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BOUGUER GRAVITY, AEROMAGNETIC, AND GENERALIZED GEOLOGIC MAPS OF PART OF THE BLACK HILLS OF SOUTH DAKOTA AND WYOMING

By M. Dean Kleinkopf and Jack A. Redden

GEOPHYSICAL INVESTIGATIONS MAP
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INTRODUCTION

The purpose of these maps is to present recently compiled geologic information and gravity and aeromagnetic data collected by the U.S. Geological Survey in the Black Hills. The region has been known as a classic domal uplift since publication of the central Black Hills folio by Darton and Paige (1925). The area is also known in the field of mineral deposits as the site of Homestake, the largest gold mine in the United States, and for the world-famous pegmatite deposits in the southern Black Hills.

During and following World War II, the U.S. Geological Survey began detailed mapping of parts of the Precambrian areas in connection with the pegmatite mineral deposits and then made detailed studies of the Mesozoic sediments in the southern and southwestern parts of the region, where uranium deposits were discovered in sandstone rocks. In connection with the general studies of the mineral deposits, aeromagnetic and gravity surveys were made in cooperation with the U.S. Atomic Energy Commission and the South Dakota Industrial Expansion Agency.

Studies by the U.S. Geological Survey are continuing in the extremely complicated Precambrian rocks, and the results of some of these investigations have been published. The geology of some areas, such as the Homestake mine, is well known, whereas in other areas it is known only by brief reconnaissance.

The gravity and magnetic data are discussed in terms of major structural features and gross distributions of crystalline rocks. It is beyond the scope of this paper to speculate about the geologic significance of each of the many geophysical anomalies apparently associated with complex structural terranes and diverse lithologies of the crystalline rocks.

In view of the continued economic interest and the existence of considerable unpublished information, a preliminary compilation of the general geology and a comparison with geophysical data seems advisable even though many of the structural and stratigraphic complexities of the Precambrian rocks have not been deciphered.

Kleinkopf is responsible for the discussion of the geophysical data, much of which has been previously released for public use through various open-file reports and publications of the Geological Survey (U.S. Geological Survey, 1969; Meuschke and others, 1963; Meuschke and others, 1962; Hazlewood, 1964; Black and Roller, 1961). R. M. Hazlewood and R. A. Black supervised the gravity fieldwork, data reduction, and map preparation. The aeromagnetic surveys were made from aircraft of the U.S. Geological Survey. Redden compiled the geologic data from many sources and has made minor changes in the published material for compilation purposes.

GEOLOGIC DATA

The sources for the geologic information shown on the map are given on the index map. In general, geologic contacts were taken from the most recent mapping available at the time of this compilation in 1970 on relatively modern topographic bases. Credit is given to C. G. Bowles for the use of a compilation of the geology of fourteen 7½-minute quadrangles mapped by the U.S. Geological Survey in the southern and southwestern Black Hills in connection with investigations related to the occurrence of uranium deposits (Gott, Wolcott, and Bowles, 1974, pl. 1).

Lithologic contacts in the Precambrian rocks are mainly based on published and unpublished work by R. W. Bayley, J. J. Norton, J. C. Ratté, and J. A. Redden. However, the grouping of various subunits and formations from these different sources into the Precambrian lithologic units on the map is the responsibility of Redden. Although the same lithologic units occur in different parts of the area, it is not our intent to imply their equivalent stratigraphic position throughout the Precambrian area.

The lithology of Precambrian rocks is not well known in several rather large areas, including the general area north of lat 44° and south of the Rochford district (T. 2 N., R. 3 E.) and the area in Custer State Park east-southeast of Custer (T. 3 S., R. 4 E.).

Although many of the contacts between the sedimentary rocks shown on the map are based on relatively recent mapping, others are derived from the central Black Hills folio by Darton and Paige (1925). The positions of contacts shown by Darton and Paige, such as the Cambrian-Precambrian contact, were shifted locally to fit the present topographic base; in other places contacts were remapped on newer topographic bases by reconnaissance methods.

GENERAL GEOLOGIC SETTING

The Black Hills are famous as an example of an elongate domal uplift where Paleozoic and Mesozoic sedimentary rocks have been breached by erosion, thus exposing a Precambrian core of metamorphic and igneous rocks. The sedimentary rocks range in age from Cambrian to

Cretaceous, although there are gaps in the section.

The uplift occurred during Laramide time and was accompanied by the emplacement of Eocene intrusive rocks in the northern Black Hills. Pre-Oligocene erosion denuded the dome, and Oligocene sedimentary rocks are preserved as remnants resting both on the Precambrian rocks and on the outward-dipping pre-Oligocene sedimentary rocks. Erosion of the Jurassic to Permian shales has resulted in the classic "red valley" ("racetrack") rimmed by resistant Cretaceous sandstones.

The Precambrian rocks consist mainly of low- to high-grade metamorphic equivalents of eugeosynclinal sediments. Older gneissic granitic rocks named Little Elk Granite are exposed in an inlier on Little Elk Creek (T. 3 N., R. 5 E.) and at Bear Mountain (T. 2 S., R. 3 E.). The Little Elk Granite has been dated at about ˆ 5 b.y. (billion years) old Precambrian W by Zartman and Stern (1967). Unmetamorphosed younger granite and pegmatite underlie the central part of the southern Black Hills and have been dated at about 1.7 b.y. old by many investigators, including Wetherill and others (1956) and Goldich and others (1966).

The Precambrian metamorphic rocks are mainly equivalents of graywacke, subgraywacke, siltstone, shale, black shale, chert, basalt, and other clastic rock types that are characteristic of eugeosynclinal environments. Clastic quartzites are generally impure, with the exception of those near Bear Mountain.

The metamorphic grade is highest in the southern part where the latitude of Hill City (T. 1 S., R. 5 E.) approximately marks the northernmost occurrence of sillimanite in schists of appropriate composition. Metamorphic intensity declines to the north and east, and some of the east-central part of the Precambrian region is probably lower in intensity than the garnet isograd. However, to the west and northwest in the Rochford-Deerfield area (Tps. 1, 2 N., R. 3 E.), garnet occurs as the highest index mineral.

