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Bald Mountain gold mining region, northern Black Hills, South Dakota

By

James J. Norton[1]

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

[1] Denver, Colorado

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Introduction

The importance of the Black Hills, South Dakota, in gold mining does not rest solely on the Homestake mine. Other deposits in the region have produced more than 3 million oz of gold. Most of these are geologically quite different from the Homestake deposit and are of early Tertiary rather than Precambrian age, yet are most abundant only a few miles away from the Homestake mine. The possibility that the gold of the Tertiary ores came from Precambrian deposits leads to the thought that investigation of the Tertiary deposits may ultimately facilitate exploration for concealed Precambrian ore.

The principal mines are in the Bald Mountain region, where ore formed by replacement of siliceous dolomite beds in the Deadwood Formation of Cambrian age. Most of the mines are in the Portland and Ruby Basin districts on the southwest rim of the Precambrian window that contains the Homestake mine (fig. 1). Outlying deposits to the northwest and west, labeled on figure 1 as the Two Johns mine and the Annie Creek area, are ordinarily treated as part of the Portland district. An outlying mine to the east, the Wasp No. 2 (fig. 1), is in the only highly productive deposit in what has generally been called the Yellow Creek area. The Bald Mountain "region" of this report extends from the Two Johns mine southeast through the Portland and Ruby Basin districts, and for some purposes will include the area around the Wasp No. 2.

The Portland district was called the Trojan district by Allsman (1940, p. 24), and the Ruby Basin district was called the Bald Mountain area by Irving (1904). Irving's usage causes some confusion because Bald Mountain is also the name of the mining company that later acquired most of the deposits in the Portland district. In the Ruby Basin district, most of the deposits were consolidated under the ownership of the Golden Reward Company, which now (1983) belongs to the Anaconda Division of the Atlantic Richfield Company.

The region has had other mining companies and a great many mines and mineral claims. The interrelationships among these are complex and perhaps not entirely traceable, and for the most part irrelevant to this article. The principal sources giving names and other information about individual mines are Shapiro and Gries (1970), U.S. Bureau of Mines (1954), Allsman (1940), and Irving (1904).

History

The gold rush to the northern Black Hills began with the discovery of rich placers at Deadwood in 1875. The first lode claims on what became Homestake property were located in that same year, and fossil placer deposits in basal conglomerate of the Deadwood Formation were found at about the same time. The original discovery at Bald Mountain was by A. J. Smith in 1877 (Smith, F. C., 1898, p. 420). The northern Black Hills also has gold deposits in Mississippian limestone and in Tertiary intrusives, but these remained unrecognized until the 1890's.

Nearly all the gold mined prior to 1891 came from the Homestake and other Precambrian deposits or from Deadwood conglomerate or modern placers. Recovery of gold from Bald Mountain ores was inadequate with the grinding and amalgamation of the time, and experiments with other techniques were at first discouraging. The primary ore, which is pyrite rich, was especially difficult to treat, but in much of the ore the pyrite was oxidized to iron oxides, freeing the gold sufficiently to make it more amenable to recovery. Success in recovering the gold arrived about 1890 and mining began to flourish when

