

# **The Life Cycle of Gold Deposits Near the Northeast Corner of Yellowstone National Park—Geology, Mining History, and Fate**

M

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# The Life Cycle of Gold Deposits Near the Northeast Corner of Yellowstone National Park—Geology, Mining History, and Fate

By Bradley S. Van Gosen

## Abstract

Henderson Mountain, near Cooke City, Mont., about 4.5 mi northeast of the northeast entrance to Yellowstone National Park (the Park), hosts identified resources of at least 2.3 million ounces of gold, 8.9 million ounces of silver, and 130 million pounds of copper. The mineral deposits formed by selective replacement of calcareous blocks and clasts in a complex breccia pipe (the Homestake deposit), and concurrent skarn development replaced limestone adjacent to the breccia pipe (the Miller Creek deposit). The breccia pipe and mineral deposits formed in the middle Eocene during intrusion of the dacitic Homestake stock.

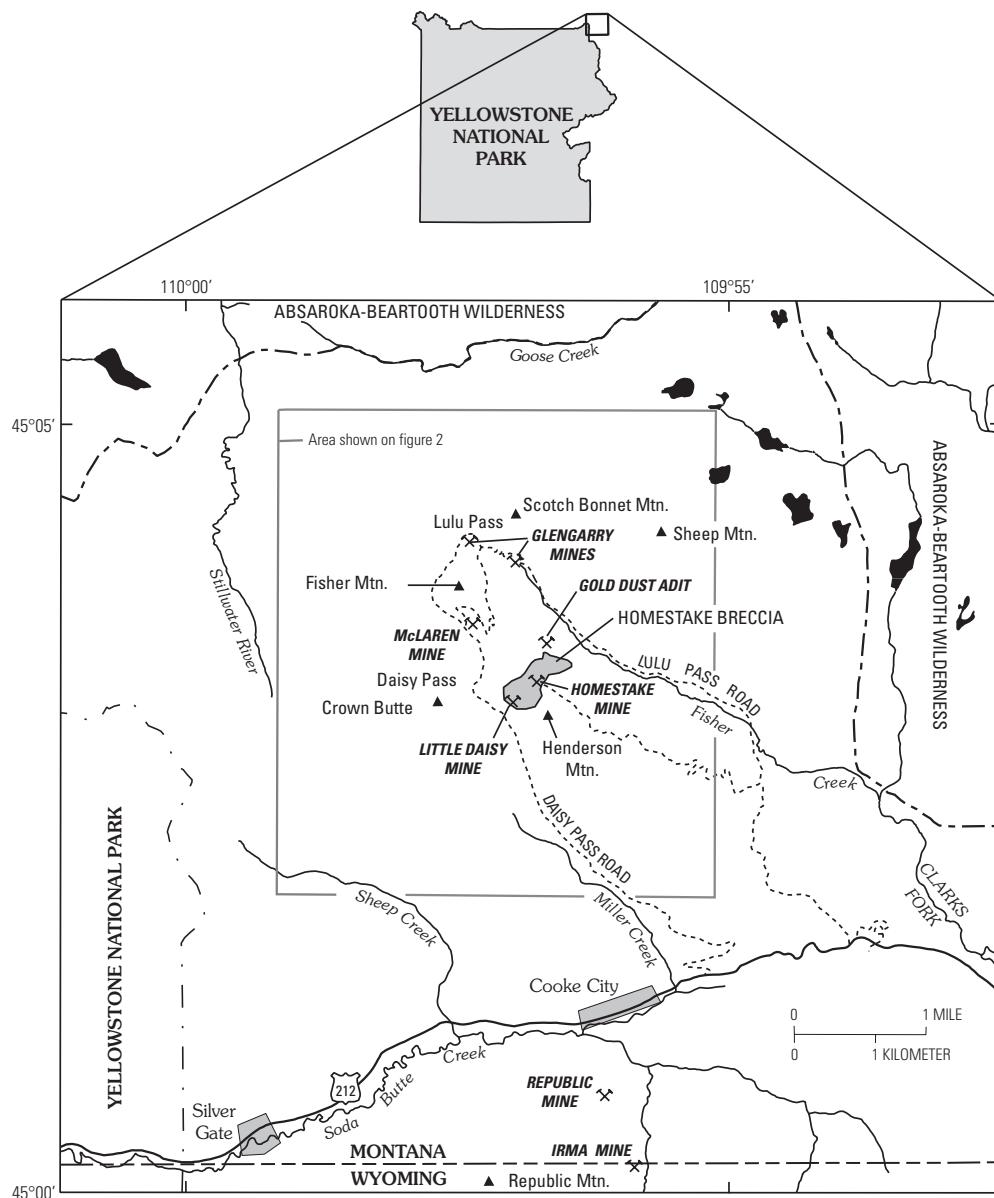
The geologic history of the Homestake and Miller Creek deposits involves Precambrian tectonics, Phanerozoic sedimentation, Eocene magmatism and hydrothermal processes, and Quaternary erosion and sediment deposition. The stocks of the Cooke City area (New World mining district) represent one of several mineralized centers of Eocene intrusive activity associated with the extensive Eocene Absaroka volcanic field in northwestern Wyoming and southwestern Montana. The Cooke City structural zone is a northwest-trending synformal zone developed in the Precambrian basement rocks of the Beartooth uplift. It was a zone of weakness that permitted calc-alkaline magmas to ascend through the crust during the Eocene to form mineralized centers. At the northern end of Henderson Mountain, intrusion of the Homestake stock during the middle Eocene was accompanied by metamorphism. The argillic Cambrian rocks locally were altered, whereas the interlayered Cambrian limestones were only weakly recrystallized and bleached. Intrusion breccias formed during magmatic stoping and injection of dacitic magma, and roof pendants composed of fractured Cambrian sedimentary rocks were lifted above the rising stock. Multiple events of hydrothermal shattering accompanied a flooding of relatively oxidized sulfur-rich fluids upward through intrusion breccias and shatter breccias (collectively and informally called the “Homestake breccia”). Intense argillic alteration formed in deep shatter zones, and limestone clasts and blocks in upper portions of the Homestake breccia were selectively replaced by

silver- and copper-bearing sulfide minerals, coeval iron-oxide minerals, and trace native gold with silver. Lateral flow of the fluids into Cambrian limestones along the perimeter of the breccia pipe formed the stratabound and tabular Miller Creek deposit.

Mineral deposits of the Homestake breccia were the target of two significant mining ventures in the 1900s. An eastern part of the Homestake breccia was explored by a haulage adit in the early 1920s, and a power plant, a smelter, and an aerial tramway to haul ore from the mine to the smelter were nearly completed and then abandoned in 1925. The adit stopped a few hundred feet from high-grade gold deposits discovered later by drilling in the 1990s. An extensive drilling program in the northern New World district by Crown Butte Mines, Inc., led to the “blind” discoveries of the Miller Creek and Homestake deposits in 1989 and 1990. In 1990, Crown Butte Mines submitted a plan to State and Federal agencies to mine these deposits by underground methods. The proposed mining venture caused a strong, organized, anti-mine opposition that drew national attention. Because of the close proximity of the proposed mine to Yellowstone National Park, the environmental legacy of historic mines, and concerns about potential threats to the environment, the Federal Government negotiated a settlement with the mining company and the majority claim owner to halt mining in the area. On August 7, 1998, all properties and mineral rights were formally transferred to the U.S. Forest Service. Later, in August 1998, the U.S. Departments of the Interior and Agriculture announced a 20-year withdrawal of Federal locatable minerals in an area of 19,100 acres (7,735 hectares) surrounding Cooke City (the New World district and a buffer zone).

## Introduction

Unexposed skarn deposits enriched in gold, copper, and silver are present at Henderson Mountain about 2.5 mi (4 km) north-northwest of Cooke City, Mont., and about 4.5 mi (7.2 km) northeast of the northeast entrance to Yellowstone National Park (the Park) (fig. 1). The deposits under Henderson Mountain are replacement bodies in a complex breccia pipe (informally called the Homestake breccia) and in tabular, stratabound bodies that formed laterally to the breccia pipe. Localization of the ore deposits



**Figure 1.** Map of the New World mining district area, Montana and Wyoming showing locations of Homestake breccia, historic mines, and geographic features.

in this particular area and along a northwest-trending zone that cuts across the region was influenced by large-scale structures that originated in the Precambrian. The ores formed in the Eocene during the regional formation of the Absaroka volcanic field (Chadwick, 1970; Smedes and Prostka, 1972; Hausel, 1982; Hiza, 1998, 1999). The gold-rich deposits of Henderson Mountain were targets of mining and (or) prospecting efforts in the 1920s, 1940s, and 1990s.

## Study Approach

Crown Butte Mines, Inc., provided to the author subsurface data they collected from their late 1980s to early 1990s exploration-and development-drilling program in the New World district. These data provided a three-dimensional view of a classic ore-forming system. The drill cores were examined as part of a mineralogical and geochemical study of the deposit (Van Gosen,

1994). The extensive drilling array included a number of core holes into the Homestake breccia and stock (fig. 2; drill-hole locations shown in Van Gosen, 1994). Samples were selected to examine the alteration and mineralization patterns within the breccia bodies and their mineral deposits, extending outward into the altered host intrusive and sedimentary rocks.

This report describes the geologic history of these deposits, from the Precambrian structures that set the stage for localization of the intrusions, to the Paleozoic sedimentation that provided the host rock for the ore, to the Eocene magmatic and hydrothermal processes that formed the deposits. The discovery, exploration, and development history of these deposits during the last 125 years also is addressed, with a discussion of the social and political influences that ultimately brought an end, in the 1990s, to possible development of the identified mineral deposits. This study is the first detailed account of the geology, mineralogy, and multiple-element chemistry of this economic breccia-hosted, skarn/replacement deposit.

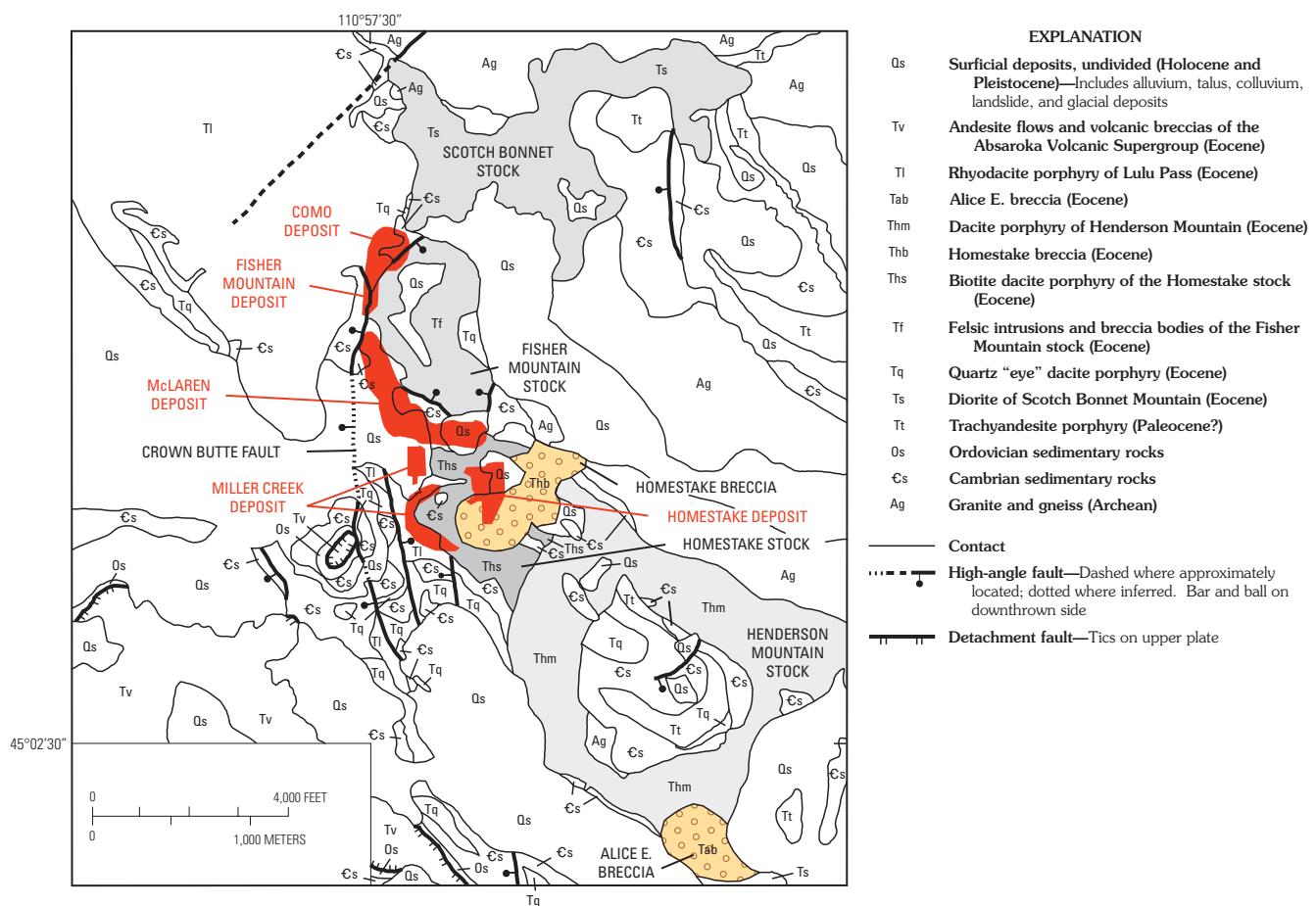
## Significance of the Homestake Deposit

The term “Homestake deposit,” as used herein, refers to all gold-silver-copper-enriched intervals within, and genetically associated with, the Homestake breccia (fig. 2). This deposit was chosen as the focus of this discussion because of its significant quantities of precious metals, its complex geologic and mining history, and the societal and political controversy that was triggered during the 1990s because of a plan proposed by Crown Butte Mines, Inc., to mine the deposit. That controversy ultimately led to a settlement agreement between the Federal Government, Crown Butte Mines, and the majority claim owner. The agreement officially ended the mine proposal in August 1998, transferring the properties and mineral rights to Gallatin National Forest. That settlement was followed later in the same month by a 20-year withdrawal of Federal locatable minerals in 19,100 acres of the surrounding Federal lands. Thus, the public controversy and Government involvement that centered around the Homestake gold-silver-copper deposit were as complex as the geologic history of the deposit.

