story Cave is above the water surface of the 1972 flood and thus, this site was not inundated during the 1972 flood. The 2nd Story contains evidence of one very large flood that dates to 740 ± 35 ^{14}C years BP. The flood unit is composed of gray, silty, very fine-grained sand that is locally slightly indurated. Some lenses of organic debris as well as fine horizontal laminations are present. Results from the HEC-RAS model indicate that a streamflow of approximately 1,700 m^3/s (60,000 ft^3/s) is required to inundate this site. This streamflow is the largest known on Boxelder Creek in the last few thousand years.

13.8 Drive north on Daybreak Ridge Road back to Louis Drive.

14.0 Turn left on Louis Drive.

14.3 Turn right on Merchen Road.

14.6 Turn right on Norris Peak Road.

15.0 Turn left on Nemo Road.

15.5 **Stop 3: Deadwood Ledges.** Park on small grass turn out on left (south side of road). Stop 3 sites red-colored outcrops of the Deadwood Formation on the north side of the road._The Deadwood Ledges site of Boxelder Creek illustrates an excellent example of the multiple paleoflood sites at different elevations. Five sites are located along this roughly 400-m reach. Four sites are located in alcoves in the Deadwood Formation along the left bank of Boxelder Creek and one site is located in a limestone cave opposite the parking area along the right bank (left and right are relative to viewing downstream). A typical site where paleoflood evidence has been preserved by the Deadwood Formation can be seen in figure 8. Paleoflood evidence indicates that the largest flood in the last few thousand years was approximately 1,275 m^3/s (45,000 ft^3/s) compared to 850 m^3/s (30,000 ft^3/s) during the 1972 flood (Schwarz and others, 1975). The radiocarbon date for this unit flood is 140 ± 30 ^{14}C years BP. The oldest dated flood unit from pits at the Deadwood Ledges site is 2,145 ± 30 ^{14}C years BP and the youngest was from the 1972 flood.

Figure 8. A typical paleoflood site along the Deadwood Ledges reach of Boxelder Creek. The bedrock alcoves protect the ancient flood deposits from weathering and erosion due to rain and snow as well as keeping the immediate area dry preventing bioturbation from vegetation.

15.5 Drive east on Nemo Road, driving back to Norris Peak Road.

16.0 Turn right on Norris Peak Road. Norris Peak Road winds through forested land and over the Boxelder Creek – Rapid Creek drainage divide, and intersects Highway 44 at the town of Johnson Siding.

20.4 **Stop 4: Lunch in Johnson Siding.** Turn right on State Route 44, park immediately in store parking lot. We will have lunch in the parking lot.

20.4 After lunch, drive east on State Highway 44 back towards Rapid City.

28.2 Turn right (a sharp turn at the bottom of a long hill!) onto Dark Canyon Road. Several paleoflood sites are located on both the right and left banks of Rapid Creek as it flows through Dark Canyon.

28.6 Bridge crosses Rapid Creek. This is the first bridge crossing Rapid Creek.

28.7 **Stop 5: Dark Canyon on Rapid Creek.** Park in open grass area near cut for an abandoned rail line. Trip participants will be guided on foot to sites. This trip guide will only cover three sites (all are close to each other), located on private property. **The landowner does not desire future visits.**

<u>Meister Brau Cave</u> (named for flotsom located near the cave) is a large cave approximately 9-m wide, 3-

m high, and 3-m deep formed in Madison Limestone. The stratigraphic pit was excavated in the upstream corner of the cave. However, multiple crystal-lined vugs located in the bedrock at the back of the cave contain small silt caps deposited during one or more large floods on Rapid Creek such as the one in 1972. These flood deposits can be seen with a flashlight and are about 1.2 m (4 feet) higher than the surface of the excavated pit. This cave floor itself is composed of multiple flood deposits spanning almost 1,200 years, the most recent being the 1972 flood. A picture of the excavated pit is shown in figure 9.

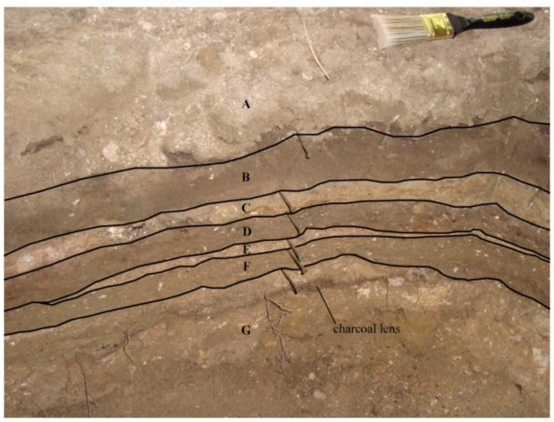

Figure 9. Stratigraphy at Meister Brau Cave. Units B, D and F are all individual flood deposits from floods on Rapid Creek, the youngest being from 1972 and the oldest from 1,195 ± 35 carbon-14 (^{14}C) years before present. Unit A is the extremely bioturbated upper half of Unit B. Units C, E, and G are of local colluvium and cave floor deposits.

Spider Cave is a small 1-m by 2-m by 2.5-m cave located about 25 m upstream from Meister Brau Cave in the Madison Limestone. The cave is about 7 m up a talus slope on the right bank and is visible from a few meters away. A pit was excavated to a depth of 44 cm and revealed a 7-cm-thick flood deposit about 5 cm below the surface (fig. 10).

This flood unit is composed of brown, silty, very fine-grained sand with fine organic detritus and rounded quartz grains. The upper 2-3 cm is siltier than the rest of the unit and locally finely laminated and slightly indurated. The lower contact is locally sharp but irregular. This unit overlies a unit of gravelly, silty fine-grained sand and organic detritus that is likely cave floor material and local roof fall clasts. Two radiocarbon dates from this layer indicate that the maximum age of the flood unit is 925 ± 30 ^{14}C years BP. This is a maximum date in that it was obtained from the unit immediately below the flood deposit. The uppermost unit at this site is composed of loose, organic rich, silty sand that may have an aeolian component and/ or was brought in and reworked by critters in the cave (exposure to the wind is possible given the small size of this cave). Peak-streamflow estimates at this site are approximately 1,840 m^3/s (65,000 ft^3/s). This streamflow is more than twice the 1972 peak streamflow (877 m^3/s or 31,000 ft^3/s; Carter, Williamson, and Teller, 2002) estimated by the USGS from slope-area calculations made a few miles downstream from this site.

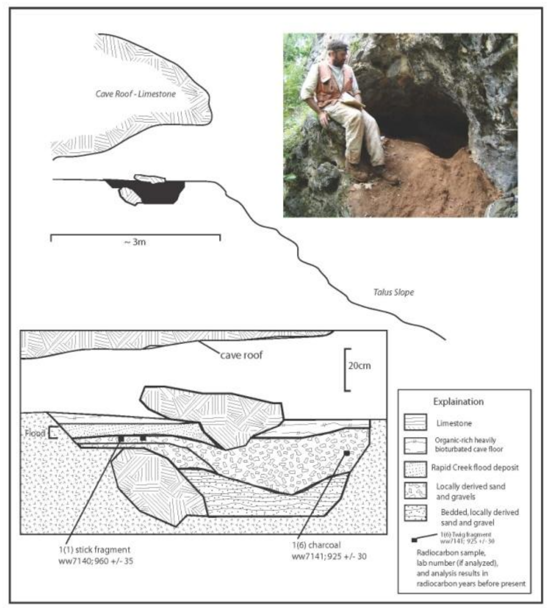

Figure 10. Stratigraphy and mouth (inset) of Spider Cave. Evidence of one very large flood from around 925 ± 30 carbon-14 (^{14}C) years before present on Rapid Creek was found at this site. Estimates from hydraulic modeling indicate a streamflow of approximately 1,840 cubic meters per second (65,000 cubic feet per second) is needed to inundate this site.

High Alcove contains evidence of the largest flood on Rapid Creek in the last several thousand years found to date. From the parking area, hike 0.4 km west (upstream direction on Rapid Creek) to the second bridge crossing of Rapid Creek (recall that the first bridge crossing was at mileage 28.6 in the road log). The site can be viewed from the road about 15 m (50 feet) upstream from the bridge. The cave is located high in the limestone outcrop visible on the right bank of the creek about 1.5 m (5 feet) below the top of the ridge and about 10 m (32 feet) above the water surface during low/mid streamflow on Rapid Creek (fig. 11).

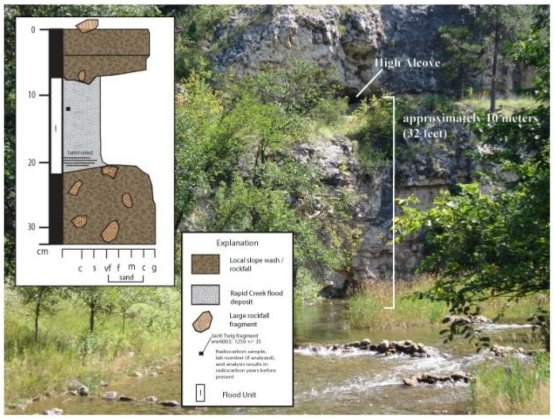

Figure 11. High Alcove on Rapid Creek contains evidence of the largest flood yet discovered on Rapid Creek. Peak-streamflow estimates at this location are approximately 3,400 cubic meters per second (120,000 cubic feet per second), nearly four times the 1972 peak streamflow of Rapid Creek just downstream from this location. Note the grain-size scale below the stratigraphic columns. Horizontal width of each stratigraphic column corresponds to grain size on the scale below. The grain sizes range from clay (c) to gravel (g). Note that in the grain-size scale, clay is labeled 'c', but the 'c' under sand indicates coarse sand.

The flood deposit is located 7 cm below the surface of a roof fall unit. The deposit is tan, very fine-grained, sandy silt, 14-cm thick with abundant small mica flakes derived from the granites and schist located upstream on Rapid Creek and carried downstream during large floods. The unit fines upward from fine-grained sand to sandy silt and is beautifully bedded with some slight cross bedding visible. The lower contact is sharp and marked by a gravelly roof fall unit. Results from the HEC-RAS model indicate that a streamflow of about 3,400 m^3/s (120,000 ft^3/s) is needed to inundate this site. This streamflow is almost four times that of the 1972 peak streamflow on Rapid Creek.

28.7 Drive on Dark Canyon Road east towards State Highway 44.

29.2 Turn right (east) on State Highway 44.

30.1 Turn right on to dirt road into Braeburn Dog Park.

30.2 Stop 6: Braeburn Addition. Continue to parking area at the end of the road. You will see an abandoned hockey rink next to the parking area (to the east). Evidence of the extreme 1972 flash flood is seen by the foundations of the former homes that remain in this once-thriving housing addition. The immediate aftermath of the flash flood near this location is shown in Figure 12. The streamflow through Rapid Creek was reduced substantially by the time this photo was taken but left a path of destruction in its wake. In 1972, most of the Rapid Creek flood plain had been developed for homes and businesses.

Figure 12. The destruction from the 1972 flood from Rapid Creek just upstream from Rapid City is evident by the foundations of former homes. This photograph was taken by the U.S. Department of Agriculture shortly after the destructive flash flood.

On the afternoon of June 9th, 1972, a line of very strong thunderstorms began building along the eastern flanks of the Black Hills centered near Rapid City. A strong low-level easterly airflow forced the moist airmasses upslope, sustaining an intense orographic effect that allowed the air to release its moisture in a series of repeating thunderstorms (Schwarz and others, 1975). Due to unusually light winds at upper atmospheric levels, the line of thunderstorms remained stationary over the area and continued to release rain unit late into the night of June 9th and early morning on June 10th. At one location near Keystone, almost 38 cm (15 inches) of rain fell in 6 hours and in all, almost 155 square kilometers (km^2) (60 square miles (mi^2)) received more than 25 cm (10 inches) of rain (Schwarz and others, 1975). The total drainage area in the Rapid Creek Basin upstream from Canyon Lake (just downstream from this site – we will pass Canyon Lake at mileage 31.0) is about 961 km^2 (371 mi^2), and of that only the area below Pactola Reservoir (132 km² or 51 mi²) contributed to the flood runoff. In fact, flow from the reservoir was cut off completely near midnight on June 9th. Most streams in the area peaked between 10:30 p.m. on June 9th and 1:00 a.m. on June 10th.

Just upstream from Canyon Lake the USGS gaging station was totally inundated. Slope-area calculations made immediately after the flood were used to estimate a peak streamflow of approximately 877 m^3/s (31,200 ft^3/s; Carter, Williamson, and Teller, 2002). For comparison, evidence of the largest paleoflood found thus far on Rapid Creek would require nearly 3,400 m^3/s (120,000 ft^3/s) to inundate the site (High Alcove at stop 5). This streamflow estimate is nearly four times that of the devastating 1972 flood. In light of this new information, the magnitude of the 1972 flash flood does not stand out as an anomalous occurrence relative to the magnitude of other paleofloods.

30.2 From the parking lot, drive north back to State Highway 44.

30.3 Turn right on State Highway 44.

31.0 Canyon Lake can be viewed to the south.

33.5 Turn left on Mountain View Road.

34.0 Turn right on Omaha Street.

34.5 Turn left into Founders Park. End of the field trip.

REFERENCES CITED

Baker, V.R., 1987, Paleoflood hydrology and extraordinary flood events: Journal of Hydrology, v. 96, p. 79-99.

Carter, J.M., Driscoll, D.G. and Williamson, J.E., 2002, Atlas of water resources in the Black Hills Area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-747, 120 p.

Carter, J.M., Williamson, J.E., and Teller, R.W., 2002, The 1972 Black Hills-Rapid City flood revisited: U.S. Geological Survey Fact Sheet *FS-037-02*, 6 p.

Ely, L.L., Enzel, Y., Baker, V.R. and Cayan, D.R., 1993, A 5000-yr record of extreme floods and climate change in the southwestern United States: Science, v. 262, p. 410-412.

Gries, J.P., 1996, The roadside geology of South Dakota: Missoula, Montana, Mountain Press Publishing Company, 358 p.

Holmes, C.W., 1998, Short-lived isotopic chronometers—A means of measuring decadal sedimentary dynamics: U.S. Geological Survey Fact Sheet 073–98, 2 p.

Hosman, K.J., Ely, L.L. and O'Connor, J.E., 2003, Holocene paleoflood hydrology of the Lower Deschutes River, Oregon, *in* O'Connor, J.E., and Grant, G.E., eds., A peculiar river; geology, geomorphology, and hydrology of the Deschutes River, Oregon: American Geophysical Union, Water Science and Application Series 7, p. 125-149.

Hydrologic Engineering Center, 2008, HEC-RAS River Analysis System User's Manual, Version 4.0: U.S. Army Corps of Engineers. *http://www.hec.usace.army.mil/software/hec-ras/*

Kochel, R.C. and Baker, V.R., 1982, Paleoflood hydrology: Science, v. 215, p. 353-361.

Kochel, R.C. and Baker, V.R., 1988, Paleoflood analysis using slackwater deposits, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., eds., Flood geomorphology: New York, John Wiley and Sons, p. 357-376.

O'Connor, J.E., Ely, L.L., and Wohl, E.E., 1994, A 4500-yr record of large floods on the Colorado River in the Grand Canyon: Journal of Geology, v. 102, p. 1-9.

O'Connor, J.E., and Driscoll, D.G., 2007, Applicability of paleoflood surveys to the Black Hills of Western South Dakota: Completion report SD2005–12 submitted to South Dakota Department of Transportation, Office of Research 59 p., accessed December 31, 2008, at *http://www.state.sd.us/Applications/HR19ResearchProjects/Projects/SD2005-12_Final_Report.pdf*.

Redden, J.A. and DeWitt, E. 2008, Maps showing geology, structure, and geophysics of the central Black Hills, South Dakota: U.S. Geological Survey Scientific Investigations Map 2777, 1:100,00-scale map and pamphlet, 44 p.

Schwarz, F.K., Hughes, L.A., Hansen. E.M., Petersen, M.S., and Kelly, D.B., 1975, The Black Hills - Rapid City flood of June 9-10, 1972, A description of the storm and flood: U.S. Geological Survey Professional Paper 877, 47 p.

Sheffer, N.A., Rico, M., Enzel, Y., Benito, G., and Grodek, T., 2008, The paleoflood record of the Gardon River, France, A comparison with the extreme 2002 flood event: Geomorphology, v. 98, p. 71-83.

Strobel, M.L., Jarrell, G.J., Sawyer, J.F., Schleicher, J.R., and Fahrenbach, M.D., 1999, Distribution of hydrogeologic units in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-743, 3 sheets, scale 1:100,000.

Stuiver, M., Polach, H.A., 1977, Discussion of ^{14}C data: Radiocarbon, v. 19, no. 3, p. 355-363.

Trace Fossils at the Cambrian/Precambrian Nonconformity, West of Rapid City, Black Hills

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INTRODUCTION

We will examine trace fossils and topographic control of Cambrian sedimentation along the nonconformity. Also, we will examine enigmatic Paleoproterozoic structures in quartzite surf boulders and outcrop. Time permitting, the trip will include a visit to examine sedimentation on the lee side of a major "island" on the nonconformity.

0.0 Depart parking lot at Holiday Inn. Turn South

0.2 Omaha Street. Turn right (west) on Omaha St. at approximately 1.2 miles you can pass through the Cretaceous sandstone hog back which more or less divides Rapid City into two parts.

1.5 Turn left on SD Highway 44 (Mountain View Road) and follow the general westerly route of Rapid Creek. At 4.9 mi. the highway passes a fish hatchery pond on the south and cliff exposures on the north provide an excellent exposure of the Minnelusa Formation.

6.2 Road goes up a major hill for the next 2 miles across the dip slope and through the upper part of the Pahasapa Limestone exposures along road also include terrace gravels of the ancestral Rapid Creek.

7.9 Road flattens at hilltop and this upper flatter surface has scattered White River deposits which are also well developed over a sizable area on the south side of Rapid Creek. The Pahasapa Limestone has a relatively flat dip but shows considerable evidence of solution believed to be due to the relatively closeness of the White River erosion surface.

9.7 Road bends to right but then back due west. Tertiary gravels west of road bend mark any early easterly drainage. This area is essentially the east side of the settlement called Hisega. The road to the west borders the north side of Hisega and is underlain by the poorly exposed lower Cambrian Deadwood Formation for approximately a mile. The north portion of Hisega along the road has scattered areas of White River deposits including some on the west side which are at a lower elevation and could not have followed an easterly drainage along route 44. These deposits had to have formed along an ancestral Rapid Creek which swings south from Hisega before turning east towards Rapid City. White River deposits are generally identified by the in bentonite layers formed from volcanic ash beds.

10.1 Road descends from Hisega and Rapid Creek is now on the left. The Precambrian unconformity is located just west of Hisega but is not well exposed.

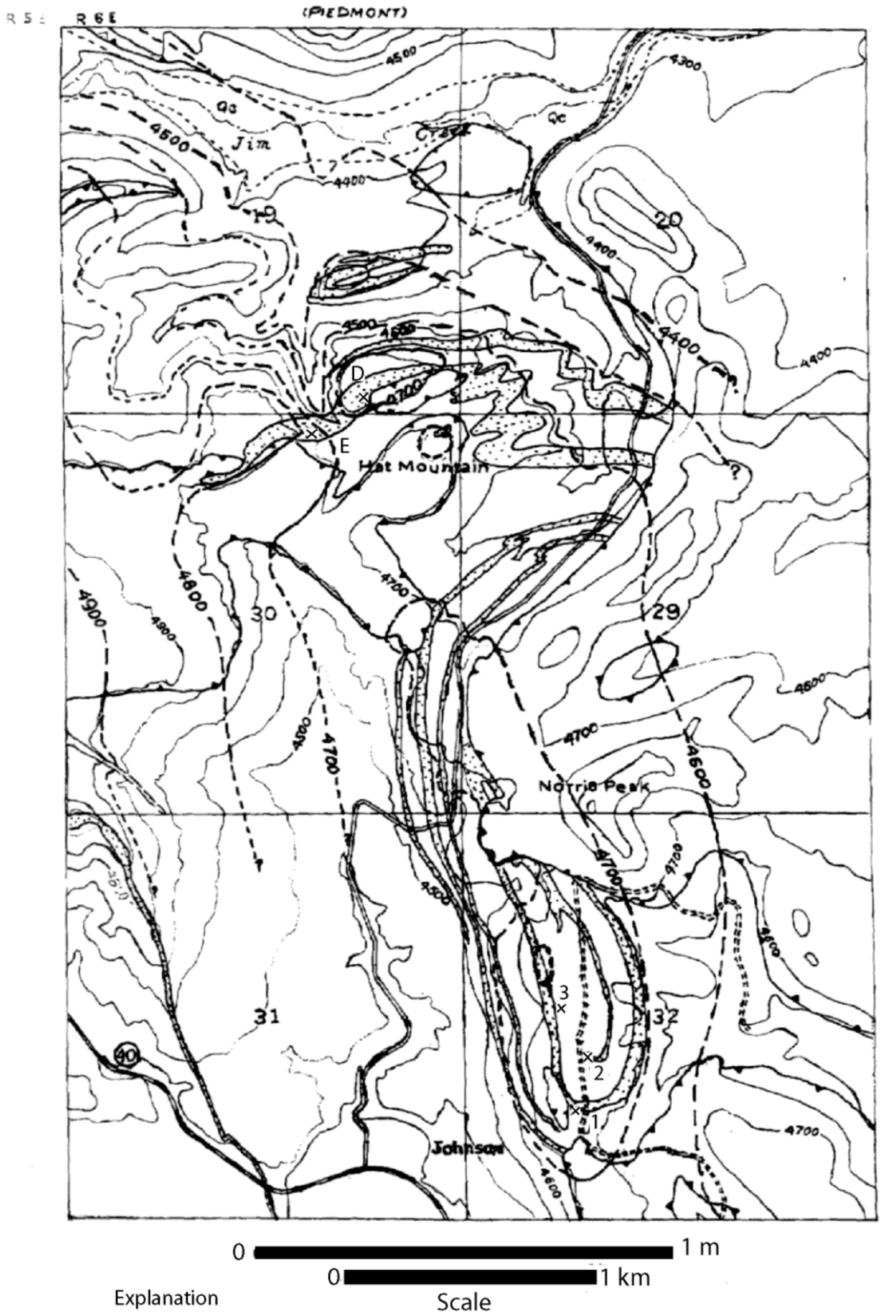
11.7 Turn right on Log Porch Road which is relatively inconspicuous but is just beyond the Rim Rock church. The road is rough but passable by vehicles of relatively high clearance. Caution is advised due to many sharp blind curves. Exposures along the road are all Precambrian metamorphic rocks consisting of phyllite or quartzite. The road gains elevation to the north and many large blocks are from the Cambrian Deadwood Formation which caps the higher elevations.

13.3 Side road to the right and small artificial watering hole

13.4 Road enters a relatively treeless area.

13.6 Stop 1. Pull over by a very large block (6' x 5') on left side of road which consists of boulder conglomerate on one side and sandstone on the other. Ii is part of the basal Deadwood which was excavated during construction of the road. Approximately 140 ft. to the north west is a large former surf boulder of quartzite exposed only a few inches above the ground. The quartzite was Paleoproterozoic originally but was incorporated into the Cambrian Deadwood Formation.

Several of these boulders remain on the gentle hill to the north and west where the Cambrian Deadwood Formation has been removed. In other words the hill was essentially the nonconformity. The exposed boulder is abundantly pitted by an unknown trace fossil. It also contains abundant enigmatic domal structures whose "shells" are rich in graphite.



Explanation

Qc	Alluvium (shown only along Jim Creek)
	Paleoproterozoic quartzite (other Precambrian rock types not shown)
	Unconformable contact between Cambrian Deadwood and Precambrian metamorphics
	Structure contours on unconformable surface, 100ft interval
x A	Localities referred to in text

Geology modified from Geologic map of Pactola Quadrangle by J.J. Norton, J. A. Redden, and F. J. Anderson 2008

South Dakota Dept. of Enviromental and Natural Resources

Figure 1. Map of the Norris Peak/ Hat Mountain Area, Pactola Dam Quadrangle, Black Hills, South Dakota.

Although somewhat resembling stromatolites, the "shells" of the domes can interpenetrate one another unlike any known stromatolites. The enigmatic structures are abundant in several of the near vertically dipping quartzites which are responsible for the general topographic high on the nonconformity. Although the enigmatic structures are believed to be biogenic in origin this cannot be proven due to the biotite grade metamorphism. The insitu outcrops of the enigmatic structures can be visited from this stop if desired.

Insitu Paleoproterozoic quartzite crops out about 150 ft farther northwest from the surf boulder on a small topographic high. On the west side of the high, boulder conglomerate is exposed adjacent to the quartzite and overlain b west dipping sandstone.

Return to vehicles and continue north to the 13.7 mi. where a side road to the left (west) enables one to turn vehicles around and return to SD Highway 44.

15.9 Highway 44. Turn right and proceed northerly along Rapid Creek.

18.2 Johnson Siding. Turn right on Norris Peak road just past the Rim Rock church.

20.0 Stop 2. Turn left on an unmarked hunting road about 0.2 mi. beyond the hill crest of Norris Peak. A house is located immediately north of this road. At approximately 0.3 mi. on this unmarked road is a fork. Bear right and the road essentially curves around the west side of Hat Mtn. Stop where this road forks. Approximately 500' to the northwest are excellent exposures of the Deadwood Formation overlying near vertical quartzites which are part of the Norris Peak Precambrian. Isolated surf boulders that contain trace fossil borings exist at several locals and there are several locals where the nonconformity is exposed. The published quadrangle map can be used to locate these areas inasmuch as there are no cultural locations in this USFS area.

22.7 Bogus Jim Creek road. Conglomerate is exposed in blocks of the Deadwood on the right and much thicker and coarser conglomerate occurs a few hundred yards farther north on the Norris Peak road. This is part of an ancestral Cambrian drainage which followed present day Bogus Jim Creek. Turn left at Bogus Jim Creek.

24.4 Green Mountain visible on heights to the northwest.

26.1 Bogus Jim Creek road turns to the right.

27.3 Duren Road. Turn right.

27.7 Road forks. Bear to the right.

28.3 Possible stop 3. Faint former road on right. Park and then walk approximately 600' SE across a slight topographic high to exposures of Deadwood Formation. The topographic high was the crest of a paleo-island approximately 1-1/2 mi. long and about 1000' wide which formed the north side of the ancestral Bogus Jim Creek drainage. The geology of the outcrops and a detailed map are described more fully in Redden (1987)

Return to vehicles and retrace route to SD Highway 44 at Johnson Side and Rapid City.

REFERENCES CITED

Redden, J.A., 1987, Early Proterozoic and Precambrain-Cambrian unconformities of the Nemo area Black Hills, South Dakota. In S.S. Beus editor, Geological Society of America Centennial Field Guide-Rocky Mountain Section v. 2 p. 219-225.

Geologic Road Log: Rapid City to Sturgis, Lead-Deadwood, Spearfish, to Rapid City

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Introduction

This road log begins by following Interstate 90 north along the eastern flank of the Black Hills from Rapid City to Sturgis, traveling along the "Red Valley" of Spearfish Formation. The hogback of Sundance to Fall River formations makes the skyline to the east. The route turns west at Sturgis and follows Boulder Canyon through the Minnekahta to Deadwood formations to the city of Deadwood. The route then passes the historic Homestake mine Open Cut in the city of Lead, crosses the Lead-Deadwood dome of Tertiary intrusives in Precambrian and Lower Paleozoic formations, and turns north through scenic Spearfish Canyon to the city of Spearfish. The route turns briefly east following Interstate 90, then turns south toward Deadwood and Lead, traveling through the Spearfish to Deadwood formations, then Precambrian rocks. Near Lead the route turns south on Highway 385, traveling through Precambrian rocks cut by Tertiary intrusives. At Brownsville, the route goes southeast on Nemo road traveling on Precambrian rocks, and then on Paleozoic rocks, ending with Upper Jurassic to Upper Cretaceous rocks back at Rapid City.

0.0 Turn right out of the Rushmore Plaza Holiday Inn parking lot onto 5th Street. On Upper Cretaceous Belle Fourche Shale.

0.1 Cross Rapid Creek.

0.2 Intersection with Omaha Street. Turn right.

0.5 Intersection with Mt. Rushmore Road. On Upper Cretaceous Mowry Shale.

0.7 Intersection with I-190 (West Blvd.). On Upper Cretaceous Skull Creek Shale.

1.1.1 In water gap of Rapid Creek through hogback with beds dipping east. Lower Cretaceous Newcastle Sandstone, Skull Creek Shale, and Fall River Formation are on the east side, Lakota Formation near the middle, and Upper Jurassic Unkpapa Sandstone and Middle-Upper Jurassic Sundance Formation are on the west side of the hogback (Fig. 1). On top of the hogback on the south side of the gap is Dinosaur Park which has several concrete dinosaur replicas.

1.5 Slumps in the Unkpapa Sandstone to the right.

Figure 1. Hogback with exposed Sundance Formation (Js) to the far left, through the Unkpapa Sandstone (Ju), Lakota Formation (Kl), Fall River Formation (Kf), Skull Creek Shale (Ks), to the Newcastle Sandstone (Knc) on the far right.

1.7 Cross Rapid Creek.

1.8 Intersection with Deadwood Avenue. Omaha Street changes to Chicago Street. There are several pits where the Unkpapa Sandstone is mined for sand northeast of the intersection. Black Hills Power and Light power plant to the right.

2.2 Cross DM&E railroad.

2.4 GCC and Pete Lien cement plants and quarries in the Lower-Upper Permian Minnekahta Limestone (Darton, 1901) to the right (Fig. 2). The limestone is a fairly uniform 40 feet (12 m) thick and is brought to the surface along a northwest trending anticline.

2.9 Intersection with Sturgis Road (Business 90), turn right. Traveling north on the Upper Permian-Lower Triassic Spearfish Formation (Darton, 1899) having some gypsum beds.

Figure 2. GCC and Pete Lien cement plants on anticline of Minnekahta Limestone, Rapid City, South Dakota.

3.4 Hills Materials processing facility and quarry in Minnekahta Limestone.

3.8 Open cut in the Minnekahta Limestone and underlying Lower Permian Opeche Shale (Darton, 1901). Abrupt fold exposed in the quarry highwall goes from near horizontal to over 45^{o} dip to the west. Lithified beds of the Spearfish Formation on the left side of the road.

4.1 Driving along axis of a syncline in the Minnekahta Limestone covered by a thin veneer of Spearfish Formation.

5.0 Grass-covered ridge to the left foreground is an anticline exposing the Minnekahta Limestone, separated by a syncline to the west from the tree-covered Minnekahta dip slope in the distance. Pete Lien quarry to the right.

5.6 To the left, quarry area with primary crusher is on an anticline in the Minnekahta Limestone. Conveyor belt passes under the road. To the right is a partially reclaimed pit with gypsum beds in the Spearfish Formation in the distance.

6.0 Gravel of Sturgis terrace (Plumley, 1948) on Spearfish Formation to the right.

6.3 Cross Boxelder Creek. Opeche and Minnekahta formations are upstream to the left. This section of the creek is normally dry due to infiltration upstream into the Lower Mississippian Pahasapa Limestone (Newton and Jenney, 1880; Darton, 1901).