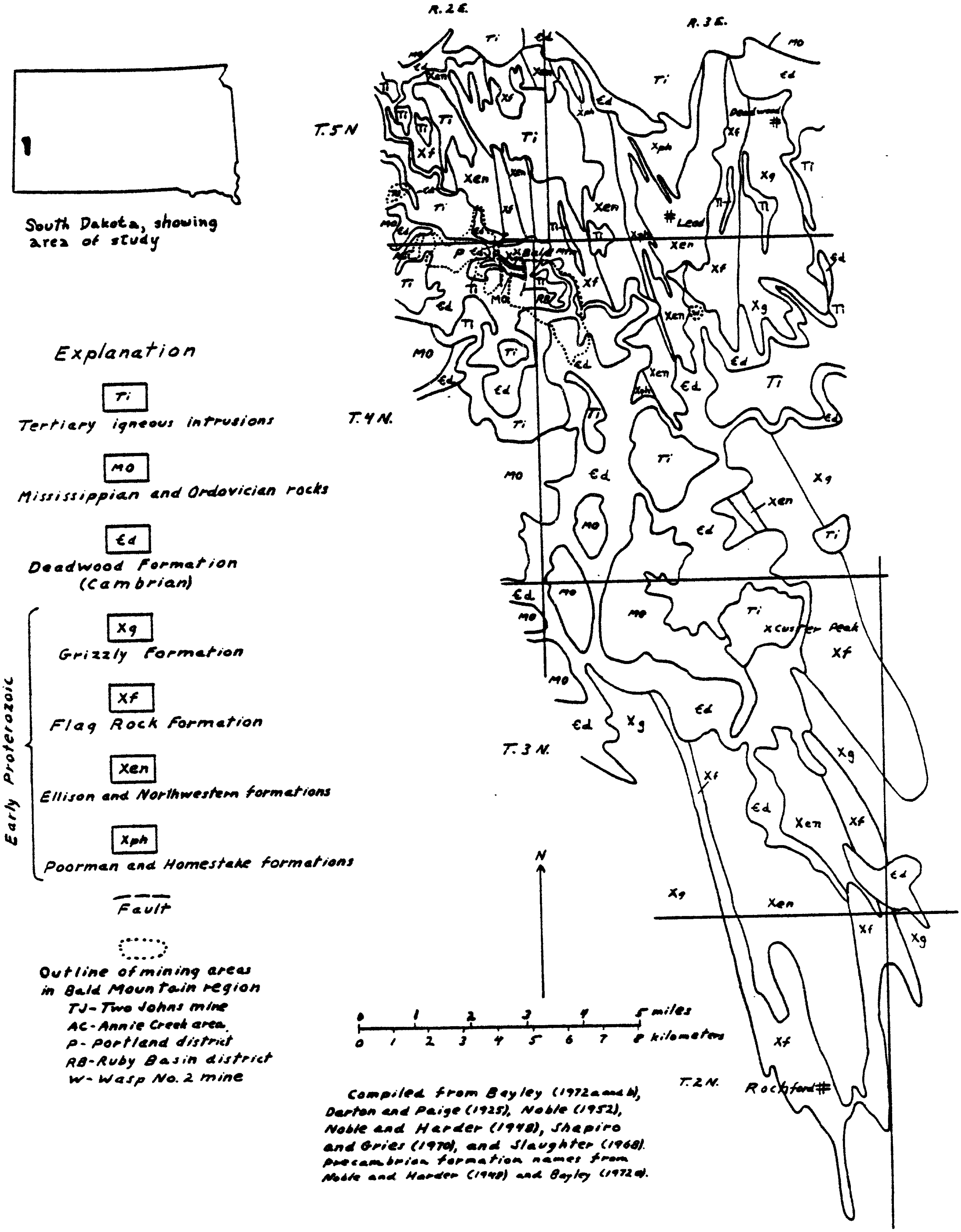

Figure 1. Generalized geologic map of a part of the northern Black Hills, South Dakota.

the Golden Reward chlorination plant and the Deadwood and Delaware smelter started operation (Smith, 1898, p. 421). Cyanidation soon came into use. Eventually it became the principal process, though the Bald Mountain Mining Company also gave primary ore a preliminary roast for a few years before World War II (Miller, 1962, p. 45-46). Experience in later years showed that most of the primary ore could be treated without roasting by means of fine grinding and modern cyanide techniques (Miller, 1962, p. 48).

The first major geologic report describing the Bald Mountain region was by J. D. Irving in 1904, based on fieldwork in 1899. His publication is still the primary source for most of the existing information about the geology of the ore deposits. The description of the area by Connolly (1927) contains important data about the mineralogy of the ores and its influence on the extractive difficulties. Allsman (1940) is the chief source of information about mining through the year 1938. A thesis by Miller (1962), mostly about the work of the Bald Mountain Mining Company, which did the only mining in the area after 1922, has a comprehensive account of operations through 1959, when mining ended. Shapiro and Gries (1970) compiled information from all previous work and made geologic maps at a scale of 1:12,000.

Production

An extensive search of the literature has resulted in the production estimates shown in table 1. The table gives the gold output as 2,100,000 oz. This is unlikely to be seriously in error: actual production probably is between 2,050,000 oz and 2,250,000 oz. The silver estimate of 3,800,000 oz has an uncertainty of perhaps as much as 300,000 oz, and is as likely to be low as it is to be high. The total value at a $400 price for gold and a $10 price for silver would be nearly $900 million. The average amount of recovered metal from 1901 to the close of mining in 1959 was about 0.2 oz of gold and 0.4 oz of silver per short ton of ore.

The production has generally been suspected of not being as large as shown in table 1. The published record has deficiencies: some reports are incompatible with others, the quality of information appears to have a wide range, and for some years preceding 1901, no production records now exist. To avert doubt about the table, fuller details about how it was compiled are in an appendix to this report. As the discussion in the appendix shows, each conflict between two estimates has been resolved by choosing the lower estimate. This has been done not for the sake of conservatism but because the lower estimate in each instance appears more likely to be the correct one. If the higher estimates had been used, the gold production would be increased by about 180,000 oz and the silver production by about 660,000 oz. The published record described in the appendix is complete enough and persuasive enough to allow a conviction that the totals in table 1 of 2,100,000 oz of gold and 3,800,000 oz of silver are reasonably reliable.

Regional geology

Figure 1 is a highly simplified geologic map made to enable the reader to visualize regional relationships in the northern Black Hills. For other purposes, one should examine the more detailed maps in the references cited on the figure.

In the north part of the map area, Precambrian rocks with Tertiary intrusions occupy a window surrounded by Paleozoic rocks and other Tertiary intrusions. This window is in a dome in which the base of the Cambrian was

Table 1.--Estimated production of gold and silver in the Bald Mountain mining region from its discovery in 1877 to the end of mining in 1959

Years	Mines	Short tons of ore	Troy ounces of gold	Troy ounces of silver	Sources of data
1938-1959	Bald Mountain	2,120,000	342,000	706,000	U.S. Bureau of Mines Minerals Yearbooks and Miller, 1962, fig. 17.
1934-1937	Bald Mountain	394,000	60,000	61,000	Allsman, 1940, p. 28, and Miller, 1962, fig. 27[1].
1901-1933	Bald Mountain[2]	1,659,000	360,000	667,000[3]	
	Mogul[4]	908,000	213,000	440,000	
	Golden Reward	957,000	371,000	734,000	
	Lundberg, Dorr, and Wilson	219,000	44,000	60,000	Allsman, 1940, and Miller, 1962.
	Reliance	188,000	27,000	10,000	
	Wasp No. 2	1,176,000	101,000	159,000	
	Others	7,000	1,000	1,000	
TOTALS 1901-1959		7,628,000	1,519,000	2,838,000	
1878-1900[5]	Golden Reward, Mogul, and other mines	Insufficient data	600,000	1,000,000	Estimated from Allsman, 1940, and reports of South Dakota Inspector of Mines.
TOTALS (rounded)			2,100,000	3,800,000	

[1] According to Allsman, the gold output was 127,000 oz, but published data for the total Black Hills production and for production from the Homestake and other mines indicate that Miller's 60,000 oz is more likely to be correct. For silver, Allsman's figure of 61,000 oz is used instead of Miller's 71,000 oz because the Miller graph looks as if it may have a 10,000-oz error for 1937.

[2] From Allsman, 1940, p. 28, but without the output of 1934-1937 or the production from six mines treated as "others" because, to judge from Miller (1962, p. 115), they are not Bald Mountain properties.

[3] Miller, 1962, implies that an additional 650,000 oz of silver was produced by Bald Mountain properties. See appendix.

[4] Production for 1901 is not known.

[5] Probably no significant production prior to 1891.

raised more than 300 m (Shapiro and Gries, 1970, pl. 7). The Homestake mine is in the Precambrian rocks at Lead, and the Bald Mountain region is along the southwest side of the window.

To the south is a broad area covered by gently dipping Paleozoic rocks, some of them intruded by Tertiary igneous rocks. Farther south the Precambrian reappears. Precambrian exposures continue far to the south, but only the small area that is particularly relevant to this article is shown on figure 1.