On the basis of more than 200 holes through the Homestake breccia, drilled from 1990 to 1992, Crown Butte Mines and Noranda Exploration estimated reserves (as of April 4, 1992)

in the Homestake deposit at 6.6 million tons of identified ore with an average grade of 0.224 opt (ounces per ton) gold, 0.71 percent copper, and 0.83 opt silver (table 1). They increased their April 1992 estimate of 1.48 million ounces of gold in the Homestake deposit (table 1) in the following 2 years on the basis of additional drilling and calculations. However, the latter estimates were not published. Additional unidentified mineral resources probably are present in the New World district and vicinity (see Elliott and others, 1992; Hammarstrom, Zientek, and Elliott, 1993; Kirk and others, 1993). The Homestake deposit contains a substantial gold deposit; it is the largest known gold deposit in the New World district (table 1).

The Homestake deposit appears to be geologically unusual in many aspects, although it probably is not unique to the region, as explained in a subsequent section. The gold-silver-copper deposits are part of a complex geologic system that includes polymetallic replacement deposits, skarn deposits, and weak porphyry-style mineralization that is superposed on igneous rocks, reactive rocks in breccia pipes, and adjacent sedimentary layers. The entire breccia-stock-ore complex is genetically related to the middle Eocene intrusion of the dacitic Homestake stock and multiple episodes of associated magmatic and hydrothermal processes.



**Figure 2.** Generalized geologic map of the northern part of the New World mining district showing locations of identified (named) gold-silver-copper deposits, stocks, and Homestake breccia. Note that the ore deposits, shown in red, are projected to the surface in this plan view. Modified from Elliott and others (1992) and Elliott (1979).

**Table 1.** Geologic ore reserves for identified gold-copper-silver deposits in the northern New World district (fig. 2), as determined by Noranda Exploration and Crown Butte Mines as of April 4, 1992.

[Data from Elliott and others (1992) with their permission. opt, ounces per ton; pct, percent]

Deposit	Tons	Grade			Ounces Au	Pounds Cu	Ounces Ag
		Au (opt)	Cu (pct)	Ag (opt)			
Como	707,318	0.110	1.03	0.546	77,805	14,570,750	386,195
Fisher Mountain	334,200	0.189	0.28	1.130	63,164	1,871,520	377,646
McLaren	2,171,035	0.091	0.70	0.381	197,564	30,394,490	827,164
Miller Creek	2,218,368	0.387	0.87	1.540	858,508	38,599,603	3,416,286
Homestake	6,600,696	0.224	0.71	0.830	1,478,616	93,733,717	5,478,801
Average grade		0.222	0.75	0.870			
Total	12,031,887				2,675,657	179,170,080	10,486,092

## Regional Geologic Setting of the New World District

The New World mining district includes areas of past mining and prospecting activity in the vicinity of Cooke City, Mont., including mines in the Republic Mountain area on the south to Lulu Pass on the north, and prospects from Sheep Creek on the west to Sheep Mountain on the east (fig. 1). The New World district is within the “Beartooth uplift,” a broad fault-bounded foreland uplift in south-central Montana and northwestern Wyoming (fig. 3). The term Beartooth uplift, as used here, includes the entire continuous mountainous region in south-central Montana between the towns of Gardiner, Livingston, Nye, and Red Lodge (fig. 3). The Beartooth uplift includes the elevated South Snowy, North Snowy, and Beartooth Plateau crustal blocks (fig. 3), named by Foose and others (1961). The blocks were uplifted during the Laramide orogeny. The northwest-trending Cooke City structural zone is the boundary between the Beartooth Plateau block, to the east, and the South Snowy block, to the west (fig. 3).

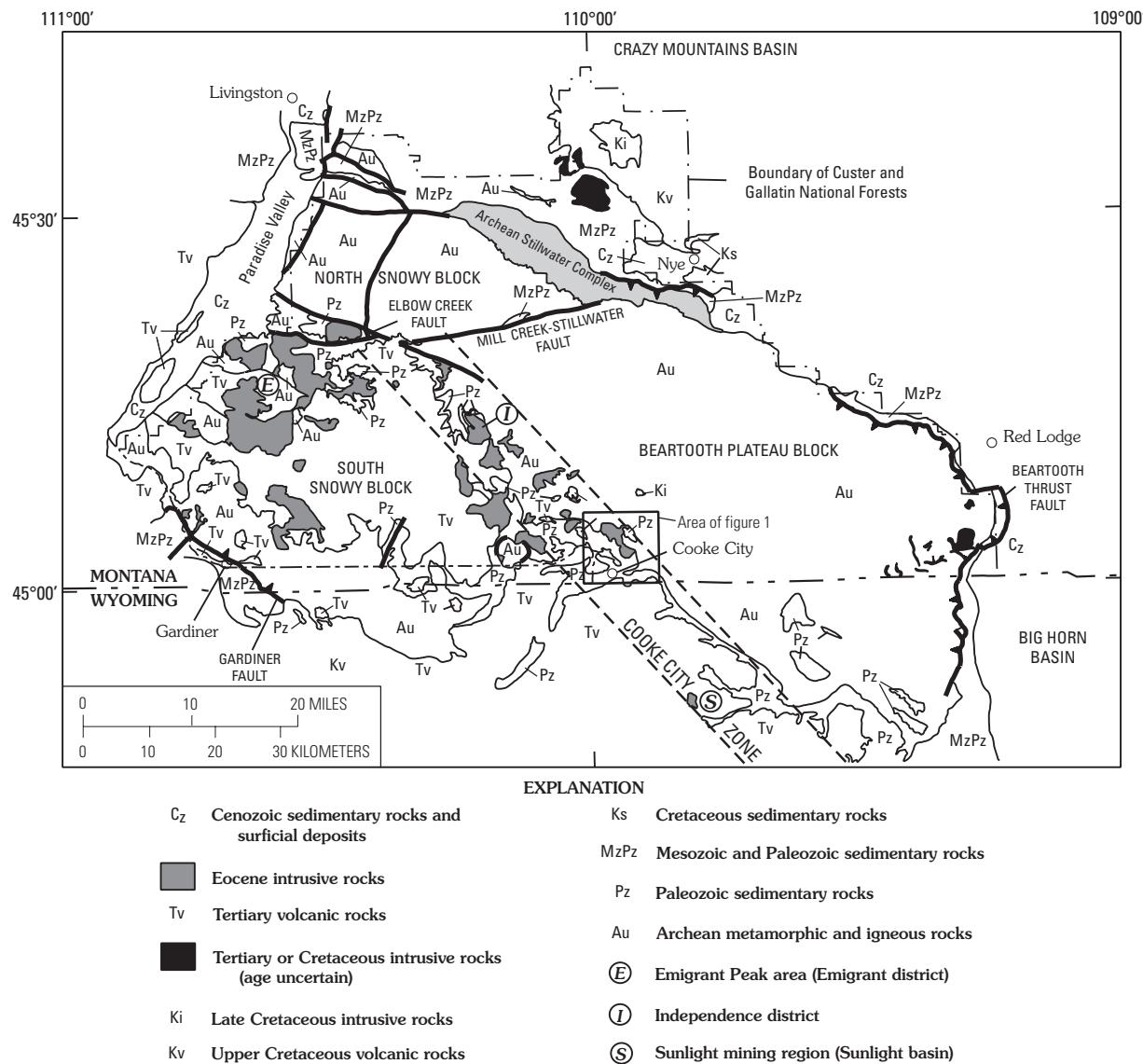
### Precambrian Structural Control

The Cooke City zone is a major structural zone or lineament that crosses the Beartooth uplift, extending from the canyon of the Clarks Fork of the Yellowstone River, on its southeast termination, to the junction of Mill Creek with the Yellowstone River on its northwest termination. Foose and others (1961) first described this zone in a regional context and suggested that it represents a zone of crustal weakness within the uplift, with Precambrian origins. This “sag zone” apparently consists of a down-warped and down-faulted zone that formed in Archean basement rocks of the uplift. Kulik (1992) suggested that the probable origin of the Cooke City zone was “local extension within the uplifted block.” The Archean rock surface of the Beartooth Plateau block slopes southwestward toward the Cooke City zone (Foose and others, 1961). Northwest of Cooke City, that surface reverses

and slopes northeastward, thereby outlining a structurally downwarped zone within the Archean rocks. Paleozoic (Cambrian through Lower Mississippian) sedimentary rocks are present in the Cooke City “sag zone.” These strata were eroded from most of the Beartooth uplift interior. Preservation of these sedimentary rocks within the zone had considerable significance to the formation of the New World district mineral deposits. Limestone units of Cambrian age, preserved in the Cooke City zone within the area of the mining district, subsequently were intruded by Eocene igneous rocks and locally replaced to form the ore bodies. Also, a belt of mineralized Eocene volcanic centers, such as the stocks in the northern part of the New World district (fig. 2), formed along the northwest-southeast trend of the zone, implying that Precambrian structural control was important in the emplacement of the Eocene intrusive centers and their mineral deposits.

In addition to the New World district, the Cooke City zone contains the Independence, Horseshoe Mountain, and Emigrant (slightly offset from the zone) districts and the Sunlight mining region (fig. 3). Each of these areas is associated with Eocene stocks. The Eocene intrusive centers are related spatially, compositionally, and temporally to the Eocene Absaroka Volcanic Province of northwestern Wyoming and south-central Montana (Chadwick, 1970, 1972a, 1972b, 1981; Hiza, 1998, 1999; Smedes and Prostka, 1972). According to Foose and others (1961), the Cooke City zone is a zone of crustal weakness within the Beartooth uplift; it formed along Precambrian structures that were reactivated during the Laramide uplift. Calc-alkaline magmas rose through the crust along this zone of structural weakness during the middle Eocene.

A Precambrian origin of the Cooke City zone is supported by at least two lines of evidence. First, Precambrian mafic dikes, which likely intruded preexisting fracture systems, commonly trend northwestward on the Beartooth Plateau adjacent to the zone (Simons and others, 1979). Second, several faults and shear zones mapped within the zone in the Cooke City area trend northwestward (Lovering, 1929; Parsons, 1958; Elliott, 1979).



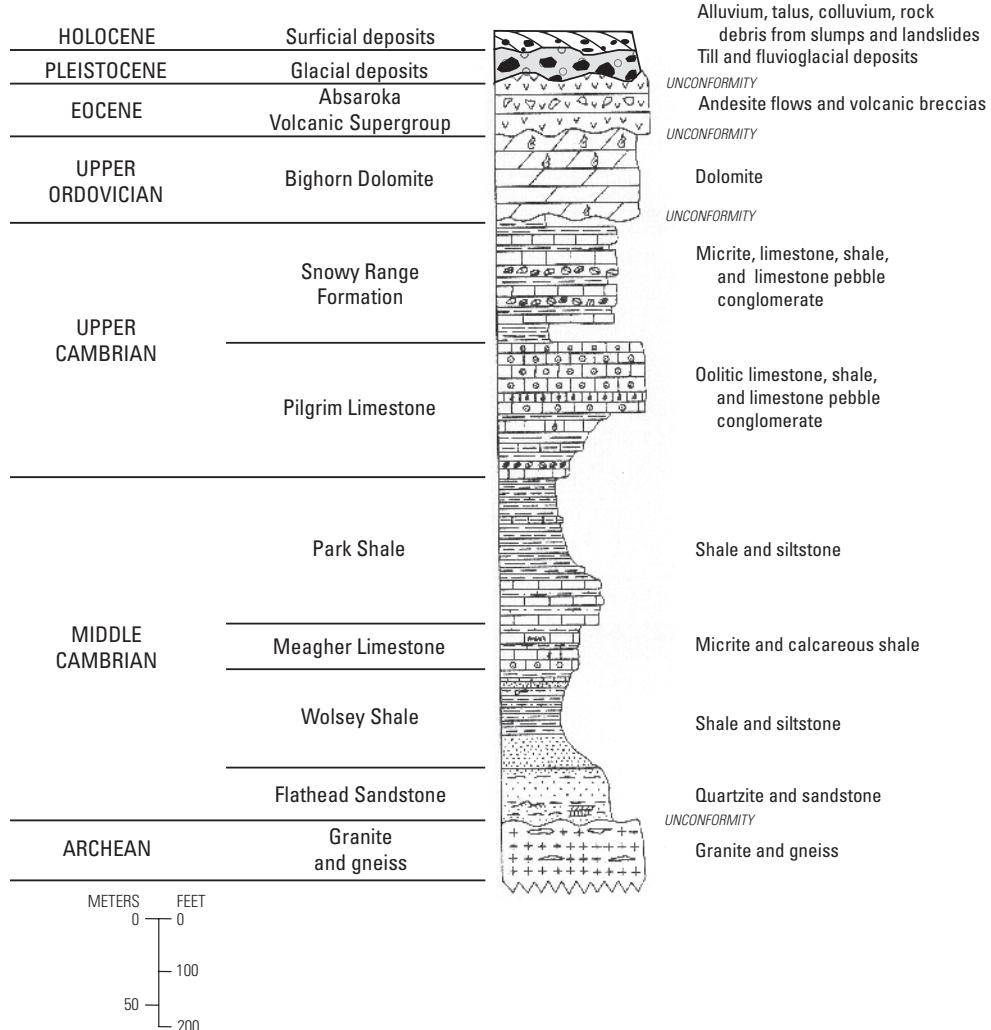
**Figure 3.** Generalized geologic map of the Beartooth uplift region, Montana and Wyoming, which includes the South Snowy, North Snowy, and Beartooth Plateau blocks as defined by Foose and others (1961).

## Phanerozoic Sedimentation and Laramide Uplift

The Beartooth uplift region, including the New World district, had a long period of relative tectonic quiescence during the Paleozoic and most of the Mesozoic. During the Late Proterozoic or Early Cambrian, an erosional plain developed across the surface of the Precambrian rocks of the Beartooth uplift (Hughes, 1933; Thom and others, 1935; Simons and Armbrustmacher, 1976). Throughout the Paleozoic and into the Early Cretaceous, the Beartooth region was a broad, stable platform of shallow-marine inundation on which cyclic offshore carbonates and nearshore and shoreline clastic facies were deposited. During the Early Cretaceous, more rapid subsidence, with concurrent marine transgression and sediment deposition, occurred across the shelf (Foose and others, 1961).