6.6 Gravel cap of Sturgis terrace on Spearfish Formation to the right.

7.0 Leaving Pennington County, entering Meade County, the largest county in South Dakota. Created and organized in 1889, it was named for Fort Meade, which was garrisoned as a U S military post in 1878 (Gilfillan et al., 1941).

7.4 Gypsum bed of the Spearfish Formation in parking lot to the right.

8.0 Town of Blackhawk, named after Blackhawk Creek. Driving on the Spearfish Formation with gypsum beds to the right. Tree-covered dip slope of Minnekahta Limestone to the left. Turn right to West I-90.

8.3 Overpass on I-90. Turn left onto West I-90. Will be on the Spearfish Formation.

9.7 Crossing DM&E railroad.

10.7 To the right, tree-capped hogback of Sundance Formation, Unkpapa Sandstone, Morrison Formation, with Lakota Formation at the top. Hummocky landslide topography is typical along the base of the hogback. The highway follows the “Red Valley” or “Race Track”, which is the valley formed in the Spearfish Formation that encircles the entire Black Hills. Tree-covered Minnekahta Limestone dip slope to the left.

11.5 Roadcut along Eastridge Hill Road to the right exposes the Sundance through Lakota formations (Fig. 3). Ahead are cliffs of Minnekahta Limestone in Stagebarn Canyon.

12.8 Area of the 2006 Eastridge fire to the right. The Tilford dome (Vanocker laccolith) is the low conical mountain ahead. The red LAK member of the Sundance Formation is visible on the hogback to the right. This red bed represents the regressive phase of the Sundance. The top of the LAK marks the disconformable Oxfordian-Callovian boundary. The hill is capped by sandstone of the Lakota Formation.

13.3 Stagebarn Canyon to the left, named for a stage station and barn used for relays of horses along the old Deadwood Trail which connected Rapid City with Piedmont (Gilfillan et al., 1941). Boulders to several feet in diameter on both sides of I-90 are from flooding in Stagebarn Canyon, and may have been carried by mud flows. Some were washed out by the flood of 1907 (Gries, 1996). The mouths of Little Elk and Elk creeks also have boulder fields.

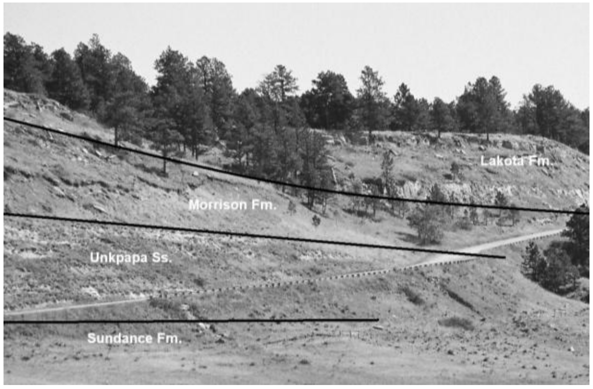


Figure 3. Eastridge Hill Road with exposures of the Sundance to Lakota formations.

14.1 Whitegate monocline ahead left, with folded Upper Pennsylvanian-Lower Permian Minnelusa Formation (Winchell, 1875; Darton, 1901) and Pahasapa Limestone is visible along the skyline (Fig. 4). Bedding becomes almost vertical where exposed along Little Elk Creek, with the area of Pahasapa Limestone being known as White Gate, and a short distance upstream, the area of upper quartzite of the Middle Cambrian-Lower Ordovician Deadwood Formation (Darton, 1901) being known as Red Gate. Piedmont Butte to the right has also been known as Piedmont Peak (Fig. 5). In 1889, the first specimen of *Barosaurus lentus* was excavated here by O.C. Marsh of Yale University from the Upper Jurassic Morrison Formation (Gries, 1996). The Timber of Ages campground is on the east end of the butte, with a trail that winds through many exposed petrified logs.

15.2 Gap of Elk Creek east of Piedmont Butte to the right. Town of Piedmont to the left. Founded in 1890, the name of French derivation meaning “at the foot of the mountain” was selected because the town was platted at the foot of the Black Hills (Gilfillan et al., 1941).

15.8 Cemetery on hill to the right is on Sundance Formation overlying Spearfish Formation. A small underground gypsum mine was developed under the hill. The old plaster mill is gone. Exposure of Spearfish Formation on the left.

16.6 To the left, is the area of the 2005 Ricco fire which was started when a front loader made a spark while moving rocks in a field west of the highway. Flatirons and dip slope of the Minnekahta Limestone are exposed. Water gap of Little Elk Creek and the Whitegate monocline is also visible.

Figure 4. Whitegate monocline with the Pahasapa Limestone and Minnelusa Formation dipping to the east.

Figure 5. Piedmont Butte, type locality of the sauropod *Barosaurus lentus*.

16.8 Boulders deposited across the valley are from Little Elk Creek. Most are Paleozoic rocks that occur 2-3 miles (3.2-4.8 km) above the mouth of the canyon and were well rounded during their short transport. Some of the boulders are in ridges with distributary channels between them that were formed by over nine different floods (Gries, 1996). Breached boulder dams formed by landslides occur upstream near White Gate and would have produced floods when they failed.

17.4 Cross Little Elk Creek and boulder field. Terraces of Little Elk Creek to the left, floodplain to the right.

18.0 Cross Elk Creek, named for the many elk early settlers found grazing along the stream (Gilfillan et al., 1941). Gravel pits in terraces to the right.

18.4 Bethlehem Road to the left goes to Bethlehem Cave in the Pahasapa Limestone and the former town site of Calcite, named for the crystalline Minnekahta Limestone that was roasted there to make lime. Calcite was established by the Homestake Mining Co. and started producing lime around 1904 for use in their mills. Kilns were operated for 10-12 years, with the lime shipped to Lead on narrow gauge rails (Gilfillan et al., 1941). Spearfish Formation with gypsum to the right has small slump scarps at the base of the hill.

19.3 Tilford rest stop. Minnekahta Limestone to the left. The town of Tilford was founded in 1888 and named for Col. J.G. Tilford of the 7th U.S. Cavalry (Gilfillan et al., 1941).

19.8 Ponds on both sides of the highway are from springs flowing from the Minnekahta Limestone that supply water for Morris Creek. Gap for Morris Creek in the distance to the right.

20.9 Multiple Tertiary latitic and trachytic intrusions about 56 Ma formed the Tilford Dome (Vanocker laccolith) to the left which is about 2 miles (3.2 km) in diameter (Gries, 1996) (Fig. 6). There is a very small area of Deadwood Formation exposed at the center of the dome. Flatirons of Minnekahta Limestone are along its flanks. The Tertiary intrusives in the Black Hills range from 39-61 Ma, are in a general N70^{o}W trend, and extend from Devils Tower to the west, east to Bear Butte northeast of Sturgis, SD. Hogback capped by Lakota Formation is to the right with hummocky landslide topography along the base.

21.8 Truck weigh station to the left on Sturgis terrace.

22.2 Cross the DM&E railroad. Gypsum outcrop to the left.

23.2 Gap of Pleasant Valley Creek to the right. Spearfish Formation capped by the Sundance Formation ahead.

26.1 To the left, is the Black Hills National Cemetery, established in 1948. VFW Memorial Park Chapel to the right.

26.6 Cross Alkali Creek, named for large alkali springs around its source. It has also been known as Warren Creek (Gilfillan et al., 1941). Passing hummocky landslide topography along the base of the hogback.

Figure 6. Multiple Tertiary latitic and trachytic intrusions make up the Vanocker laccolith.

26.8 Flat surface of the Sturgis terrace on the Spearfish Formation to the left.

27.0 Roadcut in Sundance Formation on the right has thin limestone layers and small barite nodules.

27.5 To the right, gap of tributary of Cottle Creek, sometimes known as Cattle Creek from an early misspelling. The creek was named after Frank Cottle, who in the 1870's had a store at the mouth of Elk Creek on the Fort Pierre-Deadwood Trail (Gilfillan et al., 1941).

28.2 Exit 32 north to Junction Avenue and Sturgis.

28.7 Cross DM&E railroad.

29.1 Town of Sturgis, named after Lt. J. G. Sturgis who was killed at the Battle of the Little Bighorn. Sturgis hosts the annual Sturgis Motorcycle Rally which each year has attracted over 750,000 visitors for the week long event. Bear Butte, a rhyolitic intrusion, can be seen on the horizon to the right beyond the ridge of Lakota Formation (Fig. 7).

Ft. Meade Military Reservation is east of Sturgis. Fort Meade was selected by Gen. Philip Henry Sheridan, commander of the Union forces at the battle of Gettysburg, and was named in honor of Gen. George G. Meade who was commander of the Army of the Potomac (Gilfillan et al., 1941). Units of the 1st and 11th infantry and the reorganized 7th Cavalry were stationed here. It was a strategic location by a gap in the Dakota hogback, on a favorite hunting trail of the Sioux, and near the junction of the Bismarck, Ft. Pierre, and Sidney pioneer trails. Cpt. Miles Keogh's horse Comanche, one of the surviving horses of the Battle of the Little Bighorn, was retired here with full military honors (Hasselstrom, 1994). Fort Meade became a VA hospital in 1944.

Figure 7. Bear Butte, a Tertiary rhyolitic intrusion.

30.0 Spearfish Formation capped by the Sturgis terrace on both sides of I-90.

30.5 Take exit 30 to Boulder Canyon Road (West 14A). Turn left to Deadwood and Lead.

30.7 Overpass of I-90.

30.9 Cross DM&E railroad. Spearfish Formation with gypsum capped by the Sturgis terrace to the left. In the valley of Bear Butte Creek, so named because it goes past Bear Butte (Gilfillan et al., 1941). The creek joins with the Belle Fourche River about 20 miles (32 km) to the east. Fall River and Lakota formations form the hogback ridges to the right. Minnekahta dip slope ahead.

31.9 Entering Boulder Canyon, so named by the first travelers over the Sturgis-Deadwood Toll Trail because of the numerous large limestone boulders on the canyon floor (Gilfillan et al., 1941). The gravels in Bear Butte Creek are mostly Paleozoic sedimentary and Tertiary igneous rocks. A levee has been built to help prevent flooding. Contact of the Spearfish Formation and Minnekahta Limestone is on the left.

32.0 Opeche Shale and contact with the Minnelusa Formation on both sides of the road.

32.4 Cliffs are upper Minnelusa "Converse Sand" with distorted bedding from evaporite dissolution.

32.8 Cross Bear Butte Creek. Upper Minnelusa Formation sandstone with purple shale forms the cliffs.

33.0 Leaving Meade County and entering Lawrence County. Lawrence County was created in 1875, officially organized in April 1877, and named for Col. John Lawrence, a member of the 1875 Territorial legislature from Yankton (Gilfillan et al., 1941).

33.2 High canyon walls of Pahasapa Limestone. The Pahasapa is about 500 feet (152 m) thick and is the dominant cliff-forming rock in the Black Hills. Post-Mississippian dissolution and terra rossa occur along the contact with the Minnelusa Formation. The Pahasapa Limestone is known as the Madison Limestone and Madison aquifer in the subsurface, and is one of the major aquifers in the Black Hills. The Pahasapa has numerous solution cavities and caves, many lined or filled with calcite. Bear Butte Creek is normally dry here because the water flows underground into the cavernous limestone.

33.8 Sheared Pahasapa Limestone on the right from folding of the Whitewood anticline.

33.9 Looking back is the rock "rainbow" of Rainbow Ridge, on the west flank of the Whitewood anticline which starts at the Vanocker laccolith to the south and trends north for over 100 miles (161 km). Minnelusa Formation on the left with steep, west dipping beds.

34.1 Cross Bear Butte Creek. West dipping Pahasapa and Minnelusa formations ahead. Quaternary terrace gravel on bend to the right.

34.5 Ahead, Opeche Shale-Minnekahta Limestone contact dipping west (Fig. 8). Junction of Bear Butte and Boulder creeks to the left.

34.7 On the right, flatirons of the Minnekahta Limestone dip west from the Whitewood anticline into the Boulder Park syncline which has Spearfish Formation and Minnekahta Limestone at the surface. Entering the treeless area of Boulder Park.

36.2 East dipping Minnekahta Limestone overlying the Opeche Shale on the west flank of the Boulder Park syncline to the right.

36.5 Entering the Black Hills National Forest, established by President Grover Cleveland on February 22, 1897. It includes 1,534,164 acres in

South Dakota and Wyoming. “Converse Sand” of the upper Minnelusa Formation on the right.

Figure 8. West dipping ridge of Minnekahta Limestone over grass-covered Opeche Shale, west side of the Whitewood anticline.

36.9 Collapse in the Minnelusa Formation with contorted and faulted beds (Fig. 9). Disruption of the beds is also from White River age solution during deposition of overlying gravels.

37.0 Contact of the Minnelusa and Pahasapa formations with red terra rossa along the road. There are solution cavities in the Pahasapa, and brecciation from Tertiary dissolution.

38.1 Gravel of the Mountain Meadow terrace to the right (Fig. 10), the highest terrace level of Plumley (1948) in the Black Hills.

38.3 Brecciated Pahasapa Limestone from Tertiary dissolution to the right.

38.5 Seep induced slump in gravels to the left.

38.8 Mountain Meadow terrace gravel to the right.

39.1 Slumps in gravel to the right.

39.6 Oak Ridge Cemetery on Mountain Meadow terrace to the right. This area, known as Mountain Meadow, gives a view of the flat terrace surface and the area burned by the June 29, 2002 Grizzly Gulch fire.

40.0 Gravel of the Mountain Meadow terrace to the right. Descend toward Whitewood Creek.

Figure 9. Contorted and faulted upper Minnelusa Formation from evaporite dissolution and Tertiary weathering.

Figure 10. Gravel of the Tertiary Mountain Meadow terrace of Plumley (1948).

40.9 Type section of the brownish-orange Upper Ordovician Whitewood Limestone (Darton, 1904), underlain by greenish shale of the Upper Ordovician Winnipeg Formation (Dowling, 1895) (Fig. 11). The Whitewood contains abundant burrow traces (Fig. 12), orthocone cephalopods, and the large gastropod *Maclurites* sp. The hill is capped by the Upper Devonian-Lower Mississippian Englewood Limestone (Jagger, 1901; Darton, 1901) and Pahasapa Limestone. Slag piles of the old Golden Reward smelter to the left.

41.1 Cross Whitewood Creek. Ascend through the Deadwood and overlying Winnipeg formations.

41.5 Intersection of US 14A with US 85. The Deadwood-Winnipeg formation contact is to the right. The vertically burrowed “Skolithos Sandstone” of the uppermost Deadwood directly underlies the Winnipeg. Remains of the Golden Reward smelter can be seen behind the wastewater treatment plant to the left. Follow US14A straight ahead toward Deadwood.

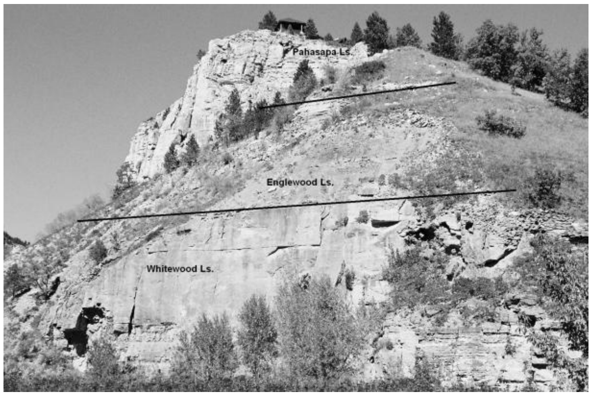


Figure 11. Whitewood Limestone type section, Englewood Limestone, capped by Pahasapa Limestone.

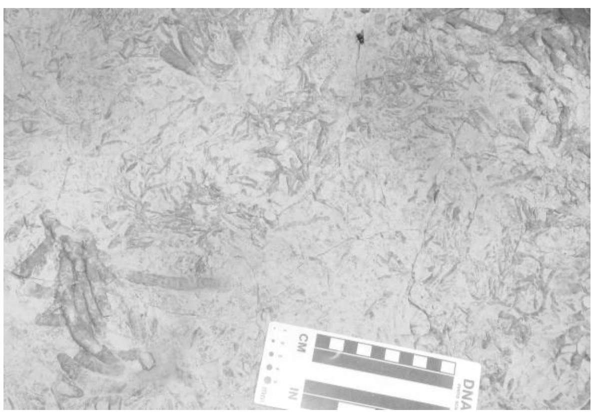


Figure 12. Horizontal burrows on bedding plane of Whitewood Limestone.

42.0 To the right is the type section of the Deadwood Formation consisting of about 400 feet (122 m) of basal conglomerate, orthoquartzite, and bioturbated glauconitic sandstone, shale, limestone, and intraformational conglomerate (Fig. 13).

42.3 On the left, the Deadwood Formation dips about 10^{o} east and lies on the upturned Lower Proterozoic Flag Rock and Grizzly formations (Fig. 14). This contact is the worldwide Great Unconformity, and represents a gap of about 1.3 billion years in the rock record between the Precambrian schist and the Deadwood Formation. Several large boulders of vein quartz are along the contact, which was mined extensively near Lead and Central City for gold eroded from the Homestake Formation and concentrated in conglomeratic channels of the basal Deadwood Formation. Known as cement ore, it only required crushing to recover the gold, with no chemical treatment. There is as much as 200 feet (61 m) of relief on the Precambrian surface in the Black Hills, but the erosional surface was fairly flat here, with little channel development and deposition of basal conglomerate. Here the basal Deadwood Formation contains small inarticulate brachiopods and herringbone cross bedding.

Figure 13. Deadwood Formation type section, Deadwood, South Dakota.

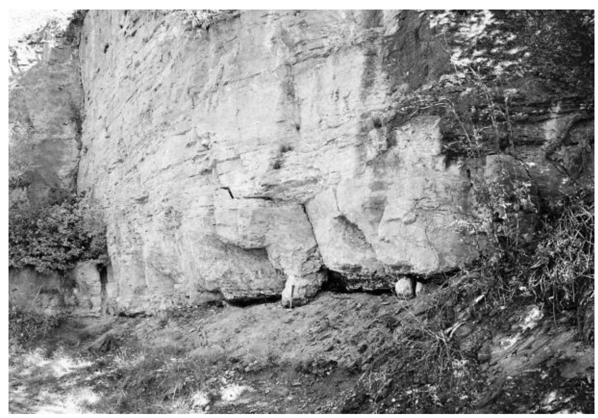


Figure 14. The Great Unconformity; contact of Cambrian-Ordovician Deadwood Formation with Lower Proterozoic Grizzly Formation. Hammer is 16 in (40.6 cm) long and is on the quartz boulder on the contact at the lower center of the photo.

42.4 Intersection of US14A and Main Street through Deadwood. Continue on US 14A. Deadwood, elevation 4,531 feet (1,381 m) above sea level, boasts of such famous Black Hills characters as James Butler “Wild Bill” Hickok, Martha “Calamity” Jane Cannary-Burke, outlaw Sam Bass, Henry Weston “Preacher” Smith, sheriff Seth Bullock, and prospector “Potato Creek” Johnny

Perrett. One can visit the graves of most of these picturesque figures at the Mt. Moriah Cemetery at Deadwood. The Adams Museum displays many historical items and a model of Potato Creek Johnny's famous gold nugget.

In the fall of 1875, John B. Pearson of Yankton, Dakota Territory, discovered rich placer diggings in Deadwood Gulch and the town of Deadwood was born, taking its name from the dead timber on the hillsides which was left from a fire. By the end of the summer, 25,000 people were in the area. Much of the town was destroyed by fire on September 29, 1879, but was rebuilt using brick and stone. A flood in 1883 again caused severe damage to the town.

Deadwood received service from the Fremont, Elkhorn, and Missouri Valley Railroad in 1890 due to the persuasion of Seth Bullock and his business partner Sol Star. Seth Bullock was the first sheriff of Deadwood, owned many local businesses, and was Captain of Troop A of Theodore Roosevelt's Rough Riders during the Spanish American War. When Bullock's and Star's hardware store burned down in 1894, they rebuilt a luxury three story hotel with steam heat on the site for $40,000. Seth Bullock died of cancer on September 23, 1919 in room 211 of the Bullock Hotel, which is supposed to be haunted by his ghost (Lewis and Fisk, 2006).

On August 2, 1876, James Butler "Wild Bill" Hickok was shot in the back of the head in Saloon No. 10 by Jack McCall while holding the "dead man's hand" of black aces and eights. McCall claimed he was avenging his brothers death, which was later determined to be untrue. He was found not guilty of murder after a two hour long trial by a miner's court and released. McCall was later rearrested after bragging about the killing and tried in Yankton, capital of Dakota Territory, and found guilty of murder. It was revealed that he had been hired by competing gamblers to make sure Hickok did not come to represent the law in Deadwood as he previously had in Kansas. Jack McCall was hanged March 1, 1877 and was the first person to be executed by U.S. officials in Dakota Territory. When his body was exhumed and moved to a different cemetery in 1881, the hangman's noose was found still around his neck (Weiser, 2010).

Henry Weston "Preacher" Smith was the first minister in the Black Hills and was shot through the heart August 21, 1876 while walking to Crook City. Before leaving he was offered a pistol, but he said "The Bible is my protection. It has never failed me yet." It was postulated he was killed by Indians, thieves, or by someone representing the various "dens of iniquity" of Deadwood who were afraid his preaching would cut into their business. His murder was never solved (Rezatto, 1983).

Sam Bass attempted gold mining in the Black Hills, but found robbing stages and trains more profitable, stealing $60,000 in gold coins from the Union Pacific Railroad, the railroads largest single robbery to this day. Bass was shot dead on July 19, 1878, in Round Rock, Texas, by Texas Ranger George Harold (Horan, 1977).

Calamity Jane died of pneumonia August 1, 1903, in a room at the Calloway Hotel near the town of Terry.

Potato Creek Johnny died in Deadwood in February, 1943, at the age of 77. The church bells rang 77 times in his memory.

42.6 Metamorphosed pillow basalt of the Flag Rock Formation to the left.

42.8 Intersection of US14A and Pine Street. Old Homestake mine slime plant on the hill to the left. Turn left on Pine Street.

42.9 Intersection with Sherman Street, turn right.

43.2 Bear right. Sherman Street changes to Charles Street. The historic Adams house is one block to the east.

43.6 Charles Street changes to Cliff Street. Grizzly Formation on the left.

43.9 Cross Whitewood Creek.

44.0 Cross Whitewood Creek.

44.4 Tertiary rhyolitic sill in the Grizzly Formation to the left (Fig. 15). Color banding of the Grizzly is relic bedding.

44.6 Cross Whitewood Creek at confluence with Gold Run Creek. Old town site of Pluma and intersection with US 385. Road changes to Main Street. Pluma is said to have been named by the Chicago, Burlington, and Quincy Railroad Company for a pioneer mining company (Gilfillan et al., 1941). It was here on the night of March 25, 1877, that bandit Sam Bass and his gang tried their fifth attempt in two months to rob the Cheyenne-Deadwood Stage bearing 11 passengers and

$15,000. The holdup failed when the horses bolted during the fatal shotgun shooting of coach driver Johnny Slaughter by gang member Robert McKimie. Follow US 85 ahead to Lead.

Figure 15. Light-colored Tertiary rhyolitic sill intruding dark-colored Grizzly Formation. Color banding of the Grizzly is relic bedding.

44.7 Entering Lead, elevation 5,213 feet (1,589 m) above sea level. The town was founded in 1876 under the name of Washington. In 1877, Washington and the adjoining town of Golden were combined as Lead City. In 1890 the town was incorporated and renamed Lead. In March of 1900 and again in March of 1907, Lead was all but destroyed by fire. Lead grew to a population of 8,392 in 1910, making it at the time the largest city in the Black Hills, and the second largest city in South Dakota. The name is derived from the rich "lead" or vein of gold-bearing quartz which formed the basis of the Homestake Mine (Gilfillan et al., 1941).

Gold was discovered in this area in 1876 by Thomas E. Carey. The Homestake deposit was located by Fred and Moses Manuel, Hank Harney, and Alex Engh on April 9, 1876. The claims were purchased by George Hearst, Lloyd Tevis, and James Ali Haggin for $70,000, and the Homestake Mining Company was incorporated in 1877.

The Homestake mine was developed to a depth of 8,150 feet (2484 m), has 60 levels with over 370 miles (595 km) of drifts, and produced over 40 million ounces of gold during its 125 years of continuous production before its closure in January 2002 (Fig. 16). Now a Deep Underground Science and Engineering Laboratory (DUSEL) for studying particle physics is being constructed underground at the mine site.

Contact of the Grizzly and Flag Rock formations is by the overhead sign for Lead.

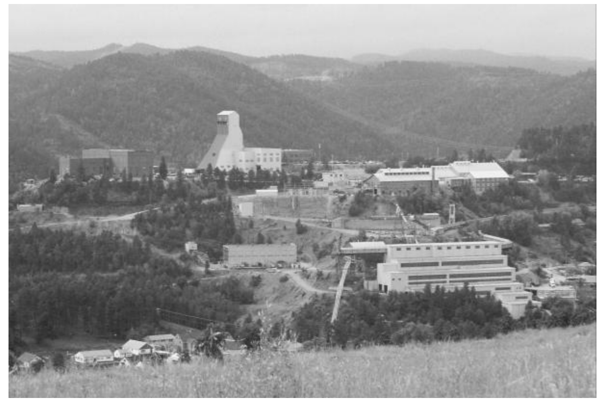


Figure 16. Yates shaft headframe and Homestake mine processing facilities.

44.9 Roadcut through Flag Rock Formation. Dark, resistant beds are dominantly metamorphosed basalts. The formation is cut by light-colored Tertiary rhyolite porphyry intrusives.

45.1 Contact of Flag Rock and Northwestern formations. Note the small southeast plunging manganese-stained folds in the Lower Proterozoic Northwestern Formation at the sharp bend in the road (Fig. 17).

45.4 Former site of the Homestake Mine cyanide treatment facility to the left. The Northwestern Formation is cut by Tertiary rhyolite porphyry intrusives.

45.5 Homestake Mill Park to the left. This park has an informative walking tour among old buildings and mining equipment.

46.0 **Stop 1**. Homestake Mine Visitor Center and Open Cut viewing area (Fig. 18). The pit is over 800 feet (244 m) deep, developed with 80 foot (24 m) benches, and follows the northwest trend of the DeSmet syncline. The Lower Proterozoic Ellison Formation is on the left side of the pit, Homestake Formation in the middle, and Poorman Formation on the right side cut by multiple Tertiary rhyolite dikes. The Deadwood Formation caps the hills on each side of the pit.

When leaving the visitor center, cross Main Street and proceed uphill on Mill Street.

46.4 Bear slightly right at the top of the hill to Houston Street. Pass South Cemetery.

46.8 **Stop 2**. Contact of Cambro-Ordovician Deadwood Formation and Lower Proterozoic Northwestern formations (Fig. 19). Note weathering of the schist and the thin layers of basal quartz pebble conglomerate.

Figure 17. Small, southeast plunging manganese-stained folds in the Northwestern Formation. Pen at lower center is 5 in (12.5 cm) long.

Figure 18. Homestake Mine Open Cut with Tertiary rhyolite dikes.

46.9 Tertiary phonolite intrusive along Precambrian contact and within the lower Deadwood Formation. The hill is capped by Tertiary rhyolite.

47.0 Normal fault with Lower Proterozoic Ellison Formation brought up against the Deadwood Formation (Fig. 20). The Deadwood Formation is slightly upturned at the fault contact from drag, and is cut by several small fault splays.

47.3 Road changes to Pavilion Street. Turn left at intersection and proceed past the Lead High School. In Poorman Formation on the east side of the Poorman anticline.

Figure 19. The Great Unconformity; Deadwood Formation-Grizzly Formation contact. Hammer at lower right center is 16 in (40.6 cm) long.

47.6 Turn left onto C.C. Curran Street. The Lead shopping center just to the right is built on bentonitic Tertiary White River Group sediments, and had to be stabilized due to movement of the bentonitic clay. These sediments are associated with channels eroded into the Precambrian rocks and have yielded fossils of the rhinoceroses *Hyracodon* sp. and *Subhyracodon* sp. and the turtle *Stylemys* sp. The Homestake Mansion on the hill ahead is also on White River Group sediments.

47.6 Turn left onto US14A/85 (Fairview Avenue). Heading down into the valley of Whitetail Creek through the Poorman Formation exposed near the core of the Poorman anticline.

48.0 Homestake and Ellison formations to the right on the west flank of the Poorman anticline.

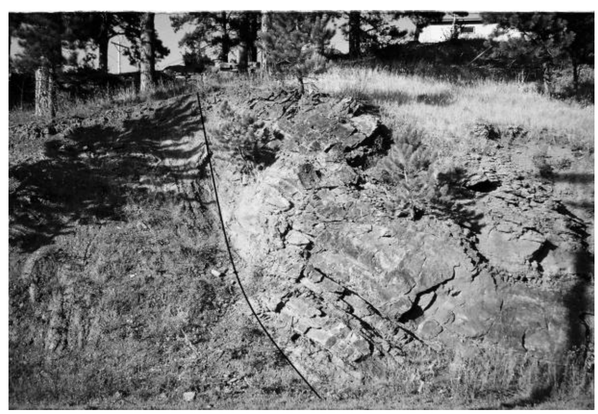


Figure 20. Normal fault with Ellison Formation on the left upthrown against Deadwood Formation on the right.

48.1 Kirk Road to the left, Ellison Formation with quartz veins and rhyolite sills to the right. The Ellison locally contains carbonate beds, and thin chloritic beds that had detrital chromite, now metamorphosed to chromium chlorite and fuchsite.

48.4 Ellison Formation with quartzite beds and quartz veins to the right.

48.7 Nevada Gulch Road on the right leads to the Terry Peak ski area, Bald Mountain mining district, and the Golden Reward mine. There are many Tertiary intrusives along the road.

The Bald Mountain mining district was located in 1877 in the area known as Portland and operated by the Mogul Mining Co. until 1900. Seth Bullock helped promote the Dakota Mining and Milling Company that operated the Gunnison and Jack-Pot mines near Portland. Chlorination of the ore was introduced in 1891, and cyanidation in 1892. Mining ended after WW I, resumed in 1934 until WW II, and reopened after WW II until closure in 1959, producing a total of 1,400,000 ounces of gold (Waterland, 1988). Mining resumed again in the 1980's when low grade gold mineralization in the Deadwood Formation became profitable by using the cyanide heap leach process.

48.9 Tertiary intrusives in Ellison Formation to the right. Mickelson Trail trailhead to the left.

49.2 Rhyolite intrusion in roadcut of Flag Rock Formation to the right, with a small adit at the west end.

49.7 Basal Deadwood Formation to the left.

49.9 Tertiary phonolite and rhyolite intrusives in the Deadwood Formation to the left. This large phonolite sill dips 5-10^{o} southwest and is at the margin of the Sugarloaf laccolith. The main body forms Sugarloaf Mountain about .3 mi (.5 km) to the east, which is capped by alkali rhyolite.

