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Gravity and magnetic features and their relationship to the geothermal system in southwestern South Dakota

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T. G. Hildenbrand and R. P. Kucks

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Introduction

The region along the southern flank of the Black Hills uplift is characterized by notably high geothermal gradients, frequently exceeding $40^{\circ}C/km$ and attaining a maximum value of $84^{\circ}C/km$. Moreover, unusually warm springs are not uncommon. Near the town of Hot Springs, South Dakota, ground water surfaces at a temperature of about $22^{\circ}C$ higher than the mean annual temperature. Because the average worldwide geothermal gradient is approximately $29^{\circ}C/km$ (Schuster, 1973) and because warm springs are present, this region is considered to have a potential geothermal resource that could be utilized, for example, in space and agriculture heating.

On the other hand, the Black Hills, a classical example of an elongated domal uplift, exhibits relatively low geothermal gradients. Hydrological and geothermal data (Head and others, 1978; Schoon and McGregor, 1974) indicate that the Black Hills function as a cool water source for aquifers trending outward to the east and west. One would then anticipate that the regions flanking the Black Hills are also characterized by low geothermal gradients. This is indeed observed except for the region south of the Black Hills. The contradictory nature of these observations presents an interesting geological problem: delineating the sources of hot waters existing in southwestern South Dakota.

The possible causes of high geothermal gradients in this region include the presence of partially cooled magma at shallow depths, high heat production from radiogenic sources, transport of heat and fluids from depth in a cyclic system, and exothermic reactions produced by chemical weathering. It is the purpose of this study to determine the sources that are responsible for producing geothermal anomalies observed within the southern Black Hills region. Discussions primarily pertain to lithologic and structural boundaries residing in the upper crust and their relationship to the geothermal system. The principal means of investigation are a regional gravity survey supplemented by a regional aeromagnetic survey. This geothermal study was supported by the Department of Energy through an interagency agreement (no. ET-78-I-01-3278) with the U.S. Geological Survey.

Geophysical Data

The complete Bouguer gravity map (fig. 1) was compiled from a data set comprised of 5326 gravity stations. This map together with station locations have been previously published at a scale of 1:250,000 (Hildenbrand and Kucks, 1981a). Gravity coverage is fairly uniform with the average spacing of about 3 km between gravity stations. Most of these data were collected by R. Black, R. Hazlewood, and D. Healey for the U.S. Geological Survey. Approximately 2700 of their gravity station principal facts (observed gravity, elevation, latitude, and longitude) were either taken from the U.S. Department of Defense data bank or retrieved from the Federal Archives and Records Center, Denver, Colorado. An additional 2031 Bouguer values and corresponding station locations were digitally acquired from a simple Bouguer gravity map of the northern Black Hills (Hazlewood, 1964) and a complete Bouguer gravity map of the southern Black Hills (Black, Hazlewood, and Healey, unpublished data; Kleinkopf and Redden, 1975). The remaining data were acquired from other sources residing in the U.S. Department of Defense data bank and from a recent survey in which we occupied 219 stations to increase uniformity of coverage.

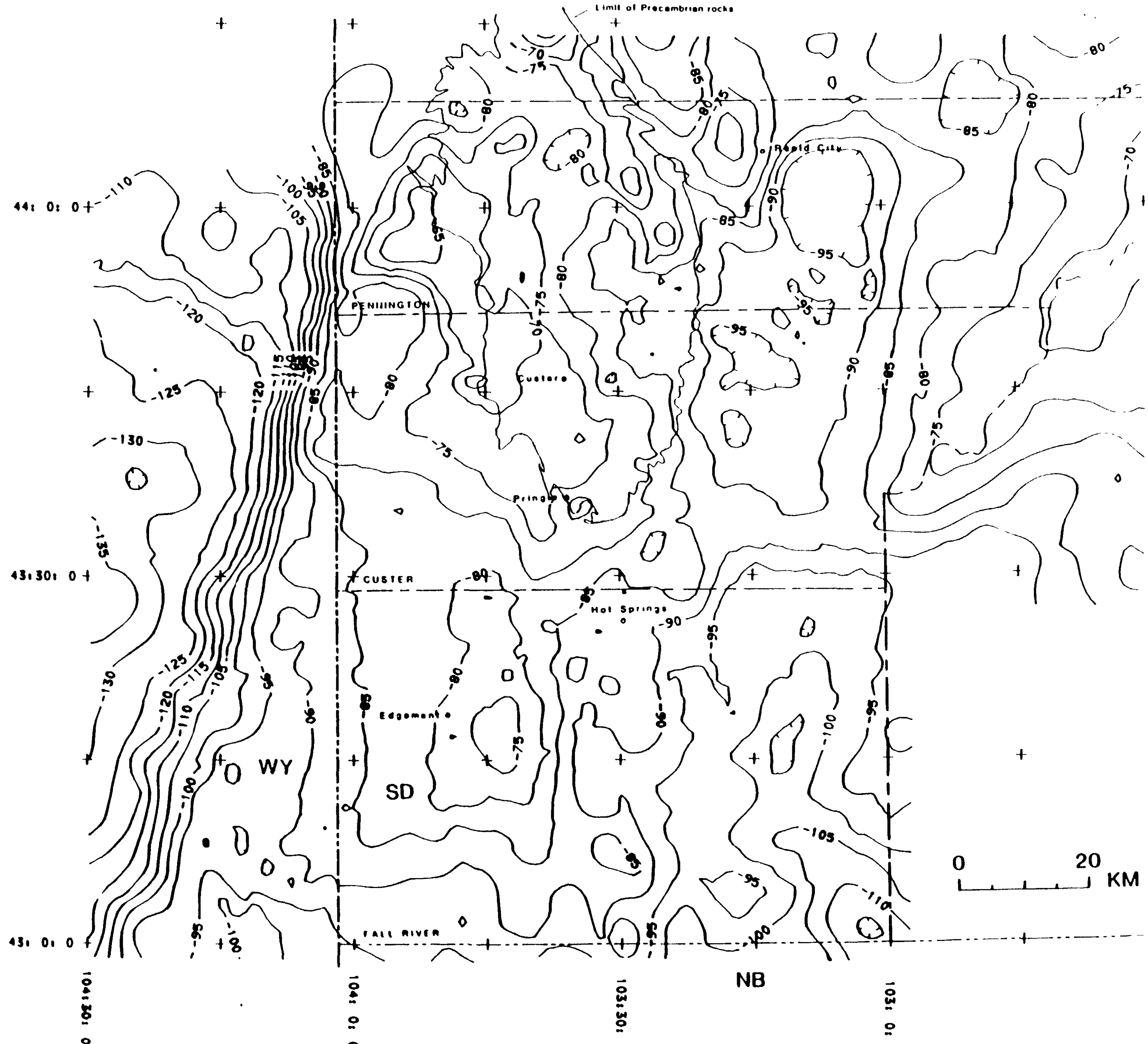


Figure 1.--Complete Bouguer gravity map of the southern Black Hills. Contour interval is 5 mgals.

For stations with known principal facts, Bouguer values were computed employing a reduction density of 2.45 g per cm^3 and the 1967 gravity formula (International Association of Geodesy, 1967). Terrain corrections were made for the region extending radially from 0.895 km to 167 km for each gravity station. The reader is referred to the publication by Hildenbrand and Kucks (1981a) for additional details regarding the data reduction process. Basically all gravity data were terrain corrected and converted or reduced to the new Geodetic Reference System 1967.

The selected Bouguer reduction density of 2.45 g per cm^3 represents the typical density of sedimentary rocks that cover about two-thirds of the study area (table 1). These low-density sedimentary units include Jurassic and Cretaceous rocks, mainly shales and sandstones. Precambrian crystalline rocks, lower and middle Paleozoic sedimentary rocks (chiefly carbonates), and uppermost Paleozoic and Triassic shales and sandstones are described by higher densities, probably ranging from 2.65 to 3.2 g per cm^3. Because their densities are much larger than the reduction density, calculated Bouguer gravity values will be erroneously high over regions where these dense rocks are exposed or lie near the surface. The areas associated with high geothermal gradients are, however, blanketed by the low-density sedimentary rocks; and thus the selected reduction density (2.45 g per cm^3) is suitable for the present study.

The map of the residual aeromagnetic field (fig. 2) was compiled by merging digital data acquired from three separate surveys (Hildenbrand and Kucks, 1981b). The aeromagnetic data were either collected at or adjusted to an elevation of 152 m (500 ft) above terrain. Flight direction was east-west for all three surveys. The residual aeromagnetic fields were determined by removing the International Geomagnetic Reference Field (1965 and 1975) or the GSFC1266 field, after updating to the epoch in which the surveys were flown.

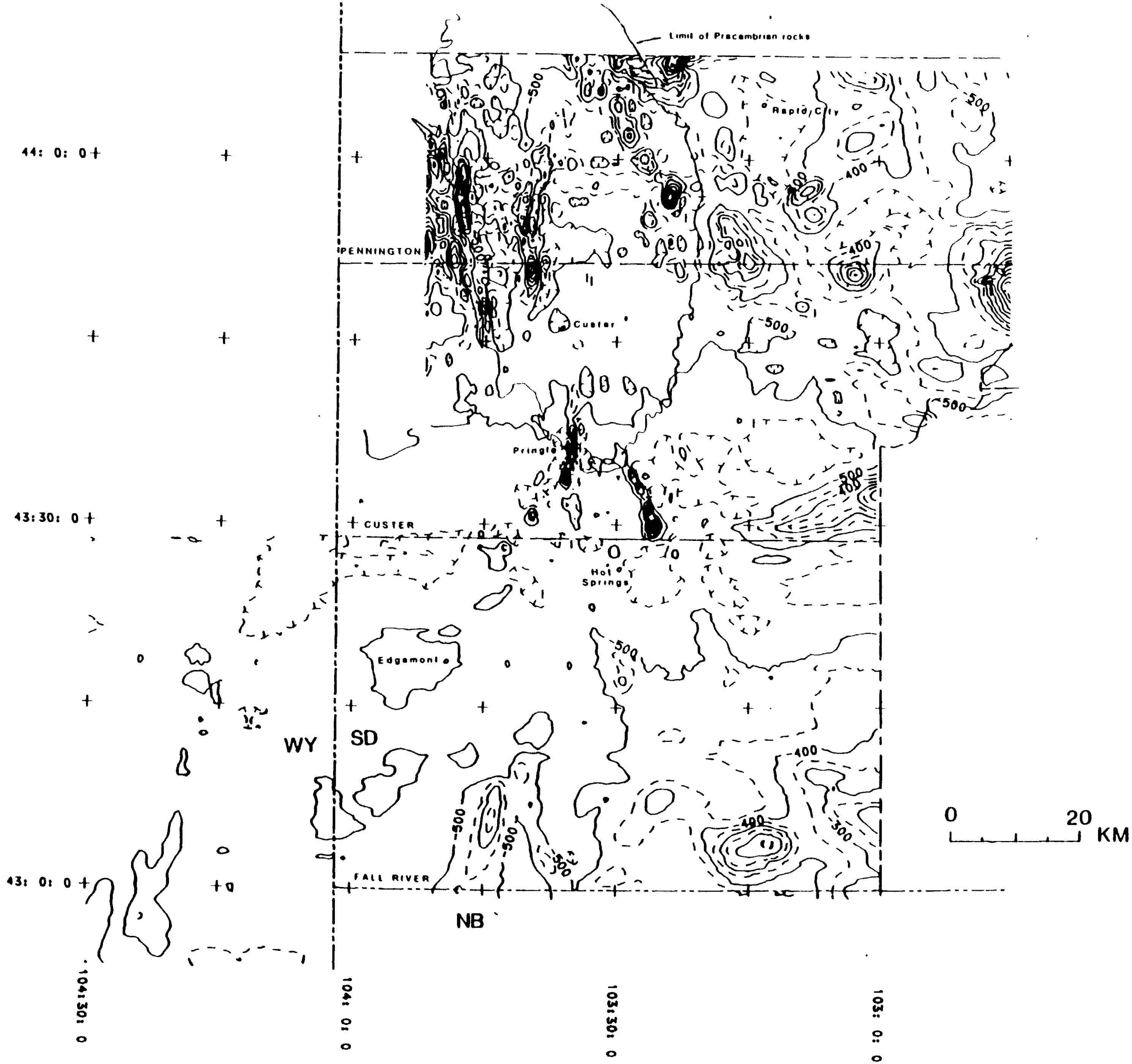


Figure 2.--Residual aeromagnetic anomaly map of the southern Black Hills. Contour interval is 50 gammas.

General Geology

The Black Hills uplift is considered the easternmost and least deformed of the Laramide uplifts associated with Rocky Mountain tectonism (Lisenbee, 1978). It consists of an arcuate north- to northwest-trending dome-shape anticline that exposes a Precambrian core of metamorphic and igneous rocks (fig. 3). Igneous activity accompanied uplift and resulted in the emplacement of dikes, sills, and laccoliths in the northern Black Hills with compositions varying from rhyolite to andesite. Sedimentary rock units mainly consist of Paleozoic carbonates and Mesozoic and uppermost Paleozoic shales and sandstones. Structures within the study area include numerous folds, faults, and domes primarily formed as a result of Laramide uplift of the southern Black Hills block and of Precambrian and Tertiary igneous activity. Discussions pertaining to lithologies and structures relevant to the present geophysical study are given below, although the reader is referred to Redden (1975), Kleinkopf and Redden (1975), Darton and O'Harra (1925), Gott and others (1974), and Lisenbee (1975, 1978) for more detailed discussions.