The Precambrian rocks consist mostly of micaceous phyllites or schists. Dips on the limbs of folds are very steep throughout the area, and the folds are isoclinal. The stratigraphy has been most rigorously worked out at Lead by Homestake geologists. The key publication is by Noble and Harder (1948), whose stratigraphic nomenclature is used here. The oldest unit at Lead, and so far as known the oldest on figure 1, is the Poorman Formation, which consists of carbonate-bearing graphitic phyllite in the cores of anticlines and on the flanks of synclines. It has been found only in the eastern part of the window and mostly near its north boundary because the folds plunge to the south. Above this is the Homestake Formation, a banded iron-formation of the carbonate facies that is too thin to show separately on the map but is especially important because it is the host for the Homestake ore. Next is the Ellison Formation, which contains quartzite and phyllite. On figure 1 it is combined with the overlying Northwestern Formation, which is a phyllite unit that is cut out in much of the area by an unconformity. Above the unconformity is a heterogeneous unit called the Flag Rock Formation by Noble and Harder (1948). It is mostly a sericitic phyllite but also has metamorphosed chert beds, iron-formation, and other rocks. The youngest formation at Lead was called the Grizzly Formation by Noble and Harder (1948), who mapped it only in a small area in which it consists almost entirely of fine-grained gray sericitic phyllite without distinctive characteristics. Bayley (1972a) used the name over a much broader area in which metagraywacke is a prominent constituent of the formation.

In the western part of the Lead window the Precambrian geology is based on a reconnaissance map by Bayley (1972a) that shows only the Ellison and Flag Rock to be exposed, and that these are in folds parallel to those at Lead.

In the southern part of the area of figure 1, near Rochford, Bayley (1972b) mapped an exceedingly complex anticlinorium in which some of his structural interpretations are unclear for lack of cross sections. On figure 1, Bayley's map has been greatly simplified so as to show the anticlinorium to have a core of Ellison and Northwestern surrounded by the Flag Rock and then the Grizzly formations. In the Rochford report Bayley (1972b) raised the Flag Rock to group status and he introduced new names for all formations of the area, but in his regional map (Bayley, 1972a) he retained the Noble and Harder nomenclature. In the east-central part of figure 1, Bayley's map (1972a) indicates the existence of a large anticlinal body of Flag Rock nosing off at its south end and surrounded by the Grizzly Formation.

The pattern of the Precambrian rocks north and south of the broad area of Paleozoic cover on figure 1 suggests a rather simple series of north-northwest-trending folds. The pattern indicates a southerly plunge, for the rocks in the cores of anticlines are oldest to the north and progressively younger to the south. Figure 1 implies that the structure and stratigraphy can be carried with some confidence beneath the Paleozoic cover. This appearance is almost certainly deceptive. The map is probably no more than an aid in visualizing how the Precambrian rocks in the window may be related to those to the south. The Paleozoic cover in the middle of figure 1 extends over an area of about 130 km^2, which is the size of a 7 1/2-minute quadrangle in the Black Hills. Experience in mapping 10 such quadrangles elsewere in the Black Hills, mostly by J. A. Redden, J. C. Ratté, and this author, shows that the geology of an area of this size cannot be reliably predicted from knowledge of the geology to the north and south.

The oldest Paleozoic unit is the Deadwood Formation, a marine unit that has an average thickness of about 120 m in the northern Black Hills. At the outcrop it is almost entirely Upper Cambrian, though its top is above the Ordovician boundary (Shapiro and Gries, 1970, p. 14-15). The most comprehensive treatment of the stratigraphy is in a thesis by Kulik (1965). The rocks include sandstone, shale, conglomerate, limestone, and dolomite with lateral changes in thicknesses and in lithologic composition that Kulik (1965) attributed to transgressions and regressions. Irregularities on the Precambrian surface influence compositions and thicknesses in the lower part of the formation. Differences in source areas and other local environmental differences may cause lateral changes elsewhere. Detailed interpretation of the stratigraphy is hampered by sparsity of outcrop, especially of the shaly middle part of the formation. Further complications result from faults and from Tertiary dikes and sills (Shapiro and Gries, 1970). In the Bald Mountain region the physical stratigraphy could be known in considerable detail if the mining had been done at a time when close geologic control was customary, or so it seems from Miller (1962, p. 87), but the compilation of available subsurface data by Shapiro and Gries (1970) indicates that the opportunity has been largely lost.

In several reports the Deadwood has been divided into informal lower, middle, and upper members, but not all writers use the same boundaries between members. They do all agree in placing the basal conglomerate and a sandstone or quartzite in the lower member. The conglomerate is rarely more than 3 m thick and is generally much thinner or even absent, but it can be as much as 15 m thick (Slaughter, 1968, p. 1442), especially near buried hills of resistant Precambrian rock. The sandstone has an average thickness of 8 m, but the range in thickness is from less than 1 m to at least 35 m (Shapiro and Gries, 1970, p. 14, 22). The lower member, in the usage of Shapiro and Gries (1970, p. 14-16), also includes 15 m of limestone, dolomite, limestone pebble conglomerate, and thin layers of shale. Their middle member has 50 m of shale with lenses of limestone pebble conglomerate. Their upper member, also about 50 m thick, consists largely of rather thin beds of sandstone and limestone but at the top has a massive sandstone called the Scolithus sandstone from its worm borings. In places on the south side of the Lead window, Darton and Paige (1925, p. 6) found this sandstone to be as much as 35 m thick.

The Deadwood Formation is followed by three thin units, totaling about 50 m in thickness, which on figure 1 are not separated from the overlying Pahasapa Limestone. The first of these units consists of the shale and siltstone of the Ordovician Winnipeg Formation. Next is the Whitewood Limestone, also Ordovician. The third is the Englewood Formation, mostly limestone, which is Lower Mississippian. The Ordovician rocks are cut out by the unconformity at the base of the Englewood in the southern part of figure 1. The Pahasapa Limestone, about 170 m thick, which was deposited during the Mississippian in the widespread Madison sea, is the youngest Paleozoic unit exposed in the area covered by figure 1. Elsewhere in the Black Hills it is followed by a series of units representing all geologic periods from the Pennsylvanian through the Cretaceous. These once covered the entire region. Evidence from a volcanic pipe indicates that Upper Cretaceous rocks remained uneroded until at least the end of the Paleocene (Redden and others, 1983).