Paleozoic sedimentary rocks totaling 2,800–3,500 ft (853–1,067 m) in thickness record deposition in the region of the Beartooth uplift (on the basis of measurements at the southwestern margin of the uplift by Ruppel (1972), at the southeastern margin by Pierce (1965), and at the northwestern (Livingston, Mont.) corner by Richards (1957)). Carbonate rocks record deposition during the Middle and Late Cambrian in the New World district, specifically the Meagher Limestone and the Pilgrim Limestone (fig. 4). The carbonate rocks later became important host rocks for the Eocene replacement mineral deposits in the district.

Triassic through Upper Cretaceous sedimentary rocks, at least 5,000 ft (1,524 m) in thickness, covered the Paleozoic rocks of the uplift prior to Laramide uplift and erosion (Foose and others, 1961; Pierce, 1965; Richards, 1957; Roberts, 1972; Ruppel, 1972). The final, eastward regression of the shallow



**Figure 4.** Schematic section showing the stratigraphy of the northern New World mining district. Modified from Elliott and others (1992).

Eagle sea from the region occurred during the Coniacian or early Santonian of the Late Cretaceous (Roberts, 1972). That regression likely coincided with initial stages of regional Laramide uplift. Studies of deposition rates in the Bighorn Basin southeast of the Beartooth uplift (fig. 3) suggest that the climax of the Laramide orogeny here occurred during the middle Paleocene (Hickey, 1980). Laramide uplift and deformation continued in the region until the latest Paleocene or early Eocene (Roberts, 1972). The Laramide orogeny, as elsewhere in the Rocky Mountain province, reactivated and utilized basement structures of Precambrian origin within the Beartooth uplift, such as the Cooke City zone.

## Eocene Magmatism

A recent study by Hiza (1998, 1999) suggests that eruptions in the Absaroka volcanic field initiated approximately 53 Ma, during a period of crustal extension. Intrusive centers in the region, such as the stocks in the northern New World district, are temporally and spatially related to thick sequences of volcanic and volcaniclastic rocks of the Eocene Absaroka volcanic field (Smedes and Prostka, 1972). The Eocene

intrusive centers are interpreted to represent stratovolcanoes (Hausel, 1982; Parsons, 1958) that now are exposed at various erosional levels. The stratovolcanoes were the sources of the Eocene volcanic and volcaniclastic deposits. Multiple phases of intrusion and eruption are evident at each center, such as the crosscutting stocks, laccoliths, dikes, sills, plugs, and volcanic deposits in the northern New World district (fig. 2) (Elliott, 1979). Hiza (1999) concluded that most of the Absaroka-related volcanic material (more than 60 percent) was erupted between 50 and 48 Ma, with local activity continuing until about 43.5 Ma. At some time during this interval, volcanic deposits blanketed the Cooke City area and buried the newly formed (middle Eocene) mineral deposits, as explained in a subsequent section.

Several studies of the mining districts in the Cooke City zone, including the New World district, have been conducted. Each confirmed the common association of gold-copper-silver mineralization with middle Eocene intrusive activity. Those studies include investigations at (refer to fig. 3) (1) the Independence district (Harlan and others, 1991; Lobanoff-Rostovsky, 1960; Meen, 1985, 1988; Meen and Eggler, 1987; Moyle and Buehler, 1989; Rubel, 1964, 1971; U.S. Geological

Survey and U.S. Bureau of Mines, 1983; Wedow and others, 1975), (2) the Emigrant district (Basler, 1965; Pfau, 1981; U.S. Geological Survey and U.S. Bureau of Mines, 1983; Van Voast, 1964; Wedow and others, 1975), and (3) the Sunlight mining region (Dreier, 1967; Nelson and others, 1980; Osterwald and others, 1966; Parsons, 1937, 1939; Pederson, 1968; Rich, 1974). Hammarstrom, Zientek, Elliott, and others (1993) evaluated the potential for undiscovered mineral deposits associated with intrusive centers in the South Snowy block.

## Pleistocene and Holocene Erosion

Much of the present topography of the Beartooth uplift and the Cooke City area formed as a result of Pleistocene glaciation. Glacial landforms, such as sharp peaks and ridges, cirques, deep U-shaped valleys, and a variety of glacial deposits, are widespread throughout the Beartooth Mountains (Elliott and others, 1993; Simons and others, 1979; Wedow and others, 1975). In the northern part of the New World district, glaciation formed hanging valleys on each side of Henderson Mountain in the present valleys of Fisher Creek and Miller Creek. The glaciers uncovered, but spared, most of the Homestake breccia and its mineral deposits. Field mapping suggests that part of the east side of the Homestake breccia possibly was removed by glaciers from the east flank of Henderson Mountain and transported down the Fisher Creek valley. Recent mass wasting also has contributed to exposure of the Homestake breccia.

## Geology and Mineral Deposits of the Northern New World District

Eocene stocks, other intrusive bodies, and associated breccia pipes crop out in the northern part of the New World district (fig. 2). These features include the Scotch Bonnet stock, the Fisher Mountain stock, the Homestake stock, the Homestake breccia, the Henderson Mountain stock, and the Alice E. breccia (an informal unit name used locally). Five copper-gold-silver deposits are genetically associated with these features (fig. 2). As summarized by Elliott and others (1992, p. 8), the deposits “are of three principal types: (1) tabular, stratiform, retrograde skarn and replacement deposits hosted mostly by [limestones of] the [Cambrian] Meagher Formation (Como, McLaren, and Miller Creek deposits), (2) replacement and vein deposits along high-angle faults (Fisher Mountain deposit), and (3) sulfide- and iron-oxide-rich replacement deposits of limestone blocks in diatreme and intrusion breccias of the Homestake breccia complex (Homestake deposit).”

## Scotch Bonnet Stock

The Scotch Bonnet stock is interpreted to be the oldest major intrusion in the northern part of the New World district (fig. 2). It forms the bulk of Scotch Bonnet Mountain. An age determination of biotite, using the potassium-argon method, indicates the stock solidified  $55.3 \pm 0.7$  Ma (Elliott, 1979). The stock is dark gray to medium-dark gray with a primarily equigranular to fine-grained, subhedral granular texture. The rock ranges in composition from diorite to monzodiorite and is commonly propylitized (Elliott, 1979). Mineral deposits are sparse within the Scotch Bonnet stock. Disseminated pyrite is present in fault zones, and quartz-pyrite veins are present locally along steeply dipping structures (Johnson, 1991). No gold-copper-silver skarn or replacement deposits, such as those associated with the Fisher Mountain and Homestake stocks, have been recognized here.

## Fisher Mountain Stock and the Como, McLaren, and Fisher Mountain Deposits

The next major intrusion that formed in the area was the Fisher Mountain stock (fig. 2), a multiphase network of felsic porphyritic intrusions and breccia bodies (Kirk and Johnson, 1993). The intrusion has an elliptical shape in plan view, covering an area of about 4,000 ft (north-south) by 3,500 ft (east-west) (1,219 m by 1,067 m). The Como and McLaren deposits (fig. 2), which are gold-copper-silver skarn and replacement deposits, are present along the perimeter of the stock. The Fisher Mountain gold-silver-copper deposit also is spatially associated with the Fisher Mountain stock. It consists of replaced fault-gouge material in the Crown Butte fault (fig. 2) and local replacement of Pilgrim Limestone and Meagher Limestone adjacent to the fault zone.

Dark-red to reddish-orange, highly fractured, iron-oxide-mineral-bearing rocks are exposed in the Como and McLaren open pits (fig. 5). The geology, alteration, and mineral deposits of the Fisher Mountain stock were described by Johnson (1991, 1992, 1994). He distinguished several phases of intrusion and brecciation in the complex, and he separated them into early and late stages. Crosscutting relationships he noted on Crown Butte (fig. 1) indicate that the Absaroka volcanic rocks in that area were extruded during an interval between the times of intrusion of the early and late stages of the Fisher Mountain stock. Deep drilling by Crown Butte Mines showed that a breccia pipe with open spaces between clasts, enclosed within the stock, reaches at least 2,430 ft (741 m) depth (Johnson, 1991, 1994). It has steep contacts. Collapse of sedimentary strata (as much as 1,700 ft or 518 m) and vertical mixing of clasts are identified in this pipe. According to Johnson (1991, 1994), sericitization and silicification of the rocks are prevalent to depths of 1,150 ft (351 m); propylitization (mainly chlorite and calcite) is dominant from 1,150 to 2,430 ft (351 to 741 m); and weak potassic and sericitic alteration occur below 2,430 ft (741 m) in the pipe.



**Figure 5.** Photograph of Fisher Mountain, site of the Fisher Mountain stock and mineral deposits, viewed toward the northeast from Daisy Pass (see fig. 1). The disturbed area in the center is the historic McLaren open-pit gold mine—last worked in 1953. Photograph taken in 1992.

## Homestake Stock

A stock of biotite dacite porphyry, herein referred to as the Homestake stock, forms the bulk of the intrusive rocks at the north end of Henderson Mountain (fig. 2). The stock is crosscut by magmatic and explosion-collapse, pipe-shaped breccia bodies, referred to here collectively as the Homestake breccia (figs. 1 and 2). The dacite porphyry of the Homestake stock is similar in composition and texture to the biotite dacite porphyry of an early phase of the Fisher Mountain stock. This observation, combined with the crosscutting relations observed by Johnson (1991) for the Fisher Mountain stock, indicate that the Homestake stock predates the extrusive Absaroka Volcanic Supergroup rocks in the immediate area. Zircon was collected from dacite porphyry of the Homestake stock near the historic Homestake mine (fig. 1). Elliott (1979) reported a fission-track age determination of the zircon of  $40.6 \pm 3.5$  Ma. Crosscutting relations between the dacite porphyry and other intrusive rocks suggest that the dacite porphyry was emplaced in several separate events. The  $40.6 \pm 3.5$ -Ma age may be a minimum age.

If so, emplacement of the stock overlaps the eruptive history of the Absaroka volcanic field in the region (53–43.5 Ma), as determined by Hiza (1998, 1999). In any case, the Homestake stock was emplaced in Henderson Mountain sometime in the middle Eocene.

The Homestake stock, including the breccia-pipe complex (the Homestake breccia) at its center, is approximately circular in plan view, and it has a north-south (longest dimension) diameter of about 4,000 ft (1,219 m) (fig. 2). The deepest core drilling into the stock, to depths of more than 2,300 ft (701 m), did not penetrate the base of the dacite porphyry. The stock is bounded on the east by Cambrian sedimentary rocks and Precambrian granitic rocks, on the south by the younger Henderson Mountain stock, on the west by Cambrian sedimentary rocks, and on the north by Cambrian sedimentary rocks and the Fisher Mountain stock (Elliott, 1979; Van Gosen, 1994, his plate 1). Sill-like bodies of dacite porphyry that radiate outward from the stock intruded Cambrian sedimentary rocks, the Fisher Mountain stock, and Precambrian rocks.

The Homestake stock ranges from dacite to rhyodacite in modal composition. Elliott (1979) mapped the stock as a quartz “eye” rhyodacite. Some parts of the stock tend toward trachytic modal compositions. This likely indicates secondary, hydrothermal, potassium enrichment of the rock as a result of crystallization of potassium feldspar, biotite, or illite. The general visual character of the Homestake stock (Eyrich, 1969; Horral, 1966; Johnson, 1991; Lovering, 1924, 1929; Van Gosen, 1994) is light-gray to very light gray rock with medium- to coarse-grained phenocrysts floating in a holocrystalline, aphanitic to very fine grained groundmass (grain size less than 60 µm). Phenocrysts compose 15–60 percent of the rock, generally forming 30–40 percent of the rock. The phenocrysts are plagioclase, quartz “eyes,” biotite, potassium feldspar, hornblende, and accessory apatite, zircon, magnetite, and ilmenite.

Phyllic and propylitic alteration are ubiquitous in the Homestake stock. No rock from this unit examined in outcrop or drill core appeared to be truly fresh and unaltered. Finely disseminated pyrite is common, typically constituting about 1 percent of the rock volume. The pyrite is encased in other alteration products (clay minerals, calcite, and albite(?)).

The Homestake stock was intruded by several dikes and sills of latite porphyry, andesite porphyry, and dacite porphyry. These dikes and sills apparently are spatially, compositionally, and mineralogically related to the main stock.

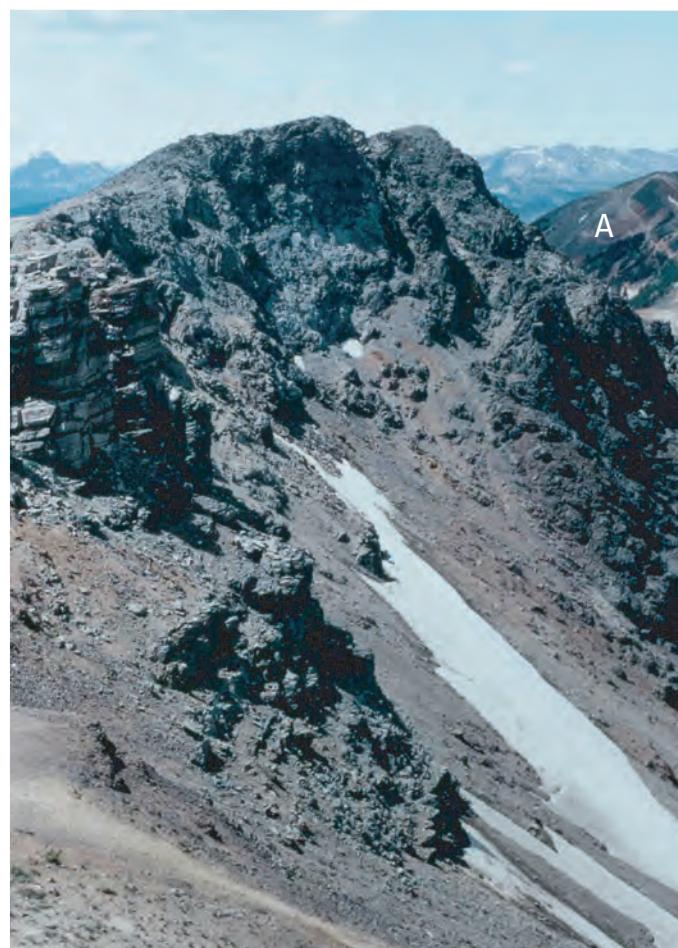
## Homestake Breccia

The Homestake breccia, at the northern end of Henderson Mountain (figs. 1 and 2), is a breccia-pipe complex composed of mineralized and altered bodies of intrusion breccia, shatter breccia composed of sedimentary and intrusive rocks, and diatreme breccia. The term “Homestake breccia” in this discussion refers to all of the brecciated bodies enclosed by the Homestake stock. The Homestake breccia is roughly elliptical in plan view, and, except for a sill-like extension to the northwest, it is elongated in a northeast-southwest direction over a distance of about 2,900 ft (884 m) (fig. 2). It is well exposed on the crest and east-facing slopes of the northern part of Henderson Mountain (fig. 6). The Homestake stock nearly encloses the Homestake breccia on its northern, eastern, and western sides. The Henderson Mountain stock (or laccolith) contacts and intrudes the southern perimeter of the Homestake breccia. In terms of rock volume, the intrusion-breccia bodies are the dominant style of brecciation in the Homestake breccia.