Sedimentary Units

Phanerozoic sedimentary rocks of the study area have been divided into two basic divisions to best portray density contrasts. These are (1) lower and middle Paleozoic rocks (mainly carbonates) and uppermost Paleozoic and Triassic shales and sandstone and (2) Jurassic and Cretaceous rocks (primarily shales and sandstones). The various formations and groups of these divisions are given in table 1. As indicated in this table, Paleozoic and Triassic sedimentary rocks are appreciably denser than the Jurassic and Cretaceous shales and sandstones.

Depths to the top of the Spearfish Formation or thicknesses of post-Triassic sedimentary units are shown in figure 4. The 49 depth values used to

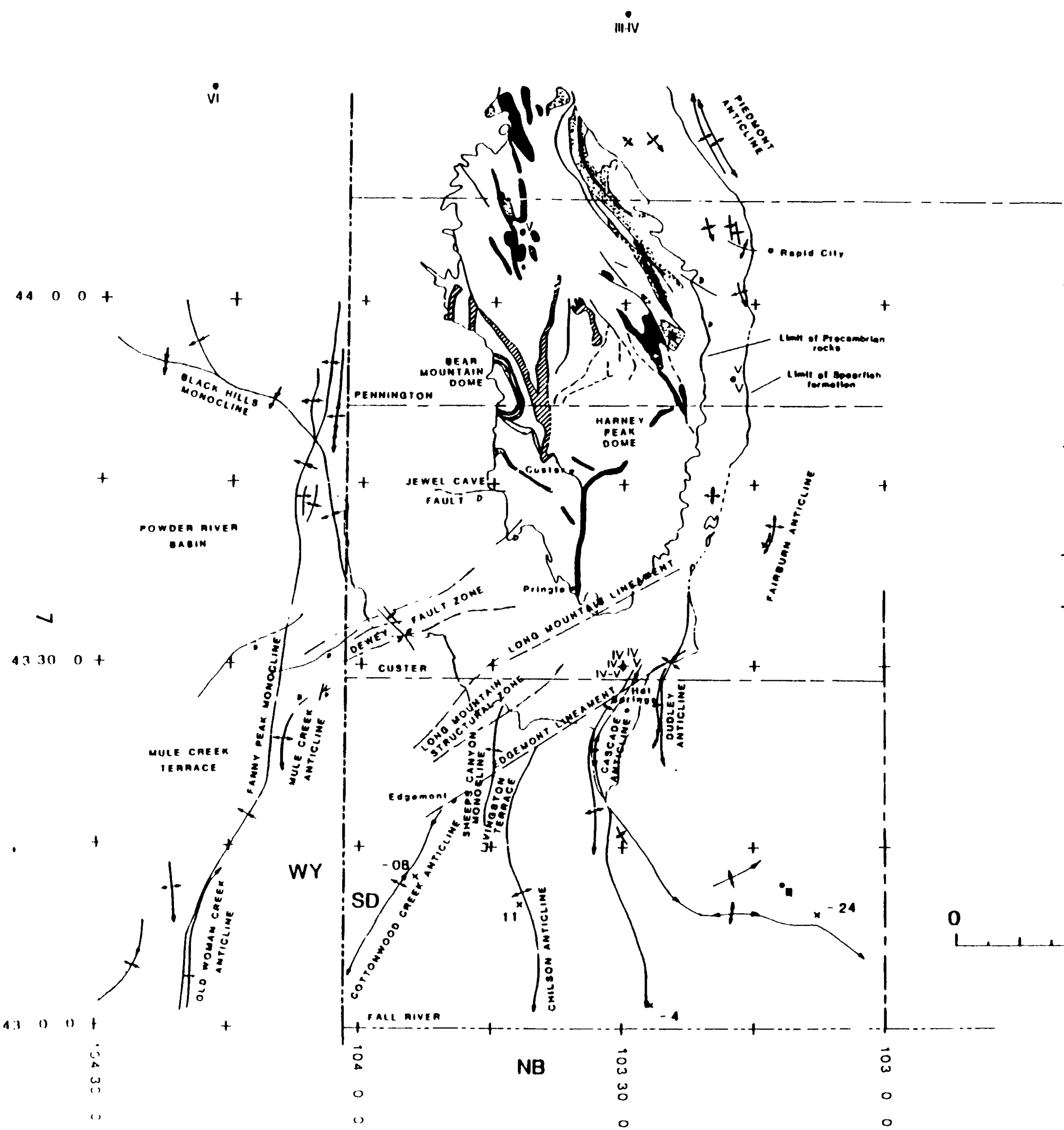


Figure 3.--Tectonic map of the southern Black Hills uplift. Geologic structures and Precambrian units are given by Kleinkopf and Redden (1975) and Gott and others (1974).

EXPLANATION

D — FAULT - D, downthrown side

ANTICLINE - Showing trace of axial plane and general plunge of axis

SYNCLINE - Showing trace of axial plane and general plunge of axis

MONOCLINE - Showing direction of dip

GEOPHYSICAL LINEAMENT - Delineated by Gott and others(1974)

• IV — EARTHQUAKE EPICENTER - Roman numeral represents modified Mercalli intensity (Nuttli,1979)

× .26 — WELL LOCATION - Number represents elevation (km) of Precambrian basement (Steece,1961)

DESCRIPTION OF GENERALIZED PRECAMBRIAN MAP UNITS

MICACEOUS PHYLLITE OR SCHIST - unit J

AMPHIBOLITE AND METAGABBRO - unit G

META-IRON FORMATION, INTERBEDDED SCHIST, IMPURE QUARTZITE, STREAKED QUARTZITE, METACONGLOMERATE, AND AMPHIBOLITE - unit F

TABLE 1. MEAN BULK DENSITIES OF PHANEROZOIC SEDIMENTARY ROCKS

Geologic Description			Wells and Associated Densities (g per cm^3)*					
Geologic Period	Lithologic Units	Predominant Rock Type	State Gary 1 (S.16-T.9S.-R.7E.)	State 3-16 (S.16-T.12S.-R.1E.)	Federal Indian Creek 1-31 (S.31-T.11S.-R.2E.)	Holmes 1-32 (S.32-T.11E.-R.4E.)	David Roll 1 (S.26-T.9E.-R.7E.)	Federal Indian Creek 1-3 (S.3-T.12S.-R.4E.)
Cretaceous	Pierre Shale	shale	2.35	-	2.4	-	-	2.35
	Niobrara Formation	siltstone	2.35	-	-	-	-	-
	Carlile Shale	shale	2.45	-	-	-	-	-
	Greenhorn Formation	limestone	2.35	-	2.4	-	2.45	2.35
	Graneros Group**	shale	2.45	-	2.47	2.5	2.45	2.47
	Inyan Kara Group	sandstone & siltstone	2.5	2.4	2.35	2.4	-	2.35
Jurassic	Morrison Formation	shale	-	2.5	2.3	2.6	-	-
	Unkpapa Formation	sandstone	2.4	-	-	-	-	-
	Sundance Formation	shale & sandstone	2.45	2.55	-	-	-	-
Triassic-Permian	Spearfish Formation	sandstone & shale	2.72	2.7	-	-	-	-
	Minnekahta Limestone	limestone	2.75	2.65	-	-	-	-
Permian	Opeche Formation	sandstone	2.7	-	-	-	-	-
Permian-Pennsylvanian	Minnelusa Formation	sandstone, shale limestone, & dolomite	2.75	2.9	-	-	-	-

*Well information obtained from Petrowell Libraries Well-Log File and Subsurface Data Micro Film File (Denver, Colorado)

**Graneros Group represents the Bell Fourche and Mowry shales, Newcastle sandstone, and Skull Creek shale.

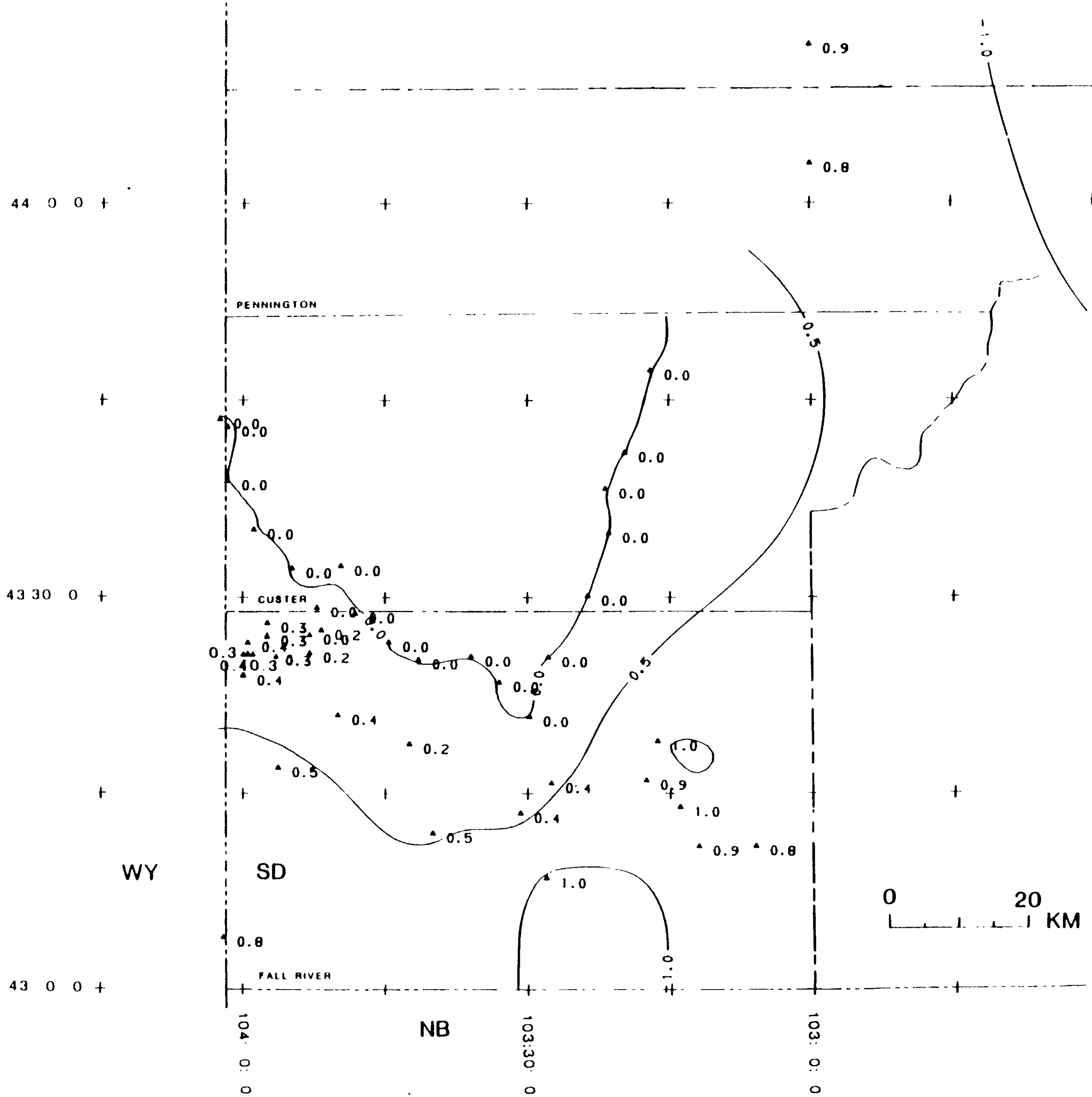


Figure 4.--Depth from ground level to the surface of the Spearfish Formation. Small closed triangles and numbers represent well and outcrop locations and corresponding depths (km) used to construct map. Contour interval is 0.5 km.

construct this map were obtained from either well logs or geologic maps showing outcrops of the Spearfish Formation. Post-Triassic sedimentary units essentially increase in thickness radially outward from the Black Hills and reach maximum thickness at the southern and eastern boundaries of the study area.

The dense Paleozoic and Triassic sedimentary units vary in thickness in different parts of the area. Well information on the Precambrian surface in Fall River County (fig. 3) together with depths to the Spearfish Formation (fig. 4) indicate an average thickness of 0.5 km for this unit. The delineation of structures developed on the Spearfish surface is especially adapted to the gravity method because a major density contrast is involved.

Precambrian Units

Exposed Precambrian rocks of the Black Hills primarily consist of metamorphic rocks of varying lithologies, predominantly phyllites, schists, and quartzites. Metabasalts and metagabbros are found in lesser amounts. The Precambrian rock units can be grouped into four divisions (fig. 3) based on their physical properties (density and magnetization). Kleinkopf and Redden (1975) describe the 12 lithologic units within these divisions and indicate that their probable densities range from 2.65 to 3.05 g/cm^3.

The first division contains dark-green amphibole schists and amphibolite (unit G on figure 3), derived from both intrusive diabase-gabbro rocks and basaltic flows. Amphibolite within the study area is predominantly hornblende and plagioclase. The second division (denoted as unit F on figure 3) is represented by interbedded schist, impure quartzite, iron-formation, streaked quartzite, metaconglomerate, and amphibolite. The iron-formation contains interlayered metachert and grunerite rocks. These first two divisions or units are characterized by rocks which possess moderate to high densities and magnetizations and which, therefore, produce significant effects in the behavior of the gravity and magnetic fields. A micaceous phyllite or schist (unit J on figure 3), belonging to the third generalized Precambrian division, contains moderate amounts of magnetite and also distorts the Earth's magnetic field. Eight lithologic units having low to moderate magnetic and density properties are grouped into the last division. These units are essentially comprised of gneissic granites, phyllites, schists, marble, and quartzites.