The Pahasapa contained ores of economic importance in the Ragged Top and Carbonate districts west and northwest of the Lead window. Otherwise the chief reason here for interest in the Pahasapa and the other post-Cambrian sedimentary rocks is that they may conceal ore deposits in Cambrian and Precambrian rocks.

The early Tertiary igneous rocks shown on figure 1 are part of a belt of intrusions that crosses the northern Black Hills (Redden, 1975). These include quartz monzonite, monzonite, rhyolite, and their porphyritic equivalents, and also phonolite and grorudite (aegerine rhyolite). The bodies include stocks and laccoliths as well as a great many sills and dikes. In much of the Portland district the total thickness of sills is greater than the thickness of the Deadwood sedimentary rocks in which they were emplaced (Shapiro and Gries, 1970, p. 58).

Sands and clays of the Oligocene White River Group appear in many places, but are omitted from figure 1. The remainder of the Cenozoic history of the region is mostly one of erosion.

Ore Deposits

The ore bodies are replacement deposits in the Deadwood Formation, especially in siliceous dolomite. They extend outward from mineralized vertical fractures suspected of being feeders for hydrothermal solutions. The description of the deposits by Irving (1904) is still the chief original source of geologic information, but knowledge of the stratigraphic position and structural arrangement of the deposits has been increased by Miller (1962) and by Shapiro and Gries (1970). Smith (1897 and 1898) and Connolly (1927) investigated the mineralogy of the gold in order to determine why it was difficult to extract. A reader of these references will obtain all the factual information now available. The many other publications describing the geology are based mainly on these sources. For this article, only a summary is necessary.

Most of the ore came from subhorizontal shoots in dolomitic beds. The long dimension is parallel with the vertical fractures, which strike generally to the north in the Ruby Basin district and to the northeast in the Portland district. Lengths of ore bodies range from a few meters to about 1,500 m. Ore bodies that follow a group of vertical fractures instead of a single fracture can be as much as 100 m wide. The maximum thickness is 6 m. Most of the ore bodies lie immediately below shale beds or sills, which are generally regarded as having impeded the upward flow of the hydrothermal fluid. Irving (1904, pl. 11) published large-scale cross sections showing the various shapes and relations to the host rocks.

Ore also occurs in the lower quartzite, where it replaces carbonate cement (Shapiro and Gries, 1972, p. 30-31). Such ore was important in at least one mine in the Portland district, probably several in the Ruby Basin district, and at the Wasp No. 2. The ore bodies were smaller, more irregular in shape, and perhaps thicker relative to their widths than in the dolomitic beds.

The zone of interbedded carbonate rocks and shales above the lower quartzite was the principal site of ore bodies in the Ruby Basin district and was also important in the Portland district and at the Two Johns mine. A similar zone in the upper Deadwood, below the Scolithus sandstone, was most important in the Portland district. The two zones are about 100 m apart stratigraphically, but the actual distance between them is increased by intervening sills. The two zones are known in the region as the "lower contact" and the "upper contact"; Shapiro and Gries (1972, p. 29) traced these terms to early usage for ore bodies at the lower and upper contacts of a sill. This nomenclature has been preserved and even extended to other districts in the northern Black Hills, largely through the writings of geologists. Ore bodies in the middle member of the Deadwood have, following a whimsical logic, been assigned to the "intermediate contact."

In mineralogic terms, the most important distinction for economic purposes has been between primary ore and oxidized ore because the gold is far more readily extracted from the oxidized ore. The primary ore has as an abundance of very fine grained pyrite, which gives a color that causes it to be named "blue ore," in contrast to the "red" or "brown" oxidized ore. Most of the ore is highly siliceous, chiefly from quartz but also chalcedony, but some dolomite was mineralized without the introduction of silica (Shapiro and Gries, 1970, p. 32). Fluorite is widespread in small amounts, and gypsum and arsenopyrite have been found in several places. Other introduced minerals are rare. Shapiro and Gries (1970, p. 33-34) made the point that the carbonate rocks of the Deadwood Formation are rarely dolomitic except in mineralized areas, and suggested that dolomitization was an early part of the mineralizing process even though the dolomite was later almost completely replaced.

There is some uncertainty about how much of the gold is in tellurides and how much is in native form. Sylvanite has been reported by several authors, but free gold has seldom been seen and then only in oxidized ore (Connolly, 1927, p. 94). Chemical analyses long ago by Smith (1897 and 1898) showed both primary and oxidized ores as containing enough tellurium to indicate the gold is in sylvanite, and he suggested this as the cause of the extraction problems. His opinion prevailed until the mineralogic investigations of Connolly (1927, p. 72-94), who said (p. 75-77) that tellurium is absent in most of the ore, and even if it were present, roasting of the ore, which would drive off the tellurium, should have achieved more success than it had. His experiments with a sample of primary ore from the Golden Reward mine showed the gold to be closely associated with the finest grained pyrite, probably as inclusions too tiny to be seen under a microscope. Connolly favored roasting the ore to alter the pyrite and fracture the quartz, so that with subsequent fine grinding the gold would become accessible to cyanide solutions. Connolly also reasoned that in oxidized ore the oxidation process performs the same functions as roasting, and that the milling problems of early years were caused mostly by the fine grain size. As a consequence of these and further experiments, the Bald Mountain Mining Company set up a roasting operation that raised the recovery of gold in Two Johns primary ore from 20 to 80 percent (Miller, 1962, p. 47). After World War II roasting became too costly to use, and Two Johns ore and some other primary ore could not be treated by the fine grinding and cyanidation that sufficed for other primary ores. Whether this experience was caused by gold being in tellurides is not known.