Intrusion of the Homestake and Henderson Mountain stocks displaced Cambrian strata to the south, southeast, and east of the Homestake breccia. Large blocks or “islands” of altered Cambrian strata that were rafted at least 400 ft (122 m) upward by the stocks now are on the crest of Henderson Mountain adjacent to the Homestake breccia (Elliott, 1979).

All of the Cambrian stratigraphic units of the northern New World district, including rocks of the Flathead

Sandstone through the Snowy Range Formation (fig. 4), are present as blocks or clasts within the Homestake breccia. The blocks and clasts that originated from clastic intervals (shales and mudstones) of the Cambrian sedimentary section were metamorphosed. They contain a calc-silicate mineral assemblage of epidote, garnet, potassium feldspar, chlorite, and apatite. Calc-silicate alteration in the clastic breccia material is characteristic of all bodies and styles of breccia in the breccia pipe. In the uplifted unbreciated Cambrian strata adjacent to the breccia pipe, shale- and mudstone-rich horizons also contain calc-silicate alteration of garnet-epidote-chlorite-potassium feldspar with subordinate pyroxene. In contrast, breccia clasts composed of Cambrian limestone, especially those of Meagher Limestone and Pilgrim Limestone (fig. 4), were selectively and nearly completely replaced by sulfide and iron-oxide minerals that constitute the Homestake gold-copper-silver deposit.



**Figure 6.** Photograph of north-facing view of Homestake breccia on the northern end of Henderson Mountain. Outcrop of strata in the left foreground consists of hornfelsed lower units of Pilgrim Limestone. Lower peak labeled “A” is Fisher Mountain (fig. 5). Homestake breccia, cut by dikes and sills, forms most of the ridge crest and east-facing slopes in the center of the view. Photograph taken in July 1992.

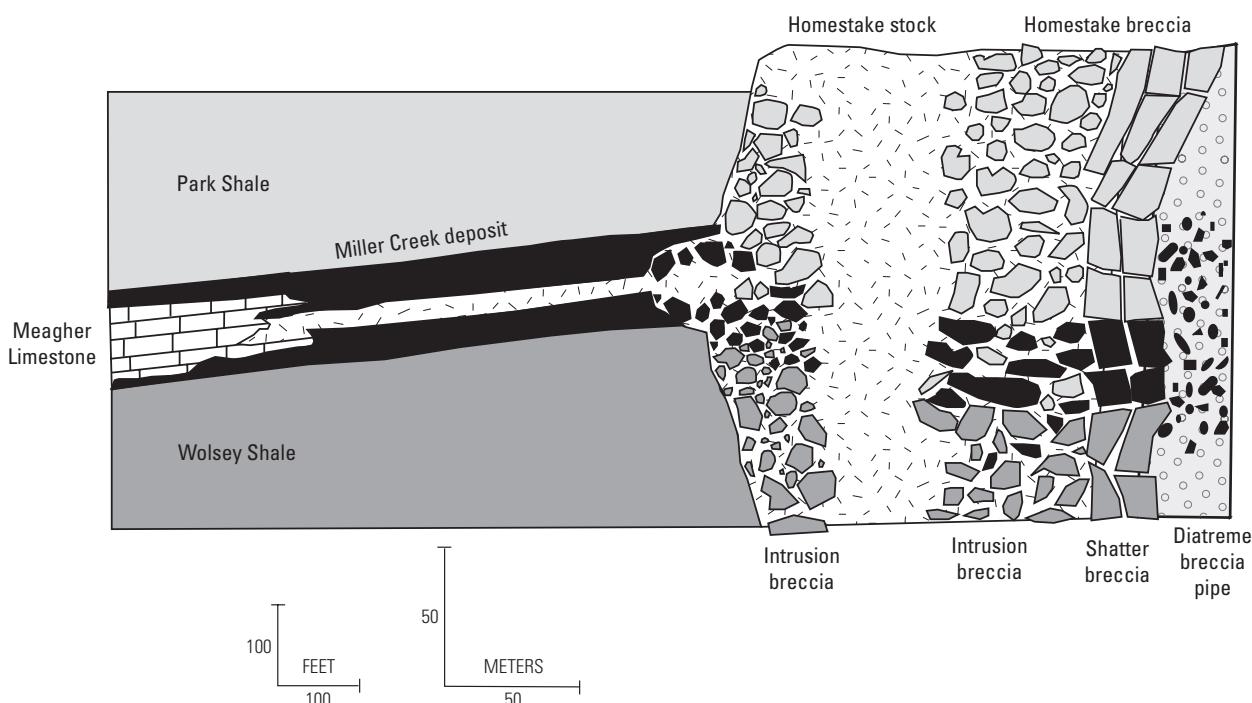
Although many of the mineral deposits in these three breccia facies are widely separated spatially, they are similar in composition. Intense hydrothermal alteration is widespread through all of the breccia types. Overlapping imprints of propylitic and phyllitic alteration in the upper zones of the Homestake breccia are indicated by assemblages of chlorite, carbonate minerals (calcite, ankerite, siderite), pyrite, chalcopyrite, hematite (specularite), vein and vuggy quartz, and subordinate epidote and potassium feldspar. The deep holes drilled into the Homestake breccia indicate that argillic alteration is prominent below a depth of about 1,000 ft (305 m). This alteration appears to be comparable to the kaolinite-rich subzone of a copper-porphyry system described by Sillitoe (1973, 1976).

The intrusion breccia bodies are composed of a variety of clasts and blocks of sedimentary and igneous rocks (fig. 7), cemented by an igneous matrix and subsequently altered. The characteristics of this breccia facies are consistent with the term “intrusion breccia” as defined by Sillitoe (1985): “\* \* \* the products of the mechanical fragmentation and incorporation of wall rocks by intrusive magma \* \* \* common \* \* \* near the walls and roofs of subvolcanic stocks, and in porphyry-type deposits.” The intrusion breccias likely formed as products of magmatic stoping and injection of magma, processes that followed emplacement of the Homestake stock. Numerous clasts and blocks of dacite porphyry from the Homestake stock are entrained by intrusion breccias, indicating that emplacement of the intrusion-breccia facies followed stock emplacement. Small- and large-scale flow banding in the igneous matrix of the intrusion breccias indicates that this breccia type formed by magmatic processes. Compositinally, the matrix appears to represent a quenched equivalent of the

magma that formed the Homestake stock (Van Gosen, 1994, p. 88–89). Considerable rotation and juxtaposition of rock fragments occurred within these breccias. Individual clasts have been displaced by at least 500 ft (152 m) from their expected stratigraphic position. However, the general relic stratigraphy of the Cambrian sedimentary section was crudely retained across the Homestake breccia, including the intrusion breccias.

Parts of the Homestake breccia as wide as 525 ft (160 m) consist of mosaics of rotated large blocks of Cambrian strata, referred to in this discussion as “shatter breccia.” These breccia bodies consist mainly of large blocks with little matrix material. Blocks range from a few feet in diameter to several tens of feet across, and they are angular to subangular in shape—suggesting the blocks were transported only short distances in the pipe. The fractures that form the blocks appear to propagate vertically and laterally into the intrusion breccias. The shattering events that formed shatter breccia appear to have concurrently fractured the adjacent bodies of intrusion breccia, indicating that the intrusion breccia was competent or at least partially lithified when fractured. The shatter-breccia zones locally host thick and laterally continuous intervals of high-grade gold concentrations, especially within the horizons dominated by limestone of the Meagher Limestone and Pilgrim Limestone.

Diatreme breccia pipes commonly intruded the bodies of shatter breccia. Fragments of shatter breccia are entrained in the diatreme pipes. Voids between blocks of shatter breccia locally are filled by chloritic-rich rock flour that contains small clasts of wallrocks. This chloritic material is similar to the matrices of the vertical, crosscutting, funnel-shaped diatreme breccia pipes. Microscopic observations indicate that chloritization of the rock flour probably accompanied diatreme emplacement.



**Figure 7.** Schematic cross section illustrating the geologic setting of the stratabound Miller Creek gold-copper-silver deposits relative to the Homestake deposits. Replacement deposit material is shown as solid black.

As is the case with the intrusion breccias, relic stratigraphy is crudely maintained in the block-dominated shatter breccias. At a given horizon in the Homestake breccia, most of the clasts were derived from a single sedimentary formation, and those fragments generally are near or below their projected stratigraphic position. Downward movement of fragments probably resulted from the collapse of the entire breccia pipe that accompanied withdrawal of magma from below.

Breccia pipes and pebble dikes with characteristics consistent with phreatic-explosion origin cut across the intrusion and shatter breccias. The largest mass of diatreme breccia, approximately 640 ft (195 m) wide (north-south), is near the center of the Homestake breccia (see plate 1 of Van Gosen, 1994). The diatreme breccia pipes share steep contacts with adjacent intrusive rocks and other breccia bodies. The diatreme breccia pipes are primarily matrix dominated; clasts compose about 20–30 percent of the mass. The matrix typically is dark green; in some places it is dark-gray rock flour that is intensely chloritized. The rock flour is composed of subangular to subrounded, microfractured lithic and mineral fragments that range in size from silt to very fine sand. The silt-size mineral grains are epidote, calcite, or a white clay mineral, likely smectite, with a silky texture. Clasts are subangular to subrounded fragments of Precambrian basement granitic rocks, local Cambrian sedimentary rocks, and dacite porphyry. The diatreme breccia contains rare blocks several tens of feet to more than 100 ft (30 m) in diameter, but clast size typically is 3 to 6 inches (8 to 15 cm) in diameter. The degree of clast rounding likely was controlled by original rock competence and vertical distance of transport. Individual clasts in the diatreme pipes are as high as 500 ft (152 m) above their expected stratigraphic position, but they also commonly are below their normal position. Thus, a late internal collapse of the entire breccia complex is indicated, which occurred subsequent to the upward movement of clasts caused by stock emplacement and breccia-forming processes.

Vertical streaming of clasts and blocks in the diatreme pipes is interpreted on the basis of common rotation of blocks and clasts with their long dimensions oriented subparallel to the dominant vertical-flow foliations defined by fine fragments. The extreme mixture of rock types and the vertical-flow structures within the pipes indicate forceful, high-energy processes such as explosions. The chlorite-rich matrix material that carried small rock fragments was also injected into adjacent wallrocks and older breccias. In addition, the diatreme breccia pipes cut across several zones of gold-silver-copper mineralization. The forceful emplacement of diatreme pipes locally reduced and diluted ore-grade material by fragmenting and vertically spreading zones of gold-copper-silver replacement mineralization. That observation supports the hypothesis that diatreme breccia-pipe emplacement in the Homestake breccia occurred after the intrusion breccias, shatter breccias, and gold-copper-silver deposits had formed. The overall characteristics of the late breccia pipes suggest that they formed from phreatic explosions; therefore they represent diatremes in the upper level of a volcanic system.

## Homestake and Miller Creek Deposits—Mineralogy and Genesis

The Homestake deposit consists of several gold-copper-silver-rich intervals of similar composition that are hosted by the Homestake breccia (Kirk and Johnson, 1993). The gold-copper-silver mineralization appears to be discontinuous on a small scale because the deposits consist of selectively replaced, discrete limestone blocks and clasts. At a larger scale, composite intervals maintain high gold grades, both laterally and vertically. Typical high-grade zones are listed in table 2. These and other intervals were the primary targets of the proposed New World mine. These deposits are present mainly as massive sulfide and iron-oxide replacements of limey blocks and clasts from calcareous intervals of the Homestake breccia, particularly breccia horizons that are dominantly clasts of the Meagher Limestone and the lower part of the Pilgrim Limestone (fig. 7). Gold-rich mineralization replaces (1) xenolithic blocks and clasts in intrusion breccias, (2) limey strata within shatter breccias, and (3) transported blocks and clasts in diatreme breccias. Less pervasive and less continuous gold mineralization is in thin pyritic veinlets that cut the bounding Homestake stock.

The primary ore mineral in the Homestake deposit is native gold, which occurs as grains and inclusions ranging from 1 to at least 700  $\mu\text{m}$  in diameter. The gold grains occur in a variety of mineralogical settings; most are associated with pyrite. Gold grains occur (1) as inclusions within pyrite (most common) (fig. 8) and chalcopyrite (less common), (2) in microfractures within pyrite grains, (3) occasionally in interstitial portions (and possibly included within aggregates) of gangue minerals, and, in some cases, (4) intergrown with specularite (Van Gosen, 1994).

## Alteration Patterns

The distribution of the gold deposits was controlled by the host protolith. Assays of drill core indicate that the gold-silver-copper-rich intervals are localized along horizons in the Homestake breccia (see plate 2 of Van Gosen, 1994): (1) about 430 ft (131 m) below the crest of Henderson Mountain, where intrusion and shatter breccias contain abundant xenoliths of rafted lower Pilgrim Limestone, and (2) about 500 ft (152 m) deep and lower, where the dominant clast lithology is Meagher Limestone. The Homestake breccia is a heterogenous mixture of fragmented sedimentary, intrusive, and Precambrian granitic rock. In each mineralized-breccia mass, limestone clasts are generally replaced by sulfide minerals. In contrast, in the same breccias, clasts and blocks of siltstone, shale, and mudstone—lithologies that form the bulk of the Park Shale and Wolsey Shale (fig. 4)—consistently contain calc-silicate mineralization and little gold-silver-copper enrichment. Clasts comprised of dacite porphyry typically show low to moderate enrichments of gold, copper, and silver in comparison to the values in calcareous rocks only inches away from the igneous clasts. Fragments of Precambrian granitic rocks, deep in the breccia pipe, are only weakly mineralized.