Steece (1975) suggested that basement south of a line extending from Edgemont to Hot Springs (fig. 3) consists of gneiss and schist that are approximately 1.4 b.y. old. Radiometric ages of exposed Precambrian rocks further north in the Black Hills indicate that the original sedimentary rocks were deposited between 1.7 and 2.5 b.y. (Redden, 1975).

Structures

The Black Hills uplift consists of two nearly flat-topped blocks separated by the Fanny Peak monocline, a north-trending fold lying approximately along the Wyoming-South Dakota border (Noble, 1952). The southeastern block, which lies within the area of interest, trends northward and topographically rises above the other block, exposing a core of Precambrian rocks. Complex Precambrian structures and lithologies are present because two metamorphic events and possibly six different episodes of deformation occurred (Redden, 1975). According to Redden (1968), three major periods of deformation resulted in the (1) formation of north-northwest-trending folds and parallel faults, (2) shear deformation along northwest trends forming nearly vertical foliation in the metamorphosed rocks, and (3) intrusion of granite and pegmatite masses that domed the rocks. Regions of doming include the Harney Peak and Bear Mountain area (fig. 3).

During the Mesozoic Era and Laramide orogeny, the Black Hills experienced deformation along northeast trends, paralleling structures of Precambrian age (Gott and others, 1974). Two resulting fault zones, Dewey and Long Mountain, located in southwestern Custer County and northwestern Fall River County (fig. 3), are characterized by steeply dipping normal faults, generally with upraised north sides. A combination of faulting and folding within the Dewey and Long Mountain fault zones resulted in 150 m and 30 m of vertical displacements, respectively. In observing abrupt terminations of magnetic and gravity features, Gott and others (1974) interpret a concealed Precambrian fault trending northeast along a possible northeastward extension of the Long Mountain fault zone. Lying to the south and paralleling this inferred fault, another concealed Precambrian structure, the Edgemont lineament, has been interpreted from magnetic data by Gott and others (1974). They suggest that this structure was reactivated during the Laramide orogeny because it apparently influenced the northward terminations of the Dudley, Cascade, Chilson, and Cottonwood Creek anticlines (fig. 3).

Three relatively large folds, the Dudley, Cascade, and Chilson anticlines, are present at the south end of the Black Hills uplift and plunge southward away from the uplift. These anticlines probably formed by an eastward compressive stress acting during Laramide time (Gott and others, 1974). They are strongly asymmetric, having a gently dipping southeastern flank and generally an associated syncline located about 1.6 km west of their crest. The Cascade anticline, the largest fold, has an amplitude of 400 m. Its steep western flank has a maximum dip of 70° SW, although an average dip of 5° SE is found on its eastern flank. The Cottonwood Creek anticline in western Fall River County is structurally different than these three folds in that it appears symmetrical and plunges to the southwest (Lisenbee, 1978).

To the west in Wyoming, the north-northeast-trending Fanny Peak monocline and the northwest-trending Black Hills monocline form a structural boundary between the Black Hills uplift and the Powder River Basin. Associated relief between the basin and uplift ranges from 600 to 1670 m (Lisenbee, 1978). In contrast, broad monoclinal flexures mark the eastern limit of the uplift. A broad (32 km) zone containing gently dipping beds separates the uplift and the Interior Lowlands province to the east (Lisenbee, 1978). Folds along the eastern flank of the uplift, such as the Fairburn and Piedmont anticlines and those near Rapid City, are structurally similar to the folds to the south. Anticlines are strongly asymmetric, having a steep west-dipping flank and a paralleling syncline to the west.

Lisenbee (1978) suggested that folds of the Black Hills region formed by the draping of sedimentary units over faulted basement blocks and that subsidiary structures developed in the form of ramps and terraces. Several terraces, roughly encompassing between 4 and 85 km^2, lie within the study area; some of these are shown in figure 3.

Applied Geophysical Methods

Magnetic methods

Correlation of gravity, magnetic, and geologic data can convey considerable information on subsurface tectonic features. For instance, the magnetic-anomaly map (fig. 2) reflects structure and lithologic contrasts in the rocks of magnetic basement. Magnetic basement is defined as any lithologic unit having a susceptibility or remanent magnetization of sufficient magnitude to produce distortion in the magnetic field. In the southern Black Hills region, magnetic basement is interpreted as Precambrian crystalline rocks and possibly igneous rocks of younger age. Phanerozoic sedimentary units observed in this region generally lack magnetic properties and, therefore, produce little or no effect on the magnetic field.

The map of the second-vertical derivative of the magnetic field (fig. 5) is very helpful in resolving or sharpening anomalies of small areal extent. The zero contour on a second-vertical derivative map is sometimes used to outline the approximate boundaries of magnetic sources (Vacquier and others, 1951). On the map (fig. 5), inferred lithologic and structural boundaries are depicted by heavied zero contours.

Gravity methods

The gravity-anomaly map (fig. 1) is useful in delineating lithologic contrasts and structures within Precambrian basement and structural features that developed on the Spearfish Formation. However, the density of some Precambrian units (gneissic granites, phyllites, schists, marbles, and quartzites) closely matches those (approximately 2.75 g/cm^3) of pre-Jurassic sedimentary units (table 1). Structural variations within these Precambrian units will probably not influence the behavior of the gravity field to any large extent, unless these structures have folded, faulted, or domed the top of the Spearfish Formation.

The horizontal gravity-gradient map shown in figure 6 aids in accurately locating lithologic or structural boundaries within the upper crustal regions. Elongate highs on a gradient map depict inflection points associated with gravity gradients and are, therefore, geographically located over lithologic and structural boundaries.

Elevation of Spearfish Formation

As the formation densities in table 1 indicate, a major density contrast exists at the top of the Spearfish Formation. Assuming an average density of 2.45 g/cm^3 for post-Triassic sedimentary units and 2.75 g/cm^3 for pre-Jurassic

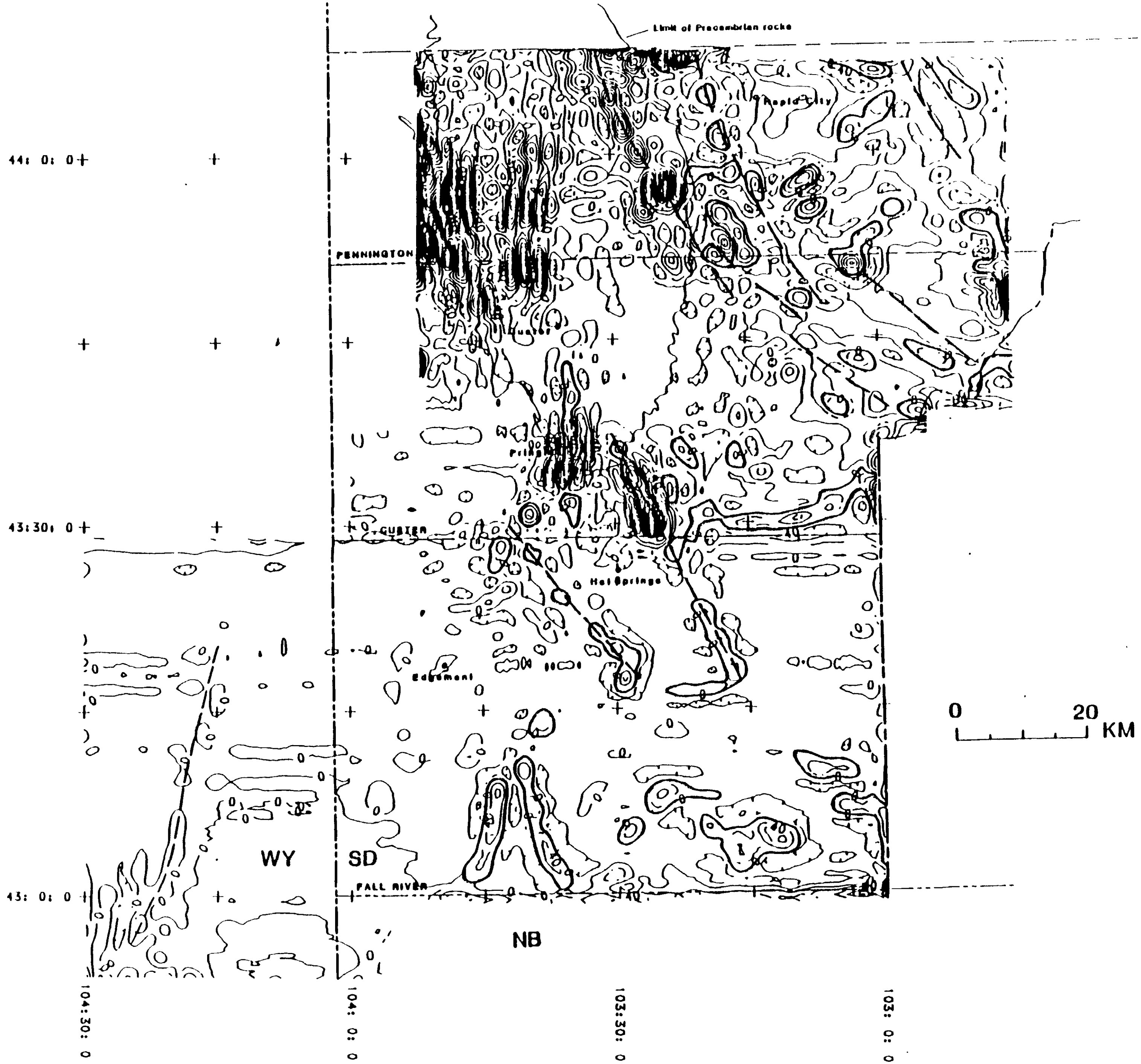


Figure 5.--Map of the second-vertical derivative of the residual magnetic field. Dashed lines denote interpreted magnetic lineaments. Heavied isogamma contours define inferred horizontal limits of magnetic sources. Contour interval is 20 gammas per km^2. In compiling the derivative map, the data were first reduced to the North Pole assuming induced magnetization (inclination = 70.5°; declination = 11.8°).

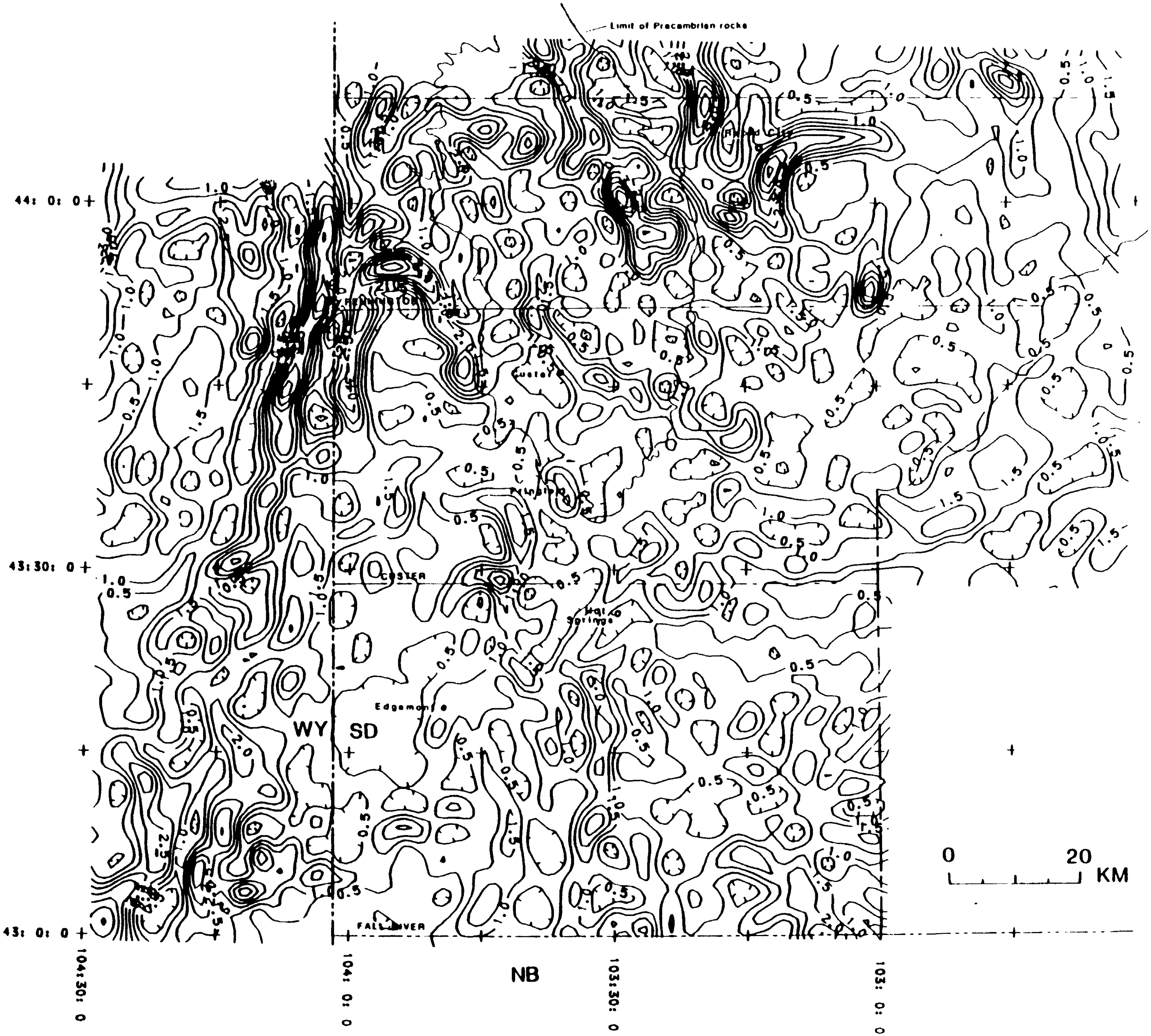


Figure 6.--Map of horizontal gravity gradient magnitudes. Contour interval is 0.5 mgal per km.

sedimentary and crystalline rocks, the top of the Spearfish Formation represents a physical boundary across which the density roughly increases by 0.3 g/cm^3. If other density contrasts are negligible, the Bouguer gravity map can then be analytically converted to a depth map, depicting estimated depths to the top of the Spearfish Formation. Utilizing a computer algorithm described by Cordell and Henderson (1968), an approximate solution to the inverse gravity problem was determined from a 4 km rectangular grid of gravity values. The resulting depth estimates to the Spearfish Formation (fig. 7) are, however, larger than the actual depths (fig. 4) collected from well logs. The cause of these discrepancies in depths is largely due to regional gravity sources located within lower and middle crustal regions. To normalize the depth estimates in order to eliminate gravity effects of deep regional sources, a grid (fig. 8) was created containing the differences between computed and actual depths to the Spearfish Formation. These data were subtracted from the grid of computed depth estimates, resulting in corrected depths that are compatible with well data and supply additional information on the Spearfish surface between well locations. Ground elevations (fig. 9) were used to obtain the final corrected elevations of the Spearfish Formation, shown in figure 10.