The work by Connolly (1927) was the last mineralogic investigation reported for the Bald Mountain ores. Techniques and equipment have changed enormously since then. A modern study would greatly increase knowledge of the mineralogy, the distribution of chemical constituents, the ore-forming processes, and how to improve extraction of the gold and silver. Any suite of samples obtainable now from the old mines should be supplemented by specimens collected at earlier times. The only old specimens that this author has traced are those of Irving, which are now at Yale (B. J. Skinner, written commun., July 21, 1983), but others probably can be found in various collections, especially in mining schools and universities.

Origin

The ore-depositing process seems, in its broader aspects at least, to be simple. Carbonate rocks were replaced by silica and pyrite, and at the same time an economically important amount of gold was deposited. The obvious transport medium is a hydrothermal fluid driven by heat from the Tertiary magmas. Much of the fracturing was caused by distention of the rocks during the intrusive activity (Noble, 1952). Heat and fracturing may, however, have been the only contributions of the magmas. The water can have been convecting meteoric water or connate water from the Phanerozoic rocks. It will be argued here that the hydrothermal fluids obtained critical parts of their solute from a source chemically similar to the ore-bearing parts of the Homestake Formation--that is, a source with magnesium, iron, sulfur, gold, and silver. Silica can have been obtained from almost any of the Precambrian rocks.

Much has been said in the literature about the orientation of fractures and the presence of dolomite as controlling the position of the ore bodies in the Bald Mountain region, and these are indeed important in mining and in searching for ore shoots. It seems inevitable, however, that a hydrothermal fluid would find its way to suitable fractures and to suitable carbonate beds among the many available in the Paleozoic section, though it might then have dispersed its solute in deposits of less than ore grade.

A larger question is what controlled the position of the mining districts. This is also a much more difficult question--for the Precambrian geology beneath the Bald Mountain region is too poorly known to indicate likely locations of source areas for the constituents of the Tertiary deposits, and the geometric arrangement and magnitude of the hydrothermal systems, especially their lateral component, are only slightly known. The Precambrian rocks are so nearly impervious that any significant flow of hydrothermal fluid must have been through fractures. In the Cambrian rocks the geology of the ore deposits indicates movement through fractures, but the relation with fracture patterns in the Precambrian rocks is unknown. Because the Tertiary intrusions are numerous and generally rather small, the system of convecting fluids must have been complex. Furthermore, dating of the intrusions (Redden, 1975, p. 47) indicates that the period of high temperature, and thus of convecting activity, may have lasted for as much a 20 million years. At any one time the fluids are likely to have been enriched in sulfur, gold, and silver only in some parts of the region and to have been barren elsewhere, and the routes of travel of the fluids are likely to have changed during the millions of years of activity. Fluids that lacked access to a source of sulfur and of economically valuable metals would yield no ore deposits, and thus leave no evidence of their existence except inconspicuous effects.

In these circumstances the convecting cells probably were small, and the constituents of the Bald Mountain ores are likely to have come from nearby sources. The impermeability of the Precambrian rocks except through fractures implies that the cells descended only a short distance below the Paleozoic contact, probably at most a few hundred meters, indicating a shallow depth for the source rocks. Hence the chief control over the positions of the Bald Mountain deposits may be proximity to source rocks. A second control was the geometry of the fracture systems that governed the routes of travel of the solutions, but about this little can be inferred. A suggestion (Burnham and Ohmoto, 1981, p. 71) that ancient hydrothermal systems can be traced out by work on the isotopic composition of oxygen and hydrogen is almost certainly impractical in the complex environment of the northern Black Hills.

Hydrothermal fluid is likely to have had little ability to react with the Precambrian rocks because nearly all of them are micaceous or quartzose and not easily changed. The solutions had their first good opportunity to react with nearby rocks where they encountered carbonates in the Deadwood Formation. That is, another control was the presence of carbonates above Cambrian-Precambrian contact. At the sites of the ore deposits the movement of the fluid seems to have been largely vertical (Irving, 1904, p. 156-157), but the flow may have been lateral at only slightly greater depth.

The sulfur and the iron of the pyrite did not necessarily enter the ore bodies at the same time. The iron may have been introduced earlier, during dolomitization of limestone. Dolomitization had been assumed to long precede the mineralizing process until Shapiro and Gries (1970, p. 34) pointed out that dolomite seems to be rare except in mineralized areas. This observation implies that the first effect of hydrothermal fluid was to substitute Mg for Ca in limestone. The only published chemical analysis of a dolomite bed, which was made by W. F. Hillebrand for Irving (1904, p. 121), shows not only a high content of MgO but also 6.47 percent FeO and 0.64 percent Fe_2O_3. Irving described the sample as containing magnetite and glauconite, but the low content of ferric iron shows these to be sparse. Furthermore, the content of CO_2 is, in molecular terms, only slightly less than the total of CaO, MgO, FeO, and MnO. Hence most of the ferrous iron in this sample is in the carbonate mineral, and probably was deposited at the same time as the Mg. The iron content is very nearly the same as in the only sample of typical sulfide ore for which both chemical and mineralogic data have been published (Irving, 1904, p. 141-142). Little or no iron need have been introduced with the sulfur if Irving's analyses are representative of the region. The introduction of sulfur can have been a later event, after evolution in the composition and behavior of the solutions caused them to dissolve Mg, Ca, and CO_2, and to deposit Si and S as well as enough Au and Ag to make ore.

The introduced constituents at Bald Mountain are also major constituents of the Homestake Formation and the ore bodies it contains. The Homestake Formation is a banded iron-formation consisting of quartz and either Fe-Mg carbonate or, above the almandite isograd, the Fe-Mg silicate grunerite-cummingtonite. The ore bodies have chlorite as an abundant ferromagnesian mineral, and they are rich in iron sulfides as well as gold and silver. The silver-gold ratio is much lower than in the Bald Mountain deposits, reflecting either a difference in the source rocks for the Bald Mountain constituents or differences in the geochemical behavior of the Tertiary fluids. Rye and Rye (1974) showed the isotopic composition of the sulfur in Tertiary deposits to indicate derivation from a Precambrian source, but only one of their samples came from the Bald Mountain region.