**Table 2.** Selected assay results for intervals of the Homestake breccia deposits as reported by Noranda Exploration and Crown Butte Mines.

[Data from Danielson (1991a, 1991c, 1992); Kirk and Johnson (1993); The Northern Miner (1990a, 1990b, 1991a, 1991d). nr, not reported; opt, ounces (troy) per short ton]

Interval thickness (feet)	Interval thickness (meters)	Gold (opt)	Silver (opt)	Copper (percent)
122.5	37.3	0.22	0.48	0.57
49.6	15.1	0.49	1.10	1.01
247.0	75.3	0.32	1.31	1.27
188.4	57.4	0.24	0.59	0.90
120.0	36.6	0.51	1.15	0.43
95.4	29.1	0.24	1.93	1.75
70.0	21.3	0.44	nr	0.66
75.0	22.9	0.27	2.67	0.98
85.0	25.9	0.24	2.01	0.82
379.2	115.6	0.30	nr	nr
126.7	38.6	0.22	0.88	0.77
73.2	22.3	0.23	0.91	0.48
87.1	26.5	0.23	1.47	0.47
117.9	35.9	0.17	0.69	0.64
90.0	27.4	0.26	0.67	0.43
182.0	55.5	0.17	nr	nr
249.0	75.9	0.22	nr	nr
558.0	170.1	0.14	nr	nr
364.0	110.9	0.20	nr	nr

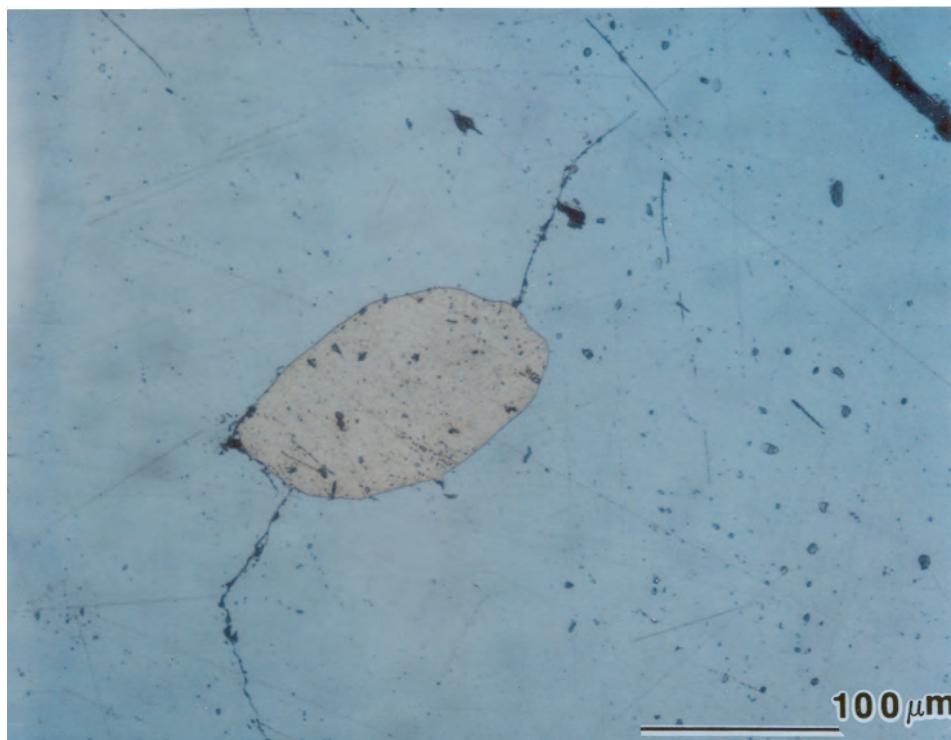
Petrographic and field observations of the Homestake breccia (Van Gosen, 1994) indicate that calc-silicate alteration of the fine-grained detrital rocks was an early phase of metamorphism localized in and around the Homestake stock. Johnson (1991, 1992, 1994) interpreted a similar early hornfels phase for clastic rocks of the Fisher Mountain area. He proposed a local prograde influx of relatively high temperature fluids (hotter than 600°C) that developed during emplacement of the Fisher Mountain stock. A similar hydrothermal process affected the Homestake stock, the Homestake breccia, and the surrounding sedimentary rocks. This early calc-silicate alteration of the fine-grained clastic rocks probably had a strong influence on subsequent gold-copper-silver deposition. The Miller Creek deposits, which consist of tabular stratabound gold-copper-silver skarn mineralization of nearly identical ore mineralogy to that of the Homestake deposit (Kirk and Johnson, 1993), extends laterally outward from the Homestake breccia (fig. 7). These deposits are best developed along the upper and lower contacts of the Meagher Limestone.

The geometries of the Miller Creek deposits (fig. 7) suggest that the early calc-silicate alteration was developed in the overlying Park Shale and underlying Wolsey Shale prior to the introduction of ore-forming hydrothermal fluids. These two clastic units, with their porosities greatly reduced by early epidote-garnet hornfels development, acted as impermeable barriers to upward ore-fluid migration, and the fluids were channeled laterally into the Meagher Limestone. Similarly, hornfelsed blocks of Park Shale apparently sealed the upwelling hydrothermal ore-bearing fluids. The fluids did not reach many of the Pilgrim Limestone blocks (shatter breccia) in the upper Homestake breccia near the

present crest of Henderson Mountain. The gold-bearing solutions locally penetrated some upper portions of the breccia pipe through conduits such as faults, fracture systems, and breccia pipes.

Argillic alteration in the dacite porphyry of the Homestake stock, deep within the Homestake breccia, appears to have been coeval with the introduction of sulfide minerals. The overall patterns of argillic alteration deep within the Homestake breccia, overlain by overlapping zones of phyllitic and propylitic alteration, suggest that a direct relationship existed between fluids that emanated from the stock below and the replacement ore bodies above. Multiple events of hydrothermal shattering and sulfide deposition within the Homestake stock are evident in core samples from lower intervals of the deepest drill holes.

At depths of about 1,150 ft (351 m) and greater, the Homestake breccia is characterized by angular to subangular clasts with a pyritic matrix and as much as 5 percent chalcopyrite; most of the clasts and matrix material at that depth are shattered dacite porphyry. Sulfide minerals, primarily pyrite, constitute as much as 75 percent of the rock in intervals as thick as 1.5 ft (0.5 m). Breccia in cores from the bottom of drill holes at slightly more than 2,000 ft (610 m) depth are characterized by intense argillic alteration; the original grains are almost completely replaced by kaolinite and quartz. Pyrite, chalcopyrite, and quartz form the matrix of the breccia (probably best described as a magmatic-hydrothermal breccia, as defined by Sillitoe, 1985). These minerals commonly are internally fractured, suggesting multiple episodes of shattering that were likely caused by the explosive pressures of hydrothermal fluids.



**Figure 8.** Photomicrograph showing the most common form of native gold in the Homestake deposit—an oblong gold inclusion along a microfracture in pyrite. Photograph taken in reflected light. Width of view approximately 0.5 mm.

## Mineral Assemblages and Paragenesis

The mineral assemblages of the Homestake breccia were studied in outcrop and in drill core samples, by means of microscopic examination of polished thin sections. X-ray diffraction techniques, reflected- and transmitted-light microscopy, and scanning electron microscopy (with semiquantitative analysis capability) were used for mineral identification. The minerals were deposited in four main stages (table 3): (1) *early metamorphism*-assemblage minerals (calc-silicate alteration) formed mostly in clastic-rich Cambrian rocks within and immediately adjacent to the Homestake breccia, (2) *massive ore-deposit-formation*-assemblage minerals that selectively replaced calcareous rocks in the Homestake breccia and limestones adjacent to the breccia pipe (the Miller Creek deposit, figs. 2 and 7), (3) *post-deposit alteration*-assemblage minerals, and (4) *recent-oxidation*-assemblage minerals.

The *early metamorphism* assemblage is characterized by fine-grained garnet (fig. 9), epidote, and potassium feldspar; locally abundant apatite; subordinate amphibole, calcite, and chlorite; and traces of quartz, clay minerals, pyrite, chalcopyrite, specularite, and magnetite (table 3). This calc-silicate hornfels alteration is best developed in the calcareous, fissile laminae of the lower part of the Park Shale. Outcrop, drill core, and microscopic examinations indicate that the early calc-silicate alteration caused the siltstone and shale clasts in the Homestake breccia to be comparatively less enriched in gold, silver, and copper than their less altered limestone and dolomite clast counterparts, which were only bleached and slightly recrystallized by the metamorphism. In breccia clasts that are dominated by closely packed epidote and garnet, the sulfide and iron-oxide ore-bearing minerals are consistently

only present in trace quantities, and gold, silver, and copper grades are low.

Following the early calc-silicate alteration, an episode (or, more likely, multiple sequential episodes) of *massive ore-deposit formation* occurred within the Homestake breccia, resulting in deposition of significant sulfide- and iron-oxide-replacement bodies. The highest concentrations of gold, silver, and copper in the Homestake breccia are associated with deposition of these replacement minerals. This mineral assemblage consists mostly of pyrite, chalcopyrite, specularite, and magnetite, with a gangue assemblage of carbonate minerals (calcite, ankerite, and siderite), chlorite, quartz, clay minerals, and potassium feldspars (table 3). Trace amounts of argentiferous galena, native gold, a silver-bismuth-sulfide (unidentified), a copper-bismuth-sulfide (unidentified), mckinstryite, aikinite, and tetrahedrite also formed (table 3).

Pyrite and chalcopyrite are the most plentiful sulfide phases in the assemblage. Pyrite surpasses chalcopyrite in total abundance, although both are common throughout the deposits. All combinations of pyrite grain size and habit are present, but medium grain size and subhedral habit are typical. Locally, pyrite forms as much as 50 percent of the breccia. Chalcopyrite typically is anhedral, but subhedral grains are common. Specularite and magnetite are very abundant in the Homestake deposit. Acicular grains of complexly zoned specularite-magnetite form radiating aggregates of needles without apparent preferred orientations (figs. 10 and 11). Microscopic observations suggest that all of these minerals were deposited simultaneously or nearly so (Van Gosen, 1994). For example, chalcopyrite aggregates in places include very fine grained inclusions of euhedral pyrite and (or) acicular, zoned specularite-magnetite grains. Similarly, the pyrite grains commonly

contain anhedral inclusions of chalcopyrite or acicular specularite-magnetite grains. No consistent relationship of mineral replacement was observed among the pyrite, chalcopyrite, and zoned specularite-magnetite minerals; rather, it appears that they grew intertwined simultaneously. Photomicrographs showing common intergrowth relations of the primary ore minerals are shown in figures 10, 11, and 12. This mineral assemblage, interpreted to have been coeval in deposition, suggests that the precious-metal-bearing fluids that flooded the Homestake breccia were relatively oxidizing, sulfur rich, and acidic. This mineral assemblage, with coeval deposition, is uncommon in the literature.

Several minerals that are common to all portions of the Homestake breccia apparently formed subsequent to the main mineral-deposit-forming stage. These are the *post-deposit alteration* minerals (table 3). Many of these minerals probably grew shortly after the sulfide and iron-oxide phases, and they possibly formed during the cooling of the ore-bear-

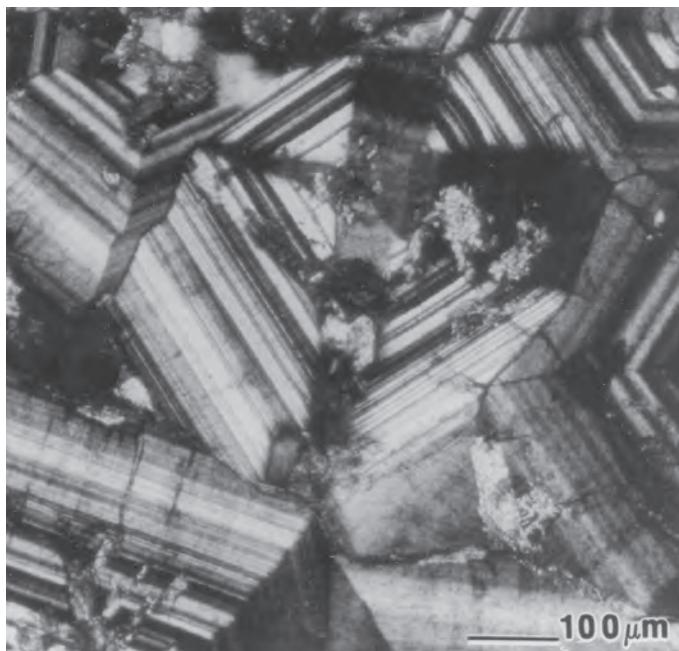
ing hydrothermal fluids. Minerals such as red hematite, maghemite, wustite, bornite, and covellite probably precipitated while the sulfide-rich, oxidizing fluids reestablished equilibrium throughout the complex immediately following the fluid-rock interactions associated with deposition of the replacement deposits. For example, the pH and oxidation potential of the hydrothermal fluids in contact with the Homestake breccia likely changed following the replacement processes, contributing to deposition of the post-deposit mineral assemblage.