In the Lead-Deadwood area (T. 5 N., R. 3 E.), lower grade rocks crop out south of staurolite-bearing rocks which are adjacent to the Precambrian-Paleozoic contact. It is not known whether sillimanite-bearing rocks occur farther to the north. In the Bear Mountain area, along the west side of the core, the metamorphic intensity increases, and small amounts of kyanite and sillimanite are present in the schist. The only other occurrences of kyanite in the higher grade rocks are restricted to veins. However, andalusite is common in schists lower than the sillimanite zone around the main granite and pegmatite unit at Harney Peak.

Pelitic to graywacke metasediments are, therefore, predominantly medium- to coarse-grained schists in the southern part of the Precambrian rocks and phyllitic to fine-grained schists in most of the central and northern parts.

LITHOLOGIC TYPES

SEDIMENTARY ROCKS

The individual sedimentary formations in general have too narrow outcrop widths to show on this map scale. Therefore, five divisions were chosen to best portray structure, physiography, and possible density contrasts. These are (1) Paleozoic rocks (mainly carbonates), (2) Mesozoic and uppermost Paleozoic shales, evaporites, and sandstones, (3) the Cretaceous Inyan Kara Group (mainly sandstone), (4) Cretaceous shales, and (5) the Cretaceous Lance Formation and the Fox Hills Sandstone. Because of the small outcrop area of the units, the Tertiary and Quaternary rocks were not included.

The Paleozoic sedimentary rock unit varies in thickness in different parts of the area but probably has an average thickness of nearly 1,500 feet. Slightly more than half this thickness is limestone and dolomite, and the remainder is dominantly sandstone.

The uppermost Paleozoic and Mesozoic shale and sandstone unit is about 1,200 feet thick. It characteristically underlies the "red valley" that encircles the Black Hills.

The Cretaceous Inyan Kara Group ranges in thickness from 350 to 500 feet and consists of sandstone and minor amounts of siltstone and mudstone. Physiographically, it forms the prominent hogback outside the "red valley."

The Cretaceous shales are 3,000–3,600 feet in total thickness. Thin limestones are present but include considerable shale detritus. Erosion of nonresistant shale has formed the plains that encircle the Black Hills. East of the Black Hills, streams have cut through flat mantles of Tertiary or younger sediments and have exposed the underlying shale in stream valleys.

The Cretaceous Fox Hills Sandstone is relatively thin, but it forms an easily identifiable marker unit in the predominantly shale strata of the Upper Cretaceous rocks.

TERTIARY IGNEOUS ROCKS

In the northern Black Hills, various sills, dikes, stocks, and small laccolithic masses of silicic porphyries intrude the older sedimentary and metamorphic rocks. The rock types are mainly quartz monzonite porphyry, rhyolite porphyry, phonolite, and monzonite porphyry. Some of the intrusive rocks occur as thin sills in the sedimentary rocks, and, although the sills crop out over large areas, they represent no large volume of material. Other intrusive rocks form the cores of domes, such as at Bear Butte (T. 6 N., R. 6 E.) and Whitewood Peak (T. 5 N., R. 4 E.). Some domal structures such as Elkhorn Peak (T. 6 N., R. 3 E.) are assumed to have a buried core of the Tertiary igneous rocks. The ages of these rocks range from about 39 to 59 million years old, according to McDowell (1966).

PRECAMBRIAN ROCKS

The Precambrian rocks are divided into 12 lithologic units on the basis of original and present lithologies. In a general way the units are described in order of decreasing age, although in parts of the area the correlation of the lithologies is problematic, and in some areas similar lithologies occupy several different stratigraphic positions. The change in metamorphic intensity from low- to high-grade rocks requires the inclusion of slate, phyllite, and schist within the same lithologic unit. Most of the units are distinctive, but a few contain diverse rock types lumped together.

The oldest rock unit is the gneissic granite (unit A) at Little Elk Creek and Bear Mountain, and the youngest is the unmetamorphosed Harney Peak Granite (unit L). Almost certainly gneissic granite of unit A occurs as large inclusions within the Harney Peak Granite, inasmuch as inclusions and schist screens of all the other lithologic types at Bear Mountain have been recognized by Redden within the Harney Peak Granite.

Gneissic granite (unit A)

Gneissic granite, which includes the Little Elk Granite, is exposed in an inlier north of Nemo (T. 3 N., R. 5 E.). The rock is gray or light gray, generally coarse grained, and somewhat gneissic. Isotope dating by Zartman and Stern (1967) indicates an age of about 2.5 b.y. old, and the rock is interpreted to be part of a basement of granitic rocks that are older than the other metamorphic rocks (Zartman and Stern, 1967).

Gneissic granite also occurs in the center of the Bear Mountain dome west of Harney Peak (T. 2 S., R. 5 E.). It is accompanied by coarse-grained biotite schist and gneiss, which are commonly more abundant than the granitic rock. About the only similarity with the Little Elk Granite is the gneissosity and a similar radiometric age. Ratté and Zartman (1970) believed that the Bear Mountain area represents a basement high of older Precambrian rocks.

Quartzite and schist or phyllite (unit B)

Included in the quartzite and schist or phyllite (unit B) are the quartzites of the "Nemo system" of Runner (1934) which are apparently the oldest metasediments of the area. Also included are younger quartzites and associated phyllites—rocks mapped as the Ellison Formation of Noble and Harder (1948) near Lead and their equivalent near Rochford (McGehee and Bayley, 1969) and near Nemo (T. 3 N., R. 5 E.) (Bayley, 1972). Thick quartzites and sillimanite schists east of Custer (T. 3 S., R. 4 E.) are included in this lithologic unit, although their relationships with the other quartzites are unknown.