50.3 Powderhouse Road and phonolite-Deadwood Formation contact to the left.

50.6 Deer Mountain Road to the right has exposures of tinguite, a bright green aegerine-rich variety of phonolite.

50.8 Upland of phonolite and Deadwood Formation.

51.1 Greenish-gray Winnipeg Formation on the right.

51.2 Junction with Rochford Road (FS 17) to the left, which goes to the town of Rochford. A group of hunters, headed by M.D. Rochford, found gold-bearing ore in that vicinity in 1877. Within two years the Standby Mine and 120 stamp mill was in full operation. One of Rochford's better known residents was Annie Donna Tallent, the first white woman in the Black Hills.

51.4 Deadwood Formation and phonolite to the right.

51.8 Phonolite on the right.

52.1 Thick grus on deeply weathered grorudite, a variety of phonolite porphyry which covers a large area around, and caps, Deer Mountain.

52.7 FS 194 on the right leads to the summit of Terry Peak, elevation 7,064 feet (2,153 m) above sea level. The road traverses Deadwood Formation with phonolite and alkali rhyolite intrusives. Terry Peak is part of a large alkali rhyolite intrusion.

53.1 Pahasapa Limestone on the right.

53.6 Englewood Limestone-Pahasapa Limestone contact on the right. Driving along slope of Icebox Gulch toward Spearfish Canyon. Icebox Gulch follows the old Deadwood-Cheyenne trail, and is the type area of the Icebox Shale Member (McCoy, 1952) of the Winnipeg Formation.

53.9 Glauconitic sandstone and shale of the Deadwood Formation. Most of the bedding planes have horizontal burrow traces. The greenish-gray Winnipeg Formation overlies the Deadwood.

54.7 Laminated to thin-bedded sandstone and shale of the middle Deadwood Formation.

55.0 The high white outcrop ahead by Cheyenne Crossing is the Pahasapa Limestone. The tree-covered Englewood Limestone overlies the reddish-brown Deadwood Formation near the base.

55.3 Cheyenne Crossing, elevation 5,333 feet (1,625 m) above sea level, and the intersection of highways 14A and 85. Cheyenne Crossing was the location of a stage station on the old Cheyenne-Deadwood Trail and was named by advance agents for the Gilmer and Salisbury Stage Lines (Gilfillan et al., 1941).

Before the coming of the railroad, Spearfish Canyon was inaccessible to travelers until a railroad spur was built in 1893 from Englewood to Spearfish. It was said that the Spearfish Canyon line was the only railroad in the world on which the freight cars had to be chained to the siding to keep them from coming home by themselves (Gilfillan et al., 1941).

On the hill south of the junction is a slump lubricated by a small seep. Turn right, following US 14A into Spearfish Canyon toward Spearfish.

55.5 Yates Pond to the left.

55.6 Raspberry Gulch to the right, so named because of the wild raspberries which grow in the area (Gilfillan, et al., 1941). Driving into Spearfish Canyon, the longest, deepest canyon in the Black Hills, and following Spearfish Creek with abundant moss-draped Black Hills spruce and Ponderosa pine. The steep canyon walls are dominantly Pahasapa Limestone having numerous small caves. Spearfish Creek was so named because Native Americans were accustomed to spearing fish in its waters. In early times, the creek was also known as "Spearfish River" because of the strength of its flow as compared with other Black Hills streams (Gilfillan et al., 1941).

56.8 Elmore town site, which was named for railroad contractor Mike Elmore. This was once an important lumber camp and trading station on the Chicago, Burlington, and Quincy railroad. In 1933 a flood caused the abandonment of the railroad (Gilfillan et al., 1941).

56.9 Greenish-gray phonolite sills to the right along the Precambrian-Deadwood contact. The cliffs here are about 900 feet (274 m) high.

57.4 Phonolite sill to the right.

58.4 Annie Creek on the right flows over phonolite sills in the Deadwood Formation upstream to the east.

59.6 Diversion dam and intake No. 2 of the Homestake Mining Company constructed in 1916. At this point, water of Spearfish Creek entered a wooden stave pipe and was conveyed 6 miles (9.7 km) to the hydroelectric plant at Maurice.

60.0 Cross Spearfish Creek. Cliff of Pahasapa Limestone ahead.

60.6 Savoy town site, originally named Spearfish Falls (Gilfillan et al., 1941). This is the location of the Latchstring Inn, which has been in operation since 1907. Behind the Inn is a trail down into the canyon that passes Spearfish Falls, where Little Spearfish Creek joins Spearfish Creek (Fig. 21). To the left is the turnoff for FS 222 to Roughlock Falls, which is about 1 mile (1.6 km) to the west and flows over the Whitewood Limestone (Fig. 22). The falls were named because freighters had to chain, or rough-lock their wheels at a steep part of the road along the creek (Gilfillan et al., 1941).

Figure 21. Little Spearfish Creek flows over the Deadwood Formation at Spearfish Falls.

61.0 Deadwood, Englewood, and Pahasapa formations to the right, with good views up and down Spearfish Canyon.

61.2 Contact of Pahasapa and Englewood limestones on the cliff ahead.

61.5 Calamity Gulch to the right leads to the old town site of Preston, and Ragged Top Mountain, named because of its ragged appearance on the skyline (Gilfillan et al., 1941). This small dome was formed by a phonolite intrusion which is exposed at its center. Gold mineralization was discovered in dolomitic zones of the Pahasapa Limestone in 1896 and was mined until 1916. Mineralization was along fractures and adjacent to Tertiary intrusions (U.S. Bureau of Mines, 1954).

Figure 22. Little Spearfish Creek flows over the Whitewood Limestone at Roughlock Falls.

61.6 Rockfall associated with the Winnipeg Formation to the left.

62.0 Deadwood Formation in roadcut.

62.4 Cross mouth of Iron Creek. The closed gravel road (FS222) to the left goes to the area of Iron Creek Lake and Potato Creek. In 1929, prospector "Potato Creek" Johnny Perrett found the largest nugget ever to be discovered in the Black Hills, in Potato Creek. It weighed 7½ troy ounces and was sold for $250 to W.E. Adams. "Potato Creek" Johnny was a prankster, and his large nugget may have possibly been several smaller nuggets melted together. A replica of the nugget is on display at the Adams Museum in Deadwood.

62.7 **Stop 3**. Icebox Shale Member of the Winnipeg Formation on the left at road level, grading upward into the yellowish Roughlock Siltstone Member (McCoy, 1952) (Fig. 23). The Whitewood, Englewood, and Pahasapa limestones are exposed farther up the cliff.

63.0 Pahasapa-Englewood contact on cliff ahead.

63.4 Whitewood Limestone at road level on the left. Will be passing a stretch of rockfalls that reactivate during heavy rains.

64.5 Large Pahasapa boulders from a 1994 rockfall in Spearfish Creek to the right. Detachment area is visible on the cliff above. Large fracture in phonolite forming Eleven Hour Gulch is ahead to the left.

Figure 23. Icebox Shale Member grading into the Roughlock Siltstone Member of the Winnipeg Formation.

64.9 Phonolite sill on the left is along the Winnipeg Formation. Cliff of Pahasapa Limestone ahead.

65.5 Phonolite intrusion on the left with alteration along fractures is overlain by the Winnipeg Formation.

65.7 Hydroelectric Plant No. 2 of the Homestake Mining Company built in 1917 (Fig. 24). The water for the turbine falls 400 feet (122 m) and produces 225 psi. At this point, the full flow of Spearfish Creek is returned to the creek bed where it flows for a mile (1.6 km) before being taken out at a second diversion dam to be carried in pipes to Hydroelectric Plant No. 1 at Spearfish.

66.0 Maurice town site. Upstream on Cleopatra (Squaw) Creek, potholes formed in the Deadwood Formation at the "Devil's Bathtub" are popular for swimming. About 2 mi (3.2 km) to the east is the Carbonate mining district which was discovered in 1881. Silver, lead, manganese, and gold mineralization occurred along fractures and solution cavities in the Pahasapa Limestone.

66.7 Homestake Mine diversion dam, where water was diverted to a tunnel following the valley to Spearfish. The Winnipeg Formation is at creek level.

67.0 Rock slide area. Pahasapa Limestone cliff ahead.

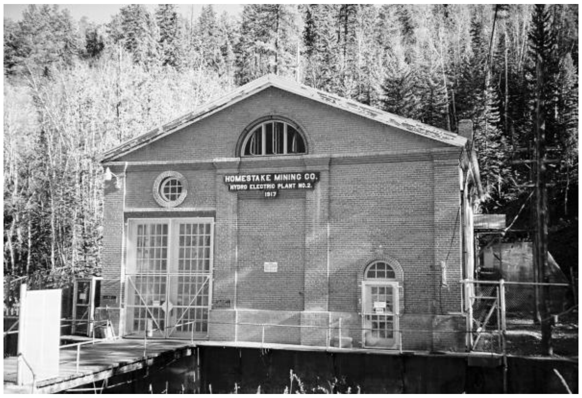


Figure 24. Hydroelectric Plant No. 2 of the Homestake Mining Company built in 1917.

67.4 South dipping Deadwood Formation to the left, with a small kink fold on the south end of the roadcut.

67.6 Winnipeg Formation overlying the Deadwood Formation above the road is often associated with slumps and slides.

67.9 **Stop 4.** Bridal Veil Falls on the right flows over a phonolite sill in the Deadwood Formation where Rubicon Gulch joins Spearfish Creek (Fig. 25). The sill has prominent flow sheeting (Fig. 26) and abundant small biotite and pyroxene crystals. Another phonolite sill overlies the Pahasapa Limestone capping the mountain ahead to the north.

68.2 Phonolite and Deadwood Formation.

68.3 Rock slide to the left.

68.5 Roadcut in middle Deadwood Formation of sandstone, shale, limestone, and intraformational conglomerate (Fig. 27). At the north end an adit follows a conglomerate bed (Fig. 28).

69.1 Steeper dipping Deadwood Formation on the margin of a phonolite intrusive to the left.

69.6 Whitewood Limestone to the right.

69.7 Muddy shelf facies of the Englewood Limestone with chalcedony-replaced evaporite nodules to the left.

69.8 Diversion dam to the right. Spearfish Creek is usually dry downstream of this point due to infiltration into the porous Pahasapa Limestone.

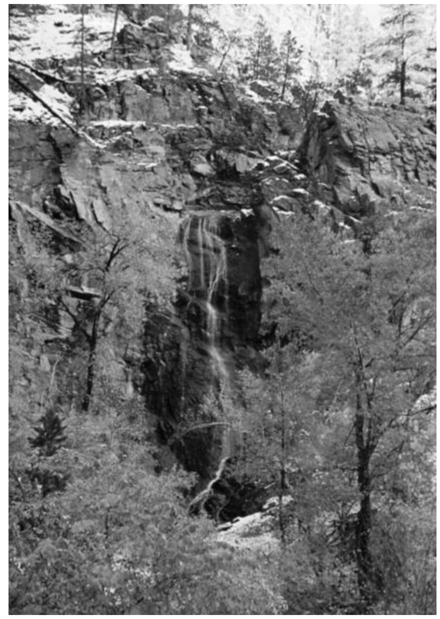


Figure 25. Bridal Veil Falls flows over a phonolite sill in the Deadwood Formation.

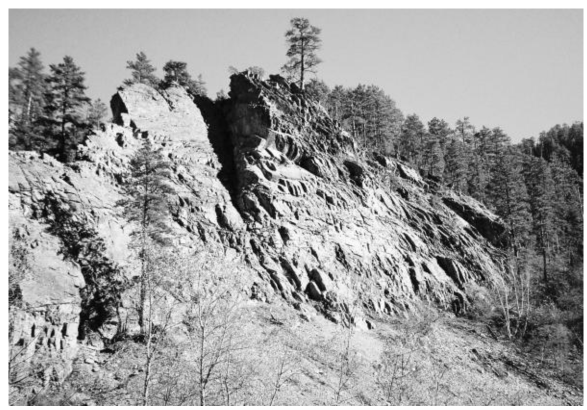


Figure 26. Flow sheeting in phonolite by Bridal Veil Falls.

Figure 27. Intraformational conglomerate bed in the middle Deadwood Formation between undisturbed layers.

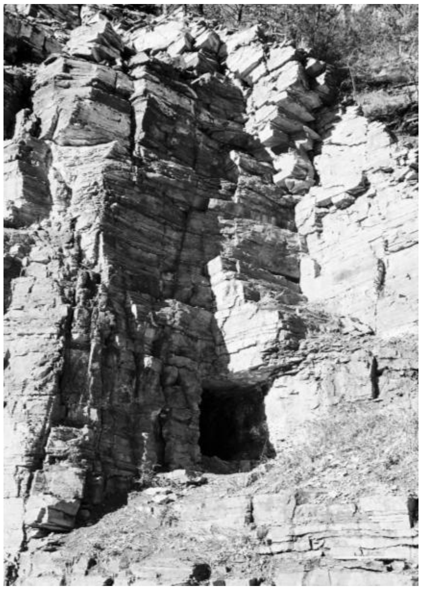


Figure 28. Adit following an intraformational conglomerate bed in the Deadwood Formation.

69.9 Englewood Limestone-Pahasapa Limestone contact to the left with transition zone into the Pahasapa Limestone (Fig. 29). The transition zone represents a short period of erosion on top of the Englewood and contains insoluble clay and rip-up clasts from the Englewood. Clay residue is absent above the transition zone, which varies from about 6 in (15 cm) to 5 ft (1.5 m) thick in the Black Hills. In the Spearfish Canyon area it contains well-rounded coarse sand (Fahrenbach, 1995).

70.5 The reddish-orange lower Minnelusa Formation is high on the canyon wall ahead. The Pahasapa Limestone dips below the surface in the next mile (1.6 km).

Figure 29. Englewood Limestone-Pahasapa Limestone contact with transition zone.

71.6 **Stop 5**. Vuggy Pahasapa Limestone. The limestone is dolomitic and has a moldic texture, rip-up clasts, cross bedding, and chert layers. The Pahasapa is part of the extensive carbonate deposits of the Wyoming shelf.

71.8 Terrace gravels on the left.

72.3 Leaving the Black Hills National Forest.

72.6 Cross dry Spearfish Creek. Cliffs of contorted sandstone beds of the upper Minnelusa Formation are to the left.

72.8 Dale Sander memorial rifle and pistol range to the right with a ridge of Minnekahta Limestone above.

73.0 Contorted and vuggy sandstone of the upper Minnelusa Formation to the right at road level.

73.1 Homestake mining company building built in 1904 to the right.

73.4 Spearfish Formation with terrace gravel cap to the right. The contact with the Minnekahta Limestone is near the base.

73.6 Intersection of US 14A with Winterville Drive on the left that goes to the D.C. Booth fish hatchery. Well house on the corner has a well in the Madison aquifer producing about 2000 gpm. Spearfish Formation with gypsum and gravel cap is on both sides of the road. Hogback of Lakota and Fall River formations ahead on Lookout Peak, elevation 4,478 feet (1,365 m) above sea level. The peak was used by early settlers as a lookout, and has also been know as Spearfish Peak and Joe's Peak, after California Joe, a prominent character of the northern Hills (Gilfillan et al., 1941)

73.9 Intersection of Spearfish Canyon Road (US 14A) with East Colorado Boulevard (Business 90). Turn right and follow East Colorado Boulevard. In Spearfish Formation with gypsum.

75.4 Entrance 14A to East I-90. Continue ahead on East 14A (East Colorado Boulevard).

76.3 Cross False Bottom Creek. Traveling over Centennial Prairie having Spearfish Formation and Quaternary terrace gravels. To the left ahead is the Middle Jurassic Gypsum Spring Formation capped by the Sundance Formation.

79.2 Cross Miller Creek. The large hill ahead is Elkhorn Peak, elevation 4,522 feet (1,378 m) above sea level, which was domed up by a Tertiary intrusion, exposing the Minnelusa Formation at the center. The peak was named for the numerous elk antlers that were annually shed here at a favorite elk feeding ground (Gilfillan et al., 1941). Turn right onto US85 toward Deadwood.

80.1 Cross Polo Creek.

81.5 Crook City Road and Hills Material Co. Centennial quarry in the Minnekahta Limestone to the left.

81.8.1 **Stop 6**. Stromatolitic Minnekahta Limestone. Stromatolite types include planar, hemispherical, and laterally-linked hemispheroids (Fig. 30). The environment was an intertidal zone adjacent to tidal flats. Many of the bedding planes are stylolite surfaces. When broken, the Minnekahta has a petroliferous odor. Across the road is the Minnekahta Limestone-Opeche Shale contact with a purplish zone caused by groundwater movement along the contact that leached iron from the top of the Opeche Shale (Fig. 31).

82.2 Large roadcut in Opeche Shale capped by Minnekahta Limestone. The soft Opeche Shale is easily weathered and is not normally well exposed. The Opeche Shale-Minnelusa Formation contact is in the valley ahead.

82.6 Entering the Black Hills National Forest. Upper Minnelusa Formation "Converse Sands" are on the left. Contorted beds from evaporite dissolution have been accentuated by Tertiary weathering. Road follows the Minnelusa down section through red shale, sandstone, and siltstone.

84.8 Covered Minnelusa-Pahasapa contact in valley.

85.4 Road (FS133) to the right goes to Mt. Theodore Roosevelt, comprised of Tertiary phonolite and rhyolite intrusions.

85.9 **Stop 8**. Cavernous Pahasapa Limestone. When the roadcut was excavated, many vugs and caves were exposed that contained large nailhead and dogtooth spar calcite crystals.

Figure 31. Opeche Shale-Minnekahta Limestone contact.

83.6 **Stop 7.** Rhythmic alternation of sandstone and shale of the middle Minnelusa Formation (Fig. 32).

84.7 Henry Weston "Preacher" Smith Monument to the left. The monument is located near where Preacher Smith's body was found.

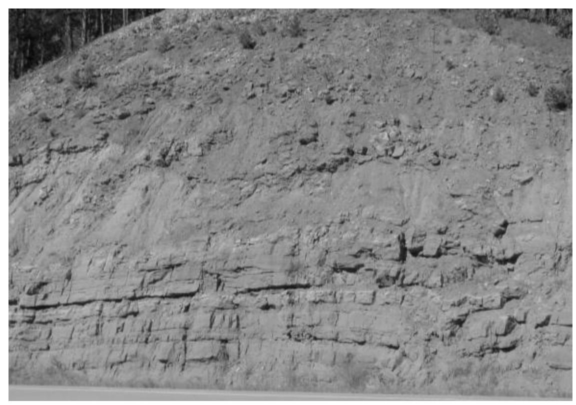


Figure 32. Alternating sandstone and shale of the middle Minnelusa Formation.

86.2 Englewood Formation of dark-gray basal shale grading into gray to purplish-pink dolomite and dolomitic limestone. The section here is about 65 feet (20 m) thick, and was deposited in a topographic low on a pre-Late Devonian erosional surface (Fahrenbach, 1995). The Devonian-Mississippian boundary is about 7 feet (2 m) below the Pahasapa contact (Klapper and Furnish, 1962). The Whitewood Limestone, Winnipeg Shale, and Deadwood Formation are exposed farther along the roadcut.

86.3 Intersection of US85 with US14A. The Deadwood-Winnipeg formation contact is to the right. The vertically burrowed "Skolithos Sandstone" of the Deadwood directly underlies the

Winnipeg. Turn right toward Deadwood, following US14A/Main Street-Pioneer Way.

87.2 Follow Pioneer Way (US14A) to South US 85/385.

87.7 Turn left onto Pine Street, then right onto Sherman Street (South US 85).

88.0 Sherman Street changes to Charles Street.

88.4 Charles Street changes to Cliff Street.

89.5 Old town site of Pluma and intersection of Cliff Street/US 85 and US 385. Turn left onto US 385.

89.7.1 Layered Tertiary rhyolitic intrusive to the right contains xenoliths of dark gray Grizzly Formation and rhyolitic breccia (Fig. 33). Laminations dip 60-80^{o} southwest. This area was burned by the June 29, 2002 Grizzly Gulch fire.

89.8 Intersection with Kirk Road to the right. This road goes through the Flag Rock, Northwestern, and Ellison formations, Tertiary rhyolite intrusives, past the Yates shaft and the reclaimed Yates waste dump of the Homestake Mine, and the old Kirk power plant.

89.9 Cross Whitewood Creek.

90.2 The road begins to climb the west side of Strawberry Ridge and follows West Strawberry Creek. This ridge took its name from the abundance of wild strawberries growing on it in season (Gilfillan et al., 1941). Numerous small Tertiary dikes and sills can be seen cutting the nearly vertical Grizzly Formation.

90.3 Grizzly Gulch on the right drains into West Strawberry Creek.

92.5 Approaching the top of Strawberry Ridge having prominently jointed rhyolite and trachyte intrusions along the Precambrian-Deadwood contact and within the Deadwood Formation.

93.0 Top of Strawberry Ridge, elevation 5,732 feet (1,747 m) above sea level.

93.1 Gilt Edge Road to the left leads to the Gilt Edge Mine superfund site (Fig. 34). Gold mining was in low grade replacement ore of the Deadwood Formation associated with Tertiary intrusives.

Figure 33. Xenoliths of Grizzly Formation in layered Tertiary rhyolitic intrusive. Hammer is 16 in (40.6 cm) long and parallel to layering.

93.5 On the right is the old LOR iron mine developed in hematitic conglomerate of the basal Deadwood Formation that was locally eroded from Precambrian iron-formation.

93.6 Strawberry Hill picnic ground to the right. Talus of Deadwood boulders to the left.

94.0 Small but complex, southeast plunging fold in the Grizzly Formation to the left (Fig. 35).

94.6 Leaving Strawberry Ridge. Galena Road (FS 534) to the left follows Bear Butte Creek 3 miles (4.8 km) to the town of Galena and the Galena mining district. The canyon of Bear Butte Creek cuts through metagraywacke schist, metabasalt, and carbonaceous phyllite.

Galena was settled as a placer camp in the spring of 1876 at a point where the Galena Trail branched off from the Custer-Deadwood Trail. Placer deposits dwindled, but silver, lead, and zinc mineralization was found in two dolomitic zones within the Deadwood Formation. The upper zone, or “upper contact,” contained oxidized ores, while the lower zone, or “lower contact,” contained unoxidized ore. The Richmond-Sitting Bull was the largest mine working the “upper contact”, while the Double Rainbow was the largest mine working the “lower contact” ores. Some galena from the “lower contact” assayed over 1,000 oz. of silver per ton. The Chicago-Burlington-Quincy Railroad built a branch line into Galena, and several large stamp mills were built, including the 120 stamp Branch Mint Mill, and the Florman Mill.

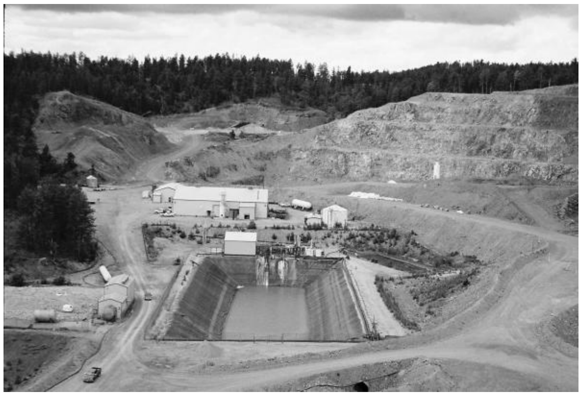


Figure 34. Gilt Edge Mine near Galena, South Dakota in September 2001.

Figure 35. Small, complex, southeast plunging fold in the Grizzly Formation. Hammer is 16 in (40.6 cm) long.

Aunt Sally (Sarah Campbell), the African American woman who was the cook for Custer's 1874 expedition to the Black Hills, is buried here at the Vinegar Hill Cemetery. She was the first woman to file a mining claim in the Black Hills, Claim No. 7 below discovery in Custer Gulch, on August 5, 1874, as part of the Custer Park Mining Company. She returned to the Black Hills in 1876, living in Crook City and having a ranch along Elk Creek east of the town of Roubaix. She filed five more claims, but the Alice Lode silver mine was the only one of value and sold for $500 dollars fifteen months before her death (Pengra, 2009)

96.5 Cross Bear Butte Creek.

96.6 Tomahawk Golf Course to the left. The only Tertiary extrusive rocks in the Black Hills occur here, and are part of the Tomahawk diatreme. Explosive volcanic activity blasted an opening to the surface, venting gases, and brecciating the vent rock. The hill just east of the club house has pitchstone having a K-Ar age of 56 Ma (Redden et al., 1983) and vent breccia. Inclusions of Upper Cretaceous Carlile Shale indicate it broke through a cover of Upper Cretaceous rocks that had not yet been weathered away from the central Black Hills, about 3,600 feet (1,097 m) above the top of the Precambrian surface. Paleozoic sedimentary and Tertiary intrusive rocks on the west side of the diatreme are faulted against schist of the Grizzly Formation, and dip east into the vent (Kirchner, 1996). On the east side of the diatreme is the Precambrian age north-south trending Tomahawk fault.

Just to the east was the site of the Hood and Scott lumber mill at the railhead of Allerton. The boarding house there burned down on March 10-11, 1883, killing eleven workers. They were buried in a common grave at Mt. Moriah Cemetery at Deadwood.

97.2 Brownsville and junction with Nemo Road (Co. Rd. 234). The outcrop at the junction is sandstone and shale of the Deadwood Formation dipping north into the Tomahawk diatreme. Brownsville, an early-day lumber camp for the Homestake Mining Company, was named for David Brown, a logging contractor who furnished the horses, sleds, skids, and tools, and who supervised the work for many years. When the sawmill was located here, the population consisted of about 600 wood choppers, haulers, and lumbermen. In 1882, the town was connected to Lead by a narrow-gauge railroad (Gilfillan et al, 1941). Turn left onto Nemo Road.

97.9 Large boulders of Deadwood to the right. Following Elk Creek.

98.0 Crossing the Tomahawk fault, and going from Grizzly Formation to metagraywacke.

98.4 Old town site of Roubaix and site of the Cloverleaf (Uncle Sam, Anaconda) mine to the right. The mine was located in 1878, with most operation prior to 1905. About $900,000 in coarse free gold associated with galena, sphalerite, pyrite, and chalcopyrite was produced from a saddle-shaped mass of milky quartz ranging from 12-20 feet (3.6-6 m) thick. Development included a 700-

foot (213 m) vertical three compartment shaft, and drifting on seven levels, the lowest at 650 feet (198 m). Quartz ore shoots were mined from the surface down to the 650-foot (198 m) level. Stopes were as much as 150 feet (46 m) long and 30 feet (9 m) wide (U.S. Bureau of Mines, 1954).

98.8 Elk Creek Road to the left leads past the Roubaix Cemetery. Cross Elk Creek.

99.7 Crossing an originally northeast trending, overturned anticline of metabasalt, metachert, and carbonaceous schist, now trending north-northwest due to refolding.

100.1 Crossing small body of Tertiary rhyolite. To the right, a view of Custer Peak, elevation 6,794 feet (2071 m) above sea level, a large rhyolite intrusion.

100.3 Back into largely proximal metagraywacke with resistant quartzose beds. Following the Hay Creek drainage.

102.2 Reausaw Lake, a man-made lake, to the right.

105.2 Old cabin and former town site of Benchmark. The ridge to the left is Lower Proterozoic Benchmark iron-formation, a primary taconite deposit. Confluence of Hay and Boxelder creeks to the right.

105.5 Cross Boxelder Creek.

105.6 Talus blocks of specular hematite of the Benchmark iron-formation on the left.

105.8 Chloritic Greenwood tongue of the Lower Proterozoic Boxelder Creek Quartzite on the left. The Boxelder Creek Quartzite is a fluvial unit with associated alluvial fan deposits.

106.2 Roadcut in stretched-pebble conglomerate of the Greenwood tongue to the left (Fig. 36).

106.4 Former town site of Greenwood. The Greenwood tongue of the Boxelder Creek Quartzite is named after this locality.

106.9 Cross Boxelder Creek.

107.0 Cross Boxelder Creek.

107.1 Former town site of Novak, now the site of the Boxelder CCC. The uraniferous Novak tongue of the Boxelder Creek Quartzite was named after this locality. Cuts through the Boxelder Creek Quartzite to the left.

108.4 Former town site of Tomahawk. The Tomahawk tongue of the Boxelder Creek Quartzite was named for this locality.

108.6 Roadcut through the Novak tongue containing fuchsite, probably from alteration of detrital chromite.

Figure 36. Stretched-pebble conglomerate of the Greenwood tongue of the Boxelder Creek Quartzite. Hammer is 16 in (40.6 cm) long.

109.1 Deadwood Formation to Pahasapa Limestone on the cliff ahead. Crossing various units of the Boxelder Creek Quartzite.

109.9 Intersection with FS26 (Vanocker Road) which leads about 15 miles (24 km) to Sturgis.

110.0 Frac-sand in the lower Deadwood Formation on the right, was mined locally in limited amounts.

110.2 Cross Boxelder Creek. Entering the town of Nemo, founded in 1877. It has been suggested that the name is "Omen" spelled backwards. The Homestake Mine had a sawmill here served by rail lines and a roundhouse. During the 1930's, CCC Camp Estes was located here. The road continues to follow the valley of Boxelder Creek.

111.5 To the left across the valley is a quarry in the Upper Archean Nemo Iron-formation.

112.0 Intersection with Merrit/Estes road (FS 208). Just west of the intersection are growth faults that displace the Boxelder Creek Quartzite, with erosional conglomerates forming along the fault scarp as fans of the Estes Formation. On the slope of the Pahasapa capped butte to the left is an avalanche track from a recent rockfall.

112.1 Cross Estes Creek.

112.9 Roadcut in fuchsite-bearing uraniferous Novak Tongue of the Boxelder Creek Quartzite.

113.9 Steamboat Rock capped by the Pahasapa Limestone, and Steamboat Recreation Site to the left. Along Boxelder Creek is talc of the lower Blue Draw metagabbro.

114.4 Terrace gravel on Deadwood Formation to the right on the bend.

114.6 Cross Boxelder Creek. Upstream to the right are prospect pits in talc of the lower Blue Draw metagabbro.

114.8 Roadcut through the upper Blue Draw metagabbro.

115.0 Blocks of conglomeratic basal Deadwood Formation with authigenic magnetite to the left.

115.7 Reddish hematite conglomerate derived from Precambrian iron-formation to the left.

115.9 Deadwood to Pahasapa formations on the hill ahead.

116.1 The Great Unconformity; contact of the Cambro-Ordovician Deadwood Formation over the near vertical Lower Proterozoic Boxelder Creek Quartzite is on the right (Fig. 37). Cross Boxelder Creek.

116.4 Basal Deadwood Formation exposed along Boxelder Creek to the left. Cross Boxelder Creek.

117.1 Cross Box Elder Creek.

117.4 Terrace gravels on the right along sharp bend.

117.5 Cross Boxelder Creek.

Figure 37. The Great Unconformity; Deadwood Formation over upturned Boxelder Creek Quartzite.

118.0 Nodular weathering in the lower 45 feet (14 m) of the Deadwood Formation is from calcite concretions believed to have formed by groundwater moving through the Deadwood when Box Elder Creek was about 60 feet (18 m) higher than its present elevation (Fig. 38).