The accuracy of computed Spearfish elevations are highly dependent on the assumptions made in reducing the gravity data and in generating the interpretational model (fig. 10). In assuming a Bouguer reduction density of 2.45 g/cm^3, elevation estimates within regions where dense Precambrian rocks are located near the ground surface will be higher than the actual elevations of the Spearfish Formation. Where Precambrian rocks are exposed, the calculated elevations are naturally meaningless. Lithologic variations related to Precambrian basement will also produce Spearfish elevations which

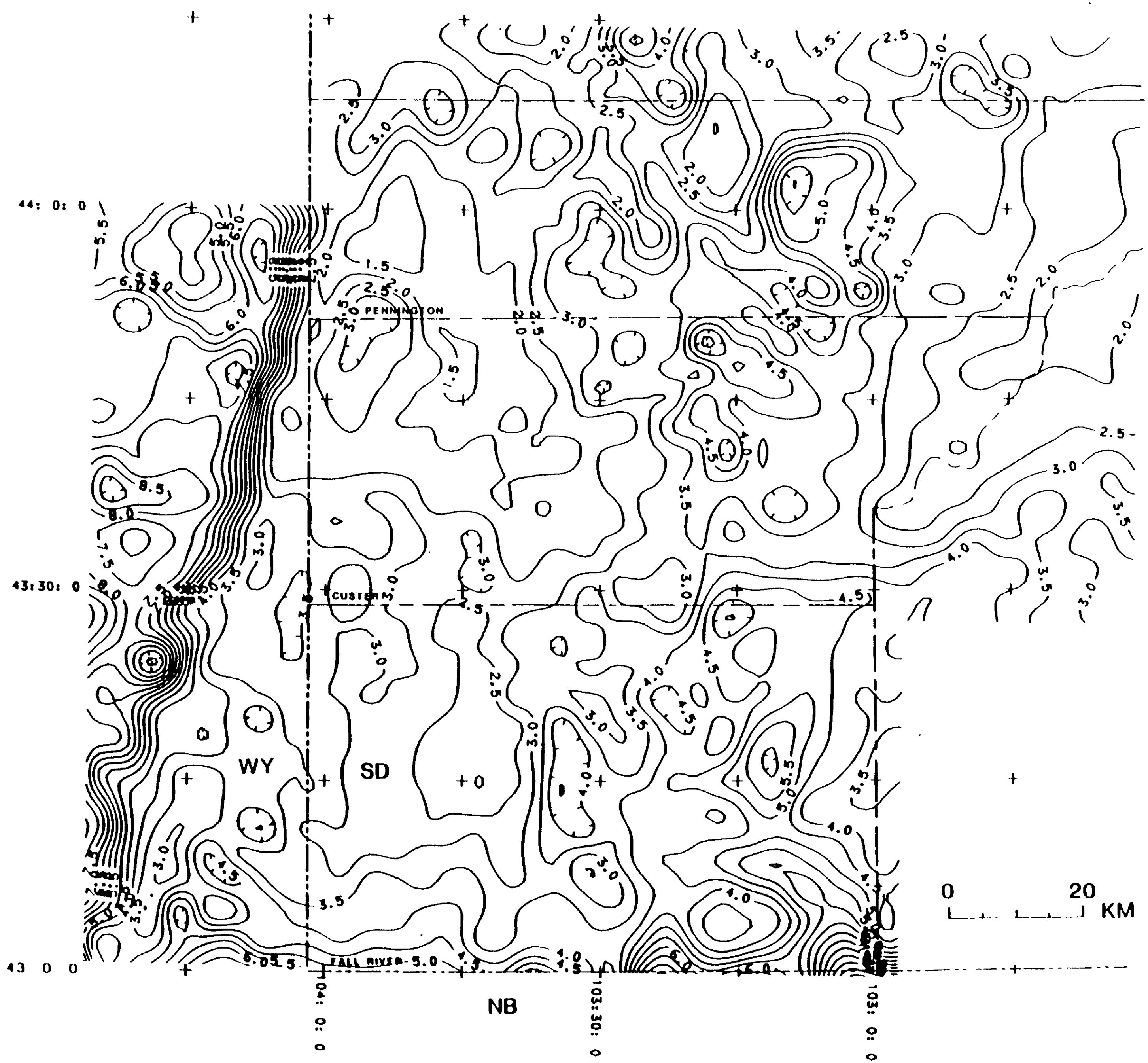


Figure 7.--Depth to the surface of the Spearfish Formation based on gravity interpretations. Contour interval is 0.5 km.

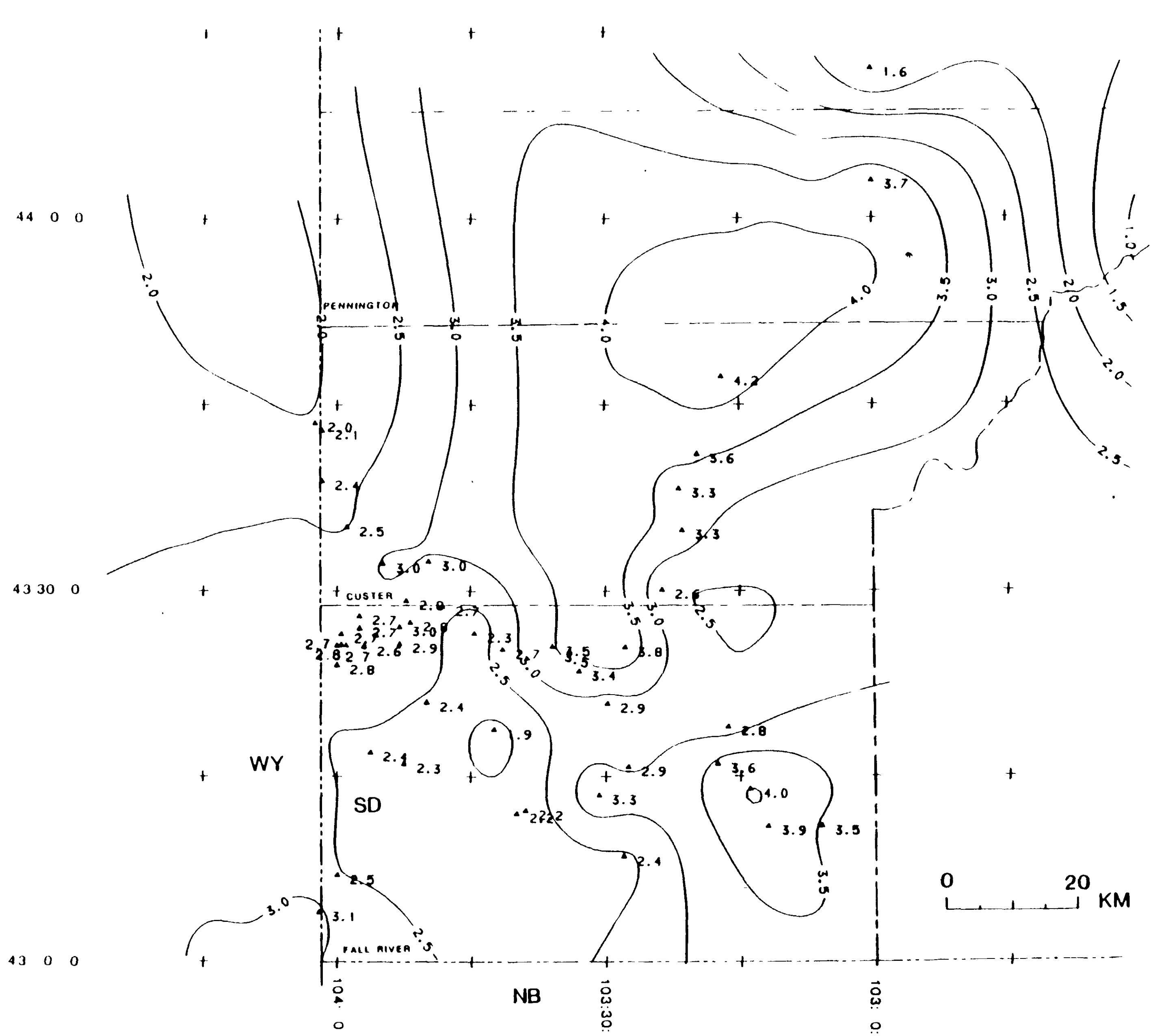


Figure 8.--Map of difference values between computed (fig. 7) and actual (fig. 4) depths to the surface of the Spearfish Formation. Closed triangles and corresponding numbers denote locations and difference values used to construct map.

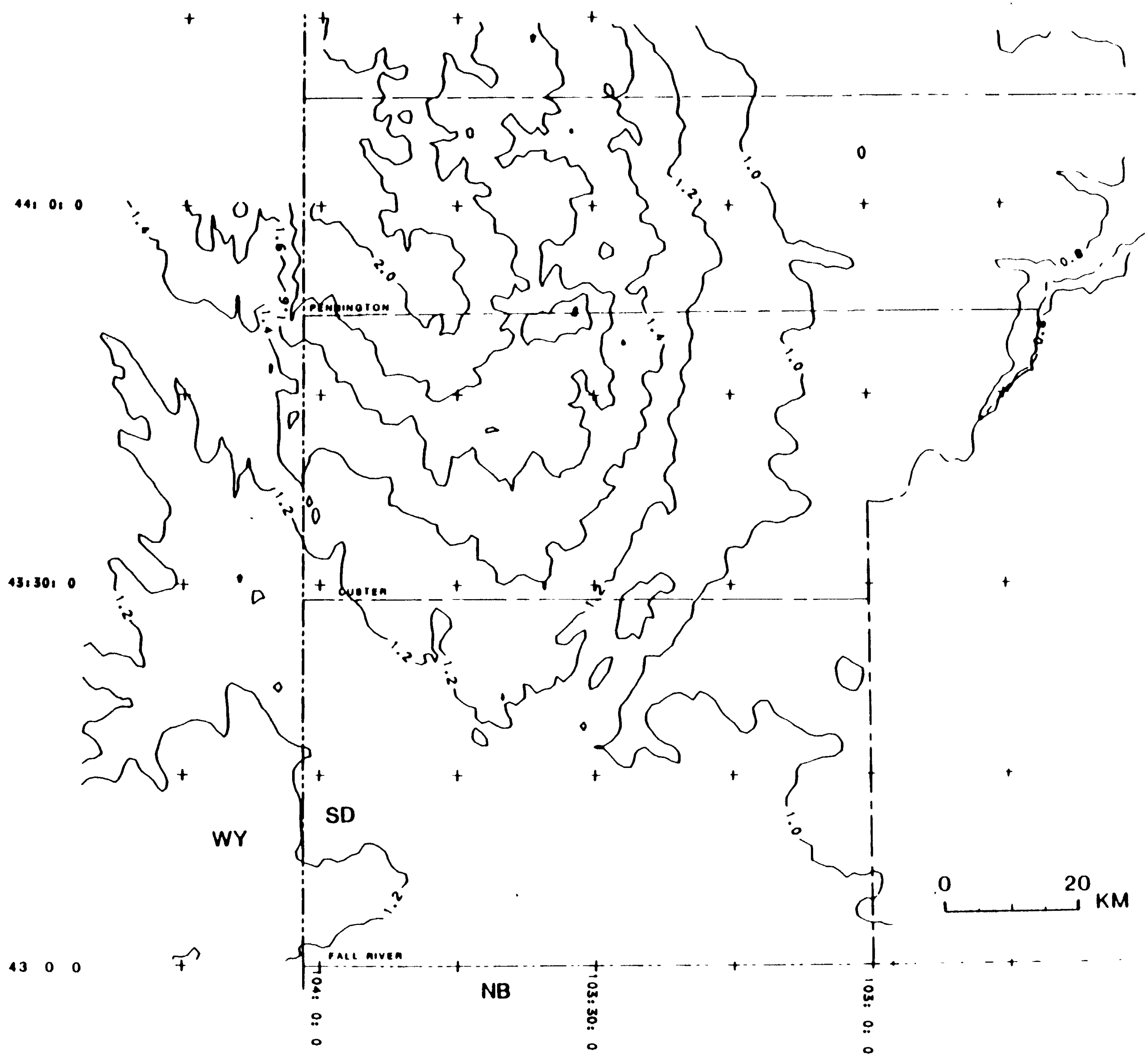


Figure 9.--Ground-surface elevation map of the southern Black Hills region. Contour interval is 0.2 km.