Taconite iron-formation (unit C)

Hematite-magnetite beds interbedded with quartzite are part of the Nemo Group and are restricted to the area near Nemo. The beds are commonly a few tens of feet thick but form thick masses in complex fold noses as mapped by Bayley (1970b). The rock is moderately to strongly magnetic and differs from other meta-iron formations in younger units in that it contains only minor iron silicate minerals. Work by Harrer (1966) indicates that the average iron content of the taconite is almost 30 percent.

Metaconglomerate and quartzite (unit D)

Unit D is restricted to the Nemo and Bear Mountain domal areas. At Nemo, the metaconglomerates are part of the "Estes system" of Runner, (1934) or the Estes Conglomerate (Bayley, 1970b) and consist mainly of coarse to fine deformed clasts of quartzite or taconite. They unconformably overlie quartzite and taconites of the older Nemo Group. Also included are thick beds of quartzite, meta-arkose, metagrit, and phyllite.

At Bear Mountain, the metamorphic grade is equivalent to the staurolite-kyanite zone, and the original sedimentary rocks were light-colored pure quartzites, pebble conglomerates, and arkoses. Similar white pure quartzites form a few scattered outcrops within the Harney Peak Granite, where they are associated with amphibolite and marble. The quartzites in the Nemo area are more impure than those at Bear Mountain and may not be equivalent.

Interbedded marble and phyllite or schist (unit E)

The lithologies of unit E are shown only in the Nemo and Bear Mountain areas, although scattered exposures of marble occur within the Harney Peak Granite. Fine-grained calcitic and dolomitic marbles in the Nemo area are generally only a few hundreds of feet thick and have been interpreted differently by Bayley (1970b) and Runner (1934). The areas on the map near Nemo are mainly various types of phyllitic rocks with or without carbonate. Schists and tremolite marble dominate the unit near Bear Mountain.

Interbedded schist, impure quartzite, meta-iron formation, streaked quartzite, metaconglomerate, and amphibolite (unit F)

These variegated rocks are distributed in the general Keystone (T. 2 S., R. 6 E.) area and extend south and west to Custer and Pringle (T. 5 S., R. 4 E.). Although petrologically diverse, the well-foliated rocks are characterized by abundant garnet. Metaconglomerates contain clasts similar to adjacent rocks and an aluminous matrix. They are thus similar to intraformational conglomerates, and the clasts are locally derived. Thin meta-iron formation, locally thickened in fold noses, consists of interlayered metachert and grunerite rocks. They resemble other thin meta-iron formations that occur in various schist lithologies shown on the map. Amphibolite is minor and may be stratigraphically equivalent to other thicker amphibolite units. Two or more separate stratigraphic intervals may be represented by unit F on the map.

Amphibolite and metagabbro (unit G)

Unit G has dominantly dark-green structureless to schistose amphibole-rich rocks. There are also interbeds and subunits of garnet-rich schist, streaked quartzite, and meta-iron formation. The latter consist of grunerite-rich layers alternating with thin sugary quartzite beds in the amphibolite-facies metamorphic grade. The amphibolite is mainly hornblende and plagioclase in areas of higher grade metamorphism and chlorite-actinolite-epidote greenstone in areas of lower grade. It was derived from both intrusive diabase-gabbro rocks and basaltic flows. The latter contain interbeds of quartzite derived from chert and also interbeds of metamorphosed iron-rich sediments. Relict pillow structures have been found by Bayley (1970a) in the Roubaix area (T. 4 N., R. 4 E.) and many other areas north of lat 44° N. (Bayley, 1972). The thin Crow Formation (Redden, 1963) is included in this map unit, although the Crow contains small amounts of many other rock types.

Quartz-mica schist and phyllite (unit H)

This unit is typically thick bedded quartz-muscovite-plagioclase-biotite schist characteristic of the thick Bugtown Formation described by Redden (1963, 1968). Garnet is relatively rare even in high-grade rocks and is generally restricted to thin micaceous interbeds. Relict grain textures are common in phyllitic equivalents. A few micaceous schists and schists bearing staurolite, andalusite, and sillimanite are included in areas of high metamorphic grade. Near Pringle, sillimanite is abundant and muscovite less common. Very minor interbeds include streaked quartzite, grunerite-bearing rocks, and garnet schist. The dominant rocks were originally subgraywackes that graded into graywackes, siltstones, and shales.

Quartzose schist (unit I)

Thick-bedded to massive quartzose schists and impure quartzites of unit I are abundant in the Hill City-Sheridan Lake areas (T. 1 S., R. 5 E.) and may be lithologic equivalents of some of the massive quartz mica schists of unit H in areas of higher metamorphic grade to the south. Many of the thick beds are structureless, but structures indicating turbidite depositional processes are common locally, especially north of Hill City. The unit includes rocks of both the Oreville and Bugtown Formations as mapped in the Hill City area by Ratté and Wayland (1969).

Micaceous phyllite or schist (unit J)

North, west, and northwest of Hill City (T. 1 S., R. 4 E.), the unit is largely massive to thin-bedded green micaceous phyllite that is rich in chlorite and contains moderate amounts of magnetite. Thin-bedded phases contain small garnet-rich beds interbedded with mica-schist.

Along strike to the south, the higher grade minerals cordierite, andalusite, and staurolite occur as porphyroblasts which increase in size until the rocks are coarse-grained streaked porphyroblastic schists rich in quartz, muscovite, and garnet. Massive subunits contain as much as 5 percent magnetite and ilmenite.

The abundant aluminous and iron-rich metamorphic minerals indicate an origin from highly aluminous shales. Some high grade andalusite-sillimanite schist near Harney Peak (T. 2 S., R. 5 E.) that are included in unit H may be stratigraphic equivalents. However, the rock type is relatively distinct, and probably all rocks shown as this unit on the map are stratigraphically equivalent.

Biotite-garnet phyllite or schist (unit K)

This lithology apparently represents several different stratigraphic levels. The largest exposed and presumably thickest part of the section occurs in the Mystic area (T. 1 N., R. 4 E.) northwest of Hill City, where its position suggests it is the youngest metamorphic rock. Thinner and presumably older lithologic equivalents occur near Bear Mountain and in the east-central part of the Precambrian rocks. In general, unit K includes the Oreville Formation mapped by Ratté and Wayland (1969) in the Hill City area.