118.3 **Stop 9**. Dominantly muddy shelf facies of the Englewood Formation in roadcut to the left (Fig. 39). It is bioturbated and contains horizontal *Planolites* sp. burrows. The Devonian-Mississippian boundary is about 10 feet below the Pahasapa Limestone-Englewood Limestone contact (Klapper and Furnish, 1962).

118.7 Gully to the left is Custer Gap, where the Custer expedition began to leave the Black Hills August 13, 1874, to return to Ft. Abraham Lincoln, North Dakota (Fig. 40). This area is a loss zone into the Pahasapa Limestone, which was noted by the Custer expedition. During high flow of Boxelder Creek, the subsurface conduits in the Pahasapa Limestone are filled, and the excess water flows along the surface. As the flow drops, the subsurface voids accommodate all the water and the creek becomes dry downstream of the loss zone. Most of the streams flowing from the central Black Hills lose water as they cross the Pahasapa Limestone. Cliff of Pahasapa ahead.

Figure 38. Calcite concretions in the Deadwood Formation produce nodular weathering.

118.4 Intersection with Norris Peak Road (Co. T238). Cross Boxelder Creek.

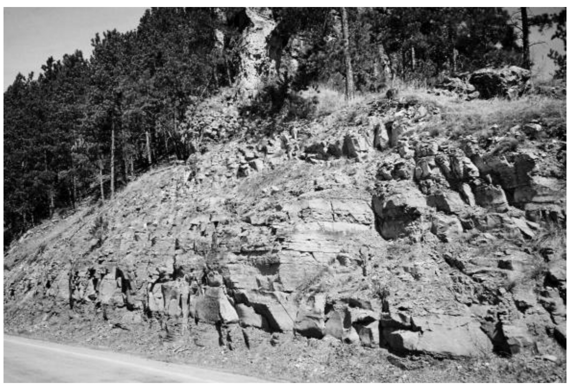


Figure 39. Dominantly muddy shelf facies of the Englewood Limestone.

119.1 Cross normally dry Boxelder Creek. Driving uphill through the Pahasapa Limestone.

119.5 Gated road to right leads to Gravel Spring.

120.3 Leaving the Black Hills National Forest.

120.4 Grave of Pvt. James A. King (1849-1874) to the right, who reportedly died of typhoid fever (probably dysentery) August 13, 1874 during the Custer Expedition (Fig. 41).

120.8 On a flat, Tertiary erosional surface. Crossing the Pahasapa Limestone-Minnelusa Formation contact having some red terra rossa. Tree-covered ridge in the distance to the left is a north-south trending anticline, with a syncline forming the foreground valley.

Figure 40. Custer Gap and loss zone on Boxelder Creek.

Figure 41. Grave of Pvt. James A. King of the 1874 Custer Expedition.

122.4 **Stop 10**. "Red Marker Zone" of the Minnelusa Formation, which is the division between the Pennsylvanian and Permian parts of the section (Jennings, 1959) (Fig. 42), and is overlain by "Converse Sands" of the Upper Minnelusa. Beds contain a small channel, algal laminae (Fig. 43), mud cracks, ripple marks, and sparse brachiopods indicating intertidal deposition.

122.8 Cross Boxelder Creek.

123.1 Terrace gravels of Boxelder Creek to the left.

123.5 Slump on right is from a small seep in the Minnelusa Formation.

Figure 42. "Red Marker Zone" of the Minnelusa Formation. Small channel is at center of picture by arrow.

Figure 43. Algal laminae associated with mudcracks in the Minnelusa Formation "Red Marker Zone." Hammer is 16 in (40.6 cm).

123.9 On Opeche Shale preserved in the trough of a small syncline. Tertiary gravel contact with the Minnelusa Formation is on the left. The calcite cement has been removed from the sandstone making it very friable.

124.9 Hills are capped by Tertiary gravels. Minnelusa Formation with layered and contorted, vuggy beds along roadcuts.

125.3 Old rockslide to the left.

125.7 **Stop 11**. Roll front oxidation deposit and solution breccia in the Minnelusa Formation (Fig. 44) with clasts to several feet long (Fig. 45). Some beds have large dune crossbeds.

125.8 West Berry Hill Road to the right and area of the July 26, 1988 West Berry Trail fire. Cross bedded Minnelusa Formation with solution breccia to the left.

126.5 Very contorted beds of the Minnelusa Formation due to evaporite dissolution to the left.

Figure 44. Oxidized roll front deposit with collapse breccia in upper Minnelusa Formation.

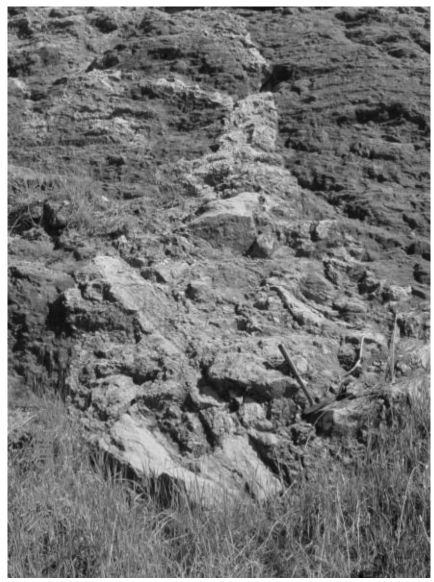


Figure 45. Detail of Minnelusa collapse structure with clasts several feet long. Hammer is 16 in (40.6 cm) long.

127.2 Mostly covered Minnelusa Formation-Opeche Shale contact dipping east on the right.

127.3 Opeche Shale capped by Minnekahta Limestone to the left. There are small box folds in the Minnekahta roadcut.

127.5 Entering a small alluvial valley underlain by Spearfish Formation. Ridge of Minnekahta Limestone to the left is along a small, southwest dipping monocline.

128.5 Intersection of South Canyon Road and Chicago Street. Bear left following Chicago Street.

128.9 Cross Lime Creek, fed by City Springs.

129.2 Intersection with Sturgis Road (Business 90). Continue ahead on Chicago Street.

129.5 Cement plants and quarries in Minnekahta Limestone on the left.

129.9 Cross DM&E railroad.

130.2 Intersection with Deadwood Avenue. Chicago Street Changes to Omaha Street. Black Hills Power and Light plant on the left. Sand pits and slumps in the Unkpapa Sandstone are ahead to the left.

130.4 Cross Rapid Creek.

130.5 Intersection with Mountain View Road. Driving through the hogback of Sundance through Fall River formations.

131.4 Intersection with I-190 (West Blvd.).

131.6 Intersection with Mt. Rushmore Road.

131.9 Intersection with 5th Street. Turn left.

132.0 Cross Rapid Creek.

132.1 Turn left into the Rushmore Plaza Holiday Inn parking lot.

End of road log.

ACKNOWLEDGEMENTS

I would like to thank Joanne Noyes of the South Dakota Geological Survey for helping with the preparation of this road log.

REFERENCES CITED

Darton, N.H., 1899, Jurassic formations of the Black Hills of South Dakota: Geological Society of America Bulletin, v. 10, p. 383-396.

Darton, N.H., 1901, Preliminary description of the geology and water resources of the southern half of the Black Hills and adjoining regions in South Dakota and Wyoming: U.S. Geological Survey, 21st Annual Report, Part 4, p. 489-599.

Darton, N.H., 1904, Comparison of stratigraphy of Black Hills, Big Horn Mountains and Rocky Mountain Front Range: Geological Society of America Bulletin, v. 15, p. 379-448.

Dowling, D.B., 1895, Notes on the stratigraphy of the Cambro-Silurian rocks of eastern Manitoba: Ottawa Naturalist, V. 9, n. 3, p. 65-74.

Fahrenbach, M.D., 1995, Sedimentation, paleontology, and paleoecology of the Late Devonian-Early Mississippian Englewood Formation, Black Hills, South Dakota: Rapid City, South Dakota School of Mines and Technology, Ph.D. dissertation, 615 p.

Gilfillan, A.B., Rice, R.L., Noble, E.E., Lord, J., Norton, C.B., Burrill, H.G., and Reese, L., 1941, South Dakota place names: South Dakota Writers Project, University of South Dakota, Vermillion, 689 p.

Gries, J.P, 1996, Roadside geology of South Dakota: Mountain Press Publishing Co., Missoula, Montana, 368 p.

Horan, J. D., 1977, The authentic wild west: The outlaws: New York, Crown Publishing Company, 312 p.

Jagger, T.A., 1901, Laccoliths of the Black Hills: U.S. Geological Survey, 21st Annual Report, pt. 3-b, p. 163-303.

Jennings, T.V., 1959, Faunal zonation of the Minnelusa Formation, Black Hills, South Dakota: Journal of Paleontology, v. 33, n. 6, p. 986-1000.

Kirchner, J.G., 1996, The geology of the Tomahawk volcanic center: in Paterson, C.J. and Kirchner, J.G., eds, Guidebook to the geology of the Black Hills, South Dakota, South Dakota School of Mines and Technology Bulletin No. 19, p. 172-179.

Klapper, G. and Furnish, W.M., 1962, Devonian-Mississippian Englewood Formation in Black Hills, South Dakota: AAPG Bulletin, v. 46, n. 11, p. 2071-2078.

Lewis, C., and Fisk, T., 2006, The South Dakota road guide to haunted locations: 210 p.

McCoy, M.R., 1952, Ordovician sediments in the northern Black Hills: Billings Geological Society Guidebook, 3rd Annual Field Conference, p. 44-47.

Newton, H. and Jenney, W.P., 1880, Report on the geology and resources of the Black Hills of Dakota: U.S. Geology and Geography Rocky Mountain Region Atlas, 566 p.

Pengra, L.M., 2009, Sarah Campbell: The first white woman in the Black Hills was African American: Buffalo Gap, Lune House Publishing, 136 p.

Plumley, W.J., 1948, Black Hills terrace gravels: A study in sediment transport: Journal of Geology, v. 56, p. 526-577.

Redden, J.A., Obradovich, J.D., Naeser, C.W., Zartman, R.E., and Norton, J.J., 1983, Early Tertiary age of pitchstone in the northern Black Hills, South Dakota: Science, v. 220, p. 1153-1154.

Rezatto, H., 1983, Tales of the Black Hills: Aberdeen, North Plains Press, 288 p.

U.S. Bureau of Mines, 1954, Black Hills mineral atlas, South Dakota, Part 1: U.S. Bureau of Mines Information Circular 7688, 123 p.

Waterland, J.K., 1988, Gold and silver or sweat and tears: Rapid City, Grelind Photographics and Typesetters, 244 p.

Weiser, K., 2010, Jack McCall-Cowardly killer of Wild Bill Hickok (online). Legends of America: Available from http://www.legendsofamerica.com/WE-JackMcCall.html (Accessed 26 May 2010).

Winchell, N.H., 1875, Report on the geology and resources of the Black Hills of Dakota: Chief Engineer Annual Report 1875, pt. 2, Appendix PP, p. 1131-1172.

The Mammoth Site of Hot Springs, SD: Field trip and road log from Rapid City to the Mammoth Site.

LARRY D. AGENBROAD, DON ESKER, and JUSTIN WILKINS *The Mammoth Site of Hot Springs, 1800 U.S. 18 Bypass, Hot Springs, SD 57747*

Introduction

This road log is meant to convey some of the geologic deposits and regional history along the Highway 79 route from Rapid City to Maverick Junction, and from Maverick Junction on US18/285 to Hot Springs. We have drawn from personal knowledge, but also from John Gries excellent book on the roadside geology of South Dakota, with some local history derived from Linda Hasslestrom's (1994) roadside history of South Dakota. Maps, figures, and some tables have been modified from John Gries (1996).

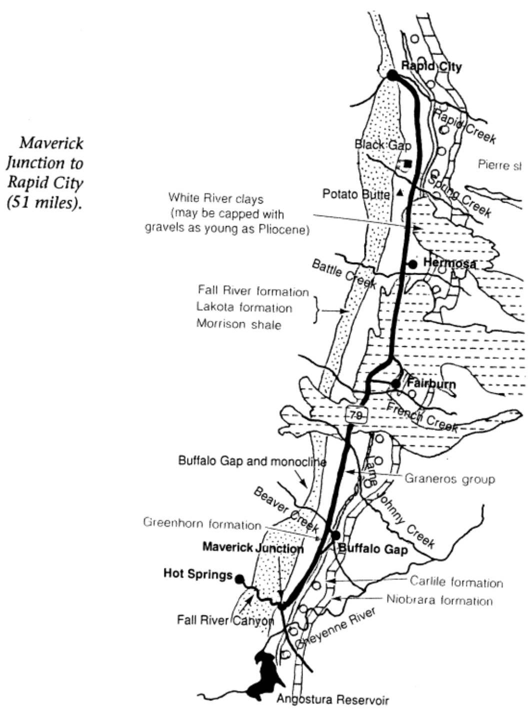


Figure 1. Overhead geologic road map, showing SD-79 from Rapid City, SD to Maverick Junction and Hot Springs, SD (Gries, 1996).

ROAD LOG

Holiday Inn (Rushmore Plaza, Rapid City, SD) – The Mammoth Site of Hot Springs
The Mammoth Site of Hot Springs

GSA Rocky Mountain Section Field Trip, 2010

0.0 *Rapid City*: Originally called "Hay Camp" for the natural grass meadows along Rapid Creek. It was an important stop on the Sidney-Deadwood stage route. Rapid City grew to the largest city in the western half of South Dakota (West River), and is the site of the Rapid City School of Mines and Technology, as well as 'home' to a major SAC air base.

Holiday Inn, Rushmore Plaza, Rapid City, SD

0.3 North 5th St. (Haines Ave.) & Omaha St. Intersection (turn left [East])

2.0 Omaha St. & Campbell St. Intersection (turn right [South])

4.8 Leaving Rapid City; Campbell St. becomes South Dakota St. Rt. 79

8.3 Small Belle Fourche/Mowry Shale outcrop (on the left [East])

8.8 Begin large exposure of Belle Fourche/Mowry Shale (known as Black Gap)

Black Gap: This is a notch in the Belle Fourche Formation uplands that was the location on the Sidney- Deadwood trail where stage drivers rested their horses, after the pull from Rapid Creek (north), or Spring Creek (south). It was therefore, a spot where robbers would hold up the stage coaches, especially the ones headed south, carrying gold from Deadwood to the Union Pacific Railroad at Sydney, NE. Oligocene gravel caps the Belle Fourche Formation, creating the uplands.

9.5 End Black Gap exposure of Belle Fourche/Mowry Shale

10.3 Lower Spring Creek Rd. & "Madonna of the Prairie"

10.8 Spring Creek

11.5 Belle Fourche/Mowry Shale outcrop (on the right [West])

12.0 Potato Butte (on the right [West])

Potato Butte: This small butte is capped by a thin lens of algal limestone, reflecting a freshwater pond location during Oligocene time.

14.3 Custer/Pennington Co. line

17.2 Belle Fourche/Mowry Shale outcrop (on the right [West])

18.4 Hermosa, SD with a Belle Fourche/Mowry Shale outcrop behind the Travel center (on the right [West]); potential contact w/ White River Group

Hermosa: Originated as a settlement on Battle Creek (Squaw Creek; Battle River) at a stage coach stop on the Sidney-Deadwood stage route, about 1882. The Chicago & Northwestern Railroad arrived in 1886, and had the name changed to Hermosa ('beautiful' in Spanish). The site was a major ore shipping point from several famous mines. In 1887 Hermosa boasted of 2 banks, 2 hotels with restaurants, 2 saloons, 2 general stores, a livery barn, and a hardware store. The town burned, several times.

18.7 South Dakota St. Rt. 44 (on the right [West])

19.4 South Dakota St. Rt. 36 (on the right [West])

22.2 Rock Shop (on the right [West]) & White River Group Cap (on the left [East])

22.7 White River outcrop (on the left [East])

23.1 White River outcrop (on the left [East])

25.2 Alluvium cap (on the left [East])

26.6 Dry Creek Rd. to 777 Bison Ranch (on the left [East])

27.3 Fairburn Rd. to Fairburn, SD (on the left [East], but continue straight [South] on SD St. Rt. 79)

Fairburn: Just east of the modern US 79, it was named from a Scottish expression for "beautiful creek". It was settled in 1883. The railroad arrived July 4, 1883. The town is famous as a location for Fairburn Agates, the stage gem stone of South Dakota. Located on French Creek, famous for the discovery of gold, during the Custer Expedition near Custer, SD. It was an important water stop for the railroad (steam engines), as were other small towns that formed along the railroad.

30.1 French Creek Rd. from Fairburn, SD (on the left [East], continue straight [South] on SD St. Rt. 79)

30.6 French Creek

32.7 White River cap (on the right [West])

33.9 Burnt Wood Creek Rd.

35.2 White River caps and wear-downs (on the left [East])

35.9 Lame Johnny Creek and Lame Johnny Rd. (on the right [West])

Lame Johnny Creek: Named for the hanging of an alleged thief (cattle rustler, stage coach robber, etc.) who had previously been a lawman. Following "outlaw tradition", this was a nickname and his real name was Cornelius Donahue.

37.3 Alluvium cut (on the left [East])

39.1 Dry Creek

40.2 Worn out dark Belle Fourche/Mowry Shale (on the right [West])

41.1 Tatanka Spirit Rd. (on the right [West])

42.5 Historic Marker: Jedediah Strong Smith's Route (on the left [East] side of the road)

42.7 Beaver Creek

43.1 Buffalo Gap (on the right [West]) & 7-11 Rd. to the town of Buffalo Gap (on the left [East])

Buffalo Gap: Named for the natural water gap caused by Beaver Creek crossing the hogback of Cretaceous sediments. These sediments are nearly horizontal a few miles west, but here, they form a steeply dipping (ca 70 º) monocline. The water gap was used by buffalo entering and leaving the Black Hills. In 1874, it was a stage coach stop which became a town when the Fremont, Elkhorn & Missouri Valley Railroad arrived. It became notorious for 23 saloons, 2 large 'sporting houses',17 hotels with restaurants, 4 blacksmiths, 2 drug stores, 4 Chinese laundries, 3 livery barns, a hardware store and a 'department' store serving approximately 2000 people.

44.3 Buffalo Gap Rd. (on the left [East])

45.2 Fall River/Custer Co. line

46.5 Elm Creek

47.3 Lone Tree Road from Buffalo Gap (on the left [East])

48.5 Worn out dark Belle Fourche/Mowry Shale (on the left [East])

51.1 Maverick Junction; turn right [West] onto US-18/US-385

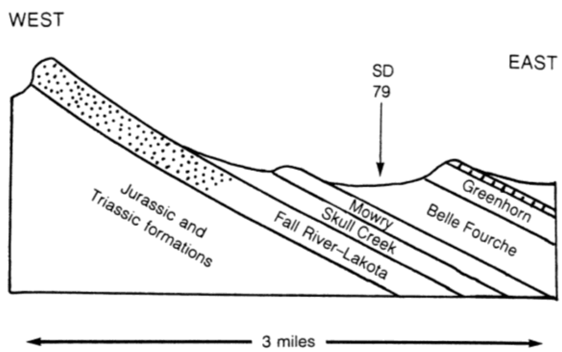


Figure 2. A cross section just north of Maverick Junction, showing the Greenhorn and underlying formations that make up the hogback of the Black Hills (Gries 1996).

Maverick Junction: The location of a branch line of the railroad and the freight road along Fall River to Hot Springs. The junction of Highways US-18/385 and SD-79. The Greenhorn Formation forms the hogback just east of Highway 79. This is a fossiliferous, marine Cretaceous formation, totaling over 150 feet of light gray shale, with the crest of the hogback protected by limestone full of fossil pelecypods and gastropods, especially fossils of the large clam *Inoceramus labiatus*. Although the unit is gray when feshly cut, it weathers to a buff color and is characterized by a slabby nature caused by separation along silt and clay layers. US Highways 18/385 is built on Pleistocene terraces of the Fall River, set back on black Cretaceous shales (Belle Fourche, Mowry, Skull Creek), also known as the Graneros Group.The Graneros Group occupies the low lands from the base of the Greenhorn Formation, to the forested sandstone outcrops to the west of Highway 79.

51.7 Entering the water gap of the Fall River.

Table 1. The Graneros Group (from Gries, 1996)

Formation	Thickness
Belle Fourche shale	600 feet
Mowry shale	150-200 feet
Newcastle sandstone	0-25 feet
Skull Creek shale	175-225 feet

Maverick Junction to Hot Springs / Water Gap: US 385-18 highway goes across the Graneros Group and enters the water gap cut by the Fall River. Fall River Falls are just south of the highway, where the river drops over 50 feet cutting through the Fall River Formation. The water gap also occurs along a fault line and tufa deposits appear to have dammed the stream in this area. Some years ago, two teen age boys were drowned here , unable to extract themselves from the force of the water in the plunge channel. Two stone quarries are visible on the north and south of the river bridge. These quarries supplied most of the stone for the unique stone architecture in Hot Springs. Fall River Canyon exposes steeply dipping sedimentary rocks from Cretaceous to Triassic age. Beginning at the top, the Fall River Formation is underlain by the Lakota Formation, composed of the Fuson member, a multi-colored mudstone/sandstone. The Fuson member overlies a sandly limestone, the Minnewaste, which in turn lies over the Chilson member, a sandstone and mudstone -- the lowest Cretaceous unit. Hot Springs is located in the 'racetrack' valley of eroded Permo-Triassic Spearfish Shale.

53.0 Flexure and fault crossing the Fall River along the Dudley Canyon alignment.

54.0 Unkpapa Sandstone--Sundance Formation contact. The Unkpapa contains a local siltstone, is crosbedded and ripple marked, and contains yellow and purple banding. The Sundance Formation is composed of siltstones, clay stones with abundant belemnites, grading downward to sandstone units. The Unkpapa and Sundance comprise the Jurassic section.

55.2 Fall River terrace conglomerates.

55.3 Left turn on US 18 truck bypass.

55.4 Cross Fall River -- driving on Permian-Triassic Spearfish Formation -- a red siltstone with gypsiferous units near the base.

56.0 Continue west (Highway 18 intersection) on US 18.

56.5 Right turn (North) on 19th Street.

56.6 Right turn (East) on Detroit Avenue.

56.7 Park--Hot Springs Mammoth Site.

Table 2. Stratigraphic Column of the Fall River Canyon (from Gries, 1996)

Age	Formation	Thickness
Cretaceous		
	Skull Creek formation: Dark gray-to-black marine shale	250 feet
	Fall River formation: Tan-to-pink fine sandstone	147 feet
	Lakota formation:	
	Fuson member: Variegated clay and sandstone	123 feet
	Minnewaste member: Gray-to-tan limestone	29 feet
	Chilson member: Buff-to-red sandstone	310 feet
Jurassic		
	Morrison formation: Grayish green shale	10 feet
	Unkpapa formation: Variegated sandstone	140 feet
	Sundance formation: Green shale and yellow sandstone	300 feet
Triassic		
	Spearfish formation: Redbeds and white gypsums	350 feet

STOP 1:

THE MAMMOTH SITE OF HOT SPRINGS, SD

Abstract

The Mammoth Site of Hot Springs, South Dakota represents a natural, geologic-hydrologic trap for late Pleistocene fauna. The site is contained within the fill of a karst feature (sinkhole), due to the collapse of an cavern within the Minnelusa Formation. Located in the southern portion of the Black Hills uplift, it also became a conduit for thermal artesian water, creating a pond within the collapse feature. It became a death trap, where animals died, decomposed, and became entombed in sediments derived from recycled bank collapse, and runoff inflow. The site represents the largest accumulation of Columbian mammoths (*Mammuthus columbi)* in primary deposition, in the world.

Introduction

A local contractor, Phil Anderson, of Hot Springs, initiated a development project on the southern limits of the city. Bulldozer operations in 1974 provided the discovery of the fossil remains. Located on the crest of a local topographic high, it represents a spectacular example of reverse topography. What now is the top of a hill was formerly a low (depression) as recently as 26,000 years ago. Located within the 'racetrack' valley of eroded Spearfish Formation, the tan colored fill sediments were a distinct contrast to the red shale of the Spearfish Formation. The Mammoth Site is located on the fourth terrace above Fall River.

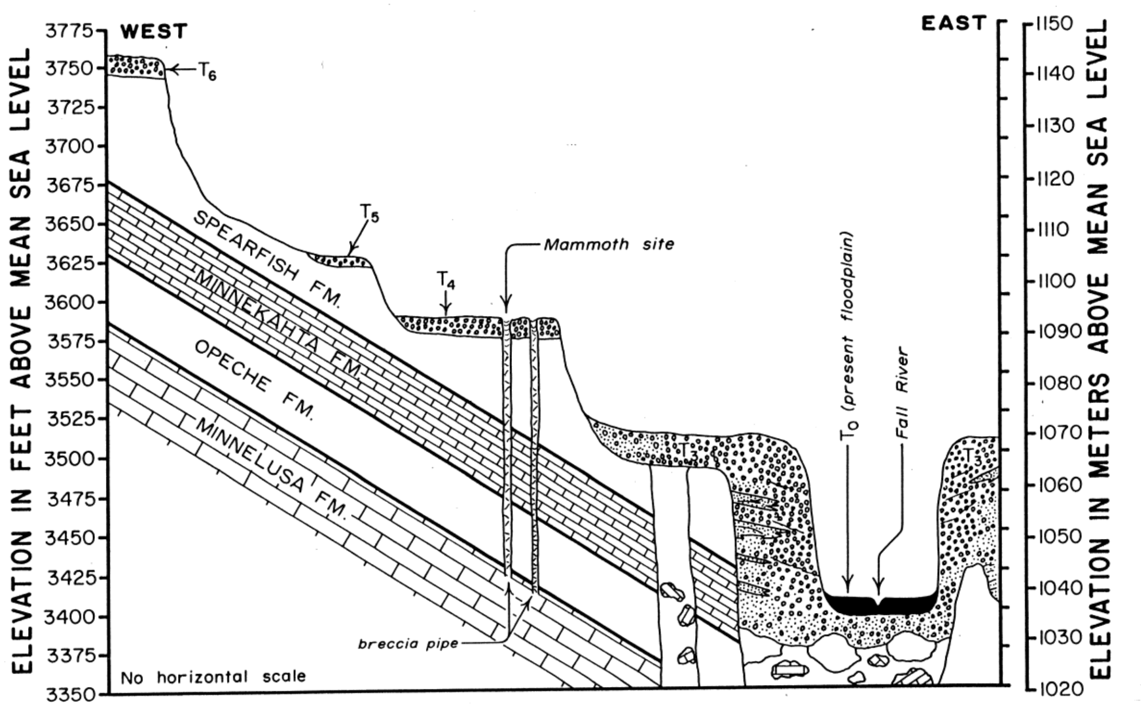


Figure 3. A simplified geologic/physiographic setting of the Mammoth Site sinkhole (on alluvial terrace IV) of Fall River (Laury 1994).

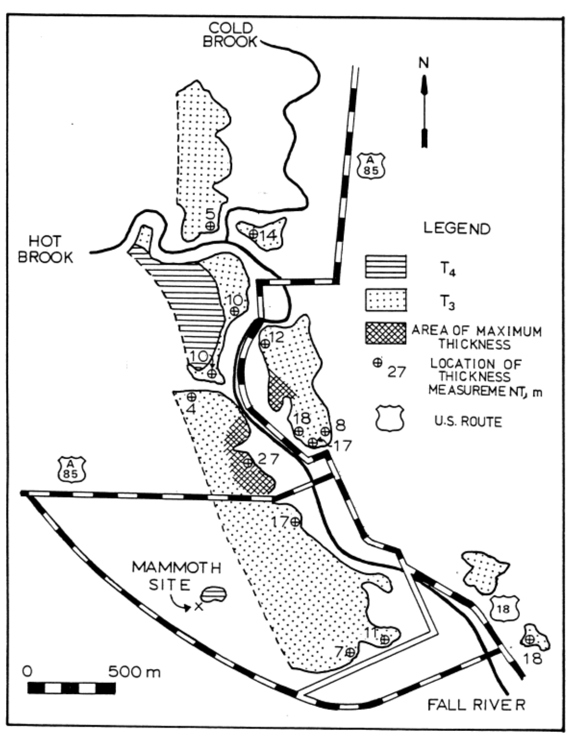


Figure 4. A map of the generalized alluvial terrace distribution and thickness, Hot Springs, South Dakota (Kempton and Laury 1994).

The exploration and testing of the deposit revealed it to be the filled karst (sinkhole) that had served as a conduit for thermal, artesian water, which accumulated as a pond within the sinkhole (Agenbroad and Mead 1994). Animals, especially immature and adolescent mammoths were lured into the feature, not for water, which was abundant in the local area, but for bank side vegetation. A young male mammoth had two options with the first major snowfall of the winter; he could use his tusks to sweep cold, wet snow off last summer's dead grass, or he could choose to feed on the green vegetation at the edge of a thermal pond within the sinkhole. It is a scenario similar to modern bison grazing near thermal pools and geyser regions of Yellowstone Park during the deep snow of winter.

The individual that decided to go for the "salad bar" had a one-way trip. Once inside the steep (>67º), moistened walls of the sinkhole, they were unable to escape. Death came from starvation, exhaustion, or drowning. Upon decomposition and disarticulation, their remains became 'clasts' in the laminated sedimentary fill of the sinkhole. As Fall River continued to erode its bed, the artesian springs that fed the sinkhole pond began to migrate, laterally, to the river (Hot Springs currently has more than 100 thermal springs in the local area). The sinkhole slowly filled with sediments, becoming essentially a mud hole during terminal visitations. It is estimated that the infilling occurred in a 300 to 750 year interval, approximately 26,000 radiocarbon years ago.

Excavation History

Test excavations began in the fall of 1974. Each exploratory pit encountered bone. In 1975, with a modest research grant from the Geological Society of America-Penrose Grant, a team of volunteers excavated for one week. On the last day of excavation, a full skull containing both tusks and the mandible slightly down dropped was discovered. (Figure 5) The photograph of that skull was sent with proposals to The National Geographic Society, and the Earthwatch Institute. With funding from both entities, we began a series of formal excavations in 1976. Mammoth remains were encountered in all areas of excavation. Mapping was accomplished by a metric grid, with a 1 square meter frame, divided by string at every 10 cm interval. The framework was positioned over the meter to be mapped, and drawn to scale on graph paper.. These field sheets were then combined to provide an excavation map for that field period and ensuing seasons. The South Dakota Geological Survey drilled three test holes in the deposit in the fall of 1978. (Figure 6) The deepest test drill went to 67 feet (20.4 m) and was still producing fragments of bone and ivory. The total depth of the fossil bearing fill is not known, at present. Hand tool excavation has currently reached approximately 25 feet (7.6 m) depth in a portion of the site. Approximately 40 % of the deposit remains undisturbed to that depth. Bones were numbered by year and the sequence number in that year. In the 1990s a Nikon EDM transit was employed, using ARCHINFO software to produce more accurate maps. In 2007, the acquisition of a robotic transit allowed a remap of the *in-situ* bone bed.