Rye and Rye (1974) also showed, chiefly from isotopic data, that most of the Homestake mineralization was Precambrian. The age had previously been in question except that some mineralization was known to be Tertiary because pyrite-calcite veins cut Tertiary dikes (Noble, 1950). Rye and Rye, however, showed the ore-forming constituents to be best explained as products of hot springs active at the time of the original deposition of the Homestake Formation. They suggested a similarity with the metalliferous brine deposits from hot springs in the Red Sea, where contemporaneous sediments are also iron-rich. Noble (1950) said the Homestake ore bodies are concentrated in cross folds and are near the almandite isograd, where carbonate was metamorphosed to amphibole. To account for these circumstances, Rye and Rye called on redistribution of the metals, sulfur, and silica to form the ore bodies during metamorphism. This redistribution is unlikely to have been extensive because almost none of the ore is outside the Homestake Formation.

Tertiary deposits of gold or other metals occur on all sides of the Lead window, mostly in the Deadwood Formaton. Bald Mountain has by far the largest production, but other districts have had important mines. Near the northeast edge of the window the Deadwood contains gold deposits, a lead-zinc deposit, and a deposit once mined for pyrite. To the southeast are gold mines in Tertiary intrusions and silver-lead deposits in the Deadwood. West of the window gold has been mined from the Pahasapa Formation, and near the northwest corner of the window are silver-lead deposits, also in the Pahasapa.

In the rest of the Black Hills, sulfide ore deposits are much more scattered than around the Lead window, and their production has been far smaller. The proximity of the Tertiary deposits of the northern Black Hills to the Homestake deposit is unlikely to be an accident. Instead it is evidence that the hydrothermal fluids forming the Tertiary ores obtained material from the Homestake ores or from similar deposits that are not now exposed. The total gold production of the Tertiary ores is about 2.5 million oz, which is only a small fraction of the Homestake production of about 35 million oz through 1983. A loss of gold from the Homestake deposit could have been noticed only from physical or mineralogic evidence for reworking in the Tertiary. Evidence for such loss has not been observed (D. R. Shaddrick, oral commun., 1974), but the loss would be too small to be readily detected in this geologically complex environment. The Homestake deposit does have some Tertiary pyritic mineralization of little importance in terms of quantity, but no one has shown that it cannot have been caused by leaching of material from the main ore bodies. Noble (1950, p. 248-249) said that pre-rhyolite iron sulfide is mostly pyrrhotite and post-rhyolite is pyrite, and that the change is sharp enough to allow interpretation of the pyrrhotite as Precambrian and the pyrite as Tertiary, though he favored other conclusions. He also said that for about about 200 to 300 m below the base of the Deadwood pyrrhotite is absent and the iron sulfide is pyrite, which is also the principal sulfide of the Tertiary ores.

The existing data suggest that the gold of the northern Black Hills originally entered sediments via hot springs in early Proterozoic time and since then has only been redistributed. The first redistribution brought the Homestake ore bodies to essentially the form they have now. The second redistribution caused the Tertiary deposits.

Implications for exploration

The implications for exploration are at three levels: first, the probable existence of unmined ore in or near the old mines; second, the possibility of discovering another group of deposits of the same kind; and third, a chance that the Bald Mountain deposits reflect the existence of Precambrian deposits at depth but perhaps not too deep to be beyond economic reach.

Miller (1962), in his descriptions of the mines of the Bald Mountain region, mentions several places that contain unmined ore. From his remarks one can infer a total of a few million tons, which if the grade is normal would contain several hundred thousand ounces of gold. These were not strictly ore at the time the mines were closed, for otherwise the mines would not have been closed, but they may be reserves now. The known deposits are owned by mining companies and have been investigated in the 1970's and early 1980's. Most of what should be and probably has been done is too obvious to review here. Miller (1962) and other authors have stressed the intermediate zone as needing exploration, and they also mention ore south of old workings in the Ruby Basin district as well as in parts of the basal quartzite. Diamond drilling and detailed reconstruction of the stratigraphy and structure seem a necessity. Also worth investigating is how much primary ore remains unmined because it once could not be treated at a profit but perhaps could be now if the mineralogy were better known.

A search for new districts of the Bald Mountain type would be essentially a search for places that had a metalliferous hydrothermal system but left little or no evidence of its existence at what is now the surface. Outside of the Bald Mountain region, the principal known gold deposits in the Deadwood are north-northwest of Lead, which also is where the Homestake Formation passes beneath Cambrian rocks. The potential for subsurface discoveries has long been obvious, but possibly has not been adequately tested since the end of the $35 gold price. Gold deposits in the Pahasapa Formation at Ragged Top, west of the window, and silver at Carbonate, near the northwest corner of the window, have caused some exploration of the underlying Deadwood, but so far without known success.

The area south of the Bald Mountain region consists of Paleozoic rocks and many Tertiary intrusions. Certainly hydrothermal systems were once active in this area; the critical question is whether they deposited ores. According to Darton and Paige (1925, p. 22-23), the larger intrusions are all sills and laccoliths lying above the older Paleozoic units. Noble and others (1949, p. 340) agreed with the essentials of the Darton and Paige interpretation, but added that these bodies probably consist of many intrusions with sedimentary partings. Possibly these intrusions conceal metals deposits. If detailed geochemical exploration has been attempted in or around these heat sources, the results have not been made known.

This same area plus the western half of the Lead window is a region that may have unexposed Precambrian deposits. The most attractive part of this area is the immediate vicinity of the Portland and Ruby Basin districts because of the concentration of known Tertiary deposits and because the hydrothermal systems probably were small and shallow and hence drew their gold from a nearby source. If the region lacked minable deposits but instead had only a geochemical anomaly indicating leakage of metals from Precambrian rocks, it probably would have stirred up exploration enthusiasm enhanced by visions of finding another Homestake deposit. A point basic to this article is that the Bald Mountain region actually is a geochemical anomaly, differing from ordinary anomalies by being rich enough in gold to have been mined.