At low metamorphic grade, the unit is mainly thin-bedded greenish-gray to dark-gray phyllite or slate containing quartz, biotite, chlorite, garnet, and muscovite. Garnet is largely absent in the area east and northeast of Pilot Knob and Pactola Dam (T. 2 N., R. 4 E., and T. 1 N., R. 5 E.). Graphite-rich and sulfide-rich beds are common. Local interbeds consist of quartzose phyllites, streaked sugary quartzite (metachert), and minor lenses of amphibole-bearing rocks.

In areas of higher metamorphic grade near and south of Hill City, the garnet-rich and biotite-rich beds are prominent. Biotite is the dominant mica in most of the rocks. Some of the lighter beds are rich in plagioclase, as well as in quartz. A few beds are staurolite-bearing, but sillimanite is visible only in thin sections of a few aluminum-rich interbeds at the highest metamorphic grade. There are at least two separate stratigraphic units of the general lithology. The compositions and thin beds indicate that the rock types are mainly derived from euxinic shale facies.

Harney Peak Granite (unit L)

The Harney Peak Granite consists of many thousands of sills, dikes, and irregular intrusive bodies ranging from a medium-grained leucocratic oligoclase-microcline-mica-granite to granitic pegmatite. Dark minerals are typically limited to accessory biotite, garnet, and tourmaline. The granitic area locally contains as much as 50 percent of country rocks; and individual sills, dikes, and irregular bodies of pegmatite occur near the periphery of the main granitic area. Pegmatite bodies are distributed throughout the Precambrian units approximately south of the latitude of Hill City. In a general way the abundance of pegmatite decreases with distance from the central composite mass. However, the distribution is asymmetric to the south, which suggests that the main Harney Peak Granite plunges to the south.

The main mass of Harney Peak Granite has resulted in a dome-shaped structure in the surrounding metamorphic rocks (Balk, 1931; Redden, 1968). Scattered inliers of metamorphic rocks east of Sylvan Lake (T. 2 S., R. 5 E.) and south of Harney Peak are characterized by nearly flat, dips, and, in general, dips of both country rock and granitic sills steepen outward from this central area.

STRUCTURAL FEATURES

Although the Black Hills is commonly referred to as a symmetric dome, it actually consists of two separate blocks, as was recognized by Darton and Paige (1925) and more recently by Noble (1952). The southeastern block is about 100 miles by 40 miles and trends northward. The northwestern block joins the southeastern one along a line beginning approximately at the LAK ranch (T. 44 N., R. 62 W.) and extending northward for a distance of almost 40 miles approximately along the Wyoming–South Dakota boundary. The northwestern block has a general northwest structural elongation for a distance of about 75 miles. The two blocks are separated by the Fanny Peak monocline, which is located about 6 miles east of Newcastle (Brobst and Epstein, 1963) and trends north for more than 30 miles to the Tinton area, which is in T. 5 N., R. 1 E. The monocline forms the west edge of a structural high that can be traced southward for more than 100 miles to the Hartville uplift in Wyoming. This segment of the monocline is therefore the east border of the Powder River Basin. The southeastern block of the Black Hills rises structurally and topographically well above most of this larger structural high.

In the Newcastle area two northwest-trending monoclines are part of the Black Hills monocline, as named by Brobst and Epstein (1963). These structures coalesce to form the southwest boundary of the northwestern block. Although the Black Hills monocline crosses the Fanny Peak monocline southeast of Newcastle, it becomes less steep to the southeast and dies out as a distinct flexural axis. Study of a geologic map of the entire area makes it apparent that the southeastern block of the Black Hills has been uplifted considerably more than the northwestern block. The wide outcrop width of the Paleozoic rocks along the west side of the southeastern block suggests a structural asymmetry of the main axis of the block. This is actually false because erosion has failed to remove the sediments from an area which is topographically quite high.

Folds in the sedimentary rocks tend to be concentrated along the edges of the southeastern block. In general, the anticlines have their steeper limbs located toward the center of the main uplift of the Black Hills. One noticeable exception is the Old Woman anticline (T. 36 N., R. 62 W.), but this fold is located very close to, and may be influenced by, the Fanny Peak monocline. Most of the folds are relatively open, and overturned limbs are rare.

Other small structures in the northern Black Hills are domelike areas, such as Bear Butte (T. 6 N., R. 6 E.) and Elkhorn Peak (T. 6 N., R. 3 E.), where the structure is almost certainly the result of emplacement of Tertiary igneous rocks. Other areas with somewhat larger domal or uplifted structures include the Lead area (T. 5 N., R.2 E.) and the Vanocker Creek area (T. 4 N., R. 5 E.). All these structurally positive areas seem to result from the intrusion of Tertiary igneous rocks.

High-angle faults in post-Cambrian rocks are uncommon, and the displacements are generally less than 100 feet. Thrust faults are almost unknown. Considerable minor faulting is known to be associated with the emplacement of the Tertiary igneous rocks.

PRECAMBRIAN STRUCTURES

The details of the Precambrian structures are extremely complicated. Several periods of folding are clearly indicated by the detailed maps of various authors (Ratté and Wayland, 1969; Redden, 1968; Bayley, 1970b). The generalized lithologic distribution on the present map illustrates the complexity, even though the Precambrian fold axes are omitted.

Although the detailed stratigraphic correlation in the Precambrian is not completely known, several major domal features influence the rock distribution. These domal areas include the Harney Peak area, the Bear Mountain area, and the Nemo area. The last two of these domes have very old rocks (about 2.5 b.y. old) that crop out in their centers. The Harney Peak Granite is believed to have inliers of very old rocks in its central area but apparently differs from the other domal areas in that the structure is largely a result of emplaced masses of much younger (1.7 b.y. old) granitic rock. The domal nature of Harney Peak was originally discussed by Balk (1931). The lithologic distribution close to these domes superficially seems to be very simple, and the pattern increases in complexity outward. This is especially evident in the detailed map of the Hill City area (Ratté and Wayland, 1969).