Faunal Remains

It was noted early in the excavation, that tusks, skulls, mandibles, and pelves were common discoveries. In an attempt to convert these data to the minimum number of animals (MNI) represented, we resorted to tusk count divided by two. At the close of the 2009 field excavation, we have determined a MNI of 58 individual mammoths. The majority of the remains represent a population of Columbian mammoths (*Mammuthus columbi*). In addition two, and possibly three, woolly mammoths (*Mammuthus prmigenius*) are represented by dentition. Normally the temperate zone Columbian mammoths are not found with woolly mammoths, at least as contemporaries. A working hypothesis is that as the ice front moved south to the present location of the Missouri River, wooly mammoths moved into the region west of the ice, while Columbian mammoths had migrated further south.

Figure 5. The 1975 skull (75HS103) that provided funding for future excavations.

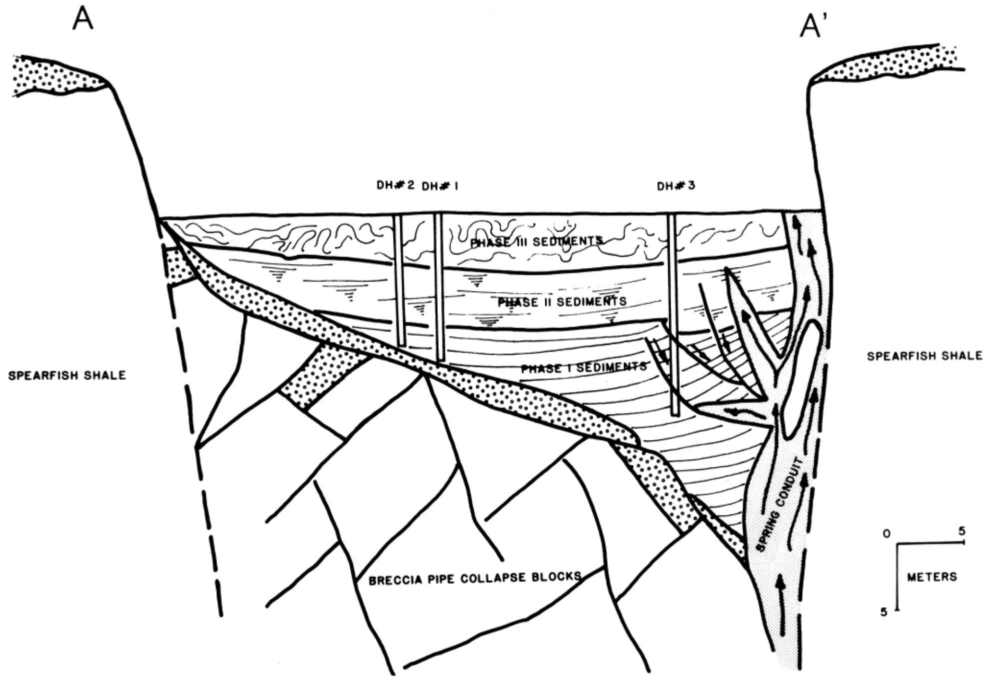


Figure 6. Drill holes provided by the South Dakota Geological Survey, allowing a tentative interpretation of the configuration of the sinkhole fill.

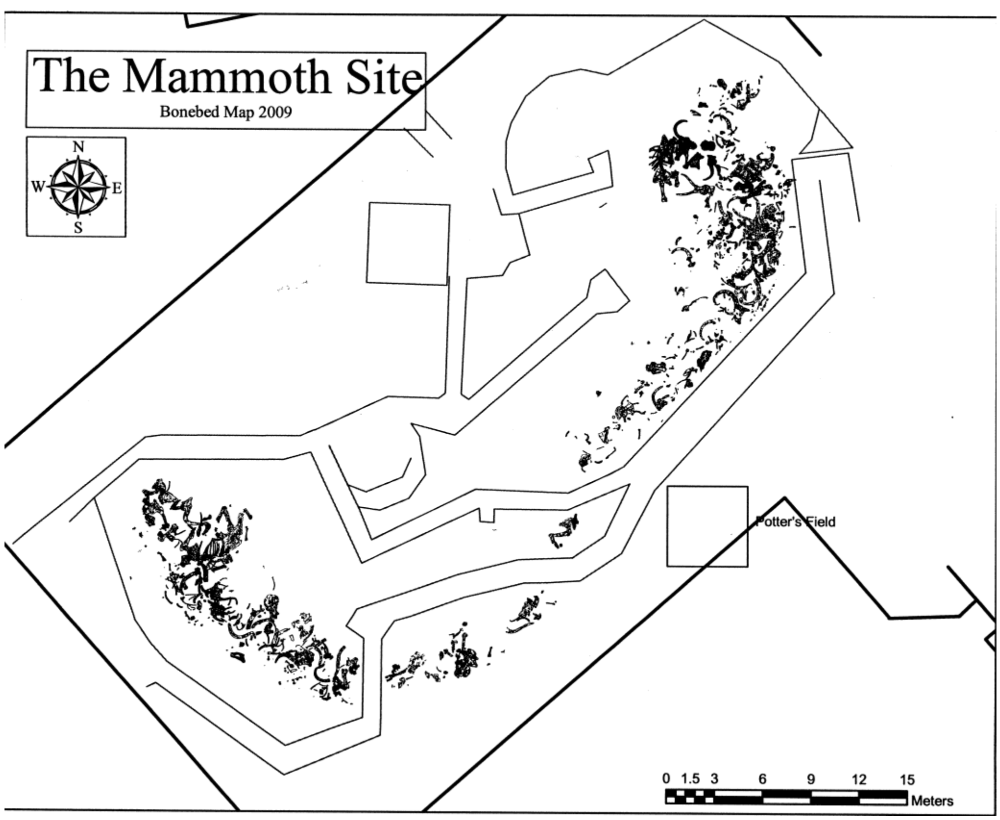


Figure 7. The 2009 map of the *in-situ* bone bed at the Mammoth Site.

Several skeletons that were nearly complete were discovered in the period from 1979-2003. The first was given the nickname of “Napoleon Bone- Apart” by the crew on a hot July afternoon. That was an anomaly, as this was the first skeleton we had found that was articulated. Napoleon was discovered beneath the city alley right-of-way. The city had not had an alley, there, for ca. 270 million years, but decided they would have one there in 1980. I agreed to move the dirt, if I could test beneath the right-of-way. The discovery of Napoleon led to the condemnation of the alley, and the purchase of the land by the Mammoth Site Corporation. In 1983-86 we discovered a second articulated skeleton, complete from the last caudal (tail) vertebra to the first cervical (neck) vertebra (Fig. 8).

Figure 8. The articulated skeleton of “Murray Antoinette”.

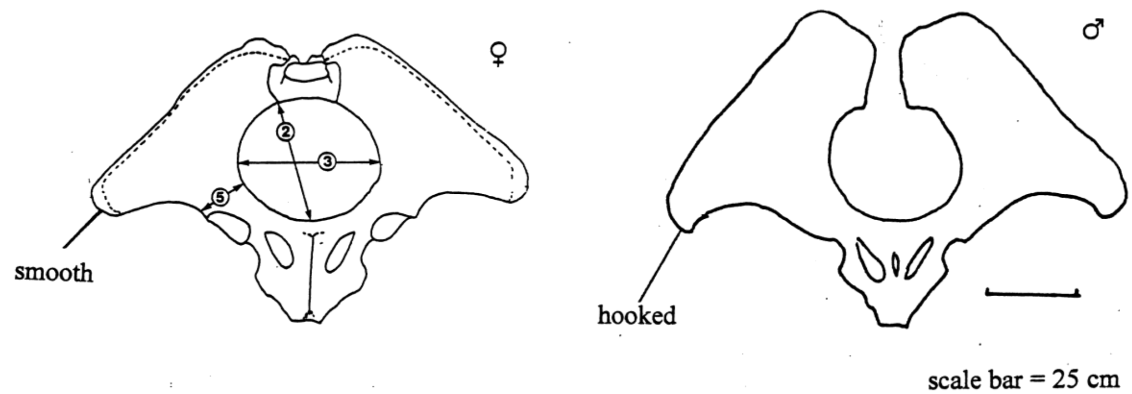
Only the skull was missing, hence the nickname “Marie Antoinette”. When taking metric dimensions of the right humerus, it proved too large to be a female, so the name has been changed to “Murray Antoinette”. In 1986 we had not yet determined a method to differentiate between male and female mammoths, from the isolate bones. I was suspicious they were male, based on the basal diameter of the tusks. At a meeting in Rome, a colleague had determined a method of sexual differentiation in woolly mammoths, from two pelvic measurements. I asked if I might use his method on the specimens at Hot Springs. Receiving his permission, I flew to Hot Springs and measured every pelvis that had been exposed. I spent the evening calculating ratios and plotting the results (Fig. 9) and found my suspicions were verified, the mammoths at Hot Springs were males. Eighty seven percent of the population was between the ages of 14 and 29. The result of that information allowed formation of a theory that the sinkhole became a death trap for the adolescent and young male mammoths.

In addition to mammoths, there have been a host of other species, invertebrate and invertebrate, plus a few insects and some floral material. Perhaps the most impressive vertebrate, other than the mammoths, was the discovery of the skull, mandible, humerus, tibia, parial ribs, vertebrae, and half a pelvis of the giant short-faced bear (*Arctodus simus*). Also discovered were the camel (*Camelops hesternus*) and a llama (*Hemiauchenia macrocephala*), wolf (*Cania lupus*) and coyote (*Canis latrans),* plus several smaller animals. It is possible some of the specimens represent remains that were washed into the sinkhole from surrounding uplands; others were probable scavengers on the mammoth remains. Invertebrates are commonly small gastropods and pelecypods; notable are the ostracods, which indicate the water temperature as 95ºF (an artesian well was recently completed, nearby, it is interesting to note the water temperature was 95ºF).

Some fossil material is removed from the excavation, taken to the preparation laboratory where the specimens are cleaned, repaired, if necessary, and stabilized. Once completed in the lab, they are cataloged and stored in an on-site repository. Some early excavation specimens are selectively removed to expose faunal material buried in the sediments below. Careful deliberation is done prior to recommendation of removal of any given specimen.

Research and Education

There have been numerous presentations, television documentaries, theses and publications resulting from the excavations at the Mammoth Site. Three international symposia have been sponsored and hosted by the Mammoth Site. In addition, the public is invited to visit the site, year-round. We have a Junior Paleontologist Dig for children ages 3-13 during the summer months. Educational material is available in age/grade levels, for distribution throughout the continent. Boy Scout and Girl Scouts can fulfill merit badge requirements. We have a yearly scholarship for students graduating from high school, through the sophomore year in college. Six interns are hired for the summer months from colleges/universities in the country. Elderhostel groups and Project Exploration have short term training on-site.



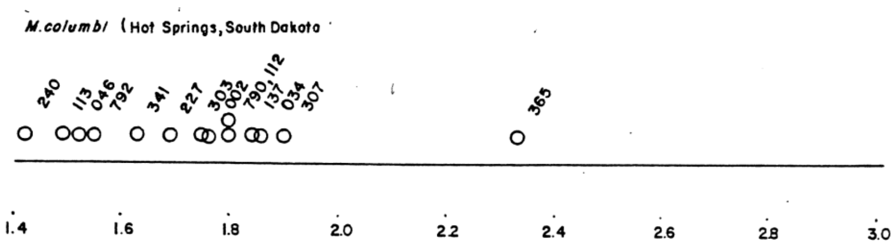


Figure 9. A plot of the ratio of pelvic aperture height versus the width of the ilium shaft. A ratio of less than 2.4 equates to male pelves (Lister and Agenbroad 1994).

REFERENCES CITED

Agenbroad, L. and J. Mead (eds.) 1994. The Hot Springs Mammoth Site: a decade of field and laboratory research in paleontology, geology, and paleoecology. Fenske Printers. Rapid City.

Gries, J. 1996. Roadside Geology of South Dakota. Mountain Press Publishing Company. Missoula.

Hasselstrom, L. 1994. Roadside History of South Dakota. Mountain Press Publishing Company. Missoula.

Kempton, P. and R. Laury. 1994. Terraces, solution collapse events and late Quaternary history of the Fall River, Hot Springs area, Fall River and Custer Counties, South Dakota. *In* L. Agenbroad and J. Mead (eds.) The Hot Springs Mammoth Site: a decade of field and laboratory research in paleontology, geology, and paleoecology. Fenske Printers. Rapid City. p. 68-112.

Laury, R. 1980. Paleoenvironment of a late Quaternary mammoth bearing sinkhole deposit, Hot Springs, South Dakota. Geological Society of America Bulletin 91: 465-475.

Laury, R. 1994. Paleoenvironment of the Hot Springs Mammoth Site. *In* L. Agenbroad and J. Mead (eds.) The Hot Springs Mammoth Site: a decade of field and laboratory research in paleontology, geology, and paleoecology. Fenske Printers. Rapid City. p. 28-67.

Lister, A. and L. Agenbroad. 1994. Gender determination of the Hot Springs mammoths. In L. Agenbroad and J. Mead (eds.) The Hot Springs Mammoth Site: a decade of field and laboratory research in paleontology, geology and paleoecology. Fenske Printers. Rapid City. p. 208-214.

Precambrian Geochronology of the Black Hills, South Dakota: Past Results and Future Directions

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ABSTRACT

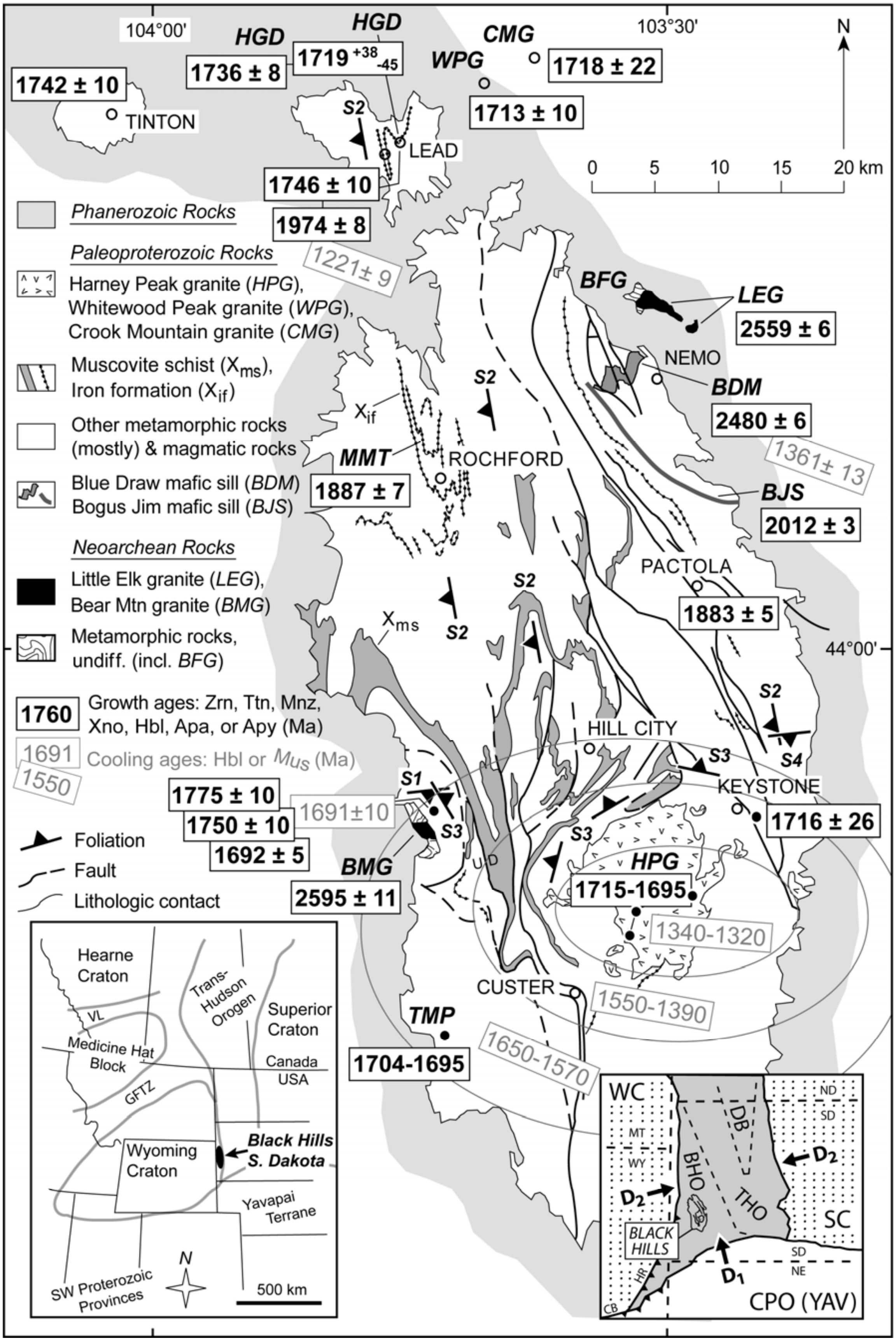
Two decades of geochronologic investigation on Precambrian crystalline rocks of the Black Hills, South Dakota, are summarized. Abundant $^{207}Pb/^{206}Pb$ growth ages of zircon, sphene, monazite, xenotime, apatite, and arsenopyrite—many of which represent unusual yet important microtextures and occurrences in key rocks—combine to provide a detailed glimpse into the region's complex history of polyphase magmatism, sedimentation, mineralization, and thermotectonism between ~2900 Ma and 1680 Ma. In addition, numerous Rb-Sr mica and $^{40}Ar/^{39}Ar$ hornblende-mica cooling ages shed light on the region's history of post-tectonic exhumation and cooling through ~550º–330 °C between ~1690 Ma and 1250 Ma. The earliest sediments in the Black Hills may have been deposited on ~2900 Ma basement and were intruded by 2600–2560 Ma syn-collisional granitoids constituting the currently exposed basement. Younger, rift-related sedimentation between 2560 Ma and 2480 Ma was followed by intrusion of the Blue Draw layered mafic sill at 2480 Ma. Following a cryptic compressional event, the prominent Estes unconformity was developed atop the ~2600–2480 Ma complex sometime between 2480 and ~2100–2015 Ma, whereupon rift-related sedimentation recommenced. Felsic tuff dated at 1887 Ma and presumably of Trans-Hudsonian origin is interbedded with sedimentary rocks of comparable age, and coeval gabbro sills intruded in the Black Hills basin may indicate a back-arc setting for ongoing deposition and early metamorphism. North-directed nappe/thrust structures, presumably associated with ~1775 Ma accretion of the Yavapai arc terrane to the south, may account for all (E)NE-trending structures observed in the metasedimentary rocks, including relict fabrics, early folds, and overturned strata. Subsequent tectonic burial beginning at ~1750 Ma and associated with Wyoming-Superior collision imposed NNW-trending folds and axial planar foliation throughout the Black Hills crystalline core. This thermotectonic event culminated in Homestake gold mineralization sometime between 1750 Ma and 1715 Ma, the onset of Harney Peak granite-pegmatite magmatism at 1715 Ma, and terminal metamorphism by 1690–1680 Ma. Collectively, these ~2900–1680 Ma geological events encompass the assembly and breakup of supercontinent Kenorland, and subsequent assembly of supercontinent Laurentia, to form the North American craton. Subsequently, the Black Hills mid-crust underwent a protracted interval of slow cooling, from ~1690 Ma to 550 Ma, prior to its eventual exhumation and the subsequent onlap of mid-Cambrian seas. Within this broad framework, remaining geochronologic issues are identified and future approaches to resolve them are suggested.

PRECAMBRIAN GEOCHRONOLOGY OF THE BLACK HILLS—A RECENT HISTORICAL PERSPECTIVE

Introduction

The Black Hills domain of the easternmost Wyoming craton (Fig. 1 and insets) includes a Laramide domal uplift exposing Paleoproterozoic epicratonic rift basins floored by a basement of Neoarchean gneisses and schists. Infilled mostly by clastic sedimentary rocks and subordinate mafic igneous rocks, this basin complex experienced multiple thermotectonic overprints in response to discrete Paleoproterozoic orogenies that ultimately welded the eastern Wyoming craton to Laurentia. Consequently, the Black Hills crystalline core records a polyphase history of deformation, metamorphism, mineralization, magmatism, and exhumation.

The first U-Pb and Rb-Sr geochronologic studies of the Precambrian crystalline core were focused on its prominent exposures of felsic magmatic rocks, namely, the Paleoproterozoic Harney Peak granite, its numerous satellitic pegmatites (Wetherill, 1956; Riley, 1970a,b; and older, 1926–1966 references therein), and the Neoarchean Little Elk granite (Zartman et al., 1964; Zartman and Stern, 1967). Following these early studies, numerous other studies were devoted to unraveling more details of the complex polyphase history indicated above. These follow-up studies applied increasingly sensitive and precise geochronologic techniques to the dating of radiogenic minerals in key magmatic and metamorphic rocks whose interrelationships were independently known


104°00'
103°30'
N
0 5 10 15 20 km
44°00'
HGD
1719 +38 -45
HGD
1736 ± 8
CMG
1718 ± 22
WPG
1713 ± 10
1742 ± 10
TINTON
S2
LEAD
1746 ± 10
1974 ± 8
1221± 9
BFG
LEG
2559 ± 6
NEMO
BDM
2480 ± 6
1361± 13
BJS
2012 ± 3
MMT
1887 ± 7
ROCHFORD
PACTOLA
1883 ± 5
HILL CITY
KEYSTONE
1716 ± 26
1775 ± 10
1750 ± 10
1692 ± 5
1691±10
BMG
2595 ± 11
HPG
1715-1695
1340-1320
CUSTER
1550-1390
1650-1570
TMP
1704-1695
Phanerozoic Rocks
Paleoproterozoic Rocks
Harney Peak granite (HPG), Whitewood Peak granite (WPG), Crook Mountain granite (CMG)
Muscovite schist (X_{ms}), Iron formation (X_{if})
Other metamorphic rocks (mostly) & magmatic rocks
Blue Draw mafic sill (BDM) Bogus Jim mafic sill (BJS)
Neoarchean Rocks
Little Elk granite (LEG), Bear Mtn granite (BMG)
Metamorphic rocks, undiff. (incl. BFG)
1760 Growth ages: Zrn, Ttn, Mnz, Xno, Hbl, Apa, or Apy (Ma)
1691 1550 Cooling ages: Hbl or Mus (Ma)
Foliation
Fault
Lithologic contact
Hearne Craton
Trans-Hudson Orogen
Superior Craton
VL
Medicine Hat Block
Canada
USA
GFTZ
Wyoming Craton
Black Hills S. Dakota
Yavapai Terrane
SW Proterozoic Provinces
500 km
WC
DB
ND
SD
MT
WY
BHO
THO
D_2
D_2
BLACK HILLS
SC
D_1
NE
CPO (YAV)

from prior field mapping. The following is a brief historical outline of these later developments, as summarized in Figures 1–6 and Table 1. The interested reader is encouraged to consult the cited literature and references therein for further details not presented in this overview.

Summary of geochronologic results during the past two decades

The modern era of Precambrian geochronologic investigation in the Black Hills began two decades ago (see Table 1), with publication of the first precise U-Pb ages for zircon and monazite growth in key magmatic rocks from the region. For example, Redden et al. (1990) published a precise $^{207}Pb/^{206}Pb$ age of 1715 ± 3 Ma for monazite growth in an early sill of the Harney Peak granite (HPG, Fig. 1; Xh unit of Redden and DeWitt, 2008), building upon Riley's (1970) Rb-Sr whole-rock age of 1711 ± 21 Ma for HPG intrusion (recalculated by Krogstad and Walker, 1994). Likewise, from precisely dated zircon ages in other magmatic rocks—including the 2549 ± 11 Ma Little Elk granite (LEG, Wgr; Nemo), the 1974 ± 8 Ma Ellison tuff (Xqg, Lead), and the 1883 ± 5 Ma Prairie Creek gabbro sill (Xgby, Pactola)—Redden et al. (1990) and Gosselin et al. (1988) were further able to constrain depositional and thermotectonic timeframes for the discrete sedimentary sequences that comprise much of the Black Hills crystalline core, as previously mapped by DeWitt et al. (1989; see Fig. 1 for locations). Before proceeding, it is noted that the Paleoproterozoic "X" and Neoarchean "W" rock unit symbols used throughout this paper refer to the terminology of Redden and DeWitt (2008).

In the 1990s other geochronologists built upon these earlier foundations in a series of complementary studies (see Table 1 and Fig. 1). First, Krogstad and Walker (1994) published a precise $^{207}Pb/^{206}Pb$ age of 1702 ± 2 Ma for initial apatite growth in the Tin Mountain pegmatite (Xh), suggesting that this body (and probably the other southern Black Hills pegmatites) represented a late stage of the HPG magmatic event. Holm et al. (1997) and Dahl et al. (1999) then published a series of $^{40}Ar/^{39}Ar$ mica-hornblende dates representing diverse crystalline rocks and documenting post-HPG, slow cooling and exhumation of the southern Black Hills between ~1690 Ma and ~1300 Ma, as first proposed by Riley (1970) based on ~1680–1440 Ma Rb-Sr cooling ages for HPG muscovite. In addition, Dahl and Frei (1998) published a composite $^{207}Pb/^{206}Pb$ age of 1760 ± 7 Ma for monazite inclusions in porphyroblastic garnet and staurolite from a structurally-deep, kyanite-zone metapelite (unit Xeq, Bear Mountain dome; Fig. 1), a result which they interpreted as representing the onset of regional thermotectonism (D_2, S_2) in the Black Hills (Fig. 1). Thus, it was now evident that the main Black Hills metamorphism actually began ~100 million years later than first envisioned by Zartman and Stern (1967; based upon their 1840 ± 70 Ma Rb-Sr whole-rock date for the LEG; recalculated as 1800 ± 70 Ma by Dahl et al., 1999). Further, Schaller et al. (1997) documented a $^{207}Pb/^{206}Pb$ metamorphic monazite age of 1716 ± 26 Ma nearer to the main HPG pluton, in unit Xgw_2. This relatively young, 1760–1716 Ma thermotectonic timeframe led to the recognition that regional metamorphism and HPG magmatism in the Black Hills were immediately sequential in their timing, and thus both could now be understood as part of a multi-phase Wyoming-Superior collisional event. Dahl and Frei (1998) referred to this event as the Black Hills orogeny,

Figure 1 (facing page). Simplified geological map of the Precambrian crystalline core of the Laramide Black Hills uplift. $^{207}Pb/^{206}Pb$ growth ages (mostly) and $^{40}Ar/^{39}Ar$ cooling ages (in Ma, with 2σ uncertainties) of minerals from selected sources are shown in black and gray text boxes, respectively; see Table 1 for corresponding age interpretations. Lithotectonic abbreviations (not identified on map or insets): BHO and CPO = Black Hills and Central Plains orogens, CB = Cheyenne fold belt, D_1 = north-directed accretion of CPO (YAV) terrane, D_2 = ~E-W collision of Archean Wyoming (WC) and Superior (SC) cratons, DB = Dakota block (Archean), GFTZ = Great Falls tectonic zone, HGD = Homestake gold deposit, HR = Hartville-Rawhide fault zone, MMT = tuff in Montana Mine (Iron) Formation, S_1–S_4 = foliation surfaces related to events D_1–D_4 (= events D_1–D_5 of Redden et al. 1990), THO = Trans-Hudson orogen, TMP = Tin Mountain pegmatite, VL = Vulcan Low, YAV = Yavapai arc terrane. Geographic abbreviations: MT = Montana, ND and SD = North and South Dakota, NE = Nebraska, WY = Wyoming. Mineral abbreviations: Apa = apatite, Apy = arsenopyrite, Hbl = hornblende, Mus = muscovite, Mnz = monazite, Ttn = titanite (sphene), Xno = xenotime, Zrn = zircon. Sources of mineral ages include: Redden et al. (1990), Krogstad and Walker (1994), Schaller et al. (1997), Holm et al. (1997), Dahl and Frei (1998), Dahl et al. (1999, 2005a, 2005b, 2006), McCombs et al. (2004), Dahl and Foland (2008), Ghosh (2009), Hark (2009), Frei et al. (2009), and Morelli et al. (2010). Map modified from DeWitt et al. (1989) and Dahl et al. (2005b); insets modified from Mueller et al. (2002) and Stock (2004). See Table 1 and text for summary and discussion of the age relationships. For a complementary regional map showing $^{40}Ar/^{39}Ar$ amphibole and Rb-Sr muscovite-whole rock dates, see Redden and DeWitt (2008).