The simplified geology of figure 1 implies that the Precambrian rocks of the Rochford area pass beneath Paleozoic rocks and enter the western part of the Lead window. Magnetic data support this view (Kleinkopf and Redden, 1975). The map further implies that the Homestake Formation, if it exists at all in this area, is beneath the Precambrian surface. This interpretation depends on Bayley's (1972b) assignment of iron-formations at Rochford to his Flag Rock Group. One of these iron-formations was regarded by Noble and Harder (1948, p. 954-955) as Homestake Formation and an adjacent phyllite as Poorman, with tops of beds the opposite of Bayley's sequence. Rye and Rye (1974, p. 300-301) found the sulfur in these units to have the same isotopic composition as in the Homestake and Poorman formations at Lead. It is hard to devise a structural explanation for how the two Rochford units could be equivalent to the Poorman and Homestake, but the complexity of Bayley's map does not allow full confidence that the correlation is impossible. Whether or not the unit at Rochford is Homestake, it is lithologically the same, and it has been mined for gold and could have deposits beneath Paleozoic cover.

The Precambrian geology of the western part of the Lead window is inadequately known. Regional information is obtainable only from the reconnaissance map by Bayley (1972a) and from a map by Noble (1952) that shows contacts of Precambrian units but does not say what those units are. Even the distribution of the Tertiary intrusions is drastically different on the maps by Bayley (1972a), Noble (1952, figs. 8 and 9), Noble and others (1949, fig. 5), and Darton and Paige (1925). On figure 1, the Tertiary rocks are from Noble (1952), and the Precambrian rocks are as shown by Bayley (1972a) but with some use of Noble's contacts. The main body of Tertiary rocks was interpreted by Noble and others (1949) as a stock, called the Cutting stock. Noble (1952) showed this to be a multiple intrusion with many schist screens, and regarded it as the cause of the doming. Darton and Paige (1925) in their structure sections showed it as having a floor not far beneath the surface. Gravity data support the stock interpretation by indicating widening at depth (Kleinkopf and Redden, 1975). The Tertiary rocks have highly irregular shapes on the maps of Noble (1952), and one must suspect similar vertical irregularities. The distribution of Precambrian rocks in screens and along bottoms of the intrusion probably can be determined only by well planned and carefully interpreted drilling.

The exploration areas discussed here include about 30 km^2 north of the Bald Mountain region and about 130 km^2 to the south beneath Paleozoic cover. How then to reduce this area to a more manageable size? Magnetometer surveys to trace iron-formations are of obvious utility. Other geophysical techniques may help determine the shapes and depths of the bottoms of the larger Tertiary intrusions. As for geochemical exploration, the nature of the trace-element suite in the Bald Mountain deposits is not known, or at least not published, and much more information is needed. The apparent simplicity of the metals suites and the low metals contents in both Bald Mountain and Homestake ores raise doubts about how much of a halo they could create and how detectable that halo would be. Mahrholz and Slaughter (1967) found useful patterns in the Homestake mine. Allcott (1975, p. 70) mentioned that tellurium may be a pathfinder element in searching for ore of the Bald Mountain type. Arsenic is associated with gold at Homestake and also occurs at Bald Mountain (Irving, 1904, p. 141). Clues to possible geochemical relationships between Tertiary and Precambrian ores may be obtainable from the Wasp No. 2, which is in Cambrian rocks near down-plunge parts of Homestake ore shoots. Its position encourages the thought that its gold was drawn from Homestake ore bodies.

Diamond drilling might have to be extensive, not just to search for ore but also in earlier stages to assist interpretation of geochemical and geophysical data and of new geologic mapping. That is, concealed units of iron-formation or of possibly mineralized Deadwood (beneath intrusions, for example) must be found before they can be tested for ore. The cost of drilling may make the short-term risks too great for the possible long-term rewards. Whether or not this is so, the area warrants accelerated geologic, mineralogic, and chemical investigations of kinds that will enlarge understanding of its ore deposits and of how exploration should be done.

Final comment

A notable aspect of the published information about the Bald Mountain region is that nearly all the available data about the ore deposits was acquired many years ago. Most readers of this article will notice the anachronistic tinge of much that it contains. The geologic data about the Bald Mountain ore deposits come chiefly from Irving's publication of 1904, and much of the rest is from the 1927 publication by Connolly. Irving's 1904 volume also had an account of the Homestake geology by S. F. Emmons and of the petrography by Irving. Their Homestake results became outdated by a long series of investigations that culminated in the 1950 article by Noble. A major reappraisal then came from the isotopic studies of Rye and Rye (1974) and Rye and others (1974). Similar attention to the Bald Mountain region would almost certainly have greatly improved the understanding of the deposits, the mineralization processes, and the exploration outlook.

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Appendix

Discussion of table 1

The chief sources of information used in compiling table 1 are U.S. Bureau of Mines Minerals Yearbooks, Allsman (1940), Miller (1962), and Annual Reports of the South Dakota Inspector of Mines. The estimating procedure for some years or groups of years involves calculating the difference between the total South Dakota production and the known or probable production from sources outside the Bald Mountain region, especially the Homestake mine. The U.S. Bureau of Mines data for South Dakota's annual production since the beginning of mining are in Norton and Redden (1975, table 3). Homestake production is in Slaughter (1968, table 1) and in Minerals Yearbooks.

The production figures for 1938-1959 are the most reliable. The Bald Mountain Mining Company's tonnage of ore and output of gold and silver were published in the Minerals Yearbooks for 1938-1945. In subsequent years the Bald Mountain Mining Company was the only producer other than Homestake. Its output of gold and silver is the difference between the South Dakota total and the Homestake production; a graph by Miller (1962, fig. 27), who was an official of the company for many years, confirms the results. The Miller graph also shows the tonnages of ore for these later years.

For 1934-1937 Allsman and Miller have a substantial disagreement in the production of gold. The Miller graph indicates an output of 60,000 oz. Allsman (1940, p. 28) places it at 126,930.39 oz, which implies a much higher grade than normal. Inasmuch as all except about 60,000 oz of the gold produced in South Dakota in the 1930's can be accounted for from other sources, the Miller figure is accepted as probably correct.