Away from the domes the dominant trend of the rock units is north-northwestward. A large tight anticlinal structure exists in the Lead area (Noble and others, 1949) and a similar structure has been mapped by McGehee and Bayley (1969) in the Rochford area. Refolding is evident in the Lead and Rochford areas and also in the Galena-Roubaix area (Bayley, 1970a). In the latter area Bayley has evidence of northeasterly folds which have been refolded along northwesterly trends. In general, the north-central part of the Precambrian area between Rochford and Nemo seems to be a synclinorium.

Although one of the latest Precambrian events, the intrusion of the Harney Peak Granite (unit L), apparently has markedly distended the metamorphic rocks, as is evident by Y-shaped outcrop pattern of unit H near Custer. Mapping by Ratté and Wayland (1969) shows that northerly trending folds northwest of Hill City are deformed by northeasterly trending isoclinal to recumbent cross folds closer to the Harney Peak dome. On the north and northeast sides of the dome, north-northwest outcrop trends are dominant, and the structure is apparently dominated by major north-northwest strike faults which terminate the cross-folded northeasterly patterns characteristic of the Hill City area.

The Nemo area is deceptively simple in that the dominant pattern would seem to be a north-northwesterly domal or antiformal structure whose center and east side are concealed by Paleozoic rocks. An inlier of unit A (T. 3 N., R. 5 E.) presumably is near the center of this dome. The metamorphic rocks in that area have been divided into at least two different sequences marked by two unconformities (Runner, 1934; Bayley, 1970b). The oldest rocks of the Nemo Group unconformably overlie the granite gneiss of unit A and include beds of taconite. These rocks have been folded and boulders of taconite occur in the next overlying unconformable sequence—the "Estes system" included in unit D. According to Bayley (1970b), the latter is in turn unconformably overlain by limestone or a fine-grained marble which was strongly cross-folded into a syncline which is now exposed over the top of the dome. A later folding produced a strong penetrative northwest-trending foliation and associated folds.

The area west and southwest of Custer seems to be a relatively simple sequence forming a major syncline, according to Redden (1963, 1968). However, the Grand Junction fault cuts off a major anticlinal limb to the east and is itself domed by the granitic rocks of unit L.

The structural relationships in the large quartzite-sillimanite schist area (unit B) east and southeast of Custer are poorly known. Possibly equivalent rocks could be in the Hill City area and the lithology may be equivalent to the thick quartzites near Norris Peak (T. 2 N., R. 6 E.).

GRAVITY DATA

Gravity measurements were made during 1957–60 at nearly 2,500 stations located mostly at bench marks and other points of known elevation established by the U.S. Geological Survey and the U.S. Coast and Geodetic Survey (now the National Ocean Survey). Planetable, transit, and altimeter surveying for about 10 percent of the stations were used to fill in broad areas where published elevations were lacking.

The gravity measurements were adjusted to the observed gravity, 980, 145 mgal (milligals), at the U.S. Coast and Geodetic Survey pendulum station 270 at Newcastle, Wyoming (Duerksen, 1949, p. 14). Readings were made using gravity meters with scale constants of approximately 0.1 mgal per scale division. Because more than 85 percent of the gravity map area is covered by sedimentary rocks, all data were reduced to Bouguer values by using an assumed rock density typical of sedimentary rocks. In this case, a value of 2.43 g/cm^3 was used based on studies of sedimentary rocks in the southern Black Hills by Black and Roller (1961). Measurements of grain densities and dry bulk densities of various crystalline rocks collected from the central core of the Black Hills were made by R. A. Black, C. G. Bowles, and J. C. Roller (written commun., 1962). They determined that rocks of the crystalline complex have a probable density variation from 2.65 to 3.05 g/cm^3 which would represent a range in rock type from granite to amphibolite. Denser rocks, such as taconite, are known to exist but make up less than 1 percent of exposed crystalline rock types. To evaluate the validity of the interpretations, gravity anomalies over the higher density crystalline rocks were compared with the topography, which generally has a maximum local relief of 400 feet. The topographic influences detected were not large enough to detract from the conclusions presented here. On the basis of rock-density assumptions, the major gravity anomalies can be attributed to lithologic variations within the crystalline complex, difference in thicknesses of the Paleozoic carbonate rocks, or topographic relief on the basement surface.

On the gravity map, contours of complete Bouguer gravity data are shown south of lat 44° N. Here, terrain corrections were made by hand on all stations through zone H of Hammer (1939). To the north of lat 44° N., contours of simple Bouguer gravity data are shown. Terrain corrections were not made because more than 75 percent of the stations are estimated to have terrain corrections of less than 1 mgal.

RELATIONSHIP OF GRAVITY FEATURES TO LITHOLOGY AND STRUCTURE

Gravity data agree with the general assumed structure of the Black Hills. The major eastern block shows as a broad, irregular gravity high of about 20 mgal relief; the -80 mgal contour delineates rather well the boundaries of the uplift in South Dakota. Woollard (1962), in regional studies, concluded that the Black Hills uplift is not locally compensated in the crust.

The highest Bouguer gravity values occur about 10 miles southeast of Lead over outcrop of mafic crystalline rocks, unit G (T. 4 N., R. 4 E.) and about 8 miles northwest of Bear Mountain on a high plateau covered by Paleozoic limestones (T. 1 S., R. 2 E.). The lowest values occur along the flanks of the Black Hills uplift, especially in Wyoming near the east edge of the Powder River Basin (T. 40 N., R. 63 W.). The -100 mgal contour in the Newcastle area (T. 45 N., R. 61 W.) approximately marks the southwest edge of the northwestern block of the Black Hills uplift.