TABLE 1. PRECAMBRIAN (~2900–550 Ma) EVENTS IN THE BLACK HILLS, SOUTH DAKOTA

Age (Ma)	Interpretation	References
2894 ± 6	Oldest-dated crustal fragment (Nemo; age of subjacent crust?)	1, 2
2900?–2560	Earliest sedimentation (e.g., Nemo Iron Fm., Wif; Nemo)	1, 2
2595 ± 11	Intrusion of Bear Mtn. granite (BMG, Wgr; near Custer; Kenorland assembly?)	2
2559 ± 6	Intrusion of Little Elk granite (LEG, Wgr; Nemo; Kenorland assembly?)	2, 3
2560–2480	Rifting and sedimentation (Boxelder Cr., Benchmark Fms., Xbc and Xbi; Nemo)	1
2480 ± 6	Intrusion of Blue Draw layered mafic sill (BDM, Xbd; Nemo)	1
2250?–2100?	Cryptic folding, Pb loss, and Estes unconformity (Nemo; terrane recollision?)	1, 4
2100–1883	Rifting, sedimentation, and magmatism (formation of main Black Hills basin)	1, 4, 5
2100?–2015?	Listric normal faulting (Nemo)	1, 5
2100–2015	Deposition of Estes and Roberts Draw Fms. (Xec-Xeq and Xd-Xds; Nemo)	1, 4
2012 ± 3	Intrusion of Bogus Jim gabbro sill (BJS, Xgbo, Nemo; Kenorland breakup)	6
2012–1974	Deposition of Homestake Iron Formation (Xif, Lead)	5, 6
1974 ± 8	Deposition of tuffaceous bed in Ellison Fm. (Xqg, Lead)	5
1887 ± 7	Deposition of alkalic tuff in Montana Mine Fm. (MMT, Xtv; Rochford)	5, 7
1883 ± 5	Intrusion of gabbro sill (Xgby, Pactola; Trans-Hudsonian back-arc basin?)	5
1845–1810	Cryptic metamorphism (related to Trans-Hudson orogeny east of Black Hills?)	8, 9
1775 ± 10	North-directed nappe/thrust/overturning event (D_1; accretion of Yavapai terrane)	10
1750 ± 10	Onset of Black Hills orogeny (BHO, D_2; Wyoming-Superior collision)	9, 10, 11
1746–1742	Continuation of BHO thermotectonism (Lead-Tinton)	10, 12
1736 ± 8	Homestake gold deposition (HGD, Lead; Re-Os arsenopyrite date)	13
1732 ± 9	Onset of differential block uplift (along shear zones) and regional unroofing?	8, 9
1732–1715	Homestake gold deposition ($^{207}Pb/^{206}Pb$ arsenopyrite date = 1719 $^{+38}_{-45}$ Ma)	12
1718 ± 22	Intrusion of granite at Crook Mountain (CMG, Xh; NE of Lead)	14
1713 ± 10	Intrusion of granite at Whitewood Peak (WPG, Xh; NE of Lead)	12
1716 ± 26	Metamorphism related to Harney Peak granite (HPG, Xh; Keystone)	15
1715 ± 3	Onset of HPG magmatic event (main pluton; D_3 = local "doming" event)	5, 6
1715–1695	Duration of HPG event (incl. 1704–1695 Ma Tin Mtn. pegmatite; TMP, Xh)	6, 16
1695 ± 3	End of HPG magmatic event (incl. pegmatites and late aplite dike, Xh)	6, 13, 16
1692 ± 5	End of BHO-related thermotectonism (D_2–D_3)	8, 9
1680?–1650?	Cryptic, north-directed? D_4 event (accretion of Mazatzal arc terrane?)	8, 9
1691 ± 10	Initial post-HPG cooling of SBH mid-crust, through ~550º–500ºC	17, 18
1650–1320	Continued slow cooling of SBH mid-crust, through ~400º–350ºC	18, 19
1510–1260	Continued slow cooling of SBH mid-crust, through ~300ºC	18, 19
1250–550	Eventual exhumation of SBH mid-crust, prior to onlap of mid-Cambrian seas	18, 19

The 2900-1695 Ma $^{207}Pb/^{206}Pb$ dates represent ages of zircon and monazite growth mostly, but single growth ages of titanite (BDM), apatite (TMP), and xenotime (HPG) are also listed. Re-Os and $^{207}Pb/^{206}Pb$ dates are given for HGD arsenopyrite and allanite inclusions therein, which coexist with the gold. The 1690-1260 Ma $^{40}Ar/^{39}Ar$ dates represent cooling ages of southern Black Hills (SBH) hornblende, muscovite, and biotite through ~550°–500°C, ~400°–350°C, and ~300°C, respectively, whereas most NBH counterparts reflect Tertiary resetting. All age uncertainties quoted at 2σ level. Deformational events and fabrics (D_1–D_3 and S_1–S_3) are depicted in Fig. 1 (right inset), where D_2 (above) includes the D_2–D_3 events of Redden et al. (1990) and D_3–D_4 (above) correspond to their D_4–D_5. Fig. 1 shows locations of BDM, BMG, BJS, CMG, HGD, HPG, LEG, MMT, TMP, WPG, and nearby towns; for equivalent Neoarchean (W) & Paleoproterozoic (X) abbreviations see Redden and DeWitt (2008). References: 1 = Dahl et al. (2006); 2 = McCombs et al. (2004); 3 = Gosselin et al. (1988); 4 = Bekker and Eriksson (2003; also Bekker et al., 2003); 5 = Redden et al. (1990); 6 = Hark (2009; Hark et al., 2008); 7, 8, 9, 10 = Dahl et al. (2008, 2005a, 2005b, 1999); 11= Dahl and Frei (1998); 12 = Frei et al. (2009); 13 = Morelli et al. (2010); 14 = Ghosh (2009; Ghosh et al., 2008); 15 = Schaller et al. (1997); 16 = Krogstad and Walker (1994); 17 = Redden and DeWitt (2008; Berry et al., 1994); 18 = Dahl and Foland (2008); 19 = Holm et al. (1997).

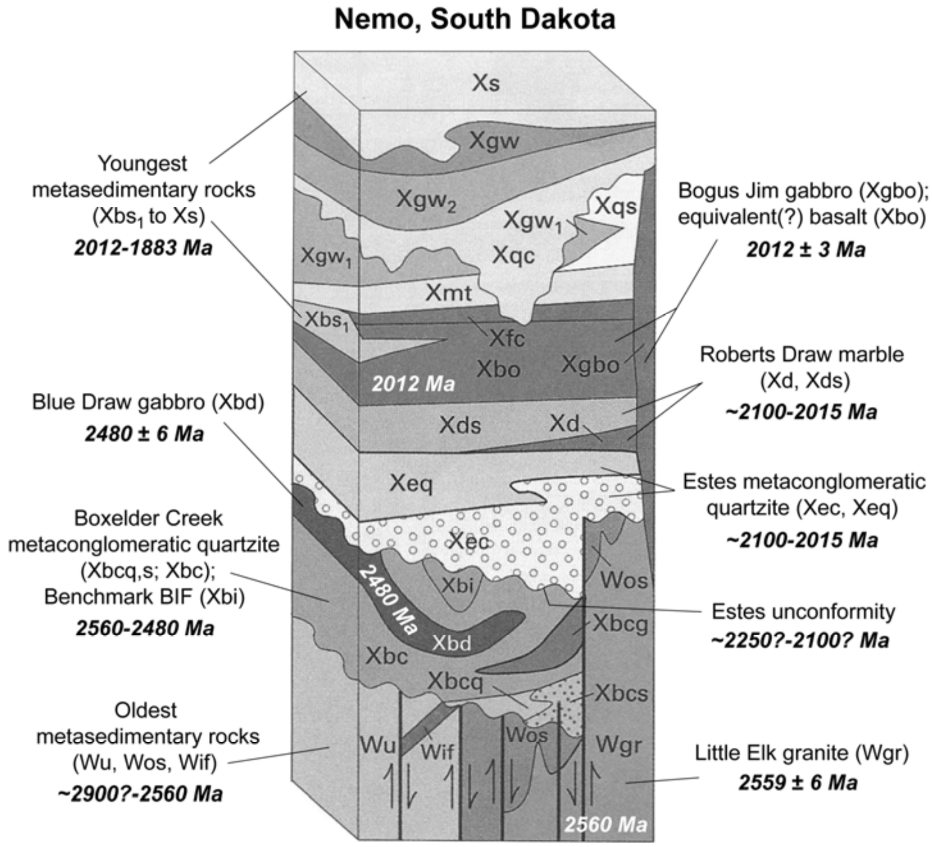


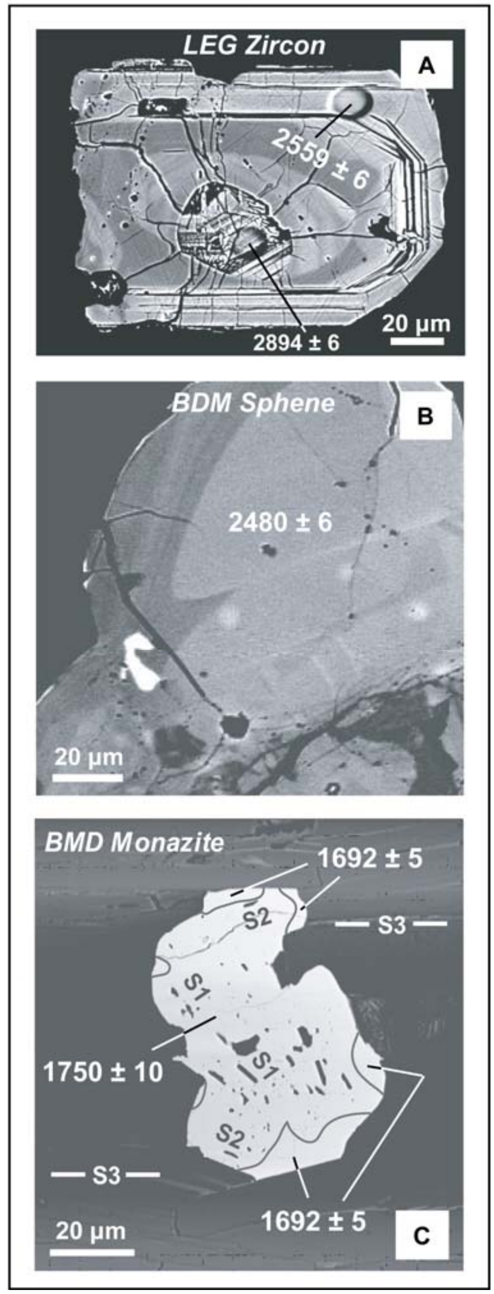
Figure 2. Schematic geologic cross-section of Neoarchean (W) and Paleoproterozoic (X) rocks and structures in the Nemo area (Fig. 1) modified after Redden and DeWitt (2008) and annotated with ages of magmatism, sedimentation, and erosion as inferred in Table 1 (Redden et al., 1990; Bekker and Eriksson, 2003; McCombs et al., 2004; Dahl et al., 2006; Hark, 2009). Units Xbo and Xbs_1 (e.g., Nemo) may correspond to lower and upper Poorman Fm. (Lead), respectively; iron-rich unit Xfc (Nemo) may correspond to Homestake Iron Fm. (Xif, Lead); gabbro Xgbo may be comagmatic with basalt Xbo (Redden and DeWitt, 2008) and thus also with lower Poorman Fm. (Yates member, Lead).

thereby resurrecting the original designation of Goldich et al. (1966), in order to differentiate it from the distinctly older, ~1850 Ma Trans-Hudson orogen which is well exposed in Canada and which has been projected south into the USA, just east of the Black Hills (see Fig. 1, both insets). This younger Black Hills orogenic timeframe also permitted a hypothesis that the north-directed nappe/thrust event documented by Redden et al. (1990; D_1, S_1; Fig. 1) was caused by accretion of the ~1780–1740 Ma Yavapai arc terrane to the south (Dahl et al., 1999; Fig. 1, both insets).

With the maturation of microprobe-based spot-dating techniques, Precambrian geochronology of the Black Hills entered a new phase of age refinement in the first decade of the 21st century. In particular, the spatial resolution inherent in $^{207}Pb/^{206}Pb$ and total-Pb spot-dating by ion and electron microprobe, respectively, meant that only the most pristine domains of zircon could be selected for analysis and that grain-scale age heterogeneity in both zircon and monazite could be resolved, thereby circumventing the problems of metamictization and averaging that can obscure the geological meaning of bulk mineral dates. Moreover, in-situ spot-dating of monazite meant that in principle the ages of deformational fabrics could also be dated. These advances facilitated refinements in Precambrian geochronology of the Black Hills, as summarized below.

Among the magmatic rocks, weighted-mean $^{207}Pb/^{206}Pb$ spot-dates of zircon, monazite, sphene, and xenotime were thus interpreted as precise magmatic ages of their respective host rocks, some of which had been dated previously (by Gosselin et al., 1988; Redden et al., 1990). As shown in Table 1 and Figs. 1–3 (see captions for unit abbreviations), these relatively refined ages include the 2595 ± 11 Ma and 2559 ± 6 Ma granite at Bear Mountain (BMG, Wgr) and Little Elk granite (LEG, Wgr; McCombs et al., 2004). Additional refinements include: (1) a 2894 ± 6 Ma zircon xenocryst in the LEG that mirrors the host rock's Nd T_{DM} age and which is thereby interpreted as preliminary evidence for pre-BMG/LEG crust of ~2900 Ma age that is no longer exposed (Fig. 3A; McCombs et al., 2004); (2) the 2480 ± 6 Ma Blue Draw mafic sill west of Nemo (BDM, Xbd; Fig. 3B; Dahl et al., 2006); (3) the 2012 ± 3 Ma Bogus Jim gabbro sill south of Nemo (BJS, Xgbo; Hark, 2009); (4) an 1887 ± 7 Ma tuff in the Montana Mine Formation west of Rochford (MMT, Xtv; Dahl et al., 2008); and (5) the 1715–1695 Ma HPG (Xh)(Custer-Keystone and environs: Hark, 2009; Lead-Sturgis and environs: Ghosh, 2009; Frei et al., 2009). Also, highly disturbed zircon coexisting with BDM titanite (sphene) yielded a lower-intercept age of ~2250 Ma, which McCombs et al. (2004) tentatively interpreted as the age of: (1) a cryptic folding event (see folded BDM in Figs. 1–2), (2) Pb loss from BDM zircon during exhumation-

Figure 3. Backscattered electron images showing selected "Rosetta grains" of polyphase (A) magmatic zircon from the Little Elk granite (LEG, Wgr; McCombs et al., 2004); (B) magmatic sphene from the Blue Draw (meta)gabbro (BDM, Xbd; Dahl et al., 2006); and (C) metamorphic monazite in micaceous matrix (foliations S_1–S_3 in metapelite PR-1, unit Xeq; Dahl et al., 2005a,b) from the Bear Mountain dome. Grains are annotated with $^{207}Pb/^{206}Pb$ weighted-mean ages (Ma, ±2σ) obtained from the original sources. Sample locations and age interpretations are given in Figure 1 and Table 1, respectively. Modified after Dahl and McCombs (2005).



related interaction with meteoric water, and (3) corresponding erosion that led to the Estes unconformity (Dahl et al., 2006). Figure 2 shows that the ~2250?–2100? Ma Estes unconformity separates the 2560–2480 Ma sedimentary sequence (below) from the younger 2100–1880 Ma sequence (above).

Some of these magmatic spot-ages, coupled with chemostratigraphic (Bekker and Eriksson, 2003; Bekker et al., 2003) and field (DeWitt et al., 1989) data, permitted further constraint of known depositional age ranges in the Black Hills. Thus, as shown in the age-annotated Nemo cross-section (Fig. 2), depositional timeframes of the Neoarchean (W) and Paleoproterozoic (X) sedimentary sequences could now be bracketed as follows: (1) ~2900?–2560 Ma for units Wif, Wos, and Wu; (2) 2560–2480 Ma for units Xbcs, Xbcq, Xbc, and Xbi; (3) ~2100 Ma to 2015–2012 Ma for units Xec, Xeq, Xd, and Xds; and (4) 2015–2012 Ma to 1887–1883 Ma for units Xbs_1, Xfc, Xmt, Xgw_1, Xqs, Xqc, Xgw_2, Xgw, and possibly Xs (modified cross-section and unit abbreviations from Redden and DeWitt, 2008). These four discrete depositional timeframes are also listed in Table 1. The 2560–1883 Ma Nemo complex (Fig. 2)—including the BDM, Estes unconformity, and BJS—was subsequently overturned on an ~E-W axis, possibly as part of the north-directed nappe/thrust event (D_1; Redden et al., 1990), which is most obviously reflected in large-scale refolded folds of the southern Black Hills (Fig. 1).

Likewise, among the 2015–1880 Ma metasedimentary rocks, total-Pb spot-dating of metamorphic monazite mostly from southern Black Hills metapelites (e.g., Fig. 3C) revealed evidence for multiple episodes of Paleoproterozoic thermotectonism. Specifically, the monazite ages inferred in multiple rocks (Dahl et al., 2005a,b; see also Yang and Pattison, 2006)—and their thermotectonic interpretations—are summarized as follows (see also Table 1 and Fig. 4): (1) ~1845–1810 Ma (no deformational fabric recognized but ages correlate with Trans-Hudsonian metamorphism); (2) 1775 ± 10 Ma (D_1, most likely related to Yavapai arc accretion); (3) 1750 ± 10 Ma (D_2, related to onset of Wyoming-Superior collision); (4) ~1715 Ma to 1692 ± 5 Ma (D_3, related to terminal HPG intrusion and terminal Wyoming-Superior collision); and (5) ~1680–1650 Ma (D_4?, accretion of Mazatzal arc terrane?). All six rocks analyzed by Dahl et al. (2005a) exhibit subordinate populations of the ~1845–1810 Ma and ~1680–1650 Ma monazites, whereas the intermediate ~1750–1715 Ma populations are predominant in all rocks. Some of these total-Pb monazite spot-dates were determined in direct microtextural context (e.g., see Fig. 3C), and they closely parallel the prior $^{207}Pb/^{206}Pb$ bulk dates that range from ~1760 Ma to 1715 Ma depending upon

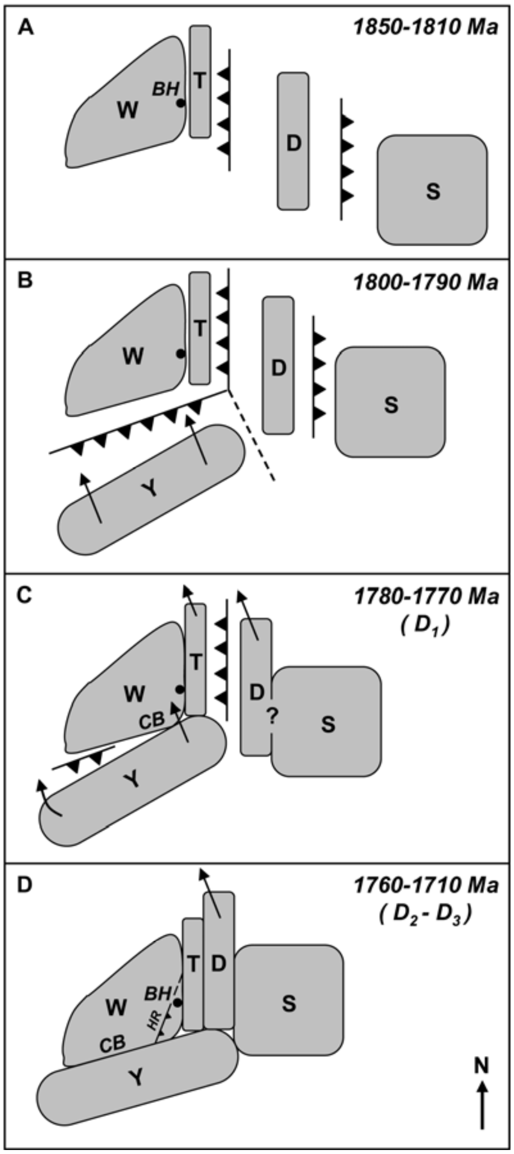


Figure 4. Schematic spatial-temporal relationships of 1850–1710 Ma terrane assembly in south-central Laurentia and resultant timing of thermotectonism in the Black Hills, modified from Dahl et al. (2005b; see Fig. 1, lower right inset). Position of Wyoming craton is arbitrarily fixed. Teeth denote upper plates of subduction zones. BH = Black Hills; CB = Cheyenne belt (Chamberlain, 1998); D = Dakota block (Baird et al., 1996); HR = Hartville-Rawhide fault; S and W = Superior and Wyoming cratons; T = Trans-Hudson arc terrane; and Y = northern Yavapai arc terrane (Karlstrom et al., 2002). NNW directions of Yavapai and Superior terrane transport, relative to the Wyoming craton, are inferred from Day et al. (1999) and Klasner and King (1990), respectively.

sample proximity to the HPG pluton (see Dahl et al., 2005a; Dahl and Frei, 1998; Schaller et al., 1997; Fig. 1).

The predominant ~1750–1715 Ma spot-ages of D_2–D_3 monazite noted above are significantly older than most amphibole $^{40}Ar/^{39}Ar$ dates inferred by Redden and DeWitt (2008), which they interpreted as indicating the age of D_2. In light of the previously published monazite dates, however, their oldest amphibole dates must be viewed as strictly minimum ages for this event. Only in the northern Black Hills, where, in contrast to the south, the ~1750–1770 Ma monazite dates dominate over their ~1715 Ma counterparts (Ghosh, 2009), does there appear to be more of an age equivalence between probable D_2 monazite (1746 ± 10 Ma, Lead; Frei et al., 2009) and probable D_2 amphibole (1742 ± 10 Ma, Tinton; Dahl et al., 1999; see Fig. 1). Finally, the preponderance of ~1715 Ma monazite dates in the wide “regional-contact” aureole surrounding the HPG (i.e., within the muscovite cooling-age envelope; see Fig. 1) supported the contention of Nabelek et al. (2006) that the mid-crustal garnet, staurolite, and sillimanite isograds were imposed at ~1715 Ma in response to HPG intrusion. In contrast, Dahl and Frei (1998; see also Dahl et al., 2005a,b) argued that the structurally deeper kyanite isograd surrounding the BMG was imposed at ~1760–1750 Ma.

Before proceeding, it is important to clarify that Redden et al. (1990) originally distinguished five Paleoproterozoic deformations, D_1–D_5, which Dahl and coworkers traditionally referred to as D_1–D_4, having chosen to combine the closely-related(?) D_2 and D_3 events into one event they referred to as simply D_2. Hence, D_3–D_5 of Redden et al. (1990; see also Redden and DeWitt, 2008) are equivalent to D_2–D_4 as designated in this review paper.

Within the 2100–1880 Ma sequence of metasedimentary rocks that areally dominates the main Black Hills basin, as inferred above, the Poorman, Homestake, and Ellison Formations (Xbo-Xbs$_1$, Xif, and Xqg; Lead and environs; Fig. 1) are all considered to have been deposited in an active rift margin some time between 2015–2012 Ma (Bekker and Eriksson, 2003; Bekker et al., 2003; Hark, 2009) and 1974 Ma (Redden et al., 1990).

In contrast, Homestake gold mineralization occurred much later, at ~1719 $^{+38}_{-45}$ Ma (maximum $^{207}Pb/^{206}Pb$ bulk age of arsenopyrite associated with the gold) and probably between ~1732–1715 Ma (Frei et al., 2009). Morelli et al. (2010) subsequently inferred a more precise Re-Os age of 1736 ± 8 Ma for this arsenopyrite, however, which they also interpreted as the age of gold mineralization. In addition, the Pb-isotopic signatures of barren and mineralized Homestake Iron Formation are systematically different, with the gold-mineralized rocks and associated sulfide minerals invariably exhibiting higher $^{207}Pb/^{204}Pb$ ratios for given $^{206}Pb/^{204}Pb$ ratios than those found in the barren rocks (Frei et al., 2009). These observations required the existence of a fluid-mediated Pb source external to the Homestake Formation, inasmuch as Pb isotopes could not have fractionated within it. Thus, both the older depositional vs. younger mineralization ages of the Homestake Formation, and its distinctive barren vs. mineralized Pb isotopics (see above), pointed Frei et al. (2009) more toward an epigenetic origin for the sulfide-hosted Homestake gold deposit rather than a syngenetic (or syngenetic but remobilized) origin. This conclusion thus supported the original epigenetic model of Caddey et al. (1991), who observed that the retrograde-metamorphic gold deposit was focused in late, brittle-ductile shear zones that postdated the 1746 ± 10 Ma growth of prograde, D_2 monazite in the Homestake Formation (Frei et al., 2009). Moreover, the precise 1736 ± 8 Ma age obtained for post-D_2 arsenopyrite coexisting with the gold (Morelli et al., 2010) is consistent not only with the nominally older, 1746 ± 10 Ma age of syn-D_2 monazite (HGD, Lead; Fig. 1) but also with an inferred 1732 ± 9 Ma timeframe for the onset of differential block uplift associated with tectonic unroofing in the southern Black Hills, as described below (Dahl et al. 2005a,b; Table 1; see also Fig. 6, inset). Thus, the emerging tectonic setting for Homestake gold mineralization appears to involve gold-bearing hydrothermal fluids having been channeled upward from deeper crust at ~1735 Ma, along a late–post-D_2 shear zone developed between differentially uplifting blocks. This timeframe for gold mineralization predates syn-D_3 granite intrusion by ~20 million years, thus appearing to preclude the cause-and-effect synchroneity of these events as envisioned by Caddey et al. (1991). In this context, the observed similarity of Pb-isotopic signatures between mineralized Homestake Formation and Harney-type granite-pegmatites (Frei et al., 2009) may indicate that both the gold and the granite shared a common deep-crustal source, which was tapped at different times.

An alternative syngenetic (syn-depositional) model for the Homestake gold deposit is mentioned by Redden and DeWitt (2008). However, in light of recent $^{207}Pb/^{206}Pb$ and Re-Os geochronology and Pb-isotopic tracer work, it now seems that future petrogenetic insights must somehow be framed in terms of this deposit having formed during the ~1750–1690 Ma Black Hills orogeny (specifically between the D_2 and D_3 events) rather than during the ~2012–1974 Ma, pre-Trans-Hudsonian deposition of the host iron formation, which clearly occurred much earlier.

Finally, new details of the regional post-HPG cooling history began to emerge with the publication of complementary $^{40}Ar/^{39}Ar$ data sets for amphiboles and micas from Precambrian crystalline rocks in the Black Hills (Dahl and Foland, 2008; DeWitt and Redden, 2008). Focusing on southern Black Hills micas, Dahl and Foland (2008) showed that both muscovite (Fig. 1) and biotite cooling ages delineate regional patterns best modeled as elliptocentric age-zones centered on the main HPG pluton, as shown in Figure 1 for muscovite only. These patterns indicated that following its 1715–1695 Ma intrusion, the HPG and its aureole cooled slowly in the mid-crust through ~400º–300ºC (see also Holm et al., 1997), and from the cooler aureole toward the warmer granite, between ~1650–1320 Ma (muscovite) and between ~1510–1260 Ma (biotite). Moreover, the observation of Dahl and Foland (2008) that "chrontours" of muscovite cooling age transect shear zones along which the adjacent Harney Peak and structurally deeper Bear Mountain blocks were differentially unroofed (Fig. 1; see also Terry and Friberg, 1990) led to the inference that the block faulting occurred between ~1650 Ma (oldest muscovite cooling age) and 1732 ± 9 Ma (i.e., the age of a monazite domain uniquely inferred within the Grand Junction fault zone, labeled with "U" and "D" in Fig. 1; Dahl et al., 2005a). Within this broad time interval, perhaps at ~1715 Ma, Nabelek et al. (2006) envisioned that the fault-bounded Harney Peak block (Fig. 1) underwent buoyancy-driven uplift.

The muscovite-biotite cooling ages from Dahl and Foland (2008) and from Dahl et al. (1999) are profiled Black Hills-wide in Figure 5, along a reference line running from Lead (north) to the center of the HPG pluton east of Custer (south). Micas occurring within the elliptocentric cooling envelope (Fig. 1) are profiled according to their positions relative to the mapped "chrontours." The north-south profile reveals a regional pattern of muscovite dates systematically older than corresponding biotite dates. In the southern Black Hills, the younging of mica dates (interpreted as cooling ages) reflects pregressively delayed slow cooling of the mid-crust with proximity to the HPG pluton, as described above (see also Dahl and Foland, 2008). However, the occurrences of younger mica dates in the central and northern Black Hills are not as readily explained, particularly the abrupt drop in mica dates immediately north of the staurolite isograd (Fig. 5). To some extent, these younger dates reflect variable progress of Tertiary resetting that was most extensive in Lead and environs (Fig. 1), where Tertiary intrusions abound. Redden and DeWitt (2008) reached the same conclusion based on a regional map of their $^{40}Ar/^{39}Ar$ amphibole-mica dates. However, there is no evidence for Tertiary magmatic activity between Nemo and Rockerville that could support a Tertiary resetting explanation in this region (Fig. 5). Alternatively, if these garnet-zone mica dates represent cooling ages rather than variably reset dates, then they are younger than their staurolite-zone counterparts either because they are finer-grained

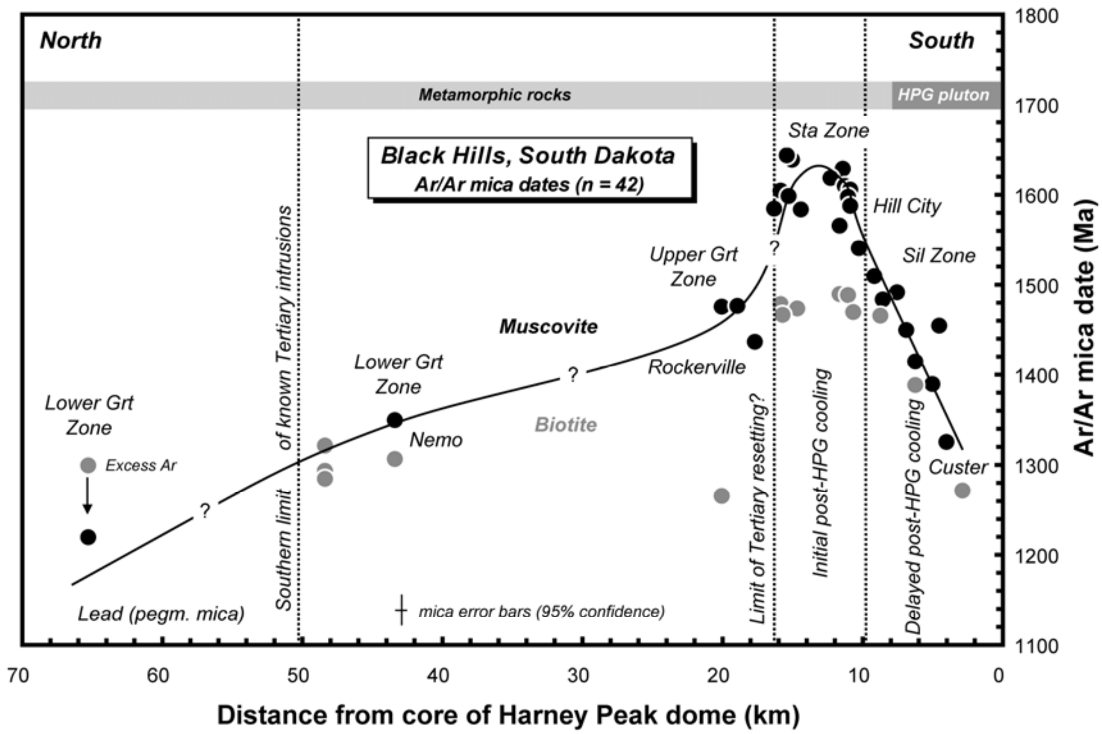


Figure 5. Summary of 42 $^{40}Ar/^{39}Ar$ mica dates in Precambrian crystalline rocks as profiled along length of the Black Hills uplift from the center of the 1715–1695 Ma Harney Peak granite (east of Custer) to the ~1719 Ma Homestake gold deposit (Lead; see Fig. 1). Most $^{40}Ar/^{39}Ar$ dates have been interpreted as cooling ages in the original sources (Holm et al., 1997; Dahl et al., 1999; Dahl and Foland, 2008), but widespread Tertiary resetting and excess argon (in at least one case) appear to have disturbed northern Black Hills micas (e.g., in Lead and environs). Several more $^{40}Ar/^{39}Ar$ dates for Black Hills micas, mapped by Redden and DeWitt (2008), are not included in this profile (see their Fig. 9 for comparison). Grt = garnet, Sta = staurolite, and Sil = sillimanite.

(thereby leading to relatively young closure ages) or because garnet-zone and staurolite-zone rocks underwent differential unroofing (which could explain the abrupt mica-age change at the staurolite isograd but for which there is no independent evidence, however).

Composite temperature-time histories of the well-studied Harney Peak and Bear Mountain blocks are shown in Figure 6 (ages from Dahl et al., 2005a,b; Dahl and Foland, 2008). These relatively low- and high-pressure structural blocks are thought to have been juxtaposed along the Grand Junction fault between 1732 ± 9 Ma (see above) and ~1715 Ma and appear to have shared a common post-HPG cooling history by ~1690 Ma (Fig. 6), at which time their cooling trajectories diverged according to sample distances from the HPG pluton (Fig. 5). As also implied in Figure 6, current exposures of Black Hills crystalline rocks were finally exhumed some time between ~1250 Ma (youngest biotite date, Table 1) and ~520 Ma (the onlap of mid-Cambrian seas).