Coarse-grained, generally euhedral quartz commonly fills and coats vugs throughout the Homestake breccia. Fine- to medium-grained, clear, euhedral dolomite crystals with a yellowish-brown tint commonly encrust the vug-filling late-stage quartz. Subhedral, fine- to medium-grained calcite replaces skeletal grains of acicular specularite-magnetite. The crystalline calcite appears “fresh” compared to earlier generations of calcite. This late-stage calcite and the

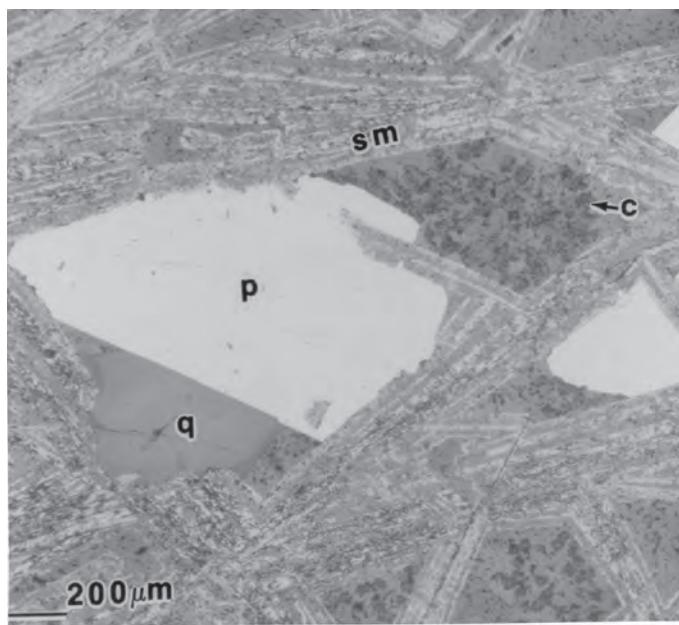
**Table 3.** List of minerals identified in the Homestake breccia, showing their position in the paragenetic sequence.

[Thick lines indicate major phases of deposition for the mineral; thin lines indicate minor phases of deposition. Query (?) indicates uncertainty of mineral's presence in that depositional phase]

	Early metamorphism	Massive ore deposit formation	Post-deposit alteration	Recent oxidation
Garnet	—	—	—	—
Epidote	—	—	—	—
Potassium feldspar	—	—	—	—
Apatite	—	—	—	—
Amphiboles	—	—	—	—
Quartz	—	—	—	—
Calcite	—	—	—	—
Chlorite	—	—	—	—
Clay minerals	—	—	—	—
Pyrite	—	—	—	—
Chalcopyrite	—	—	—	—
Specularite	—	—	—	—
Magnetite	—	—	—	—
Native gold	—	—	—	—
Ankerite	—	—	—	—
Siderite	—	—	—	—
Galena	—	—	—	—
Ag-Bi sulfide	—	—	—	—
Cu-Bi sulfide	—	—	—	—
Mckinstryite	—	—	—	—
Aikinite	—	—	—	—
Tetrahedrite	—	—	—	—
Dolomite	—	—	—	—
Red hematite	—	—	—	—
Wustite	—	—	—	—
Bornite	—	—	—	—
Maghemite	—	—	—	—
Covellite	—	—	—	?
Hydrous iron oxides	—	—	—	—
Manganese hydroxides	—	—	—	—
Malachite	—	—	—	—



**Figure 9.** Photomicrograph showing banded garnets from the core of Homestake breccia exhibiting concentric-growth zonation. Garnets such as these are commonly associated with epidote in mudstone-rich breccia clasts of Homestake breccia; they represent an early calc-silicate hornfels alteration of the detrital rocks. Photograph taken with crossed polarizers. Width of view approximately 1 mm.



**Figure 10.** Photomicrograph showing coexisting intergrowth of zoned acicular specularite-magnetite (sm) with euhedral pyrite (p) grains and interstitial quartz (q) and chlorite (c, dark blotches) in quartz. Notice that the specularite-magnetite needles are oriented parallel to the edges of the pyrite grains, which is common in the Homestake ores. Photograph taken in reflected light. Width of view approximately 2 mm.

vuggy dolomite probably were derived from magnesium and carbonate liberated during the dissolution and replacement of limestone and dolomite by ore solutions. Some of the clay minerals, ankerite, and siderite that are interstitial to the breccia also may have formed during this stage.

As a result of mass wasting and relatively recent glacial erosion of the Homestake breccia, oxidation of the Homestake deposit has occurred, but only to shallow depths. Core drilling showed that the zone of oxidation extends no more than a few tens of feet (less than 20 m) beneath the surface. Thus, supergene processes negligibly enriched the Homestake ores.

However, outcrops of the Homestake breccia generally are covered by a thin, dark-brown gossan composed of hydrous iron oxides (limonite, goethite) and manganese hydroxides (pyrolusite). The gossan is a product of near-surface *recent oxidation* of specularite, magnetite, and pyrite. The surficial gossan layer typically yields weakly anomalous (<0.05 opt) or trace amounts of gold. Maghemite also replaces magnetite in outcrops and near-surface rocks. Malachite and fine-grained aggregates of covellite locally replace chalcopyrite.

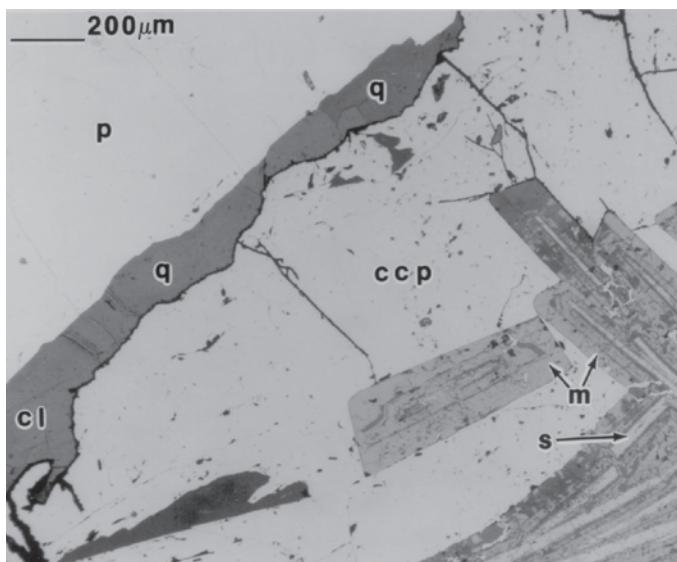
## Geochemistry

Coprecipitation of pyrite, chalcopyrite, specularite, and magnetite in the gold-copper-silver-rich mineral assemblage suggests that the precious metal-bearing hydrothermal fluids were oxidizing and were sulfur rich. Inspection of geochemical data (Van Gosen, 1994) and deposit mineralogy indicate that the Homestake mineral deposits contain anomalously high concentrations of Ag, As, Au, Bi, Cu, Fe, Pb, and S, relative to unaltered examples of the host rocks in the region, plus a less substantial enrichment of Nb and, likely, Co. This suite of metals in anomalous amounts, combined with the geology of the Homestake deposit, is consistent with descriptions of gold skarn deposits that are genetically associated with the upper levels of copper-porphyry systems (Cox, 1986; Einaudi, 1982; Meinert, 1989; Sillitoe, 1988, 1991; Theodore and others, 1991; Titley, 1982).

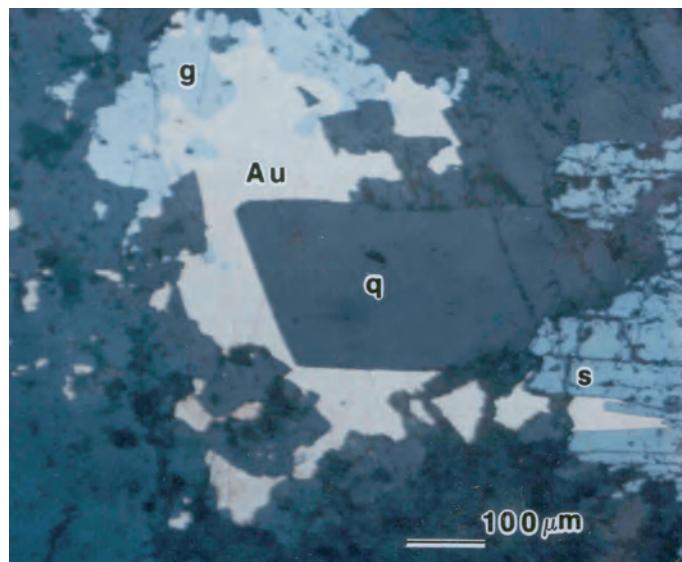
## Summary of Eocene Ore-Forming Processes

Based on the relationships described above, the list that follows is a brief summary of the main middle Eocene events and processes (from oldest to most recent) that combined to form the gold-copper-silver-enriched replacement bodies of the Homestake deposit and the closely related Miller Creek deposit.

1. During the middle Eocene, a magma chamber formed deep beneath the present locality of northern Henderson Mountain.



**Figure 11.** Photomicrograph showing zoned acicular crystals of specularite (s) and magnetite (m) enclosed by chalcopyrite (ccp). Pyrite (p), quartz (q), and calcite (cl) also form parts of this assemblage. Photograph taken in reflected light. Width of view approximately 2 mm.



**Figure 12.** Photomicrograph of a gold-rich ore. Native gold (Au) forms an intergrowth with acicular specularite (s), galena (g), and euhedral late-stage quartz (q). The groundmass of this ore is turbid, fine-grained carbonate minerals, chlorite, and moderate amounts of quartz. Photograph taken in combined reflected and transmitted light for enhancement. Width of view approximately 1 mm.

2. Dacitic magma rose through the crust and the Homestake stock was emplaced concurrently with emplacement of the nearby Fisher Mountain stock (fig. 2). The rising melt utilized a structural zone of crustal weakness with Precambrian ancestry—the Cooke City zone (fig. 3).
3. Intrusion of the Homestake magma was accompanied by calc-silicate metamorphism and low-grade gold mineralization of the clastic Cambrian rocks surrounding the intrusion (“early metamorphism” mineral assemblage, table 3). Interlayered Cambrian limestones were weakly recrystallized and bleached.
4. Intrusion breccias formed during magmatic stoping and injection of dacitic porphyry. This probably followed emplacement of the Homestake stock (on the basis of the presence of numerous dacite porphyry clasts entrained in the intrusion breccias). Cambrian sedimentary wallrocks were assimilated partially, or almost completely, by the ascending dacitic magma. Large sections (roof pendants) of caprocks were rafted upward.
5. Following solidification of the intrusion breccias, multiple events of hydrothermal shattering accompanied a flooding of relatively oxidized, sulfur-rich fluids upward throughout the newly formed Homestake breccia. The hydrothermal shattering formed facies of rotated shatter blocks (“shatter breccia”) in the roof pendants. Intense argillic alteration developed in deep shatter zones. Concurrently, limestone clasts and

blocks in upper parts of the Homestake breccia were selectively replaced by silver- and copper-bearing sulfide minerals and coeval iron-oxide minerals, accompanied by trace amounts of gold (“massive ore-deposit formation” mineral assemblage, table 3). Blocks and clasts of brecciated Cambrian Meagher Limestone and Pilgrim Limestone were particularly receptive to massive replacement, and they formed the bulk of the Homestake deposit. The lateral flow of the same fluids into Meagher strata along the perimeter of the Homestake breccia formed the adjacent, stratabound and tabular Miller Creek deposit (figs. 2 and 7).

6. Phreatic explosions occurred within the complex breccia pipe, forming vertical pipe-like bodies of diatreme breccia. The explosions probably followed a period of local fracture and fault development. Several diatreme breccia pipes formed in the upper levels of the Homestake breccia. They cut across and violently fragmented several previously formed mineral deposits and spread mineralized fragments upward. The effects were to *locally* dilute and expand previously continuous zones of mineralization.
7. An internal collapse of the entire Homestake breccia complex probably followed formation of the diatreme breccia pipes. Collapse likely accompanied withdrawal of an underlying magma chamber. The result was placement of the Cambrian sedimentary rocks in the Homestake breccia and their replacement deposits at positions below their original stratigraphic position.

## Post-Ore Henderson Mountain Stock

The Henderson Mountain stock, possibly a laccolith (Horral, 1966), intruded the southern flank of the Homestake stock and breccia pipe. It is predominantly dacite porphyry. No mineralization is associated with the contacts between the Homestake breccia and the Henderson Mountain stock. Elliott (1979) reported an age of  $44.0 \pm 4.1$  Ma for the porphyry at Henderson Mountain, based on fission-track data from zircon. That age is older than his fission-track age determination for the Homestake stock ( $40.6 \pm 3.5$  Ma). The Henderson Mountain stock clearly intrudes, cuts across, and thereby postdates the Homestake stock (Horral, 1966). Although the crosscutting relations indicating the Henderson Mountain stock is younger than the Homestake stock appear to disagree with the age determinations, they do not disagree when the accuracy range of the age-determination method is considered. For example, on the basis of fission-track data, a minimum age of 39.9 Ma is possible for the Henderson Mountain stock, compared to a possible maximum age of 44.1 Ma for the Homestake stock (Elliott, 1979).

## Alice E. Breccia

No gold-copper-silver ores are known to occur in the Alice E. breccia (an informal unit of local usage) (fig. 2); however, the breccia shares several alteration and geologic characteristics with the Homestake breccia (Van Gosen, 1994, p. 78–79). The Alice E. is an altered, heterolithologic breccia pipe on the southern boundary of the Henderson Mountain stock (fig. 2). The breccia pipe consists of fragmented and metasomatized Middle Cambrian sedimentary rocks that are mixed with sericitically and propylitically altered porphyritic rocks related to the Henderson Mountain stock (or laccolith) (Cope, 1984). Blocks and clasts of the sedimentary units in the breccia are metamorphosed, and they have alteration assemblages that are similar to those in the subeconomic rocks of the Homestake and Miller Creek deposits. Drilling of the Alice E. breccia by Crown Butte Mines-Noranda Exploration intercepted several sulfide-rich zones with anomalous gold and copper concentrations, mainly in breccia blocks of Meagher Limestone. The grades, however, were below the ore grades for the district. Crown Butte Mines (written commun., 1992) noted that the Meagher is noticeably thinner (50–80 ft or 15–24 m thick) and more silty near the Alice E. breccia than in outcrops near the Homestake breccia and Fisher Mountain stock. The thin and silty character of the Meagher Formation may have contributed to the lack of massive replacement mineralization and the low-grade gold concentrations ( $<0.05$  opt).