In the sedimentary sequence, Paleozoic carbonate rocks are from 500 to 800 feet thick and relatively massive and should have a definite density contrast with the overlying younger Paleozoic and Mesozoic section, which is mainly shales, sandstones, and minor amounts of gypsum and other evaporites. Data from several authors indicate that most of the evaporites in Paleozoic rocks have been dissolved from the section near the areas of outcrop around the Black Hills. Presumably, the contrast in densities between the carbonate rocks and the overlying dominantly shale section would produce a detectable gravity anomaly if the rocks were disturbed. Doming of the denser carbonate rocks is illustrated by the structure at Bear Butte (T. 6 N., Rs. 5, 6 E.) where a small gravity high correlates with the domal structure which seems to be the result of a Tertiary intrusion that did not pierce the carbonate rocks. Exposed Tertiary rocks immediately east of the main structure appear to have no gravity expression, although this may be the result of insufficient gravity control.

Another small gravity high, also believed to be the result of structure resulting from a Tertiary intrusive, occurs north-northeast of Rapid City (Tps. 4, 5 N., R. 8 E.). The anomaly is similar in amplitude to that at Bear Butte, and geologic field checking by J. M. Cattermole and E. E. McGregor (oral commun., 1970) revealed surface dips suggestive of a small domal structure. This structure was previously unrecognized because the thick Pierre Shale is the only formation exposed across a wide interval at the surface and marker units in the Pierre are not conspicuous.

Other anticlinal folds are in general marked by very slight gravity highs in areas where the carbonate rocks are not buried too deeply. This is evident in the up-plunge part of the Cascade Springs (Tps. 7, 8 S., R. 5 E.) and Chilson (Tps. 8, 9 S., R. 3 E.) anticlines west-southwest of Hot Springs and in the Whitewood anticline (T. 6 N., R. 5 E.) southwest of Sturgis. Adjacent synclines have parallel gravity lows positioned slightly offset toward the steeply dipping limb. Down the plunge of the structures, the effect on gravity is less pronounced or is masked by other effects. For example, the Cascade Springs anticline bifurcates to the south (T. 9 S., R. 5 E.), and the eastern limb tends to follow a gravity low. This possibly could be the result of high density limestone (Mississippian Pahasapa Limestone) having been removed by erosion over an earlier structural high. The Pahasapa Limestone does have an unconformity at its top and is known to pinch out in the subsurface several tens of miles to the southeast. According to subsurface information from drill holes, the continuation of the axis of the western part of the bifurcated Cascade Springs anticline to the south also does not correlate with the axis of the gravity high. Deeper buried structures, such as the Old Woman anticline (T. 36 N., R. 62 W.), the Mule Creek anticline (T. 39 N., R. 61 W.), the Cottonwood Creek anticline (T. 9 S., R. 2 E.), and other small folds north of the Black Hills, are along regional high gradient zones in the gravity data, and the local correlation between high gravity values and the anticlinal axes is obscure, owing to inadequate gravity control.

The Fanny Peak monocline (T. 46 N., R. 60 W., to T. 36 N., R. 62 W.) and its extension to the south-southwest toward the Hartville uplift in Wyoming show as pronounced zones of high gradients in the gravity data which mark the east boundary of the Powder River Basin. The gradient zone can be readily projected across the area of no data nearly to the north end of the Black Hills (T. 5 N., R. 2 E.). In general, a noticeable gravity high exits just east of, and parallel to, the monocline. The northwest-trending Black Hills monocline near Newcastle also is recognizable in the gravity data as a high gradient zone that is truncated by the gradient of the Fanny Peak monocline.

A broad gravity high just east of Moon (T. 1 S., R. 1 E.) contrasts with elongate lows to the north and south, all of which are underlain by carbonate rocks. Although differences in the thickness of the latter might be the cause, it is more likely the result of density contrasts within the Precambrian basement lithologies.

In general, a disconnected series of irregular lows parallels the east edge of the Black Hills uplift and presumably reflects the edge of the uplift. The high (T. 2 N., R. 7 E.) just west of Rapid City transects this belt of gravity lows along the east side of the hills and appears to result from high-density rocks in the crystalline basement. It is assumed that the area is underlain by relatively dense Precambrian rocks similar to those of units C and G in the Nemo area (T. 3 N., R. 5 E.).

No surface explanation is apparent for several other large gravity anomalies in areas of sedimentary rock outcrop near both the south and north edges of the area, and subsurface geologic information is not available. However, prominent anomalies, such as the closed gravity low 5 miles northwest of Newell (T. 9 N., R. 5 E.) and the large elongate high 7 miles to the northeast (Tps. 9–11 N., R. 6 E.), probably reflect structure and lithologic contrasts in the crystalline basement.

Within the exposed Precambrian core, pronounced gravity anomalies correlate with northerly and northwesterly trending rock units and structures, many of which were first mapped by Darton and Paige (1925). The gravity highs, especially, are located in the northern and northeastern parts of the Black Hills, where taconite (unit C) and stratigraphically higher rocks of amphibolite-metagabbro and meta-iron formation (units G and F) crop out. These units are generally more dense than the schists and quartzose rocks. The largest of the taconite outcrops —about 2 miles southwest of Nemo (T. 3 N., R. 5 E.), where several of the largest amplitude magnetic anomalies are found—apparently is not of sufficient mass in the subsurface to produce a gravity high. In general, the amphibolite and metagabbro (unit G) on the west side of the Nemo dome are expressed as a northwest-trending linear high which turns to the north beneath the sediments. An extension of the high curves to the east where Tertiary igneous rocks occur at the surface (T. 4 N., R. 4 E.). Similarly trending but narrower magnetic highs, which give greater resolution of individual rock units, will be discussed in the next section. A high gravity axis continues to the northwest into the Deadwood area (T. 5 N., R. 3 E.) and correlates with outcrops of amphibolite near Galena (T. 4 N., R. 4 E.).

A sharp low (T. 5 N., Rs. 2, 3 E.) west of Lead, correlates with Tertiary igneous rocks known as the Cutting stock in the Lead-Deadwood area. This suggests that the intrusion is less dense than enclosing metamorphic rocks and is wider at depth.