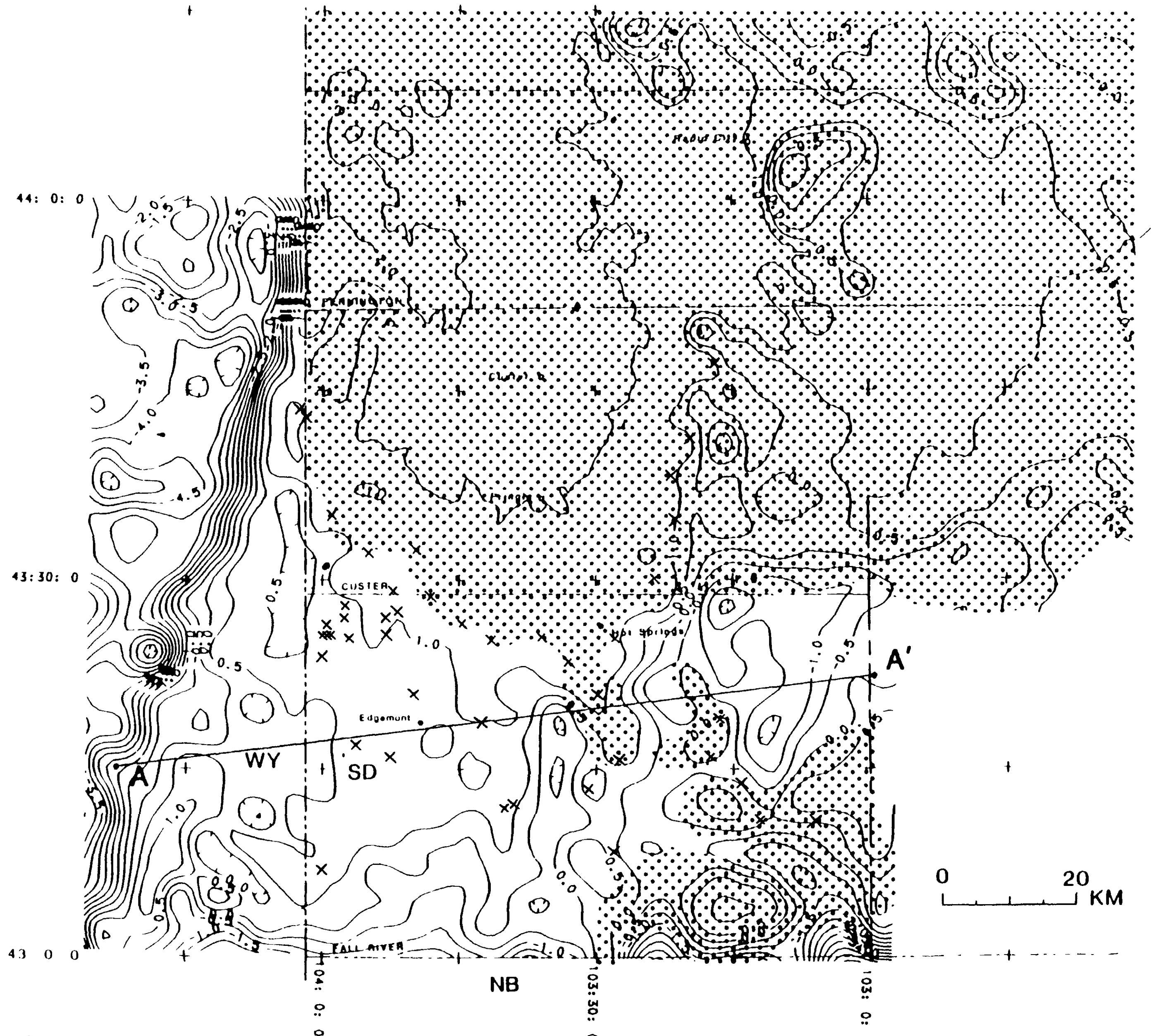


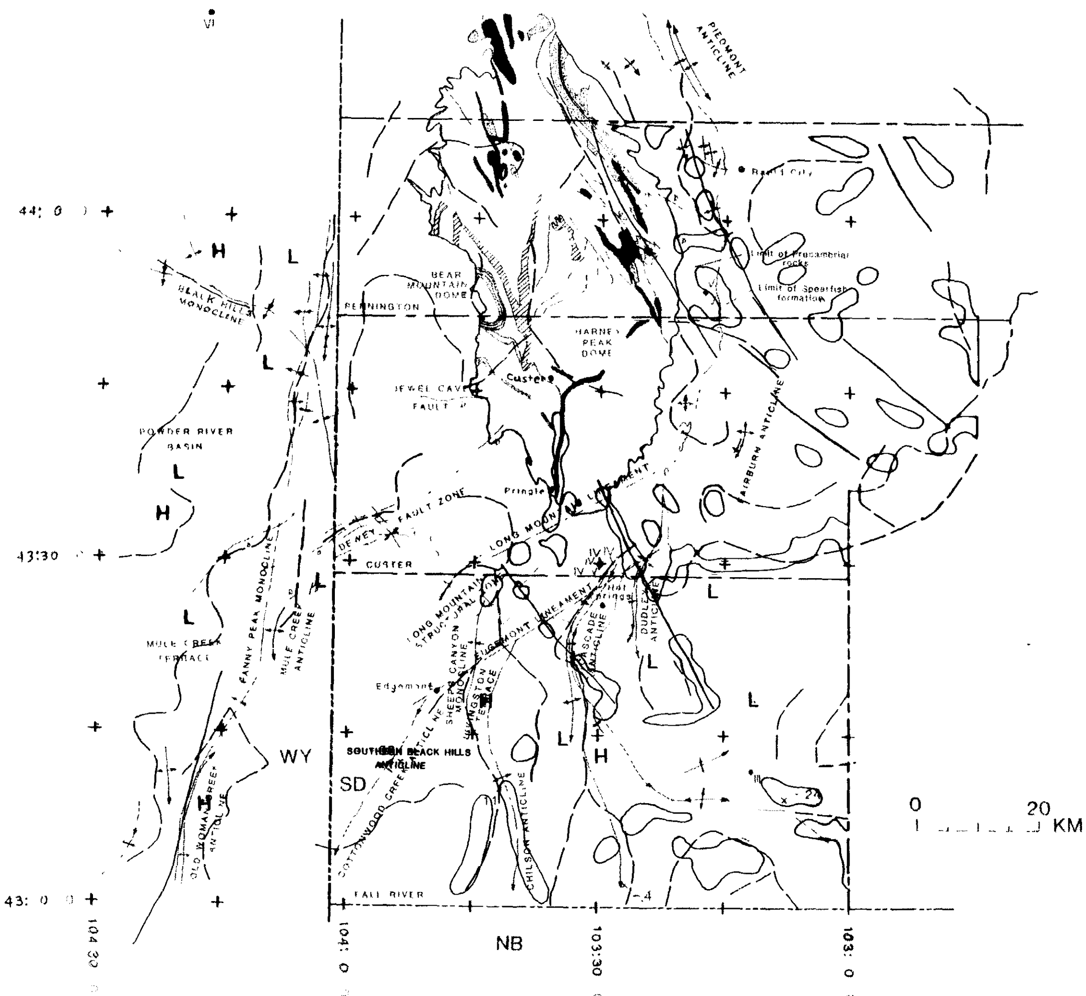
Figure 10.--Elevations of the Spearfish Formation based on gravity interpretations. Stippled pattern depicts areas where computed elevations may be inaccurate, as discussed in text. Locations where computed elevations are compatible with well data, are denoted by x's. Elevation estimates along profile AA' are shown in figure 12. Contour interval is 0.5 km.

are too high. An excellent example of a Precambrian lithologic variation occurs in southeastern Fall River County (lat 43°05′ N., and long 103°15′ W.), where a local gravity high (fig. 1) and a corresponding magnetic high (fig. 2) indicate the presence of very dense and highly magnetic rocks. Elevations markedly increase in this region because of the added density contrast associated with varying Precambrian rock types. Those regions where calculated elevations may be inaccurate for the described reasons are indicated on figure 10.

Interpreted Geophysical Features

Major interpreted lithologic and structural boundaries reflected in the geophysical data are shown in figure 11. Inferred gravity boundaries were determined by connecting elongated highs observed on the horizontal gradient map (fig. 6), a generally simple procedure. However, ambiguity as to the length and direction of gravity gradients occasionally arose. For these unclear situations the Bouguer gravity map (fig. 1) and Spearfish elevation map (fig. 10) were used to help define lithologic and structural boundaries on the gradient map. Magnetic features shown on figure 11 are also depicted on the second-vertical derivative map (fig. 5).

To simplify the following discussions pertaining to the delineation of geophysical features, the study area is divided into four generalized regions. The first region encompasses exposed Precambrian rocks of the Black Hills uplift. The remaining three regions flank the Precambrian outcrops to the east, southwest, and south. Geophysical features lying along the southern flank of the Black Hills uplift are emphasized because numerous drill holes in this region have encountered water having abnormally high temperatures.



E X P L A N A T I O N

——— Interpreted magnetic lineament delineating a major lithologic or structural boundary

— — Interpreted gravity lineament delineating a major lithologic or structural boundary, defined by elongate gravity-gradient highs

O Large buried Precambrian mass composed of basic rock types. Approximate boundary of mass interpreted from zero contour of associated anomaly on the second vertical derivative map (figure 5)

Figure 11.--Geophysically inferred structures and lithologic contrasts superimposed on tectonic map (fig. 3). Interpreted structural highs and lows of the Spearfish Formation (fig. 10) are denoted by the symbols H and L, respectively.

Exposed Precambrian units

Analyses of geophysical data of exposed Precambrian rocks allow insight as to the type of probable basement lithologies producing effects on the magnetic and gravity fields within the study area. Exposures of the amphibolite and metagabbro unit (unit G) and the iron-formation (unit F) correlate well with significant gravity and magnetic highs. This is compatible with earlier interpretations made by Kleinkopf and Redden (1975). An excellent example of this correlation occurs along an elongate magnetic and gravity high (figs. 1, 2, 5, and 6) trending northwest and coinciding with outcrops of units G and F at the northeastern edge of the exposed Precambrian region (fig. 1 and 11). Amphibolites (unit G) and iron-formation (unit F) near lat 44°05′ N. and long 103°42′ W. also generate geophysical highs. The narrow outcrop of iron-formation extending from Pringle to Custer (fig. 3) correlates with a prominent magnetic high (fig. 2 and 5).

The western edge of exposed Precambrian rocks is coincident with the axis of a broad gravity high, which Gott and others (1974) called the gravity axis of the Black Hills uplift. Intense, small-wavelength magnetic anomalies also overlie this region. Apparently, a thick section of the amphibolite and metagabbro unit and the iron-formation is present at depth along the western edge of outcropping Precambrian rocks and extends westward beneath the Paleozoic sedimentary rocks. The approximate horizontal limits of this interpreted massive body, comprised of units F and G, are described by the gravity lineaments in figure 11. It is interesting to note that the associated magnetic highs (figs. 2 and 5) and gravity gradients (fig. 6) abruptly terminate southward in the region of the Jewell Cave fault. The fault probably represents a lithologic boundary formed by vertical displacements, resulting in the presence of units F and G at shallow depths on its northern side.

Micaceous phyllites and schists (unit J on figures 1 and 11) which contain moderate amounts of magnetite also contribute to the anomalous behavior of the magnetic field along the western edge of exposed Precambrian rocks. The particular v-shaped outcrop of unit J east of Bear Mountain dome appears to produce a striking magnetic high (figs. 2 and 5). The eastern limb of this outcrop is better defined in the magnetics, indicating that a thicker section of unit J is present.

Geophysical lows generally overlie exposed granites, schists, phyllites, and quartzites that have low to moderate magnetic and density properties (Kleinkopf and Redden, 1975). The Harney Peak Granite is reflected by nondescriptive and low-intensity magnetic anomalies and a low gravity gradient. Northwest-trending gravity and magnetic lows located within the central region of exposed Precambrian rocks suggests the presence of thick sections of relatively low-density and low-susceptibility granites, schists, phyllites, and quartzites.

Eastern flank of uplift

Correlation of magnetic and gravity data along the eastern flank of the Black Hills uplift indicates that Precambrian basement consists of a complex variety of lithologies. Near lat 44°08′ N., long 103°21′ W., the nose of a southeast-trending gravity low coincides with a pronounced magnetic high. The related source is presumably a low-density phyllite or schist characterized by high susceptibility, such as unit J. A gravity high and an associated magnetic high northwest of Rapid City may reflect underlying amphibolites and metagabbros (unit G) or iron-formation (unit F). The eastern extent of these basic rock types is marked by a steep gravity gradient southeast of Rapid City (fig. 11).

A broad gravity low trending north-northeast from about lat 43°35′ N. and long 103°15′ W. to the northern boundary of the map (fig. 1) conceivably represents thick sections of underlying granites, schists, phyllites, or quartzites. The horizontal limit of these low-density rocks is partially defined by the irregular gravity lineaments shown in figure 11. Two magnetic highs east of Rapid City lie within the gravity low and may indicate buried phyllites or schists (unit J). The broad gravity low is also transected by northwest-trending gravity highs having coincident magnetic highs. Gravity and magnetic lineaments (fig. 11) depict the northwest-trending bodies producing these anomalies. One particular magnetic lineament extends northwestward into the region of exposed Precambrian rocks, where it geographically correlates with surface faults that flank outcrops of amphibolites and metagabbros (unit G) and iron-formation (unit F). Apparently, the northwest-trending geophysical lineaments reflect fault-formed lithologic boundaries associated with basic rock types.