## Postmineralization Dikes and Sills

A number of dikes and sills cut across the Homestake breccia and its replacement deposits. The dikes and sills are compositionally and spatially related to the Homestake and Henderson Mountain stocks. Porphyritic dikes of dacite (most

common) and latite-filled dilation zones in the Homestake breccia intruded along contacts between dissimilar masses (such as different types of breccia bodies). The dikes also filled preexisting open fractures and faults in the country rocks surrounding the stock-breccia-pipe complex, forming concentric and radial patterns centered around the Homestake stock. These dikes and sills commonly are intensely altered, characterized by strong propylitic alteration and weak to moderate phyllitic alteration. Replacement minerals include calcite, quartz, iron oxides, and disseminated fine- to very fine grained pyrite. The dikes formed very minor skarn alteration zones ( $<2$  ft or 0.6 m in width) in the rocks they intruded. These late dikes and sills cut breccia masses that are only weakly mineralized, in spite of the favorable presence of dolomite clasts. Thus, the late dikes and sills were not conduits for the ore-bearing fluids. However, possibly they occupy preexisting structural zones that previously had served as plumbing systems for the gold-copper-silver-bearing solutions. Concentric and radial patterns of faults and fractures that formed around an intrusive center are common features in the subvolcanic levels of porphyry copper systems (Heidrick and Titley, 1982). Such patterns are thought to occur early during the emplacement of the pluton; typically they form at high levels in an intrusion system (Knapp and Norton, 1981).

## Recent History of the Homestake Deposit—Exploration, Discovery, Mining Attempts, and Controversy

The Cooke City area has been the site of many mineral discoveries and development since the arrival of the first European settlers in the Yellowstone region. The New World district was explored almost continually for more than 125 years. The discovery of the Fisher Mountain, Miller Creek, and Homestake deposits, between 1987 and 1990, was the culmination of the most recent exploration in the area. These resources will be protected for at least the near future by a mineral withdrawal for the area, enacted in 1997.

## 1860s to 1985—Early Prospecting and Mining

Most of the early mining history of the New World district that follows is summarized from Lovering (1929), who noted that “\* \* \* in the pioneer days of Montana the New World mining district was regarded as one of its most promising camps \* \* \*,” and “\* \* \* in the early [eighteen] eighties Cooke [City] had a population of over 2,000.”

The earliest exploration for mineral wealth in the New World district area preceded the establishment of Yellowstone National Park by several years. Rich discoveries of lead, silver, and gold within the district apparently were reported (or at least rumored) as early as 1868. However, the first documented discoveries were made in 1869 by four trappers who entered the

area to avoid pursuit by Indians. The trappers were robbed of their horses and supplies by the Indians along Cache Creek in Wyoming. They reportedly “\* \* \* narrowly escaped death and fled north up Cache Creek and crossed the divide that separates its headwaters from Republic Creek [about 5 mi or 8 km south of Cooke City]” (Lovering, 1929). The trappers noted manganese-stained outcrops at the future site of the Republic mine (fig. 1); they panned gold from the streams and reported their findings to the Crow Agency at Columbus, Mont. The district at that time was designated as part of the Crow Indian Reservation. Their news induced prospectors to stake mining and placer claims the next summer (1870) at Miller and Republic Mountains, short distances north and south of the soon-to-be town of Cooke City. A furnace was built in 1875 and lead ore was extracted from the Republic mine (fig. 1) and Miller Mountain (Gardner, 1914). Nez Pierce Indians destroyed the furnace and the mining records in 1878. They absconded with lead bullion, presumably to make bullets.

In 1882, the U.S. Government unilaterally removed the district from the Crow Indian Reservation and several mining claims were quickly established (Gardner, 1914). The “Cooke City or Republic” smelter was built in 1883 and went into production in 1884. Difficulties in smelting the complex ores from the Republic Mountain mine and costly freight rates closed the smelter and mine for the next 20 years. While the Republic mine and smelter remained closed, ore production in the district was intermittent and modest (Gardner, 1914; Brooks, 1921).

“Rich” gold ore was discovered at Henderson Mountain around 1888, at the Little Daisy and Homestake claims. During 1888 and 1889, about 420 tons of ore was produced from those claims (Reed, 1950). From the early 1900s to about 1930, the district and surrounding area was actively developed and several shafts were sunk. However, total district production was modest.

Henderson Mountain, including the Little Daisy and Homestake mines, was a site of development from 1904 until 1925. A 250-kilowatt power plant was built on the Clarks Fork of the Yellowstone River 4 mi (6 km) east of Cooke City in 1915 (Lovering, 1929). A 350-ton copper smelter was nearly completed along Fisher Creek (fig. 1) in 1921, but apparently it never went into production. At that time (1921) an adit was begun at the Gold Dust claim (fig. 1). It entered at the eastern base of Henderson Mountain, in Precambrian granitic rock, and was advanced westward into the Homestake breccia. From the autumn of 1923, until the autumn of 1925, (Lovering, 1929) an aerial tramway was constructed to connect this adit to the unfinished smelter along Fisher Creek. A few of the tramway towers remain standing today.

The high-grade Homestake deposits were not encountered by the Gold Dust adit, and no ore was mined or shipped during this period of development. The financiers of the Gold Dust and tramway developments abandoned the project in 1925, and the claims remained idle until 1947 (Reed, 1950). Stories (no written record) (Allan Kirk, oral commun., 1992) suggest that the primary fundraiser for the Gold Dust mine project embezzled

the money collected from investors and fled to Germany with the stolen money. Ironically, the Gold Dust adit came within a couple hundred feet of intercepting high-grade gold deposits that later were delineated by the core drilling of Crown Butte Mines in the 1990s. The Gold Dust adit was driven horizontally into the base of Henderson Mountain as a main haulage adit (see plate 2 of Van Gosen, 1994). However, construction stopped in 1925 when the financial support ended. The workings were less than 200 ft (60 m) from a highly mineralized zone with grades of more than 0.3 opt gold.

In the early 1920s, Lovering completed the first thorough geologic investigation of the New World district. His Ph.D. dissertation (Lovering, 1924) and a report for the U.S. Geological Survey (Lovering, 1929) described the district’s general geology and the exposed mineral deposits. Lovering witnessed the development of the Gold Dust adit during the early 1920s, but he completed his field studies before that mining venture was abandoned in 1925.

Modest production (70 tons daily) came from an open pit cut into the Homestake breccia (near the Homestake mine, fig. 1) during the 1940s (Reed, 1950). That modest open-pit operation also only scratched the surface of the Homestake breccia, and it did not encounter the high-grade deposits farther inside the mountain.

Most of the district’s production came from the McLaren open-pit mine (fig. 5), which began operation on a small scale in 1933 on the south flank of Fisher Mountain. Production records indicate that from about 1938 to 1953 the McLaren gold mine (operated by Gold Mines, Inc.) yielded 337,000 tons of ore with average grades of 0.184 opt gold, 0.26 opt silver, and 0.59 percent copper (Elliott and others, 1992; Johnson, 1991). A mill along Soda Butte Creek, a short distance east of Cooke City, processed the ores until it burned in 1953, halting all production from the McLaren mine. Tailings at the old mill site and unconsolidated mine material used to fill the old mine pit both assayed at more than 0.1 opt gold (Johnson, 1991).

The Irma and Republic mines (fig. 1) also produced ores from 1938 to 1950. Krohn and Weist (1977) reported that those operations produced about 12,500 tons of ore, averaging 10 percent lead, 5 percent zinc, and 20 opt silver.

From 1962 to 1982, several companies explored the New World district for large-tonnage porphyry copper-molybdenum deposits (Elliott and others, 1992; Lawson, 1981, 1982). Bear Creek Exploration Co. (then part of Kennecott Copper Co.) discovered and drilled the Como copper-silver-gold skarn and replacement deposit (fig. 2) between 1962 and 1973. Additional drilling was completed in the Como area during 1981–1982 by Ranchers Exploration (Hecla Mining Co.) (Engineering and Mining Journal, 1980; The Mining Record, 1980).

Mine Finders and Gulf Resources also actively explored the district for porphyry copper-molybdenum potential during the early 1980s. Apparently, those companies drilled exploratory holes from the top of Henderson Mountain that penetrated the Homestake deposit. However, assays for gold and copper were not conducted because molybdenum was the primary target and the molybdenum values were not considered to be economic.

## 1985 to 1996—Rich Discoveries, Controversy, and Federal Government Involvement

An exploration program within the district was initiated in 1985 by Plexus, Inc. (Allan Kirk, oral commun., 1992). In 1987, Crown Butte Mines, Inc., was founded by Plexus, Inc., to coordinate drilling for undiscovered reserves at the McLaren deposit area. Noranda Exploration, Inc., became the project manager in late 1987, forming a cooperative effort with Crown Butte Mines. Noranda Exploration–Crown Butte Mines concentrated efforts on exploration for skarn and replacement deposits in Cambrian carbonate rocks adjacent to and within the Eocene stocks in the northern part of the district (Kirk and Johnson, 1993). In the first phase of exploratory drilling, they expanded and delineated the copper-silver-gold reserves at the Como and McLaren deposits (fig. 2). An aggressive drilling program in the northern part of the district led to discovery of three “blind” deposits designated as the Fisher Mountain deposit (found in 1988), the Miller Creek deposit (1989), and the Homestake deposit (1990) (fig. 2). The progress of this exploration program was followed by articles in *Rocky Mountain Pay Dirt* (1990) and *The Northern Miner* (1990a,b, 1991a–e, 1992a–c; and Danielson, 1991a–c, 1992) and also discussions by McCulloch and others (1988) and McCulloch (1989).

From 1987 through 1993, Noranda Exploration–Crown Butte Mines drilled a total of 327,031 ft (99,674 m) in 856 exploratory and development holes within the district (Allan Kirk, project manager, written commun., 1994) using reverse circulation and core drilling. Their estimates of the in-place geologic reserves calculated at that time are listed in table 1.

During 1990, Noranda Exploration–Crown Butte Mines submitted a Hard Rock Mine Permit Application to the Montana Department of State Lands and the U.S. Forest Service. The plan included underground mining of the Miller Creek and Homestake deposits by room-and-pillar (or panel) methods, gaining access to the deposits through a 4,000-ft tunnel opening on the east side of Henderson Mountain. As explained by Kirk and others (1993), the extracted ore “will be transported via conveyor through an underground tunnel to the plant site that will be located in the Fisher Creek valley.” To avoid controversies associated with cyanide heap-leach ore processing, they proposed fine grinding of the ore, followed by sequential floatation processes to segregate the gold and copper (Kirk and Johnson, 1993; *The Northern Miner*, 1992a). A tailings impoundment was to be built in the Fisher Creek valley (Satchell, 1995, p. 41). The proposal did not include plans to mine the McLaren and Como open pits and Fisher Mountain underground reserves because of their lower grade; cyanide heap-leach processing was thought necessary to extract the gold from those oxidized materials (Kirk and Johnson, 1993; Kirk and others, 1993). In April of 1993, the permit application was accepted as complete

by the authorizing agencies, and an Environmental Impact Study was initiated.

From 1993 until 1997, including the time period in which negotiations occurred between the Federal Government and Crown Butte Mines (in 1996 and 1997, described in a subsequent paragraph), a massive Draft Environmental Impact Statement (DEIS) was prepared. It outlined possible alternatives for mining and “no mine” scenarios, and it analyzed the predicted impacts of each alternative (environmental, social, economic, scenic, and other impacts). This draft was written during a 4-year period by a contractor, using information provided by several Federal and State agencies. The final draft was more than 800 pages in length, not including appendixes and related documents.

The original draft (DEIS) addressed nine alternatives—a “no mine” alternative and eight other possibilities that placed the mill site, tailings disposal, and discharge of mine excess waters at different sites. One of the alternatives required trucking of the “pyritic tailings” (fine-grained mill-processed tailings or waste containing as much as 90 percent pyrite) out of the mine area to a disposal impoundment north of Cody, Wyo. A later draft reduced the alternatives to the “no mine” option and seven scenarios for placements of the mine and mill site, tailings disposal site, and excess mine-water discharge. The last DEIS consisted of 17 chapters and 6 appendixes, addressing issues such as Yellowstone National Park, geology and ground-water hydrology, surface-water hydrology, aquatic resources, cultural resources, area highways, grizzly bear habitat and population, economic conditions, social conditions, and others. A copy of the final DEIS is available through offices of the Gallatin National Forest or the Montana Department of Environmental Quality, the lead agencies responsible for the EIS and the analyses contained in it. The DEIS was not formally published because it never was officially approved for use.

The proposal for a “New World mine” provoked immediate, intense, and organized opposition, including groups such as the Greater Yellowstone Coalition and the Sierra Club. At least four factors were very strong influences on the ultimate success of the anti-mine effort:

1. Proximity of the proposed mine to Yellowstone National Park.
2. Publicity and impact of the 1992 Summitville mine environmental disaster in southwestern Colorado.
3. Environmental legacy of historic mines in the New World district.
4. Opposition to the mine by officials of the Federal Government Executive Branch, including President William Clinton and Secretary of the Interior Bruce Babbitt.

## Yellowstone National Park

Yellowstone National Park is regarded as a national and international treasure, at least in part because it was the first national park in the United States and the first designated national park in the world. The unique geothermal, scenic, and ecosystem features of the Park contribute to its stature. The proximity of the proposed New World mine to the Park boundary (less than 5 mi (8 km) from the northeast entrance) contributed to public sentiment in opposition to the mine. In regard to the proposed New World mine, Yellowstone National Park employee Dave Shaver stated that “\*\*\*the overriding National Park Service concern is the potential for adverse effects of mine operations on park water quality and related resources of the ecosystem” (Shaver, 1996). He added that “\*\*\*it would be difficult to find an environmentally more sensitive or controversial place to develop a large gold mine.” Paul Pritchard, president of the National Parks and Conservation Association, said the mine would cause “\*\*\*incredible demands on a pristine environment \* \* \* It’s about as bad a place to have a human intrusion as you can imagine” (Bama, 1996, p. 10). In December 1995, the World Heritage Committee, affiliated with the United Nations, declared that Yellowstone’s status as a United Nation’s designated World Heritage Site was in danger due to the mining proposal (Bama, 1996; Wilkinson, 1994). Michael V. Finley became superintendent of Yellowstone National Park in November 1994. He quickly announced his opposition to the proposed mine, stating “How can the logical mind approve this?” (Bama, 1996).

Ironically, during the period of debate over the proposed New World mine, the Mineral Hill gold and silver mine operated about 4 mi northeast of Gardiner and about 2.5 mi north of the Yellowstone National Park boundary; it was visible from Mammoth Hot Springs. The gold at the Mineral Hill mine was extracted from sulfide-bearing, arsenic-rich, iron-formation and quartz veins and boudins adjacent to the iron-formation. The gold is associated with pyrrhotite, pyrite, and arsenopyrite (Hammarstrom, Zientek, Elliott, and others, 1993).