In the central Precambrian area just west of Placerville (T. 2 N., R. 5 E.), a large elongate gravity low suggests the presence of a thick section of thin-bedded phyllitic rocks (unit K) probably metamorphosed shales and siltstones. To the west, a gravity high (Tps. 1, 2 N., Rs. 3, 4 E.) apparently reflects the anticlinal structure of amphibolite and meta-iron formation in the Rochford area (McGehee and Bayley, 1969). The gravity lows (T. 2 N., Rs. 2, 3 E.) farther northwest and about 10 miles north of Deerfield may indicate the presence of rocks in the subsurface similar to those in the Placerville region (T. 2 N., R. 4 E.). However, these are largely covered by Paleozoic rocks. A northwest-southeast-trending elongate high, which may be part of a major regional gravity high of the same trend, occurs about 3 miles east of Seth Bullock Peak (T. 1 N., R. 5 E.) and southeast of Pactola Dam. This is centered above thin-bedded dark phyllites and slates (unit K) which do not produce gravity highs elsewhere. It is probable that the surface rocks are domal and, as suggested in discussion of the magnetic data, are underlain by amphibolite and meta-iron formations (units G and F) which crop out as narrow units immediately east of the high. These units continue south to Storm Hill (T. 1 S., R. 6 E.) where they are extensively repeated by folding or faulting. The result is a sharp gravity high in that area. Rocks of similar lithology to the south west can be traced to Keystone (T. 2 S., R. 6 E.). Because the units are thin and probably partly removed by faulting, according to an unpublished map by J. J. Norton (written commun., 1971), no gravity expression is evident near Keystone.

In the southern Precambrian area, the Bear Mountain dome (T. 2 S., R. 3 E.) shows as a poorly defined residual low across exposures of metaconglomerate and schist (unit D) and gneissic granite (unit A) exposed in the core. The Harney Peak dome (T. 2 S., R. 5 E.) is marked by a low gradient zone across outcrops of Harney Peak Granite (unit L). Moderately steep contours mark a terrace edge (T. 3 S., Rs. 4, 5 E.) on the southwest side of the Harney Peak dome and follow the contacts of the lithologic units.

A small high 7 miles southeast of Custer (T. 4 S., R. 5 E.) may be caused by small bodies of amphibolite which occur locally. The gravity high (T. 3 S., R. 3 E.) beneath the Paleozoic limestone about 4 miles northeast of Jewel Cave (T. 4 S., R. 2 E.) has no known explanation, inasmuch as the area should be underlain by Precambrian quartz mica schist according to projections from the east. The east-trending fault along the highway past Jewel Cave National Monument is expressed as a linear feature in the gravity data.

The narrow outcrop of meta-iron formation (unit F) and associated rocks that extends south from Custer (T. 3 S., R. 4 E.) to Pringle (T. 5 S., R. 4 E.) correlates with the west edge of a high gravity gradient zone that also extends over outcrops of quartzite and sillimanite schist (unit B) to the east. A strong magnetic high correlates with the outcrop of meta-iron formation.

In summary, many of the prominent gravity anomalies are related to lithology and structure. In many places, individual rock types, such as carbonate and specific Precambrian lithologic units could be correlated directly with diagnostic gravity features. It is beyond the purpose of this report to treat the gravity data quantitatively or to discuss the many other interesting, but generally less significant, gravity anomalies on the map.

AEROMAGNETIC DATA

The aeromagnetic mapping consists of nearly 4,200 miles of traverse lines compiled from three surveys that have been published previously as U.S. Geological Survey maps at larger scales (U.S. Geological Survey, 1969; Meuschke and others, 1963; Meuschke and others, 1962). The index map shows the areas covered and the elevations of the flight lines. The contoured data are from total-intensity magnetic measurements made with continuously recording fluxgate magnetometers. An arbitrary datum was assumed for each survey. No regional or geomagnetic field has been removed. Although the three surveys are not tied together, owing to differences in flight elevations and reference datums, trends in the data, in many places, can be extended across survey boundaries. Topographic maps were used for navigation, and flight paths were photographed with a gyrostabilized 35-mm continuous-strip camera. Flight elevations were maintained by radar altimeters and barometers.

RELATIONSHIP OF MAGNETIC FEATURES TO LITHOLOGY AND STRUCTURE

Magnetic data are available for only the central part of the area, and most of the prominent anomalies and high gradient zones are clustered in the northern part of the Black Hills. The trends of the magnetic anomalies generally correlate well with the gravity anomalies and gradients.

Inspection of the map indicates that the most magnetic rock units are the taconites (unit C) in the Nemo area (T. 3 N., R. 5 E.) where magnetic highs with amplitudes exceeding 4,000 gammas correlate with the known taconite distribution. The next largest anomalies are in adjacent areas underlain by amphibolite and meta-iron formation lithologies (units G and F), particularly in areas where the meta-iron formation is thickened. An example is the large anomaly at Storm Hill (T. 1 S., R. 6 E.), north-northeast of Keystone where extensive exposures of amphibolite and quartz-grunerite rocks occur. Magnetite is common in some of the meta-iron formation (unit F) elsewhere, and the highly magnetic areas are probably rich in magnetite as well as other iron silicate minerals. Smaller magnetic highs a few miles southwest of Storm Hill and in the general Keystone area (T. 2 S., R. 6 E.) correspond to thin belts underlain by these same rock types.

In the Nemo area, the large-amplitude magnetic highs that are elongated northwesterly and that overlie amphibolite and meta-iron formation lithologies (units G and F) curve to the north-northeast beneath the sedimentary rocks, thus suggesting that these rocks are wrapping around a domal or anticlinal structure. These trends agree basically with the gravity data interpretation. However, the magnetic data do not extend far enough to the east to include the east side of the structure.