The northwest-trending magnetic lineaments appear to be offset in the region of a transecting northeast-trending magnetic lineament (figs. 5 and 11), possibly representing a transcurrent fault. Approximately 3 km of implied left-lateral displacements has occurred along this interpreted fault. If continued further southwestward, the fault coincides with the proposed lineament (Gott and others, 1974) extending to the northeast from the Long Mountain structural and fault zone. The interpreted transcurrent fault is considered here as a continuation of the Long Mountain fault zone and will be discussed in more detail later. It is interesting to note that the proposed northeastward extension of the Long Mountain fault zone abruptly truncates gravity lineaments (fig. 11) at their southeastern termini along the eastern flank of the Black Hills uplift.

To the east the broad gravity low is paralleled by an equally pronounced gravity high. Corresponding highs on the magnetic-anomaly map (fig. 2) and associated derivative map (fig. 3) suggest that the causative bodies are massive volumes of amphibolite and metagabbro (unit G) or iron-formation (unit F). The horizontal limits of these Precambrian units are defined by the magnetic bodies shown on figure 11.

Southwestern flank of uplift

The most prominent gravity anomaly within the study area is the steep north-northeast-trending gravity gradient, reflecting the Fanny Peak monocline on the southwestern flank of the Black Hills uplift. The rapid descent of the Spearfish Formation along this monocline is amply demonstrated in figures 10 and 12. Figure 12 contains computed Spearfish elevations along profile AA′, identified in figure 10. Above lat 43°30′ N. the Spearfish Formation descends into the Powder River Basin along a relatively linear structural boundary described by the gravity lineament shown in figure 11. Flexures of the Spearfish elevation contours below lat 43°30′ N. suggest that slumping or terracing (e.g. the Mule Creek terrace) has resulted in a irregular structure boundary.

Although the magnetic field is rather nondescript along the southwestern flank of the Black Hills uplift, a persistent, low-amplitude high is geographically coincident with the trend of the Fanny Peak monocline. The cause of this magnetic anomaly may be due to a structural high on magnetic basement, produced by folding as in the case of the Old Woman Creek anticline. Another plausible explanation for the magnetic high is that magnetite has been deposited by the settling out of detritus along faults

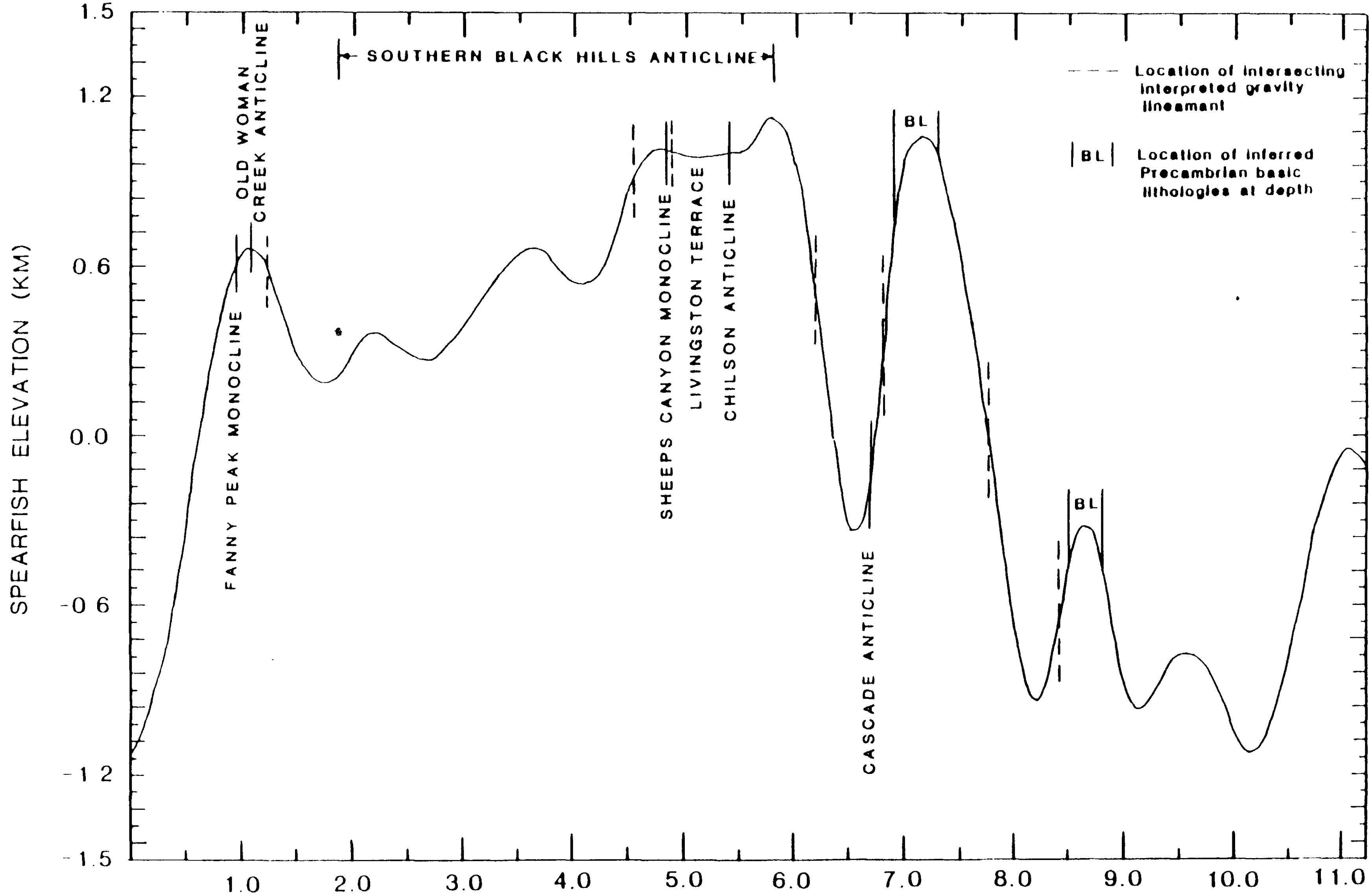


Figure 12.--Computed elevations of the Spearfish Formation along profile AA'. defined in figure 10. Vertical exaggeration in 25x.

underlying and paralleling the Fanny Peak monocline. The magnetic signatures flanking this high to the east and west are similar in character, indicating that weakly magnetized rocks characterize Precambrian basement in this region and that the descent of Precambrian basement into the Powder River Basin produces little effect on the magnetic field.

A structural closure (fig. 10) trending north-northeast (lat 43°06′ N. and long 104°06′ W.) may describe folding associated with the Old Woman Creek anticline. Profile AA′(fig. 12), which crosses this anticline, indicates that folding has elevated the Spearfish Formation by about 0.5 km. The approximate boundaries of the fold are given by the interpreted gravity lineaments shown in figure 11. Another structural feature paralleling the Fanny Peak monocline near the Wyoming-South Dakota State boundary (lat 43°30′ N.) possibly corresponds to a north-trending syncline with an associated relief of about 0.3 km. The west edge of this inferred syncline is marked by a gravity lineament (fig. 11).

Further north several noteworthy depressions and uplifts are revealed on the Spearfish surface (fig. 10). The northwest-trending Black Hills monocline is represented by the southwestward deepening of the Spearfish Formation and by the gravity lineament depicted in figure 11. North of the intersection of the Fanny Peak and Black Hills monoclines, a conspicuous structural high implies the presence of a broad terrace.

Southern flank of uplift

High geothermal gradients as well as folds and fault zones characterize the southern flank of the Black Hills uplift. Lithologic variations related to Precambrian basement and major structural features that developed on the Spearfish surface are indicated in the analyses of gravity data. Magnetic-anomaly maps express several Precambrian lithologic and structural boundaries along the southern flank of the Black Hills uplift (fig. 11). As previously discussed errors in the estimated elevations to the top of the Spearfish Formation are generated in those regions where density variations in Precambrian rocks occur. It is, therefore, advantageous to define these regions before discussing Phanerozoic structures.

Well data indicate that Precambrian basement within Fall River County primarily consists of gneiss and schist (Steece, 1975). Although these rock types characteristically have low to moderate density and magnetic properties in this region, the magnetic-anomaly maps (figs. 2 and 5) reveal several prominent highs with amplitudes indicative of more basic sources at depth. This interpretation is further supported by corresponding gravity highs. Amphibolites and metagabbros (unit G) or the iron-formation (unit F), similar to those observed in outcrops of the Black Hills region, are interpreted as the probable basic lithologies producing most of the distinguishable magnetic highs located along the southern flank of the uplift. Localized areas where underlying Precambrian rocks may be comprised of units G and F are indicated in figure 11. Their structural configurations conceivably describe igneous masses such as basaltic flows, dikes, sills, plugs, and plutons. The interpreted smaller bodies may represent igneous plugs or dike, whereas the feature in southeastern Fall River County (lat 43°05′ N. and long 103°15′ W.) seemingly depicts a large plutonic mass. In the vicinity of the eastern boundary of Fall River County, the large areal extent of magnetic highs (fig. 2) suggest that Precambrian basement contains basaltic flows or sills.

The geometries of the two dike-like bodies in south-central Custer County (figs. 5 and 11) are very similar to those located in southwestern Fall River County. The lack of strong gravity expressions over these bodies may indicate that their volumes are insufficient to distort the gravity field. Another plausible explanation is that these geophysical bodies consist of low-density phyllites or schists bearing magnetite (unit J). The former explanation is preferred because one of these dike-like bodies in Custer County coincides with exposed iron-formation (unit F).

Lithologic boundaries are delineated by some of the gravity lineaments (fig. 11), particularly those located in eastern and southeastern Fall River County. A gravity lineament and related magnetic lineament trending west-southwest in southeastern Custer County are interpreted as reflecting a major lithologic boundary. The inferred horizontal limits (fig. 11) of the basic rock unit lying along this boundary describe a 3 km wide body that is linear and remarkably continuous over an appreciable distance. Conceivably extensive faulting formed this lithologic boundary.

A concealed Precambrian structure expressed as the Long Mountain lineament has been interpreted by Gott and others (1974) as a northeast-trending wrench fault with right-lateral displacements. The inferred sense of movement was probably determined from the indicated offset in the broad gravity highs related to the Black Hills uplift (fig. 1). Kleinkopf and Redden (1975), however, suggested left-lateral displacements have occurred along a fault of similar orientation. Their interpretation is based on offsetting the once alined dike-like bodies in south-central Custer County by 6 miles of left-lateral displacements. The present geophysical maps do not depict any prominent northeast-trending geophysical feature coinciding with the Long Mountain lineament. As previously discussed a magnetic lineament trending northeast along the eastern flank of the Black Hills uplift is interpreted as delimiting the northeastward extension of the Long Mountain lineament and as reflecting a fault with about 3 km of left-lateral displacements. The implied offset along the fault lends support to the interpretations made by Kleinkopf and Redden (1975).

Two northwest-trending magnetic lineaments (figs. 5 and 11) are sharply terminated at their intersection with the Long Mountain lineament in south-central Custer County. These two lineaments probably represent basic lithologic boundaries formed by faulting, similar to those interpreted along the eastern flank of the Black Hills uplift.

The northeast-trending Edgemont lineament does not generate a geophysical expression on the present maps, except for a short gravity lineament coinciding with its southwest end (figs. 1 and 11). Precambrian geophysical features in this region generally trend northwest uninterrupted across the Edgemont lineament. The curvature and northern termini of folds near the region of the Edgemont lineament in Fall River County do, however, supply strong indirect evidence that the lineament does exist and probably reflects a structural barrier, having influenced the northward development of folds during Laramide time. In addition, Steece (1975) on the basis of well data proposes that a Precambrian lithologic boundary approximately extends through Edgemont and Hot Springs.

Ignoring geophysical anomalies associated with lithologic variations in Precambrian basement, the general pattern of the gravity field (fig. 1) along the southern flank of the Black Hills uplift depicts a broad north-trending high and low in western and eastern Fall River County, respectively. From the Spearfish elevation model (figs. 10 and 12), the gravity high delineates an appreciably large uplifted region that apparently represents the southward extension of the Black Hills uplift. Along long $103^{o}45'$ W. from north to south (fig. 10), the structural high begins approximately at the level of the top of the Black Hills uplift in southern Custer County (lat $43^{o}30'$ N.), maintains a relatively flat crest for about 35 km down to lat $43^{o}12'$ N., and then gently dips (5^{o}) southward into Nebraska. Its geometrical configuration as depicted along profile AA′ (fig. 12) resembles an asymmetric anticline facing east. Consequently, this structural feature will be, herein, called the southern Black Hills anticline.

On the anticline′s west side, the Spearfish surface (fig. 12) gently deepens at an average dip of 2^{o}. Secondary structures superimposed on this ramp-like limb of the Southern Black Hills anticline include two implied anticlines of small amplitudes, the Sheeps Canyon monocline, and the Livingston terrace. The latter two structures are described by Gott and others (1974). The Chilson anticline located on the east edge of the Southern Black Hills anticline is offset to the east from its mapped position. This offset may be due to structural complications at depth or to the coarse grid interval (4 km) used in computing the model of Spearfish elevations. The structural high (fig. 10) associated with the Chilson anticline is well defined further south at lat $43^{o}06'$ N. and long $103^{o}12'$ W. A gravity lineament paralleling the Chilson anticline to the east (figs. 11 and 12) depicts the fold′s western limb.