The records for 1901-1933 are mostly statistics furnished to Allsman (1940) by C. W. Henderson, whose name appears in the literature as a compiler of South Dakota gold and silver data at least as far back as 1908 (U.S. Geological Survey, Mineral Resources of the United States). Miller (1962, table 8) also gives details of the production, but nearly all his figures are the same as Allsman's. Miller is in conflict with other sources on one important issue: he gives a silver production of 2,522,590 oz for the Bald Mountain and Mogul mines between 1901 and 1959, and this is about 650,000 oz greater than the 1,874,000 oz indicated by the data of Allsman and the Minerals Yearbooks. Because Miller's graph (1962, fig. 27) for 1912-1959 is compatible with other sources, the discrepancy must be in the period 1901-1911. The total Black Hills silver production for 1901-1911 was 1,960,000 oz, of which probably more than 500,000 oz came from the Homestake mine and about 1,400,000 oz is readily accounted for from other mines. Hence the extra 650,000 oz reported by Miller is excluded from table 1. Another anomaly is in Allsman's (1940, p. 39) recorded 205,663 oz of silver from the Golden Reward in 1901, which has been included in the amounts reported in table 1 even though the total Black Hills silver production in that year supposedly was only 78,000 oz. A later paragraph will bring up the possibility that this discrepancy is a result of confusion in the Black Hills totals for 1900 and 1901.

Production data are much less complete in the 19th Century. Clearly, however, mining operations were at a substantial scale in the 1890's. The field study in 1899 by Irving (1904) resulted in descriptions of 51 deposits. The annual reports of the South Dakota Inspector of Mines show that the Golden Reward was a major mine in the 1890's and many smaller mines were active in the Bald Mountain region.

The mine inspector reports and old records of the Bureau of Mines enabled Allsman (1940) to make production estimates that can be used to gauge the pre-1901 output of the Bald Mountain region, though uncertainties arise from differences in the ways in which he presented the estimates for individual mines. Only for the Mogul did he give a direct estimate of the pre-1901 production, which he placed at $3 million worth of gold and silver bullion. For the Golden Reward, he estimated the production over the whole history of the mine to be $21 million; the recorded production from 1901 onward (table 1) would have been worth about $8,100,000, which leaves $12,900,000 as the value of the earlier production. A similar calculation for the Wasp No. 2 puts the early production at only $300,000. For the Bald Mountain mine, Allsman (1940, p. 27-28) said that the production for 1901-1937 added to "a rough estimate of the early production" indicates a total of about $12 million, but actually the production he showed for 1901-1937 would have been worth somewhat more than $12 million, thus leaving nothing for the earlier years. Whatever the cause of this odd result, it seems clear that Allsman had evidence for only small pre-1901 production.

Allsman's estimates indicate a value for the pre-1901 production of about $16 million. From this value the quantity of gold can be calculated from the formula

$$20.67\,x + abx = 16{,}000{,}000$$

in which $\underline{x}$ represents ounces of gold, $\underline{a}$ the price of silver per ounce, and $\underline{b}$ the ratio of silver to gold by weight. The average price of silver produced in the Black Hills from 1890 through 1900 was about $0.70. The ratio of silver to gold from the Golden Reward and Mogul after 1900 was 2.0. If this may be taken as representative of the region in earlier years, the pre-1901 output of gold was 725,000 oz. A somewhat lower, and more probable, silver-gold ratio would increase the gold estimate by only a few thousand ounces.

Another way of estimating the pre-1901 production is by use of the annual reports of the State Inspector of Mines. Copies of these reports for the years 1891, 1893, 1894, 1897, 1898, 1899, 1902, and 1903 were furnished by the South Dakota School of Mines and Technology. The 1899 report is available only in an undated special edition of the Black Hills Mining Review, probably published in 1900. Other early reports, with the possible exception of the 1892 report, appear to be unobtainable (Lincoln, 1945, p. 5). The 1898 report lacks production data. In the 1899 report the production figures are questionable because they total of $9,131,000, which is far greater than the $6,558,000 in records of the Bureau of Mines (Norton and Redden, 1975, table 3).

The report for 1891, which to judge from F. C. Smith (1898, p. 421-422) was the first year of successful mining, shows a production of $170,000 from the Bald Mountain region. By 1893 the production exceeded $1 million, but it fell back to $760,000 in the following year. In 1897 the production went slightly above $2 million. It was about the same in 1899 if the reported total of that year should be discounted as much as appearances imply. In 1902, the production was still a little above $2 million. These figures indicate a production of about $8 million from 1897 through 1900, and about $5 million from 1891-1896, and thus a total pre-1901 production of $13 million. This is equivalent to about 600,000 oz of gold. Whether this estimate is better than the 725,000 oz calculated from Allsman's figures is questionable, but because 600,000 oz seems to be the maximum that can be supported by published data, it is used in table 1.

If a silver-gold ratio of 2.0 is assumed for those years, the silver production was 1,200,000 oz, but the ratio was probably lower because some of the extractive plants did not recover silver. The only independent means of estimating the pre-1901 silver production is to subtract the probable production of other districts from the total Black Hills production. For the period 1891-1899 the circumstances are rather simple: the total for the Black Hills was 1,192,000 oz; the Homestake and other mines outside the Bald Mountain region probably produced at least 400,000 oz; and thus the Bald Mountain region can at most have yielded 800,000 oz. This simplicity disappeared in 1900. In that year the total Black Hills silver production supposedly was 536,000 oz, which is much greater than in any year before or since then, yet is unexplained in the literature. Furthermore, the records show the production as dropping to 78,000 oz in the following year, which is equally peculiar because Allsman (1940, p. 39) reported 205,663 oz from the Golden Reward alone, and the Homestake, Mogul, and other mines must have contributed a large additional amount of silver. Then in 1902 the recorded Black Hills production rose to 340,000 oz before diminishing in subsequent years to much lower levels. Apparently a mixup in the 1900 and 1901 results has caused a sizable share of the production that was attributed to 1901 in the compilation of table 1 to be assigned to 1900 in the yearly totals. In both 1900 and 1901 the actual production is likely to have been about 300,000 oz. The Bald Mountain production in 1900 may be guessed at 200,000 oz. Adding this to the 800,000 oz estimated for earlier years yields the 1,000,000 oz used in table 1.