The large area of Tertiary igneous rocks 6 miles south of Sturgis (Tps. 4, 5 N., R. 5 E.) was considered to be a laccolith by Darton and Paige (1925) and was named the Vanocker laccolith. The extension of the magnetic highs from the Nemo area into this area of Tertiary rocks plus the gravity evidence mentioned earlier is consistent with a laccolithic structure. In fact, R. W. Bayley (oral commun., 1970) made ground magnetic measurements from which he concluded that the Tertiary rocks in the upper Vanocker Creek area are laccolithic and are lying on a highly magnetic, high density basement. Northwest of Nemo in the Galena area (T. 4 N., R. 4 E.), smaller magnetic highs that lie along the axis of a broader gravity anomaly suggest the presence of locally thickened masses of amphibolite and meta-iron formation. However, the possible effects of Tertiary intrusive bodies in the same area complicate the interpretation.

Magnetic highs correlate well with the location of some of the Tertiary intrusive bodies and suggest the presence of others. The contiguous positive and negative anomalies or dipole anomalies near Elkhorn Peak (T. 6 N., R. 3 E.) and Whitewood Peak (T. 5 N., R. 4 E.) indicate that the magnetic sources are reversely polarized with respect to the earth's present magnetic field. Whitewood Peak has an exposed Tertiary core, and the magnetic pattern at Elkhorn Peak confirms the existence of an intrusive core in the domal structure. Dipole anomalies near Richmond Hill (T. 5 N., R. 2 E.) and at Englewood (T. 4 N., R. 3 E.) indicate reversely polarized rocks associated with Tertiary intrusive centers. Another smaller, but clearly reversed dipole anomaly occurs at Crook Mountain (T. 5 N., R. 4 E.) and indicates a buried Tertiary intrusive mass.

One of the most interesting large anomalies on the map is a large magnetic low centered in the southeastern part of T. 4 N., R. 3 E. It trends northwestward and has closed contours covering an area about 3 by 8 miles. Biotite-garnet phyllites (unit K) crop out here; however, the large amplitude suggests the presence of a thick wedge of weakly magnetized rocks of unit H. There is no supporting evidence, but the presence of extensive mineralization in the Lead area suggests the possibility that destruction of magnetite by mineralizing solutions may be the cause of the low. Petsch (1967) also called attention to the anomaly on his compilation map of ground magnetic data for South Dakota.

Five miles to the southwest, an elongate magnetic high suggests that the amphibolite and quartz grunerite rocks (units G and F) exposed in the Rochford area (McGehee and Bayley, 1969) probably extend 5 miles to the northwest beneath Paleozoic rocks.

A pair of moderate-size magnetic highs southeast of Pactola Dam (T. 1 N., R. 5 E.) and another, 2 miles west of Placerville (T. 2 N., R. 5 E.), occur in areas of biotite-garnet phyllite or schist (unit K). The two highs near Pactola Dam correlate in part with an elongate gravity high, but additional gravity stations along the north are needed. Elsewhere, unit K appears less magnetic, and it seems more probable that these anomalies result from underlying amphibolite and meta-iron formation (units G and F).

Another magnetic unit is the micaceous phyllite or schist (unit J) which typically is magnetite bearing. Its thickest exposures are about 6 miles east-southeast of Bear Mountain (T. 2 S., R. 3 E.) in what Redden (1968) believes is the nose of a south-plunging anticlinal fold. A pronounced magnetic high correlates with the nose, and its asymmetry suggests a south-southwest plunge, which agrees with plunge data of Redden. Outcrops of unit J on the limbs of the fold are in general marked by relatively continuous magnetic highs. One unexplained feature about 6 miles east of Bear Mountain is the lack of continuity in the magnetic high between the eastern limb and the large high at the nose. Surface exposures here indicate unit J is continuous as a wide belt, yet the drop in magnetic intensity suggests either a lower magnetic intensity or a lack of continuity of the lithology at depth. If the latter, some type of low-angle fault is indicated.

The magnetic correlation with unit J is also not apparent about 10 miles north-northwest of Bear Mountain. However, the unit may be partly removed in this area by the Grand Junction fault. West of this general area and south and southwest of Deerfield Lake (T. 1 N., R. 3 E.) are two north-trending narrow hills of unit J lithology which produce similar-trending magnetic highs. The easternmost high extends southward beneath Paleozoic rocks along the west side of the Bear Mountain dome but dies out on the southwest side of the dome. The westernmost magnetic high stops near the Paleozoic boundary, but the magnetic pattern suggests that the northern end turns to the northwest. The geology of the area is based only on reconnaissance work, and it is likely that the magnetic pattern more closely represents the distribution of unit J.

Some areas of unit J lithology occur northeast and north of Hill City (T. 1 S., R. 5 E.), but their correlation with magnetic highs is uncertain. Some of the dips in these areas are relatively low, and possibly the unit is not thick enough to cause significant magnetic anomalies.

The central part of the Bear Mountain dome corresponds to a well-defined magnetic low which supports an interpretation of a granitic core (unit A) surrounded by metaconglomerate and schist (unit D). The Harney Peak dome (T. 2 S., R. 5 E.) is expressed as a broad terrace in the magnetic contours. The granitic rocks (unit L) contain virtually no dark minerals, and a relatively low magnetic response is observed.

Meta-iron formation and associated rocks (unit F) extend south of Custer to Pringle (T. 5 S., R. 4 E.) and produce a long narrow magnetic high or "nose" in the contours. The anomaly increases to an amplitude of 900 gammas in the Pringle area and is traceable across the sedimentary rocks for about 2 miles to the south. There, the anomaly apparently terminates. The north end of a linear magnetic high of comparable intensity occurs about 6 miles N. 70° E. from the termination(?) and it is very tempting to infer that a fault with 6 miles of apparent horizontal displacement has offset the unit in the Precambrian basement. Gravity contours also have a northeasterly trend and form a moderate gradient to the southeast in this same area. However, there is no readily identifiable displacement of the gravity trends, and the basement is entirely covered by younger sedimentary rocks.

In summary, many of the magnetic features can be related to general configurations of crystalline rock bodies, particularly the more basic lithologic units which can be projected in the subsurface with a fair degree of confidence. All the many interesting magnetic anomalies could not be treated in this report, but for purposes of studies in specific areas, the reader is referred to the larger scale magnetic maps already published (listed in the "Introduction") and the individual geologic reports referenced on the index map.

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