The rapidly descending eastern limb of the southern Black Hills anticline appears to coincide with a limb of a paralleling syncline (figs. 10 and 12). An irregular gravity lineament (figs. 11 and 12) reflects this deeping of the Spearfish Formation. The abrupt ascent of the syncline′s eastern limb, depicted by a gravity lineament, is partially due to folding of the Cascades anticline (fig. 12). The structural high is also related to computational errors associated with the presence of dense Precambrian basic lithologies. It is anticipated that the amplitude of the structural high would be much less in the absence of underlying lithologic variations. The same conclusions apply to the anticlinal feature located further east, where inferred basic rock types are also present.

A depression or basin delimited at the east end of profile AA′ (fig. 12) seemingly generates the broad gravity low observed in eastern Fall River County. The implied relief of this basin relative to the crest of the southern Black Hills anticline is about 2 km. As previously discussed, lithologic variations in Precambrian basement occur within this depressed region, and thus the approximate boundaries of the basin are difficult to determine.

Geothermal Gradient and Chemical Geothermometer Data

Variations of geothermal gradients supply near-surface evidence of the nature of the geothermal system characterizing the study area. The thermal gradient map shown in figure 13 was compiled utilizing 115 values previously determined by Schoon and Gregor (1974) and 20 values calculated from well data residing in the water quality data bank maintained by the National Water Data Exchange, U.S. Geological Survey. All gradients were computed by first determining the difference between the formation temperature and the mean annual temperature (7.2°C) and then dividing by the formation depth. Because of channeling and stratification of thermal and cold waters, the reported thermal gradients should be cautiously used in evaluating geothermal prospects in the area. Temperature measurements made in wells deriving discharge from cool strata will result in gradients that are much lower than the actual gradients representing the sedimentary column. Additional problems arise if isotherms within the aquifer systems are present from substantial mixing of meteoric water. Thermal gradient anomalies produced by one measurement are not, therefore, regarded as important thermal indicators, although clustering

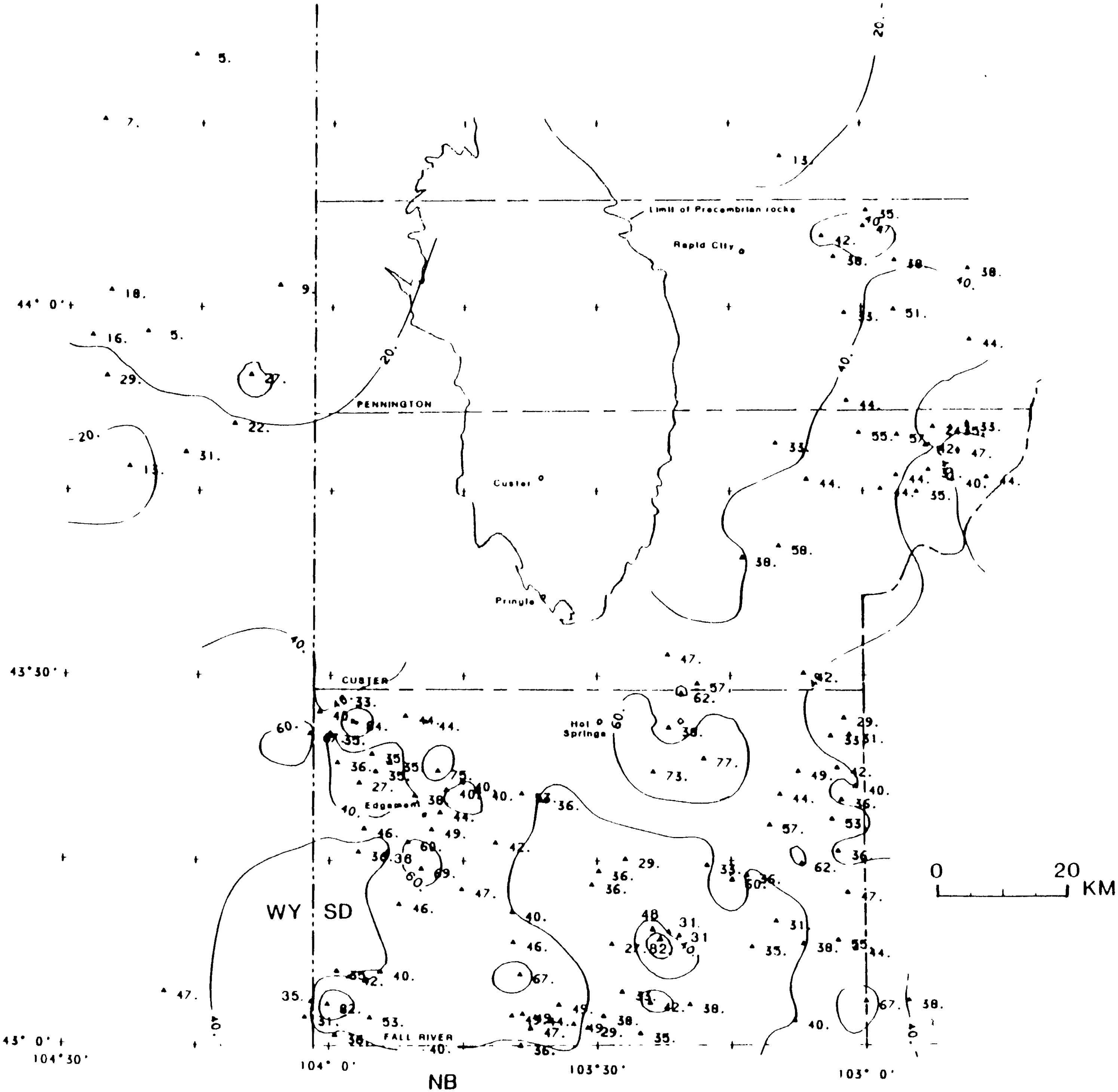


Figure 13.--Geothermal gradients of the southern Black Hills region. Closed triangles and corresponding numbers denote well locations and geothermal gradients used to construct map. Contour interval is 20°C per km.

or alinement of anomalously high gradients may be considered as reflecting principal thermal discharge areas.

The indicated thermal gradients range from 5 to 84°C/km and define broad areas along the southern and eastern flanks of the Black Hills uplift where values exceed 40°C/km. Because the average thermal gradient within north-central United States is about 19°C/km (Combs and Simmons, 1973, table 7), anomalously high heat flow apparently characterizes the upper crust of the southern Black Hills region.

Of particular interest are two generalized regions where exceptionally high thermal gradients exist. Within a large area east of Hot Springs values commonly exceed 60°C/km. It is also interesting to note that narrow thermal anomalies extend northeast and southeast from the Hot Springs area. Another generalized area typified by high thermal gradients occurs in western Fall River County, conspicuously coincident with the interpreted horizontal limits of the Southern Black Hills anticline. Along the western flank of the Black Hills uplift in Wyoming, gradients are characteristically low and probably reflect the regional flow system, in which surface runoff from the Black Hills region migrates westward through aquifers into the Powder River Basin (Head and others, 1978).

Although geothermal gradient data aid in delineating thermal discharge areas and in describing the nature of the geothermal system, they supply little information pertaining to the temperature of the geothermal reservoir at depth. Temperatures measured in shallow wells may not be indicative of the temperatures at which ground water last interacted with rock. For example, deep circulating waters migrating near molten rock may be substantially cooled in their ascent to near-surface regions. Geothermal reservoir temperatures or the temperatures at which water has last reacted with rock can, however, be estimated utilizing an empirical method (Fournier and Potter, 1978), based on molar Na, K, Ca, and Mg concentrations in natural waters. This method, called geothermometry, assumes that aqueous Na-K-Ca-Mg relationships are related entirely to temperature-dependent silica reactions. Major assumptions include that silica is freely available in the reservoir rock and that the water has remained in contact with the rocks for a suitable length of time to reach chemical equilibrium. Forty-eight estimated reservoir temperatures depicted in figure 14 have been calculated using the Na-K-Ca-Mg geothermometer. Chemical compositions of natural waters were taken from the water quality data bank, maintained by the National Water Data Exchange, U.S. Geological Survey.

Geothermometers based upon water chemistry are adversely affected by mixing of ascending geothermal waters with local meteoric waters and by additional water-rock reactions possibly occurring during the ascent. Because the degree that these adverse effects have influenced the geothermometer measurements cannot be determined, the temperatures in figure 14 must be regarded as rough estimates of the geothermal reservoir temperature. Temperatures range from 14^{o} to $125^{o}C$ and have a mean value of $64^{o}C \pm 30^{o}C$.

Sources of Geothermal Waters

Although thermal gradients (fig. 13) frequently exceed $50^{o}C/km$ along the southern flank of the Black Hills, geothermal investigations by Adolphson and Le Roux (1968) and Schoon and McGregor (1974) indicate that relatively low temperatures and thermal gradients characterize the Black Hills area. From 42 wells Adolphson and Le Roux (1968) determined an average geothermal gradient of $29^{o}C/km$ and concluded that low thermal gradients are due to the rapid descent of recharging cold waters in permeable Paleozoic formations. Their conclusion is supported by two heat flow measurements (1.84 and 1.96 HFU) collected by Roy and others (1968) near Lead, South Dakota (lat $44^{o}20'$ N.,

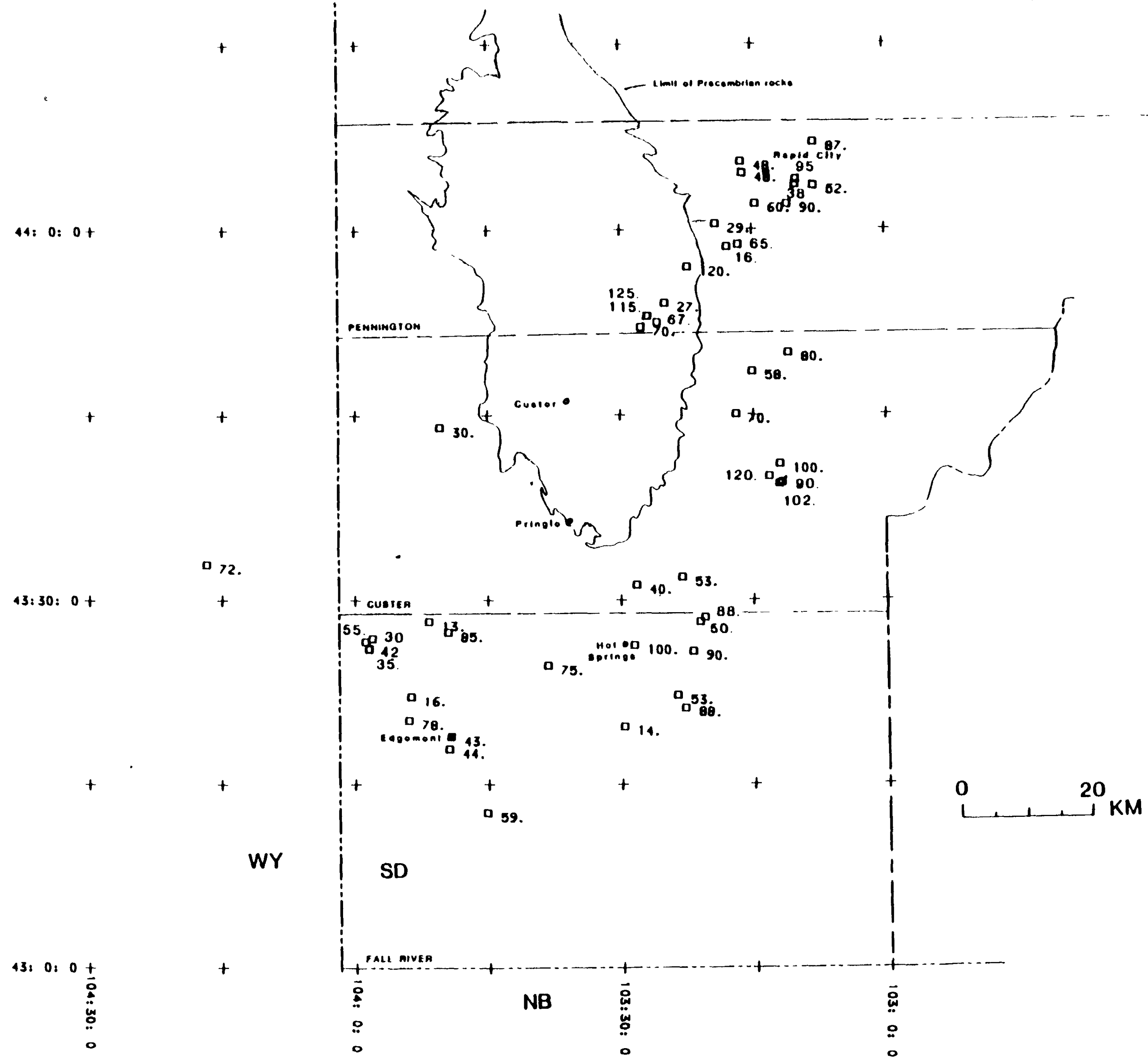


Figure 14.--Calculated geothermal reservoir temperatures utilizing a NA-K-Ca-Mg geothermometer. Open squares denote locations of wells from which the chemical compositions of ground water were employed to calculate indicated temperatures.

long 103°47′ W.). Assuming a mean thermal conductivity of 4 mcal per cm sec °C (Comb and Simmons, 1973, table 7) for Paleozoic rocks in South Dakota, the anticipated geothermal gradient employing a heat flow of 1.9 HFU is about 48°C/km, which is representative of reported values along the southern flank of the Black Hills uplift (fig. 13). These observations indicate that cool ground waters derived from surface run off reduce geothermal gradients in the Black Hills area. Two problems, however, must be addressed and pertain to the cause of high flow within the Black Hills region and, more importantly, to the particular geothermal system generating higher heat production along the southern flank of the Black Hills. The latter problem arises because recharging cool waters also descend along aquifers along the southern Black Hills, but nevertheless the geothermal gradients are high.