PRECAMBRIAN GEOCHRONOLOGY OF THE BLACK HILLS—FUTURE PRIORITIES AND THE WAY FORWARD

Timing of pre-LEG/BMG magmatism, sedimentation, and deformation

Little is known about the timing of pre-BMG/LEG (i.e., earlier than 2600–2560 Ma) sedimentation and deformation in the Black Hills. Nor has the unexposed older crustal platform on which these sediments were deposited been dated with any reliability, beyond indirect inferences from the single ~2900 Ma, U-Pb concordant spot-date of a zircon xenocryst obtained within the LEG (McCombs et al., 2004; Fig. 3A) and from a growing data set of ~2900–3800 Ma Nd model ages for Black Hills granitic rocks generally (e.g., Walker et al., 1986; Krogstad et al., 1993; Frei et al., 2008; and references therein). The LEG and BMG essentially represent geochemical probes of unexposed portions of the lithotectonic units they intrude. In

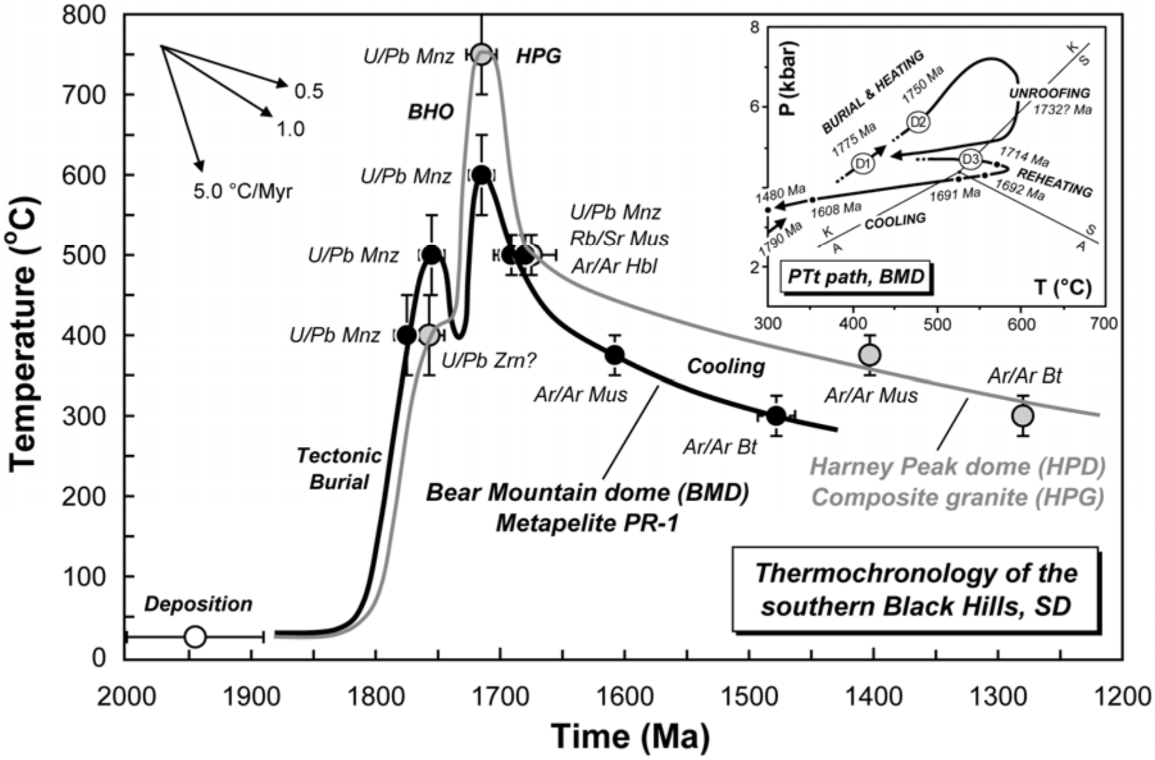


Figure 6. Temperature-time plot summarizing the Precambrian thermochronology of two southern Black Hills rocks representing different initial structural levels: metapelite PR-1 (unit Xeq, kyanite zone) from the Bear Mountain dome (BMD) and composite granite (unit Xh, second sillimanite zone) from the Harney Peak dome (HPD). These domains were juxtaposed along mapped shear zones (e.g., as labeled with “U” and “D” in Fig.1) prior to ~1650 Ma and perhaps as early as 1732 ± 9 Ma (Table 1). Mineral abbreviations are defined in Fig. 1. Mineral ages are from: Ratté (1986), Redden et al. (1990), Dahl and Frei (1998), Dahl et al. (1999, 2005a,b), and Dahl and Foland (2008). Prograde metamorphic and magmatic temperatures are from Terry and Friberg (1990) and Nabelek et al. (1992), respectively. Inset shows pressure-temperature-time (*PTt*) path inferred for BMD as modified from Dahl et al. (2005b; see also Holm et al., 1997). The *PTt* path for the HPD (not shown) is nested within the BMD path, but peak *P-T* conditions are uncertain due to HPG-related overprinting. K, S, and A = kyanite, sillimanite, and andalusite. BHO = Black Hills orogeny.

principle, therefore, finding and dating additional xenocrysts of magmatic zircon therein would better constrain the nature of pre-BMG-LEG crust. Likewise, in the biotite-feldspar gneiss (BFG) adjacent to the LEG (northwest of Nemo; Fig. 1), finding and dating metamorphic monazite in its pre-LEG fabric (Gosselin et al., 1988) should in principle establish the fabric age and thus constrain its tectonic origin, although initial efforts thus far have yielded only ~2560 Ma reset ages related to the adjacent LEG (Hark, 2009).

Timing and interpretations of mafic and related magmatism

The respective 2480 ± 6 Ma and 2012 ± 3 Ma ages of the Blue Draw (Xbd) and Bogus Jim (Xgbo) metagabbro sills determined by grain-by-grain spot-dating of magmatic zircon (Table 1, Figs. 1–2; Dahl et al., 2006; Hark, 2009) replace the 2170 ± 110 Ma and 1964 ± 15 Ma TIMS dates originally estimated by Redden et al. (1990) from bulk dating of zircon populations. Whereas only one thick Xbd horizon is recognized in the Black Hills (BDM, Fig. 1), there are numerous thinner sills and flows of the Xgbo and of the presumably comagmatic metabasalt, Xbo, that occur within diverse sedimentary horizons (Redden and DeWitt, 2008), as schematically indicated in Fig. 2. However, there is no guarantee that all mafic rocks mapped as Xgbo or as Xbo are the same age; likewise, there is no such guarantee among the younger metagabbros (Xgby, Xgb), metabasalts (Xby), and related metatuffs. In future studies, therefore, individual mafic sills and flows must be dated one by one in order to establish the full duration of mafic magmatism among the (mostly ~2012 Ma?) Xgbo-Xbo units and among the (mostly ~1885 Ma?) Xgby-Xgb-Xby units. Indeed, U-Pb dating of magmatic zircon in tuffs of the upper Poorman Formation (potentially younger than Xbo, Lead) and in the Crow Formation (northwest of Custer) represents work in progress. This and related studies will serve to refine depositional age ranges of a wide array of intervening sedimentary rocks—for example, the maximum depositional age of the Homestake Formation (Xif, Lead) and the contact age of proximal and younger distal graywackes (Xgwp and Xgwd, west of Custer). Likewise, more dating of mafic sills and flows in the Black Hills will constrain the duration of regional rifting involving this easternmost margin of the Wyoming craton and perhaps also the identity of the rifted crustal fragment itself.

The tholeiitic Xgbo, Xgb, Xgby, Xbo, and Xby units are perhaps unambiguously interpreted in terms of rifting of the easternmost Wyoming craton—i.e., at times corresponding to their apparent ~2012 Ma and ~1885 Ma magmatic ages. Indeed, Halls et al. (2008) documented a long-lived mantle plume event beginning at ~2100 Ma along the southern margin of the Superior craton (see also Buchan et al., 1996; Schmitz et al., 2006), and Cox et al. (2000) documented an episode of 2010 Ma rifting in southeasternmost Wyoming (Kennedy dike swarm). The identity of the crustal fragment from which eastern Wyoming rifted at ~2.0 Ga remains uncertain, as noted above, but recent proposals include the Slave craton (Cox et al., 2000) or, perhaps more likely, the southern Superior craton (Roscoe and Card, 1993; Dahl et al., 1999, 2006; Hark, 2009). In addition, Heaman et al. (2009) have recognized the ~1.88 Ga Molson (Circum-Superior) igneous belt, which includes Trans-Hudson and Penokean mafic and ultramafic magmatic rocks of possible back-arc affinity, and of which the Black Hills now appears to comprise the southwestern part, judging from occurrences of coeval ~1887–1883 Ma felsic tuffs and mafic magmatic rocks (Fig. 1, Table 1).

However, this level of interpretive certainty does not carry over to the older Blue Draw metagabbro (BDM, Xbd), whose composite silica content upon recombining all individual layers is more that of a basaltic andesite typical of a volcanic arc. Indeed, van Boening and Nabelek (2008) inferred a convergent setting for BDM intrusion, based upon where it plots on various geochemical discrimination diagrams, whereas Dahl et al. (2006) interpreted the 2480 Ma BDM age as indicative of incipient rifting at this time, based partly on the BDM's layered character and its intrusion into sedimentary rocks previously deposited in a rift setting (see also Redden et al., 1990). So, the BDM is related either to terminal assembly or incipient breakup of Kenorland at 2480 Ma. Outside the Black Hills, however, Dahl et al. (2006) further appealed to BDM age counterparts like the giant radiating Matachewan-Hearst dike swarm and East Bull Lake Intrusive Suite in the central and southernmost Superior craton, respectively, both of which are unequivocally rift-related and thus associated by others with incipient Kenorland breakup (Heaman, 1997; James et al., 2002). Moreover, Pearce (2008) showed that unequivocally rift-related mafic magmatic rocks of the British Tertiary commonly plot nonetheless in the volcanic arc rather than MORB field on his Th/Yb-Nb/Yb discrimination diagram, an occurrence that he explained in terms of 90% assimilation-fractional-crystallization (AFC) of MORB in a continental-rift setting. Interestingly, Pearce's AFC model applied to N-MORB also duplicates the composite Th-Nb-Yb signature of individual BDM layers as determined by van Boening and Nabelek (2008), which nominally permits a rift setting for BDM intrusion. On the other hand, just because the 2560–2480 Ma Boxelder Creek and Benchmark Formations may have been deposited in a rift setting (Redden et al, 1990; Dahl et al., 2006), the same is not therefore required of the 2480 Ma BDM that intruded them. Additional geochronologic investigation on multiple presumed margins of Kenorland, including the easternmost Wyoming cratonic margin represented by the Black Hills, may resolve current ambiguity regarding the tectonic setting of BDM intrusion at 2480 Ma.

Timing and nature of terrane assembly and related Black Hills thermotectonism

Whereas the Wyoming craton (including the Black Hills) may have separated from Kenorland some time between 2480 Ma (incipient?) and 2012 Ma (final?), with an intervening recollision (folding of BDM, possibly as late as ~2250–2100 Ma; Figs. 1–2, Table 1), many details of its subsequent reassembly as part of southwest Laurentia between ~1850–1700 Ma also remain to be verified. Figure 1 (right inset) depicts inferred relationships between the Black Hills domain and surrounding Precambrian terranes (Sims et al., 1991; Sims, 1995; Stock, 2004), and Figure 4 schematically shows how and when these terranes may have been assembled (modified from Dahl et al., 2005b). However, this terrane reconstruction model is by no means unique, in part because the relative timing of Wyoming and Superior collisions with the intervening Dakota block (Baird et al., 1996) are not constrained. Thus, the Superior craton may have collided with the Dakota block prior to their ~1750–1715 Ma collision with the Wyoming craton (Fig. 4). Alternatively, a Dakota-Wyoming collision at ~1750 Ma may have preceded collision with the Wyoming craton at ~1715 Ma, with the ~1715 Ma Hartville-Rawhide shear zone delineating the suture associated with this terminal collision (Chamberlain et al., 2002). Nonetheless, Black Hills magmatic and metasedimentary rocks of diverse Precambrian age record Nd T_{DM} model ages and U-Pb detrital zircon ages of 3.8–2.6 Ga (e.g., Walker et al., 1986; Frei et al., 2008; Dahl et al., 2008), which suggest that the Black Hills was always part of the Wyoming craton rather than welded to it for the first time at ~1715 Ma. Perhaps these are not mutually exclusive hypotheses, however, insofar as pre-1715 Ma rifting (at ~1880 Ma and/or ~2010 Ma, for example) may have caused initial separation along, say, the Hartville-Rawhide fault (Day et al., 1999; HR, Fig. 4), which then later became a ~1715 Ma suture. Lu-Hf isotopic studies of the Black Hills detrital zircons already dated by U-Pb methods would go a long way toward constraining their provenance, whereas occurrences of elevated $^{207}Pb/^{204}Pb$ ratios for given $^{206}Pb/^{204}Pb$ ratios documented in diverse Black Hills granitoids (Krogstad et al., 1993; Frei et al., 2008) also point to a Wyoming cratonic affinity. Beyond these lines of evidence, any further discernment among the various south-central Laurentia reconstruction hypotheses awaits detailed geophysical imaging and geochronologic study of Precambrian rocks and terrane boundaries occurring largely outside the Black Hills, primarily those which lie immediately to the east (Fig. 1, right inset) and which are buried under Phanerozoic cover.

During the assembly of south-central Laurentia, mid-crustal rocks in the Black Hills underwent polyphase thermotectonism and differential block uplift associated with the ~1750–1690 Ma Black Hills orogeny and then cooled slowly for several hundred million years between ~1690–1250 Ma (Holm et al., 1997; Dahl and Frei, 1998; Dahl et al., 1999, 2005a,b; Dahl and Foland, 2008). However, these inferences are based upon mineral-isotopic analysis of relatively few rocks, such that a full understanding of the spatial distribution of mineral growth and cooling ages has yet to emerge. Accordingly, in the southern Black Hills, more details of the spatial relationships among subordinate, ~1750 Ma regional-metamorphic assemblages and predominant, ~1715 Ma "regional-contact" metamorphic assemblages nearer to the main HPG pluton will soon be published (Dahl and Frei, in prep.). In contrast, however, and as already noted above, the northern Black Hills appears to be dominated by the ~1780–1750 Ma regional-metamorphic events whereas evidence of the ~1715 Ma overprint is relatively sparse in keeping with the paucity of coeval granitoids there (Ghosh, 2009). More U-Pb dating of metamorphic monazite in more Black Hills metapelites is necessary, however, in order to sharpen this emerging glimpse of the BHO in both space and time. More monazite dating targeting mapped shear zones is especially needed in order to constrain the regional timing of differential block uplift beyond the earliest ~1732 Ma timeframe tentatively suggested by Dahl et al. (2005a,b; see also Table 1 and Fig. 6, inset) and by this means to also determine if the D_2–D_3 events of Redden et al. (1990) constitute diachronous events or represent the single event designated as D_2 (Dahl et al., 1999, 2005a,b). Likewise, in-situ dating of micas or (preferably) monazites lying within the cryptic S_4 fabric (Fig. 1, Table 1) would reveal its age, at least in principle, thereby shedding light on the suggestion that this fabric represents a far-field effect of north-directed, Mazatzal arc accretion to the Yavapai arc terrane (see Magnani et al., 2004; Dahl et al., 2005b).

Timing of post-orogenic cooling and regional uplift/unroofing/exhumation

Present knowledge of the spatial-temporal nature of post-BHO/HPG cooling and unroofing is limited by the distribution of $^{40}Ar/^{39}Ar$ dates of Precambrian amphiboles and micas (Figs. 1, 5–6; see also Fig. 9 of Redden and DeWitt, 2008) within fault-bounded structural blocks. Interpreted mostly as cooling ages instead of as reset dates, they indicate an areally extensive regime of mid-crustal cooling through ~550°–300°C between ~1690–1250 Ma. Moreover, mid-crustal crystalline rocks apparently stayed warm for several hundred million years after the ~1715–1695 Ma HPG event (Holm et al, 1997; Dahl and Foland, 2008) and did not all cool below ~300°C (biotite closure) until some time before their final exhumation between ~1250 Ma and ~550 Ma. Only in the northern Black Hills (e.g., Lead) is there clear evidence of Tertiary disturbance of the few dated Precambrian micas (Fig. 5), whereas the few, apparently older micas representing the central Black Hills appear to be relatively less disturbed.

Additional insight regarding cooling and unroofing history throughout the Black Hills requires much more sampling and mica dating, particularly within recognized structural blocks (e.g., as defined by Nabelek et al., 2006). In the relatively densely sampled southern Black Hills, the envelope of elliptocentric "chrontours" delineating both the spatial-temporal pattern of muscovite slow cooling through ~400°C and the delayed cooling of the HPG (Fig. 1) is primarily constrained in the northern and western sectors, where the muscovite pattern is independently mirrored by a parallel pattern of systematically younger biotite cooling ages (see Fig. 5). These reinforcing cooling-age patterns led Dahl and Foland (2008) to suggest that the structurally deeper and shallower Bear Mountain and Harney Peak blocks, respectively, were juxtaposed prior to ~1715 Ma. Likewise, the occurrence of sharply younger muscovite dates immediately north of this cooling envelope (upper garnet zone, Fig. 5) led these workers to propose that selective unroofing of the relatively buoyant, granite-cored Harney Peak block (Nabelek et al., 2006) and Bear Mountain block (Duke et al., 1990) —accommodated by mapped faults (Fig. 1)—may have triggered initial ~1650 Ma closure of muscovite within the inferred elliptocentric cooling envelope. Following this scenario, $^{40}Ar/^{39}Ar$ and Rb-Sr muscovite cooling ages of ~1650–1600 Ma and ~1690–1670 Ma, respectively, would have dominated the Harney Peak block were it not for delayed mid-crustal cooling of the voluminous and relatively warm HPG itself (Figs. 1, 5-6; Dahl and Foland, 2008; Riley, 1970a,b). Further, this scenario or some semblance thereof may account for the abrupt younging of $^{40}Ar/^{39}Ar$ mica dates from south to north across the staurolite isograd (Fig. 5). Even in the densely sampled southern Black Hills, however, many more $^{40}Ar/^{39}Ar$ and Rb-Sr dates of magmatic and metamorphic micas, and Lu-Hf dates of apatite (e.g., Barfod et al., 2005), are needed in order to verify and constrain the regional cooling patterns and these preliminary tectonic interpretations thereof.

In contrast, there is absolutely no thermochronologic record whatsoever of the temperature-time (*T-t*) interval between ~300º–25°C and ~1250–545 Ma, i.e., when the youngest mid-crustal biotite was exhumed prior to the onlap of Cambrian seas and deposition of the Deadwood Formation. This knowledge gap can be bridged only with a comprehensive, Black Hills-wide study of U-Th-He thermochronology targeting U-bearing minerals like zircon, monazite, sphene, and apatite, whose He closure temperatures ranging from ~200º–70°C are well established.

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REFERENCES CITED

Baird, D.J., Nelson, K.D., Knapp, J.H., Walters, J.J., and Brown, L.D., 1996, Crustal structure and evolution of the Trans-Hudson orogen: Results from seismic reflection profiling: Tectonics, v. 15, p. 416–426.

Barfod, G.H., Krogstad, E.J., Frei, R., and Albarède, F., 2005, Lu-Hf and PbSL geochronology of apatites from Proterozoic terranes: A first look at Lu-Hf isotopic closure in metamorphic apatite: Geochimica et Cosmochimica Acta, v. 69, p. 1847–1859.

Bekker, A., and Erikkson, K.A., 2003, A Paleoproterzoic drowned carbonate platform on the southeastern margin of the Wyoming Craton: a record of the Kenorland breakup: Precambrian Research, v. 120, p. 327–364.

Bekker, A., Karhu, J.A., Eriksson, K.A. and Kaufman, A.J., 2003, Chemostratigraphy of Paleoproterozoic carbonate successions of the Wyoming Craton: tectonic forcing of biogeochemical change?: Precambrian Research, v. 120, p. 279–325.

Berry, J.M., Duke, E.M., and Snee, L.W., 1994, $^{40}Ar/^{39}Ar$ thermochronology of Precambrian metamorphic rocks of the Harney Peak granite, Black Hills, South Dakota: Geological Society of America Abstracts with Programs, v. 26(4), p. 4.

Buchan, K.L., Halls, H.C., and Mortensen, J.K., 1996, Paleomagnetism, U-Pb geochronology, and geochemistry of Marathon dykes, Superior Province, and comparison with the Fort Frances swarm: Canadian Journal of Earth Sciences, v. 33, p. 1583–1595.

Caddey, S.W., Bachman, R.L., Campbell, T.J., Reid, R.R., and Otto, R.P., 1991, The Homestake gold mine, an Early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota: United States Geological Survey Bulletin 1857-J, 67p.

Chamberlain, K.R., 1998, Medicine Bow orogeny: Timing of deformation and model of crustal structure produced during continent-arc collision, ca. 1.78 Ga, southeastern Wyoming: Rocky Mountain Geologist, v. 33, p. 258–277.

Chamberlain, K.R., Bauer, R.L., Frost, B.R., and Frost, C.D., 2002, Dakotan orogen: Continuation of Trans-Hudson orogen or younger, separate suturing of Wyoming and Superior cratons: Geological Association of Canada – Mineralogical Association of Canada Abstracts Volume, v. 27, p. 18.

Cox, D.M., Frost, C.D., and Chamberlain, K.R., 2000, 2.01-Ga Kennedy dike swarm, southeastern Wyoming: record of a rifted margin along the southern Wyoming province: Rocky Mountain Geology, v. 35, p. 7–30.

Dahl, P.S. and Foland, K.A., 2008, Concentric slow cooling of a low *P*-high *T* terrain: Evidence from 1600-1300 Ma mica dates in the 1780-1700 Ma Black Hills orogen, South Dakota, USA. American Mineralogist, v. 93, p. 1215–1229.

Dahl, P.S., and Frei, R., 1998, Single-phase dating of coexisting garnet and staurolite in the Black Hills collisional orogen (South Dakota), with implications for Early Proterozoic tectonism: Geology, v. 26, p. 111–114.

Dahl, P.S., Frei, R. and Whitehouse, M.J., 2008, Occurrences of ~3400 and ~2700 Ma detrital zircon populations in 2560-2480 Ma quartzite and in mafic phyllite interlayered with 1887 Ma felsic tuff, northern Black Hills, South Dakota: Geological Society of America Abstracts with Programs, v. 40(6), abstract 145-15.

Dahl, P.S., Hamilton, M.A., Wooden, J.L., Foland, K.A., Frei, R., McCombs, J.A., and Holm, D.K., 2006, 2480 Ma mafic magmatism in the northern Black Hills, South Dakota: A new link connecting the Wyoming and Superior cratons: Canadian Journal of Earth Sciences, v. 43, p. 1579–1600.

Dahl, P.S., Hamilton, M.A., Jercinovic, M.J., Terry, M.P., Williams, M.L., and Frei, R., 2005a, Comparative isotopic and chemical geochronometry of monazite, with implications for U-Th-Pb dating by electron microprobe: An example from metamorphic rocks of the eastern Wyoming craton (U.S.A.): American Mineralogist, v. 90, p. 619–638.

Dahl, P.S., Holm, D.K., Gardner, E.T., Hubacher, F.A., and Foland, K.A., 1999, New constraints on the timing of Early Proterozoic tectonism in the Black Hills (SD), with implications for the docking of the Wyoming province with Laurentia. Geological Society of America Bulletin, v. 111, p. 1335–1349.

Dahl, P.S. and McCombs, J.A., 2005, “Rosetta grains” of Precambrian accessory minerals, Black Hills, South Dakota: 2900-1700 Ma microprobe ages and implications for regional tectonic history: The Compass, v. 78(2), p. 59–75.

Dahl, P.S., Terry, M.P., Jercinovic, M.J., Williams, M.L., Hamilton, M.A., Foland, K.A., Clement, S.M., and Friberg, L.M., 2005b, Electron probe (Ultrachron) microchronometry of metamorphic monazite: Unraveling the timing of polyphase deformation in the eastern Wyoming craton (Black Hills, South Dakota): American Mineralogist, v. 90, p.1712–1728.

Day, W.C., Sims, P.K., Snyder, G.L., Wilson, A.B., and Klein, T.L., 1999, Geologic map of Precambrian rocks, Rawhide Buttes West Quadrangle and part of Rawhide Buttes East Quadrangle, Hartville Uplift, Goshen and Niobrara Counties, Wyoming: United States Geological Survey Investigation Series I-2635, 14p.

DeWitt, E., Redden, J.A. Wilson, A.B., and Buscher, D., 1989, Geologic map of the Black Hills area, South Dakota and Wyoming: USGS Geological Survey Miscellaneous Investigation Series Map I-1910, scale 1:250,000.

Duke, E.F., Shearer, C.K., Redden, J.A., and Papike, J.J., 1990, Proterozoic granite-pegmatite magmatism, Black Hills, South Dakota, *in* Lewry, J.F. and Stauffer, M.R., eds., The Early Proterozoic Trans-Hudson Orogen of North America. Geological Association of Canada Special Paper 37, Ottawa, pp. 253–269.

Frei, R., Dahl, P.S., Frandsson, M.M., Apel-Jensen, L., Hansen, T.R., Terry M.P., and Frei, K.M., 2009, Lead-isotope and trace-element characterization of Paleoproterozoic metasediments in the Lead and Rochford basins (Black Hills, South Dakota, USA): Implications for genetic models, mineralization ages, and sources of ore leads for the Homestake gold deposit: Precambrian Research, v. 172, p.1–24.

Frei, R., Dahl, P.S., Duke, E.F., Frei, K.M., Hansen, T.R., Frandsson, M.M. and Jensen, L.S., 2008, Trace element and isotopic characterization of Neoarchean and Paleoproterozoic iron formations in the Black Hills (South Dakota, USA): Assessment of chemical change during 2.9-1.9 Ga deposition bracketing the 2.4-2.2 Ga first rise of atmospheric oxygen: Precambrian Research, v. 162, p. 441–474.

Ghosh, A. K., 2009, Reconnaissance U-Pb geochronology of Precambrian crystalline rocks from the Northern Black Hills, South Dakota: implications for regional thermotectonic history [M.S. Thesis]: Kent State University, Kent, Ohio, 140p.

Ghosh, A., Frei, R., Whitehouse, M.J., and Dahl, P.S., 2008, Timing of Paleoproterozoic thermotectonism and magmatism, northern Black Hills, SD: Implications for provenance of the Homestake gold deposit: Geological Society of America Abstracts with Programs, v. 40(6), abstract 145-16.

Goldich, S.S., Lidiak, E.G., Hedge, C.E., and Walthall, F.G., 1966, Geochronology of the mid-continent region, United States 2. Northern area: Journal of Geophysical Research, v. 71, p. 5389–5408.

Gosselin, D.C., Papike, J.J., Zartman, R.E., Peterman, Z.E., and Laul, J.C., 1988, Archean rocks of the Black Hills, South Dakota: Reworked basement from the southern extension of the Trans-Hudson Orogen: Geological Society of America, v. 100, p. 1244–1259.

Halls, H.C., Davis, D.W., Stott, G.M., Ernst, R.E., and Hamilton, M.A., 2008, The Paleoproterozoic Marathon Large Igneous Province: New evidence for a 2.1 Ga long-lived mantle plume event along the southern margin of the North American Superior Province: Precambrian Research, v. 162, p. 327–353.

Hark, J.S., 2009, Zircon, monazite, and xenotime as provenance indicators in selected Precambrian crystalline rocks, Black Hills uplift, South Dakota [M.S. Thesis], Kent State University, Kent, Ohio, 143p.

Hark, J.S., Frei, R., Whitehouse, M.J. and Dahl, P.S., 2008, New evidence for 2.01 Ga rifting in the easternmost Wyoming craton (Black Hills, SD): Implications for break-up of a supercraton (Superia), Geological Society of America Abstracts with Programs, v. 40(6), abstract 145-17.

Heaman, L.M., 1997, Global mafic magmatism at 2.45 Ga: remnants of an ancient large igneous province: Geology, v. 25, p. 299–302.

Heaman, L.M., Peck, D., and Toope, K., 2009, Timing and geochemistry of 1.88 Ga Molson Igneous Events, Manitoba: Insights into the formation of a craton-scale magmatic and metallogenic province: Precambrian Research, v. 172, p. 143-162.

Holm, D.K., Dahl, P.S., and Lux, D.R., 1997, $^{40}Ar/^{39}Ar$ evidence for Middle Proterozoic (1300-1500) slow cooling of the southern Black Hills, South Dakota: Implications for Proterozoic P-T evolution and post-tectonic magmatism: Tectonics, v. 16, p. 609–622.

James, R.S., Easton, R.M., Peck, D.C., and Hrominchuk, J.L., 2002, The East Bull Lake Intrusive Suite: remnants of a ~2.48 Ga large igneous and metallogenic province in the Sudbury area of the Canadian Shield: Economic Geology, v. 97, p. 1577–1606.

Karlstrom, K.E., and CD-ROM Working Group, 2002, Structure and evolution of the lithosphere beneath the Rocky Mountains: Initial results from the CD-ROM experiment: GSA Today, v. 12(3), p. 4–10.

Klasner, J.S., and King, E.R., 1990, A model for tectonic evolution of the Tran-Hudson orogen in North and South Dakota, *in* Lewry, J.F. and Stauffer, M.R., eds., The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada Special Paper 37, Ottawa, pp. 271–285.

Krogstad, E.J., Walker, R.J., Nabelek, P.I., and Russ-Nabelek, C., 1993, Lead isotopic evidence for mixed sources of Proterozoic granites and pegmatites, Black Hills, South Dakota, USA: Geochimica et Cosmochimica Acta, v. 57, p. 4677–4685.

Krogstad, E.J., and Walker, R.J., 1994, High closure temperatures of the U-Pb system in large apatites from the Tin Mountain pegmatite, Black Hills, South Dakota, USA.: Geochimica et Cosmochimica Acta, v. 58, p. 3845–3853.

Magnani, M.B., Miller, K.C., Levander, A., and Karlstrom, K., 2004, The Yavapai-Mazatzal boundary: A long-lived tectonic element in the lithosphere of southwestern North America: Geological Society of America Bulletin, v. 116, p. 1137–1142.

McCombs, J.A., Dahl, P.S., and Hamilton, M.A., 2004, Ion microprobe study of zircon geochronology in basement granitoids from the Black Hills, South Dakota, USA, with implications for evolution of the Archean Wyoming Province, western Laurentia: Precambrian Research, v. 130, p. 161–184.

Morelli, R.M., Bell, C.C., Creaser, R.A., and Simonetti, A., 2010, Constraints on the genesis of gold mineralization at the Homestake Gold Deposit, Black Hills, South Dakota, from rhenium-osmium sulfide geochronology: Mineralium Deposita, in press.

Mueller, P.A., Heatherington, A.L., Kelly, D.M., Wooden, J.L. and Mogk, D.W., 2002, Paleoproterozoic crust within the Great Falls tectonic zone: Implications for the assembly of southern Laurentia: Geology, v. 30, p. 127–130.