## The Summitville Mine Environmental Disaster

From 1985 through 1992, the Summitville mine in southwestern Colorado extracted gold from a large, low-grade, pyritic ore using cyanide heap-leach methods. The mine’s operator had ceased mining and had started environmental remediation in 1992. The mining company declared bankruptcy in December of 1992, and abandoned the site. Environmental problems left at the Summitville mine included increased acidic and metal-rich drainage and leakage of cyanide-bearing solutions into nearby rivers. The Environmental Protection Agency immediately took control of the site, and it estimated the cost of cleanup to be \$100 million to \$120 million. The history and science applied to the Summitville mine were summarized in U.S. Geological Survey Bulletin 2220 (King, 1995). The Summitville mine disaster gained national

exposure, thereby focusing public attention on the possible negative effects of metal mining.

The Summitville environmental disaster was used as the showcase example in arguments against the New World mine project. Several national publications described worst-case environmental scenarios for the proposed New World mine (see Parks, 1994, and Wilkinson, 1994), and many of the articles also invoked comparisons to the Summitville mine. For example, an article in U.S. News & World Report (Satchell, 1995) made analogies to the Summitville disaster and said, regarding the New World mine operation, “\* \* \* depending on where the tailings are put, acidic runoff could leach poisonous heavy metals into one of three local creeks that flow into tributaries of the Yellowstone River.”

## Historic Mines in the New World District

Mining activity in the New World district in the 1950s and earlier left behind abandoned adits and open pits, mine wastes, and acidic drainage near the mines, such as at the McLaren (fig. 5) and Glengarry mines (fig. 1). Photographs of these features are included in articles by Parks (1994), Satchell (1995), and Wilkinson (1994). The poor environmental practices of past mining in the district, although the activities were legal during their times of operation, were used prominently in arguments against the proposed New World mine. For example, Wilkinson (1994, p. 32) wrote the following about the past and proposed mining in the district: “Evidence of what can go wrong ecologically is visible in nearby streams that today run red and sterile with acidic effluent from mining that ceased 40 years ago.” Using the historic mines as examples, Satchell (1995, p. 36) wrote, regarding the proposed New World mine, “\* \* \* by far the most feared long-term threat is acid drainage from abandoned mine tunnels and waste-rock tailings.”

The compositions of mine-drainage waters collected from several skarn- and polymetallic-replacement-deposit mining districts in the Rocky Mountain region, including the New World district, were studied by Plumlee and others (1999). They noted the following: “Mine-waters draining the skarn deposits at New World are quite acidic and have relatively high levels of dissolved metals \* \* \* We interpret this to reflect the lack of neutralizing reactions between the acid waters and the calc-silicate alteration minerals in the skarns, and the lack of reactions with any carbonate minerals that may remain in the original sedimentary host rocks.” Plumlee and others (1999) considered these results to be “intriguing” because in a ranking of acid-drainage potential for seven types of common ore deposits, Kwong (1993) judged skarn deposits to have the least potential to produce acid drainage. Kwong (1993, p. 6) stated that acid drainage “\* \* \* is not known to associate with skarn deposits.” It should be noted here that the water samples used in the analyses of Plumlee and others (1999) were obtained from adits and dumps of the Glengarry mine and dumps of the McLaren mine. Those samples thus were waters in contact with the McLaren and Como deposits (fig. 2), and they do not necessarily reflect the chemistry

of waters interacting with the Homestake and Miller Creek deposits, the main target of the proposed New World mine.

Gurrieri (1998) conducted a reconnaissance study of benthic organisms, water quality, and sediments in the upper Stillwater River headwaters downstream from the McLaren mine. Due to natural oxidation of the pyritic materials left exposed in the McLaren open pit (fig. 5), metals and sulfuric acid are released into the waters draining from the mine site in tributaries of the Stillwater River. In this area, Gurrieri (1998, p. 98) found elevated levels of metals in the waters and in the streambed sediments. He stated, “\* \* \* though chronic aquatic life water quality criteria were not exceeded at most main stem sites during the synoptic sampling event, the macroinvertebrate and periphyton communities were impaired.” He also modeled the pre-mining sediment conditions and concluded “\* \* \* the magnitude of pre-mining metal enrichment is shown to be small compared to the amplification from mining disturbances” (Gurrieri, 1998, p. 99). Critics of the New World mine argued that similar effects to Fisher Creek and Miller Creek (fig. 1) would result from the new mining operation proposed for adjacent Henderson Mountain.

Other studies in the northern New World district suggested that pre-mining metal concentrations in ground and surface waters might have been underestimated because natural acid drainage has occurred there for thousands of years. A study by Furniss and others (1999) of undisturbed ferricrete deposits at the headwaters area of Fisher Creek, and near Daisy Pass (fig. 1), showed that natural acid drainage carrying heavy metals from the mineral deposits of the northern New World district occurred long before mining began in the area. The ferricrete deposits record ancient acidic runoff in seeps and springs that date to at least 8,800 radiocarbon years before present (Furniss and others, 1999). Geochemical studies of peat bogs, overbank stream deposits, and tree rings in the district by Chamberlain (2000) revealed that (1) these streams have been naturally acidic, with high background levels of metals, for at least 8,000 radiocarbon years; (2) periods during which streams had high metal concentrations correlated with long-term climatic variations; and (3) tree rings show the effects of recent mining and also show that “\* \* \* the streams have a natural buffering capacity that returns streams to background levels within a few 10s of years.”

The host rocks and the ore bodies of the Homestake deposit contain large quantities of calcite, and thus they are expected to have an inherent capacity to neutralize acidic solutions produced by oxidation of the pyrite-rich mineral deposits. As noted previously, the Homestake ore minerals selectively replaced carbonate rocks. The calcium, magnesium, and carbon dioxide liberated from the carbonate rocks during replacement and ore deposition were reprecipitated in the mineral deposits and wallrocks as calcite, dolomite, and ankerite. The propylitic alteration that is ubiquitous in the Homestake stock also contains secondary calcite.

In a study of the waters draining from the historic Gold Dust adit (fig. 1), Miller and Gurrieri (1997) determined that “\* \* \* sulfide oxidation is occurring \* \* \* however, a near neu-

tral pH (7.3) and moderate bicarbonate ( $112 \text{ mgL}^{-1}$ ) [ $\text{mg/L}$ ], calcium ( $94 \text{ mgL}^{-1}$ ) and magnesium ( $27 \text{ mg/L}$ ) concentrations indicate that acidity is buffered by the deposit geology.” Based on the qualities of the Gold Dust adit waters and the results of humidity cell tests, Miller and Gurrieri (1997) predicted that adit discharges during operation of the New World mine would have “\*\*\*neutral pH, moderate bicarbonate ( $>120 \text{ mgL}^{-1}$ ), sulfate (circa  $500 \text{ mgL}^{-1}$ ), and metal (10 to 100  $\text{mgL}^{-1}$  total recoverable Al + Fe + Cu + Ag + Cr + Mn + Pb + Ni + Zn) concentrations.”

Because the host-rock environment is so heterogeneous within the Homestake deposits, it is impossible to accurately calculate the gross acid-generating/acid-neutralizing capacity of these rocks. Thus, it would be difficult to estimate the qualities of waters that could emit from an adit that cuts across the Homestake breccia or from seeps that could form on the flanks of Henderson Mountain due to mining. However, processed mill tailings, in which the pyritic material has been concentrated by ore processing, would produce more acidic solutions when finely ground and exposed in oxidized conditions than would the raw, massive ore material.

## Administration Policy

On August 25, 1995, President Clinton took a helicopter tour over the New World project. Later he told groups that he was concerned that the proposed mine could endanger the Yellowstone ecosystem, and he expressed his intent to invoke a moratorium on further mining claims on Federal lands in this area for 2 years (the *Federal Register*, Sept. 1, 1995). On August 28, 1995, Secretary of the Interior Bruce Babbitt approved a request to pursue withdrawal of approximately 19,000 acres in the Cooke City area from mineral location and entry for a 20-year period. The request and approval included implementation of a 2-year temporary withdrawal to allow studies to be completed, including preparation of an Environmental Impact Statement. The 2-year moratorium on new mining claims in the area, which did not include the active New World project claims, took effect on September 1, 1995, when it was announced in the *Federal Register*.

During 1996, President Clinton ordered senior Government officials, including Department of Agriculture Secretary Dan Glickman, to negotiate with officials of Crown Butte Resources and its parent company (Noranda Exploration) for a possible buyout or swap of the company’s holdings in the New World district for Federal lands elsewhere (Wilkinson, 1996a; The Denver Post, 1996). President Clinton announced on August 12, 1996, at the foot of Barrenette Peak in the northeast part of Yellowstone National Park, that an arrangement had been negotiated with the mining companies during the preceding year (Wilkinson, 1996b). Initially, the plan included a swap of the New World claims for Federal lands worth \$65 million.

## 1997 and 1998—Contract Settlement, Congressional Appropriation, and Mineral Withdrawal

In March of 1997, negotiators on behalf of the Executive Branch of the Federal Government, an attorney for the Sierra Club Legal Defense Fund, and representatives of the Greater Yellowstone Coalition offered a settlement agreement to Crown Butte Mines for the New World mine acquisition (Miniclier, 1997). In the settlement, the land and mineral rights of the New World project claims were to become the property of the U.S. Government; Crown Butte Mines would receive \$65 million for their claims and mineral rights, \$22.5 million of which would be set aside for reclamation and remediation of historic mine sites in the district. In addition, groups that had sued the company regarding water-quality standards on their properties would refrain from further legal actions (Miniclier, 1997). After a 30-day review of the proposal by Crown Butte Resources, Ltd., of Toronto and Crown Butte Mines, Inc., of Houston, the companies agreed to the deal. Margaret Reeb owned an estimated 65 percent of the mining claims in the project area (Miniclier, 1997) and had leased her claims to Crown Butte-Noranda. In September 1997, Ms. Reeb also agreed to the settlement, and the deal was complete (Billings, 1997). Margaret Reeb reportedly received an undisclosed sum of money from Crown Butte, and she was allowed to keep her claims as long as she agreed not to develop them. She understood that her claims could be mined in the future if allowed by the President and Congress (Billings, 1997).

Some members of Congress were opposed to the settlement plan. However, lawmakers in both parties stated that they wanted the company to leave the district. Also, the buyout concept and the means originally proposed to fund it, such as temporary borrowing from the Conservation Reserve Program, were issues of debate (The Washington Post, 1997). As late as July 1997, some key members of Congress, including House Interior Appropriations Subcommittee Chairman Ralph Regula (R-Ohio), were opposed to inclusion of land purchases in their version of the fiscal year 1998 Department of the Interior appropriations bill (Bettelheim, 1997). Later in 1997, an accord was reached on the terms of funding the settlement.

The New World mine acquisition was authorized by Congress as part of a complex rider attached to the fiscal year 1998 Department of the Interior appropriations bill (Public Lands News, 1998a). The rider included \$65 million for acquisition of the New World properties and their mineral rights and \$12 million for repairs to the Beartooth Scenic Highway. Crown Butte agreed to transfer \$22.5 million to the U.S. Forest Service to remediate historic mine sites in the district.

The proposed contract settlement was filed in Federal court in Montana on June 25, 1998 (Public Lands News, 1998a). A Federal judge approved the contract, and on August 7, 1998, the properties of the New World mine project were formally transferred to the U.S. Forest Service (Public Lands News, 1998b), under the administration of Gallatin National Forest.

The Secretary of Interior earlier (August 1995) had proposed a 20-year withdrawal of Federal locatable minerals in an area of 19,100 acres surrounding Cooke City (basically the historic New World district and a buffer zone). In 1996, public meetings and preparation of an Environmental Impact Statement (EIS) were initiated for the proposed mineral withdrawal. A Draft EIS was released in March 1997. The New World mine issue was not to be considered a “connected action” to withdrawal of the surrounding Federal lands. However, upon completion of the “New World Mine acquisition” on August 7, 1997, the New World project claims, now under the supervision of Gallatin National Forest, were added to the “Cooke City Area Mineral Withdrawal.” In August 1997, shortly after transfer of the New World Project claims, the Assistant Secretary of the Interior and the Under Secretary of Agriculture released a joint Record of Decision (MTM84500) that stated their decision to “\* \* \* withdraw from mineral entry, subject to valid existing claims, 22,065 acres of Federal land near Cooke City, Montana.” The Cooke City Area Mineral Withdrawal will remain in place for 20 years beginning in August 1997, unless Congressional action makes the withdrawal permanent.

So, after surviving two attempts to develop a mine, one in the 1920s and one in the 1990s, the Homestake gold-silver-copper deposits remain intact inside Henderson Mountain, under the protection of Gallatin National Forest. Geologic inferences suggest that similar deposits possibly are present around Eocene intrusions at Emigrant Peak, in the Independence district, in Sunlight Basin (Sunlight mining region), and potentially elsewhere in the region (Hammarstrom, Zientek, Elliott, and others, 1993).

As noted previously, the settlement agreement between the United States and Crown Butte Mining, Inc., provided \$22.5 million for cleanup of specific historic mine sites in the New World district, including properties previously owned and leased by the mining company (such as the McLaren and Glengarry mine properties). Using this funding, the “New World District Response and Restoration Project” was established in 1999, with the U.S. Forest Service acting as the lead agency in charge of administering the project. The main goals of the project were “\* \* \* to assure the achievement of the highest and best water quality practicably attainable” and “\* \* \* to mitigate environmental impacts that are a result of historic mining” (quoted from the project’s Web site: <http://www.maximtechnologies.com/newworld/index.htm>; accessed 3/10/04). The project was to “\* \* \* initially focus on stabilizing the solid mine wastes to prevent or reduce erosion onto adjacent lands or into streams.” The project Web site stated that other restoration actions may include temporary water-treatment systems, creating repository sites for waste materials, making capping systems on the waste dumps to minimize further oxidation and acid production, closing adits and shafts, revegetating mining-disturbed areas, and monitoring water quality. This effort (2001) involved several Federal Government agencies with specific responsibilities to the project, including the U.S. Forest Service, the Environmental Protection Agency, the U.S. Department of Agriculture Office of the General Council, and the U.S. Department of the Interior, all in cooperation with the State of Montana through the Montana Department of Environmental Quality.

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