The cause of high heat flow beneath the Black Hills region is somewhat beyond the scope of this study but will be briefly included for completeness. On heat flow maps (e.g., Lachenbruch and Sass, 1977) the Black Hills uplift lies within a broad region, extending from New Mexico northward to Montana and North Dakota, where heat flow measurements commonly exceed 1.5 HFU. The number of heat flow measurements used to define this region is, however, rather small. Moreover, recent studies by Blackwell and others (1981) indicate that some of these measurements made within shale units may be 50-60% too high. It is, therefore, difficult to ascertain from the available data whether the Black Hills uplift can be considered a localized high heat flow area, or lies within a much broader region typified by high heat flow. In any case, the heat sources underlying the Black Hills are conceivably similar to those discussed in the literature for nearby high heat flow regions. Lachenbruch and Sass (1977) attributed high heat flow beneath the Basin and Range province primarily to the extension and thinning of the lithosphere, resulting in excess heat by the convective transfer of magma rising into the lower crust or across the base of the crust. In studying a higher temperature in the upper mantle beneath the northern Great Plains as compared to that underlying the Interior Lowlands, Combs and Simmons (1973) discuss compositional differences of the upper mantle or a partially molten zone at shallow depths in the upper mantle. Another plausible explanation for high heat flow is that the Black Hills uplift is tectonically active such that deep-seated structures, like faults formed or reactivated during Laramide time, are presently acting as conduits for heat concentrations. Historical earthquakes (fig. 3) suggest that structural adjustments are occurring. Regional gravity studies conducted by Woollard (1962) indicate that the Black Hills uplift are not locally compensated in the crust. Whatever the cause, high heat flow within the Black Hills region contributes to the high geothermal gradients observed along its southern flank.

Common causes of geothermal phenomena at the Earth's surface include (1) partially cooled magma at depth, (2) exothermic reactions from oxidation and hydration weathering, (3) generation of heat from radiogenic sources, and (4) convective transport of heat and fluids from depths in a cyclic system. The first three are unlikely as the major cause for the observed high thermal gradients. The youngest igneous intrusion emplaced in the Black Hills region is Tertiary in age. On the basis of calculations made for the Long Valley, California, geothermal area (Lachenbruch and others, 1976), buried Tertiary masses would have certainly cooled to ambient temperatures by the present time. Moreover, there is no geophysical evidence of igneous bodies at depth in western Fall River County where high thermal gradients occur. Chemical weathering such as the conversion of anhydrite to gypsum is also eliminated because thermal springs near Hot Springs are 22°C higher than the mean annual temperature and too warm to be explained by exothermic reactions. Due to the appreciable horizontal extent of the region characterized by high geothermal gradients, heat production by radioactive decay is highly improbable; and, in addition, the thermal springs are not particularly radioactive.

Although chemical weathering and radioactive decay may contribute to the heat content of the geothermal system, deep circulation of meteoric water appears to best explain the high thermal gradients along the southern flank of the Black Hills. In the conceptual model proposed for this system, ground waters in the topographically high areas of the Black Hills percolate downward along the many southward- and southeastward-trending faults and fracture zones, formed during periods of deformation in Precambrian and Laramide time. Assuming a gradient of $40^{o}C/km$, the dense cool water need only descend to a depth of about 1.6 km (1 mi) before attaining a temperature of $64^{o}C$, the mean calculated temperature at which the water last reacted with rocks. The meteoric water, having become lighter during the heating process, then migrates upwards through conduits closely associated with major faults. Most of the water does not reach the surface but spreads outward through permeable zones. Geothermal waters can also mix with local meteoric water, resulting in variations in ground water temperatures. Some of the heated waters migrate to the surface forming thermal springs like those observed near Hot Springs. The analyses of the geophysical data within the study area aid in identifying structures influencing the distribution of geothermal waters.

Geophysical Features Related to the Geothermal System

Regions characterized by prominent thermal gradients are presumably located near fracture zones along which geothermal waters ascend and then, in general, migrate outwards in aquifers. A few of the geophysically inferred structures may play an important role in the channeling of geothermal waters. It will be assumed that interpreted elevations of the Spearfish Formation (fig. 10) roughly describe undulations associated with major aquifers of the Fall River (of the Inyan Kara Group), Morrison, Sundance, Minnelusa, and Pahasapa (Mississippian) Formations.

The most pronounced thermal gradient anomaly encompasses a large area east of Hot Springs. Three geophysical features located in the vicinity of this anomaly may represent fault-related conduits that permit reasonable flow of hot waters. Two of these features, the Long Mountain and the Edgemont lineaments previously interpreted by Gott and others (1974), occur northwest of the thermal gradient anomaly. From the general flow pattern of ground water in this region (Rahn and Gries, 1973), hot waters emerging from inferred faults associated with these lineaments will conceivably migrate southeastward within aquifers and produce the observed geothermal gradient anomaly. The northwest-trending magnetic lineament crossing lat $43^{\circ}24'$ N. and long $103^{\circ}21'$ W. has been interpreted as a fault-formed lithologic boundary (fig. 5 and 11). This lineament bisects the thermal gradient anomaly, suggesting that the corresponding fault influences the distribution of hot waters.

Narrow thermal gradient anomalies extend to the northeast and southeast from the gradient anomaly east of Hot Springs. The southeastern extension geographically correlates with the interpreted basin in eastern Fall River County (fig. 12). The basin may channel hot waters flowing southeastward from the Hot Springs area. The northeast-trending high thermal gradient, located along the eastern flank of the Black Hills uplift, appears to be intimately related to the inferred extension of the Long Mountain lineament (fig. 11). Ground waters descending along northwest-trending faults within the topographically high eastern block of the Black Hills apparently encounter the interpreted Long Mountain fault zones, ascend to the near surface regions, and migrate southeastward within aquifers. Thermal gradients are higher southeast of the interpreted extension of the Long Mountain fault and structural zone.

Another generalized region typified by high thermal gradients is coincident with the inferred location of the southern Black Hills anticline (fig. 11 and 12) in western Fall River County. In particular, thermal gradient highs are observed near Edgemont, along a north-south trend approximately paralleling the Chilson anticline, and within the southwest corner of Fall River County. Local gradient highs in the vicinity of Edgemont may also reflect geothermal waters migrating roughly southward from the Long Mountain fault zone and from the suggested fault represented by the Edgemont lineament. Fracture zones underlying either the Chilson anticline or the southern Black Hills anticline may be responsible for the distribution of geothermal waters. If drape folding of sedimentary units over faulted basement blocks is commonplace within the southern Black Hills region as suggested by Lisenbee (1978), then either of these anticlines may be associated with deep-seated structures representing channel-ways for hot waters. The eastern limb of the southern Black Hills anticline may especially reflect faulting at depth because it is impressively steep (fig. 12) and correlates well with the north-trending thermal gradient anomaly. Faults, related to the Cottonwood Creek anticline and the southern Black Hills anticline, may also be conduits for geothermal waters in the southwest corner of Fall River County.

Summary

Analyses of gravity and magnetic data have provided much information on subsurface geological structures underlying the southern Black Hills region. In particular, geophysically inferred features within the area of Precambrian outcrops and along the eastern flank of the Black Hills uplift primarily

consist of fault-formed lithologic boundaries associated with amphibolites, metagabbros, iron-formation, and micaceous phyllites or schists. Monoclines, terraces, and ramps characterize the region separating the Black Hills uplift from the Powder River Basin. The southern flank of the Black Hills has apparently experienced a long and complex history involving the formation of a broad basin and anticline, named the southern Black Hills anticline. Numerous folds and Precambrian lithologic contrasts are also observed within this region.

The interpretation of thermal gradient and geothermometer data has led to a conceptual model describing the geothermal system of the southern Black Hills. In this model, ground waters in the topographically high areas of the uplift descend along southward- and southeastward-trending fault zones, migrate upwards through fault-related conduits, and spread outward through permeable sedimentary zones. Inferred geophysical structures, that may be closely related to the convective transport of heat and fluids, include the southern Black Hills anticline, the basin in eastern Fall River County, and faults corresponding to the Long Mountain and Edgemont lineaments. The suggested channeling of waters along southward- and southeastward-trending fault zones is probably the reason for the absence of high geothermal gradients along the western and eastern flanks of the Black Hills uplift.

The geothermal resource of southwestern South Dakota, particularly east of Hot Springs, may eventually become utilized for space and agriculture heating or for the production of electrical power. Future utilization of the geothermal resource will probably involve additional exploration that will be concerned with the drilling of deep wells and the acquisition of chemical and isotope data. Although the additional information will certainly refine and modify the geophysical and geothermal interpretations presented here, this study will hopefully aid in the future development of the hydrothermal system in southwestern South Dakota.

References

Adolphson, D. G., and Le Roux, E. F., 1968, Temperature variations of deep flowing wells in South Dakota: U.S. Geological Survey Professional Paper 600-D, p. D60-62.

Blackwell, D. D., Steele, J. L., and Steeples, D. W., 1981, Heat flow determinations in Kansas and their implications for midcontinent heat flow patterns (abs.): American Geophysical Union Transactions, v. 62, n. 17, p. 392.

Combs, J., and Simmons, G., 1973, Terrestrial heat flow determinations in the north central United States: Journal of Geophysical Research, v. 78, n. 2, p. 441-461.

Cordell, Lindrith, and Henderson, R. G., 1968, Iterative three-dimensional solution of gravity anomaly data using a digital computer: Geophysics, v. 33, no. 4, p. 596-601.

Darton, N. H., and O'Harra, C. C., 1925, Description of the central Black Hills, South Dakota: U.S. Geological Survey Geol. Atlas, Folio 219.

Fournier, R. O., and Potter, R. W., II, 1978, A magnesium correction for the Na-K-Ca chemical geothermometer: U.S. Geological Survey, Open-File Report 78-986, 24 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 Prof. Paper 763, 57 p.

Hazlewood, R. M., 1964, Simple Bouguer gravity map of the northern part of the Black Hills, South Dakota: U.S. Geological Survey, Open-File Report.

Head, W. J., Kilty, K. T., and Knottek, R. K., 1978, Maps showing temperatures and configurations of the tops of the Minnelusa Formation and the Madison Limestone, Powder River Basin, Wyoming, Montana, and adjacent areas: U.S. Geological Survey Open-File Report 78-905, 12 p.

Hildenbrand, T. G., and Kucks, R. P., 1981a, Complete Bouguer gravity map of the southern Black Hills, parts of southwestern South Dakota and eastern Wyoming: U.S. Geological Survey, Open-File Report 81-760.

_____ 1981b, Aeromagnetic map of the southern Black Hills, parts of southwestern South Dakota and eastern Wyoming: U.S. Geological Survey, Open-File Report 81-759.

International Association of Geodesy, 1967, Systeme geodesique de reference 1967: International Association Geodesy Publication Special no. 3, 115 p.

Kleinkopf, M. D., and Redden, J. A., 1975, Bouguer gravity, aeromagnetic, and generalized geologic maps of part of the Black Hills of South Dakota and Wyoming: U.S. Geological Survey Geophys. Inv. Map GP-903, scale 1:250,000.

Lachenbruch, A. H., and Sass, J. H., 1977, Heat flow in the United States, in The Earth's crust, ed. Heacock, J. G.: American Geophysical Union, Geophysical Monograph 20, p. 626-675.

Lachenbruch, A. H., Jr., Sass, J. H., Munroe, R. J., and Moses, T. H., Jr., 1976, Geothermal setting and simple heat-conduction models for the Long Valley caldera: Journal of Geophysical Research, v. 81, n. 5, p. 769-784.

Lisenbee, A. L., 1975, Structural geology--Black Hills, in Mineral and water resources of South Dakota: Washington, D. C., U.S. Govt. Printing Office Report to the Comm. on Interior and Insular Affairs, U.S. Senate, p. 52-56.

Lisenbee, A. L., 1978, Laramide structure of the Black Hills uplift, South Dakota-Wyoming-Montana, in Matthews, Vincent, ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 165-196.

Noble, J. A., 1952, Structural features of the Black Hills and adjacent areas developed since Precambrian time: Billings Geol. Soc., 3rd Ann. Field Conf., Guidebook, p. 31-37.

Nuttli, O. W., 1979, Seismicity of the central United States: Geological Society of America, Reviews in Engineering Geology, v. 4, p. 67-93.

Rahn, P. H., and Gries, J. P., 1973, Large springs in the Black Hills, South Dakota and Wyoming: South Dakota Geological Survey Rept. Inv. 107, 46 p.

Redden, J. A., 1968, Geology of the Berne quadrangle, Black Hills, South Dakota: U.S. Geological Survey Professional Paper 297-F, p. 343-408.

_____1975, Precambrian geology of the Black Hills, in Mineral and water resources of South Dakota: Washington, D. C., U.S. Govt. Printing Office Rept. to the Comm. on Interior and Insular Affairs, U.S. Senate, p. 21-28.

Roy, R. F., Decker, E. R., Blackwell, D. D., and Birch, F., 1968, Heat flow in the United States: Journal of Geophysical Research, v. 73, n. 16, p. 5207-5221.

Schoon, R. A., and McGregor, D. J., 1974, Geothermal potentials in South Dakota: S. Dakota Geological Survey, Rept. Inv. 110, 78 p.

Schuster, E. J., 1973, The search for hot rocks, geothermal exploration, northwest: Reprint no. 11, Pacific Research, Department of Nat. Resources, Division of Mines and Geology, 4 p.

Steece, F. V., 1961, Preliminary map of the Precambrian surface: S. Dakota Geological Survey, Mineral Inv. Resource Map no. 2.