Nabelek, P.I., Labotka, T.C., Helms, T., and Wilke, M., 2006, Fluid-mediated polymetamorphism related to Proterozoic collision of Archean Wyoming and Superior provinces in the Black Hills, South Dakota: American Mineralogist, v. 91, p. 1473–1487.

Nabelek, P.I., Russ-Nabelek, C., and Denison, J.R., 1992, The generation and crystallization conditions of the Proterozoic Harney Peak leucogranite, Black Hills, South Dakota, USA: Petrologic and geochemical constraints: Contributions to Mineralogy and Petrology, v. 110, p. 173–191.

Pearce, J.A., 2008, Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust: Lithos, v. 100, p. 14–48.

Ratté, J.C., 1986, Geologic map of the Medicine Mountain Quadrangle, Pennington County, SD: United States Geological

Survey Miscellaneous Investigation Series Map I-1654, scale 1:24,000.

Redden, J.A., and DeWitt, E., 2008, Maps showing geology, structure, and geophysics of the Central Black Hills, South Dakota: United States Geological Survey Scientific Investigations Map 2777, scale 1:100,000.

Redden, J.A., Peterman, Z.E., Zartman, R.E., and DeWitt, E.R., 1990, U-Th-Pb geochronology and preliminary interpretation of Precambrian events in the Black Hills, South Dakota, *in* Lewry, J.F. and Stauffer, M.R., eds., The Early Proterozoic Trans-Hudson Orogen of North America: Geological Association of Canada Special Paper 37, Ottawa, pp. 229–251.

Riley, G.H., 1970a, Isotopic discrepancies in zoned pegmatites, Black Hills, South Dakota: Geochimica et Cosmochimica Acta, v. 34, p. 713–725.

Riley, G.H., 1970b, Excess ^{87}Sr in pegmatitic phosphates: Geochimica et Cosmochimica Acta, v. 34, p. 727-731.

Roscoe, S.M., and Card, K.D, 1993, The reappearance of the Huronian in Wyoming: rifting and drifting of ancient continents: Canadian Journal of Earth Sciences, v. 30, p. 2475–2480.

Schaller, M., Steiner, O., Studer, I., Frei, R., and Kramers, J.D., 1997, Pb stepwise leaching (PbSL) dating of garnet – Addressing the inclusion problem: Schweizerische Mineralogische Petrographische Mitteilungen, v. 77, p. 113–121.

Schmitz, M.D., Bowring, S.A., Southwick, D.L., Boerboom, T.J., and Wirth, K.R., 2006, High-precision U-Pb geochronology in the Minnesota River Valley subprovince and its bearing on the Neoarchean to Paleoproterozoic evolution of the southern Superior Province: Geological Society of America Bulletin, v. 118, p. 82–93.

Sims, P.K., 1995, Archean and Early Proterozoic tectonic framework of north-central United States and adjacent Canada: United States Geological Survey Bulletin 1904-T, 12p.

Sims, P.K., Peterman, Z.E., Hildenbrand, T.G., and Mahan, S., 1991, Precambrian basement map of the Trans-Hudson orogen and adjacent terranes, northern Great Plains, U.S.: United States Geological Survey Miscellaneous Investigations Map I-2214, scale 1:1,000,000.

Stock, B.J., 2004, Compilation of a Precambrian basement map and geodatabase of South Dakota: Geological Society of America Abstracts with Programs, v. 36(5), abstract 568.

Terry, M.P. and Friberg, L.M., 1990, Pressure-temperature-time path related to the thermotectonic evolution of an Early Proterozoic metamorphic terrane, Black Hills, South Dakota: Geology, v. 18, p. 786–789.

Van Boening, A.M., and Nabelek, P.I., 2008, Petrogenesis and tectonic implications of Paleoproterozoic mafic rocks in the Black Hills, South Dakota: Precambrian Research, v. 167, p. 363–376.

Walker, R.J., Hanson, G.N., Papike, J.J., and O´Neil, J.R., 1986, Nd, O, and Sr isotopic constraints on the origin of Precambrian rocks, southern Black Hills, South Dakota: Geochimica et Cosmochimica Acta, v. 50, p. 2833–2846.

Wetherill, G. W., 1956, Discordant uranium-lead ages: Transactions of the American Geophysical Union, v. 37, p. 320–326.

Yang, P., and Pattison, D.R.M., 2006, Genesis of monazite and Y-zoning in garnet from the Black Hills, South Dakota: Lithos, v. 88, p. 233–253.

Zartman, R.E., Norton, J.J., Stern, T.W., 1964. Ancient granite gneiss in the Black Hills, South Dakota: Science, v. 145, p. 478–481.

Zartman, R.E., and Stern, T.W., 1967, Isotopic age and geologic relationships of the Little Elk Granite, northern Black Hills, South Dakota: United States Geological Survey Professional Paper 575-D, p. D157-D163.

The Black Hills Uplift in its Regional Context

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ABSTRACT

The Black Hills Uplift is the easternmost topographically discernable Laramide feature relative to the central and northern Rocky Mountains within the U.S.A. and is surrounded by the northern Great Plains. It is a portion, however, of a positive feature that extends southeastward from Central Montana into west-central Nebraska. It is proposed that this positive feature, composed of the Porcupine Dome, Miles City Arch, Black Hills Uplift, and the Chadron Arch, overlies a mid-crustal, east-vergent thrust. In this model the uplifts formed as a broad fault propagation fold (arch) above a ramp in the fault and ends on the east above the blind fault tip. Abundant west-vergent anticlines and monoclines in the Black Hills formed in Phanerozoic strata above back thrusts within the underlying Precambrian basement. Localization of the arch may have been guided to some degree by basement terrain boundaries (Wyoming Archean Province, Trans-Hudson Province, Yavapai Province), although the arch crosses these boundaries. Within the Black Hills uplift {with ~7,000 ft (~2,120 m) of structural relief}, correlation of Laramide fold axes with basement anisotropy (faults, schistosity, and layering) and geophysical anomalies suggests reactivation of, or younger control on basement rupture, by these features.

INTRODUCTION

In its largest context the Black Hills Uplift represents a 180 mi (290 km) long, 65 mi wide (104 km), north-northwest trending and doubly plunging arch (Fig. 1) along the eastern margin of the Wyoming craton. Although separated from other uplifts of the northern Rocky Mountains by the Powder River basin, and seemingly representing an isolated mountain range in the prairies of the northern Great Plains, this is the easternmost of the many Laramide uplifted blocks extending southward from central Montana to at least the Mexican border.

GENERAL CHARACTERISTICS OF THE BLACK HILLS LARAMIDE UPLIFT (abstracted from Lisenbee, 1978; Lisenbee and DeWitt, 1993)

- It is a broad, doubly plunging arch trending NNW and with ~8,000 ft (2,400 m) of structural relief
- It is formed of two blocks separated by the north-trending Fanny Peak monocline
- A dominantly Proterozoic metamorphic core is exposed in the eastern, more elevated block
- Xenoliths in Tertiary diatremes and rafted blocks in Tertiary plutons indicate an Archean granitic basement beneath the western block
- Major monoclines (Black Hills and Fanny Peak) bound the uplift on the west with structural relief of 3,000 (900) to 5,000 feet (1,500 m)
- A broad half dome forms the eastern flank
- Multiple smaller folds with structural relief of less than 1,000 feet (300 m) generally parallel the overall NNW-trend of the uplift
- Almost all folds have west vergence
- Prior to 64 Ma streams flowed eastward from the area of the future Powder River Basin, i.e., there was no uplift, but beginning at that time flow changed to NNW away from the rising uplift area indicating the initial pulse of tectonic activity. A second pulse may have occurred at about 56 Ma
- From 58 Ma to 46 Ma (Duke, 2009) intrusions of carbonatite, pyroxenite, rhyolite, trachyte, phonolite, and monzonite formed dikes, sills, laccoliths and stocks along a N.70^{o}W.-trending zone across the uplift
- Late Eocene (~37 Ma) and Oligocene strata were deposited with angular unconformity across the eroded roots of the eastern flank of the uplift showing that uplift and erosional stripping has ceased by that time.

LARAMIDE REGIONAL SETTING

Tectonic

The Laramide orogeny was coincident with subduction of the Farallon plate along the western margin of the North American plate (e.g., Dickinson and Snyder, 1978). The details of the evolution of this event throughout the Rocky Mountains have been outlined in numerous studies (e.g., Chapin and Cather, 1983, 1990; Gries, 1983, Dickenson and others, 1988 and Chapin and Cather, 1990), but generally describe

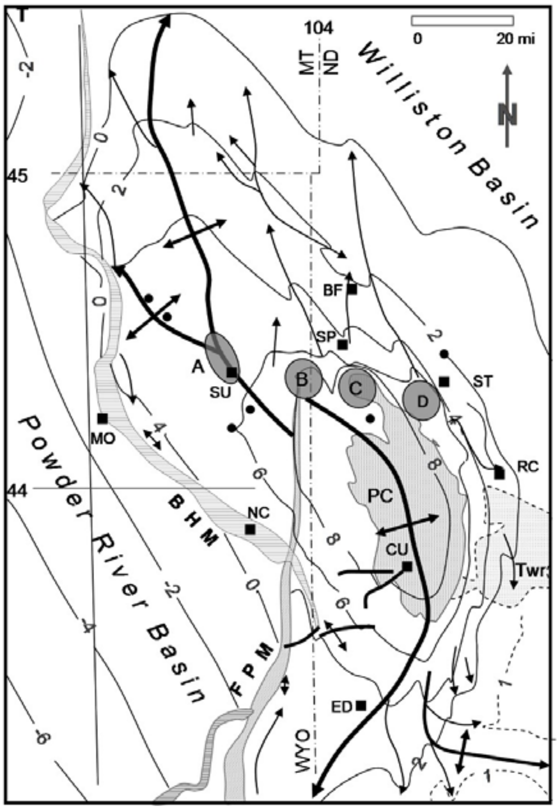

Figure 1. Tectonic map of the Black Hills Uplift. Structure contours (feet relative to sea level) are on the Cretaceous Fall River Formation with 2,000 ft contour interval. BHM = Black Hills Monocline; FPM = Fanny Peak Monocline. Lines with arrowheads are anticlinal folds. Tertiary igneous-cored domes are: A = Bear Lodge; B = Tinton; C = Lead; D = Vanocker. Twr = White River Group. Black circles are some of the igneous bodies outside of domes. Towns are: BF = Belle Fourche; CU = Custer; ED = Edgemont; MO = Moorcroft; NC = Newcastle; RC = Rapid City; SP = Spearfish; ST = Sturgis; SU = Sundance. PC = Precambrian core of the eastern block of the uplift.

two stages, the older beginning in the Late Cretaceous and the younger, of which the Black Hills is a part, beginning in the Early Tertiary.

Although the northern Laramide uplifts are seen topographically to begin at the bold fronts of the Big Horn Mountains, Laramie Range and Front Range, large Laramide structures are present in the prairie region to the east. Indeed, a continuously uplifted zone extends in an arc from Porcupine Dome in central Montana southeastward along the Miles City Arch to the Black Hills Uplift and on to the Chadron Arch (Fig. 2). The

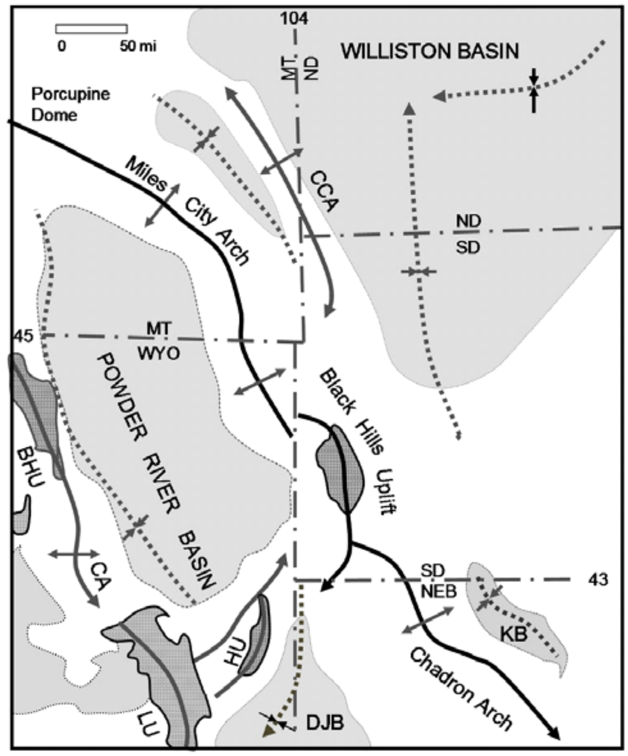

Figure 2. Regional tectonic map showing Laramide basins and uplifts of a portion of the Great Plains and adjacent Rocky Mountains. Abbreviations are: BHU = Big Horn Uplift; CA = Casper Arch; CCA = Cedar Creek Anticline; DJB = Denver-Julesburg Basin; HU = Hartville Uplift; KB = Kennedy Basin; LU = Laramie Uplift.

southern end of the Black Hills Uplift forms a junction with the Hartville Uplift of Wyoming to the southwest: The Chadron Arch joins the uplift on the southeast and continues into Nebraska. The length of the Porcupine Dome through Chadron Arch positive feature is greater than 500 miles (800 km), but only in the Black Hills, which is the most structurally elevated portion, is there a topographic expression.

To the west of this extensive arch (Fig. 2) are the northern end of the Denver-Julesburg Basin and the Powder River Basin, both of Laramide (early Tertiary) age and containing continental sedimentary fill. The large Williston Basin lies northeast and east of the arch. Although this feature has a long Phanerozoic history of development (e.g., RMAG, 1972) there is an early Tertiary (Laramide) phase of deposition as well. Indeed, as the nearer Laramide uplifts rose above a near-sea-level plain (Lisenbee and DeWitt, 1993) in the early Paleocene, streams carried sediments to the Cannonball Sea which remained in southwestern North Dakota. The smaller Kennedy Basin lies just east of the Chadron Arch. A large, west-vergent Laramide structure, the Cedar Creek Anticline, lies to the north of the Black Hills Uplift and separates the Williston Basin from a smaller, unnamed basin to the west.

Magmatic

The Laramide orogeny consisted of a magmatic as well as a tectonic aspect and resulted in widely scattered igneous centers, including the Colorado Mineral belt, the Absaroka Volcanics of the Yellowstone region and the Challis Volcanics of Idaho. Armstrong and Ward, (1991) referred to this extensive magmatic area as the "Kamloops–Challis–Absaroka" volcanic belt. Early Tertiary igneous activity in the Black Hills represents the easternmost of such Laramide igneous centers and is farthest from the zone where the Kula, Resurrection, and Farallon plates subducted toward the east/northeast. Duke (2005) recognized that the Black Hills also lies at the southeastern end of a N.40^{o}W.-trending linear belt which extends for 430 mi (700 km northwestward through eastern Montana and into southern Alberta: She called this the Great Plains Alkalic Province. Duke (2005, 2009) defined the carbonatite, kimberlite, and alkalic bodies along this trend as Group I-type magmatism. In contrast, she noted that Group II alkalic bodies, which lie to the southwest of this belt, "…have significantly lower initial epsilon-Nd values and different trace-element contents (e.g. higher Ba, but lower REE, U, and Th)." She ascribed such differences between groups to varying degrees of assimilation of lithosphere by asthenospherically derived parent magmas.

Emplacement of plutons within the Black Hills began approximately nine million years after initiation of the uplift. In an excellent examination of this magmatism, Duke (2005) recognized that younger (>46 Ma) akalic plutons are present in the western portion of the N.70^{o}W.-trending magmatic belt, and that older (<58 Ma) sub-alkalic plutons are present in the eastern portion. The two areas are separated by the Fanny Peak monocline and the magmas ascended through Archean granitic crust on the west and Proterozoic metamorphic crust on the east of this feature. Duke (2005) ascribes the differences in composition of the igneous masses to varying amounts of lithospheric assimilation (greater on the east compared to the west) during magma ascent.

An origin of the Laramide magmatic event has been linked to melting of the subducted Farallon slab (e.g., Dickinson and Snyder, 1979). The distance from the subduction zone would require flat-slab subduction to allow magmatism in the Black Hills ~1,000 mi (1,600 km) from the subduction zone. Based upon synchronous ages and similarities in trace element geochemistry, Duke (2005, 2009) placed the Black Hills magmatism with the carbonatite-kimberlite-alkalic pluton event extending northwestward to Canada. She proposed a model for this magmatism in which asthenospherically-derived carbonatitic melts rose from the upper, southwest edge of the descending Kula slab. These melts assimilated varying amounts of continental lithosphere during ascent and evolved to the alkalic and sub-alkalic magmas of the Black Hills.

PRECAMBRIAN BASEMENT

As shown in Figure 3, the Black Hills Uplift is formed at, or near to, a triple junction of Precambrian basement terranes. The south-southeast trend of the uplift in southeast Montana and northeast Wyoming crosses the eastern margin of the older than 2.5 Ga Wyoming Archean Province (Sims and others, 2004) to approximately the Fanny Peak monocline at the Wyoming-South Dakota state line. This portion corresponds with the western block of the Laramide

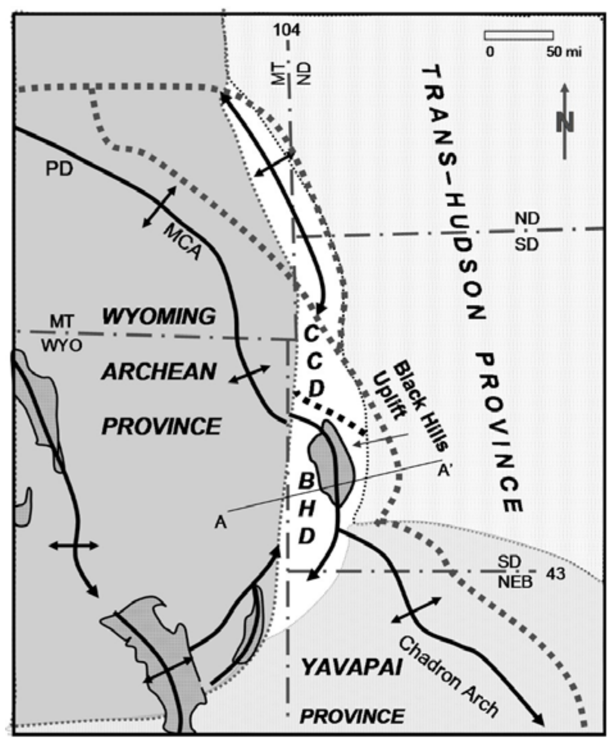

Figure 3. Regional tectonic map showing Precambrian basement terranes of a portion of the Great Plains and adjoining Rocky Mountains and the Laramide uplifts which affect them. The heavy dotted lines indicated eastward limits of crustal faults which are interpreted to underlie, and to cause, the Laramide uplifts along the Porcupine Dome-Chadron Arch trend. BHD = Black Hills Domain and CCD = Cedar Creek Domain. Province boundaries from Karlstom and others (2002) and McCormick (2010). Diagonal pattern indicates exposed Precambrian basement in the cores of uplifts.

uplift. East of the Fanny Peak monocline in South Dakota, the uplift is within the southwestern corner of the complexly deformed Proterozoic metamorphic and minor Archean rocks of the Trans-Hudson province (Sims and others, 1991). McCormick (2010) utilized geophysical patterns, geologic maps, and drilling information from petroleum exploration wells to define the Black Hills and the Cedar Creek Domains as subdivisions of the basement terrain. She interpreted these as composed of Archean basement fragments within Proterozoic-aged metamorphic and granitic rocks along the eastern margin of the Wyoming Archean Province. Dahl (this volume) refers to this region as the Black Hills Orogen.

The Chadron Arch, which continues southeast the Black Hills Uplift into Nebraska, joins the uplift at the terrane boundary between the Yavapai Province and the Black Hills Domain. The 1.7-1.8 Ga Yavapai Province consists of Proterozoic metamorphic and granitic rocks.

Based upon the diagonal trend of the Laramide axis of the Porcupine Dome-Chadron Arch positive features across the Precambrian terrane boundaries, the basement does not appear to have controlled the localization of the uplift in its largest aspect. Some influence may be indicated, however, based upon the geographic association of both the eastern block of the Black Hills Uplift and the Cedar Creek Anticline with basement subdivisions defined by McCormick (2010). Although the correlation of the Laramide features with proposed basement domains is striking, the origin of the relationship is unclear.

Control of individual features within the uplift, may also have occurred. The Fanny Peak monocline, for example, lies along one of the interpreted common boundary of the Wyoming Archean and the Black Hills Domain. The south termination of the uplift is interpreted to lie within the Black Hills Domain and to overlap with the northern end of the Chadron Arch are in the Yavapai Terrain. The contrast in basement composition and/or structural fabric may have played a part in the location of these features.

The major Precambrian fabric of faults, schistosity, and layering seen in the core of the Black Hills parallels individual Laramide structures in the Phanerozoic strata along the eastern flank of the uplift as well as magnetic and gravity anomalies (Kleinkopf and Redden, 1975) produced by the basement there. Such a parallelism suggests a possible reactivation of basement structures beneath the Laramide folds or that anisotropy of the basement has guided in some fashion the younger deformation.

SUMMARY: A MODEL FOR THE LARAMIDE TECTONIC DEVELOPMENT OF THE BLACK HILLS UPLIFT

Lisenbee and DeWitt (1993) showed five models of possible origin for the Black Hills uplift. Two that were considered to be unsupported by the exposed rocks of the uplift included upward push by batholith emplacement and accordion-like folding of the basement at the boundary between the Wyoming and Trans-Hudson province boundaries. The other three were variations on crustal-scale thrust faults and associated folding. An adaption of one of these models, presented here as Figure 4, is now favored as it seems to best include the characteristics of the uplift. This model is similar to balanced sections by Erslev (2005) and

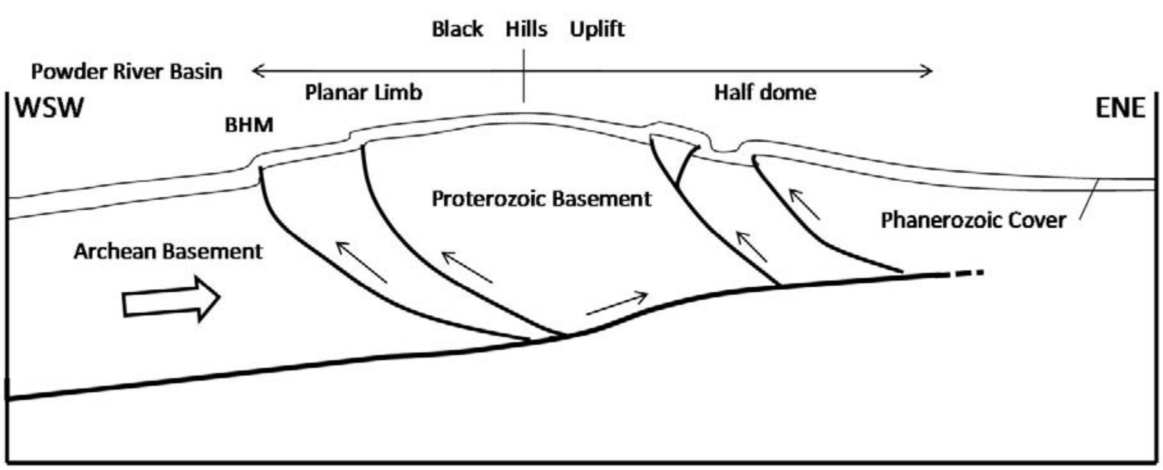

Figure 4. Diagrammatic theoretical cross-section of the Black Hills uplift. The uplift is interpreted to lie in the hanging wall of a mid-crustal, easterly directed, low-angle thrust fault. The uplift ends on the east at the blind tip of the large fault. In this scenario the uplift is a fault-propagation anticline in the hanging wall of the large thrust with most folds in the Phanerozoic section formed above back thrusts in the Proterozoic and Archean basement.

Sterne (2006) for the Front Range of Colorado, but is diagrammatic only.

As shown in Figure 4, the essential features of this model include an east-directed, mid-crustal thrust which ramps upward beneath the mid-portion of the Black Hills uplift and ends as a blind fault tip beneath the prairies east of the Black Hills. The dominance of west-vergent folds (monoclines) result from back thrusts in the hanging wall of this deep-seated fault. The monoclines separating the uplift from the Powder River Basin overlie the largest of the back thrusts and the half dome forming the eastern flank of the uplift is a fault-propagation fold above the area of strongest ramping.

The blind fault tip shown in Figure 4 would extend NNW and SSE along the eastern margin of the long arch extending from Montana through Wyoming and South Dakota and into Nebraska. A further reach of the mid-crustal thrust fault in this model would be required to extend beneath the Cedar Creek anticline which would represent a hanging wall back-thrust above it.

TOPICS FOR FUTURE RESEARCH CONCERNING THE BLACK HILLS UPLIFT

1. Does some aspect of the basement "grain" control the location of individual Laramide structures or of magmatic features?
2. In what way, if any, is localization of the Black Hills uplift affected by the Archean-Proterozoic crustal boundary beneath it? By the composition or internal fabric of the Black Hills Domain proposed by McCormick (2010)?
3. What happened in the mid(?)-crust to cause crustal arching of the magnitude seen in the BH uplift?
4. Was there a single pulse of uplift or were there multiple separate pulses?
5. What was the rate at which uplift occurred?
6. What is the origin of Laramide magmatism at such a great distance in-board from the Cordilleran subduction zone? Is it some form of flat subduction or is it controlled by the gap in descending plates proposed by Duke (2005)?
7. What was the orientation of the Laramide stress field or changing fields that produced the Black Hills uplift? Note: Initial work by Tielke and others (2010) found only one period of E-W compression, based upon study of twinning in calcite grains.
8. And, on a scale much larger that this individual uplift, what is the origin of the stress field that caused the most centrally located uplift within the North American plate?

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REFERENCES CITED

Armstrong, R. L. and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial associations of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, p. 13,201-13,224.

Chapin, C. E. and Cather, S. M., 1983, Eocene tectonics and sedimentation in the Colorado Plateau—Rocky Mountain area, *in* Lowell, J. D. *editor*, Rocky Mountain foreland basins and uplifts: Denver, Rocky Mountain Association of Geologists, p. 33-56.

Chapin, C. E. and Cather, S. M., 1990 Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain regions; Alternative interpretation and reply: Geological Society of America Bulletin, v. 102, p. 256-260.

Dahl, P. S., 2010, Precambrian geochronology of the Black Hills, South Dakota: Past results and future directions, this volume.

Dikinson, W. R. and Snyder, W. S., 1978, Plate tectonics of the Laramide orogeny, *in* Matthews, V., III, *editor*, , Laramide folding associated with basement block faulting: Geological Society of America Memoir 151, p. 355-366.

Dickenson, M. A., Klute, M. A., Hayes, M. J., Hanecke, S. U., Lundin, E. R., McKittrick, M. A., Olivares, M. D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountains region: Geological Society of America Bulletin, v. 100, p. 1023-1039.

Duke, G. I., 2005, Geochemistry and geochronology of Paleocene-Eocene Alkalic Igneous Rocks, Northern Black Hills, South Dakota and Wyoming: unpublished Ph. D. dissertation, South Dakota School of Mines and Technology, Rapid City, SD., 291 p.

Duke, G. Ide, 2009, Black Hills-Alberta carbonatite-kimberlite linear trend: slab edge at depth? Tectonophysics, v. 464, p. 186-194.

Erslev, E. A., 2005, 2D Laramide geometries and kinematics of the Rocky Mountains, Western U.S.A., *in* K. E., Karlstrom and G. R. Keller *editors*, 2005, The Rocky Mountain Region – An Evolving Lithosphere: Tectonics, Geochemistry, and Geophysics: American Geophysical Union, Geophysical Monograph 154, p. 7-20.

Gries, R., 1983, North-south compression of Rocky Mountain foreland structures, *in* Lowell, J. D. *editor*, Rocky Mountain foreland basins and uplifts: Denver, Rocky Mountain Association of Geologists, p. 9-32.

Harlan, S. S., Snee, L. W.,, and Geissman, J. W., 1996, $^{40}Ar/^{39}Ar$ geochronology and paleomagnetism of Independence volcano, Absaroka Volcanic Supergroup, Beartooth Mountains, Montanan: Canadian Journal of Earth Sciences, v. 33, p. 1648-1654.

Irving, A. J. and Hearn, B. C., 2003, Alkalic rocks of Montana: kimberlites, lamproites, and related magmatic rocks: 2003: Guidebook prepared for the VIIIth International Kimberlite Conference, Montana Field Trip 16-21, June, 2002, Ottawa, Geological Survey of Canada.

Karlstrom, K.E., and the CD-ROM working Group (Continental Dynamics of the Rocky Mountains), 2002, Structure and Evolution of the lithosphere beneath the Rocky Mountains: Initial results from the CD-ROM Experiment: GSA Today, v. 12, no. 3, p. 4-10.

Kleinkopf and Redden, J. A., 1975, Bouguer gravity, aeromagnetic, and generalized geologic maps of parts of the Black Hills of South

Dakota and Wyoming, U.S. Geol. Surv., Geophys. Inv. Map GP-903.

Lisenbee, A. L., 1978, Laramide structure of the Black Hills uplift, South Dakota-Wyoming-Montana: *in* Matthews, V., III, *editor*, Laramide folding associated with basement block faulting: Geological Society of America Memoir 151, p. 165-196.

Lisenbee, A. L. and DeWitt, E., 1993, Laramide evolution of the Black Hills uplift: *in* Snoke, A. W., Steidtmann, J.R., and Roberts, S. M., *editors,* Geology of Wyoming Geological Survey of Wyoming Memoir No. 5, p. 374-412.

McCormick, K., 2010, Terrane map of the Precambrian Basement, South Dakota: Geological Society of America, 62nd Annual Meeting (21-32 April, 2010), Rapid City, SD, Paper No. 29-1.

RMAG, 1972, Geologic Atlas of the Rocky Mountain Region, William Wyman Mallory *editor in chief,* A. B. Hirschfield Press, Denver, CO, 331 p.

Sims, P. K., Peterman, Z. E.., Hildenbrand, T. G., and Mahan, S., 1991, Precambrian basement map of the Trans-Hudson orogeny and adjacent terranes, northern Great Plains, U.S.A., U. S. Geological Survey Miscellaneous Investigations Series Map, I-2214, 1 sheet, scale 1:100,000.

Sims, P. K., O'Neill, J. M., Bankey, v., and Anderson, E., 2004, Precambrian basement geologic map of Montana; an interpretation of aeromagnetic anomalies: U. S. Geological Survey, Scientific Investigations Map, No. SIM 2829, scale 1:100,000.

Sterne, E. J., 2006, Stacked, "evolved" triangle zones along the southeastern flank of the Colorado Front Range: The Mountain Geologist, Rocky Mountain Association of Geologists, Denver, Co., v. 43, no. 1, p. 65-92

Tielke, J. A., Terry, M. P., and Lisenbee, A. L., 2010, Examining the paleostresses responsible for the Black Hills uplift through analysis of calcite deformation twins using electron backscatter diffraction: Geological Society of America, 62nd Annual Meeting, Rocky Mountain Section, Rapid City, SD.