

U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

**Mineral resource assessment of the Absaroka-Beartooth study area,
Custer and Gallatin National Forests, Montana**

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¹Reston, VA

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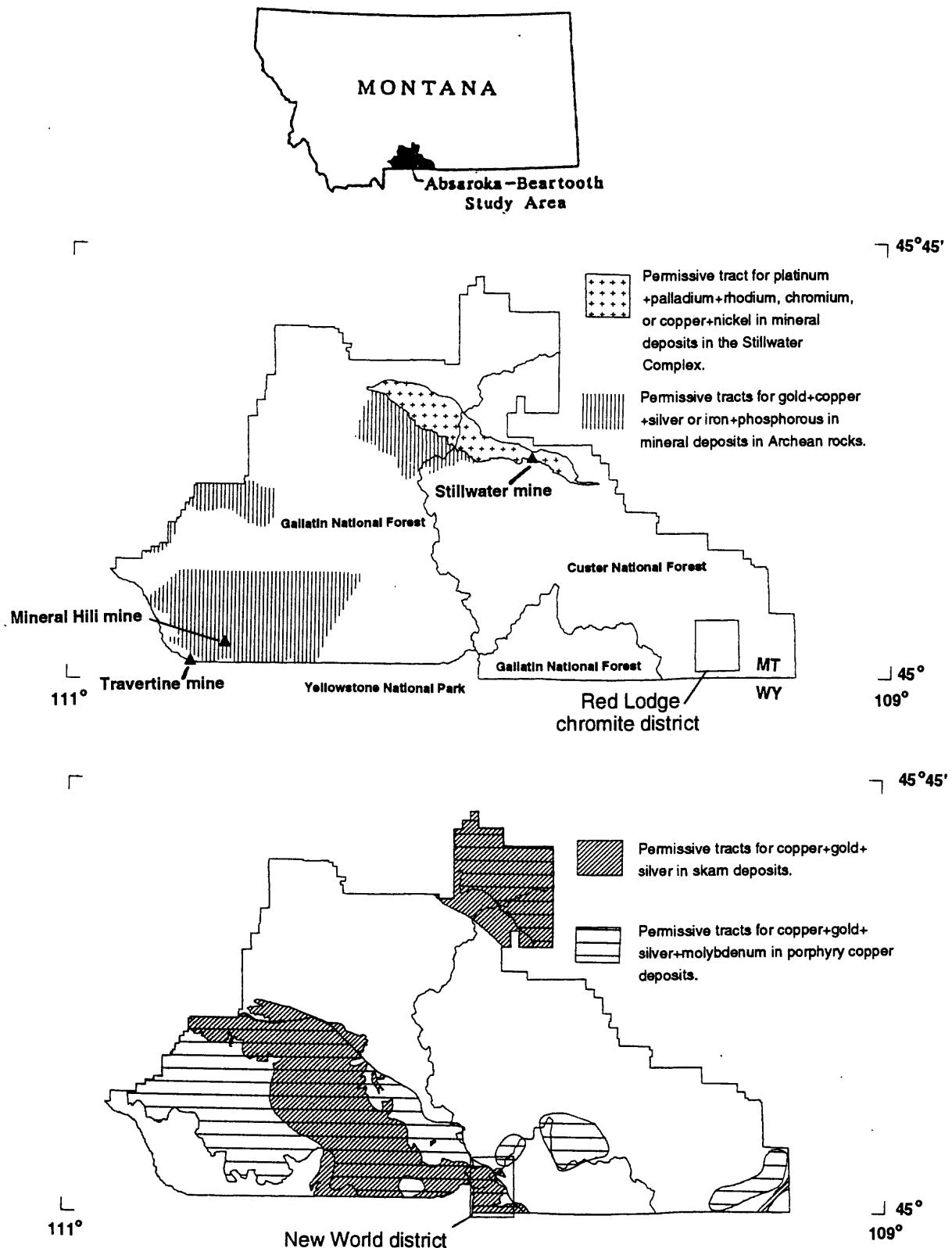
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NONTECHNICAL EXECUTIVE SUMMARY

Mineral Resource Assessment of the Absaroka-Beartooth Study Area, Custer and Gallatin National Forests, Montana

U.S. Geological Survey Open-File Report 93-207

- The Absaroka-Beartooth study area (ABSA) is a tract of approximately 1.4 million acres (5,700 km²) of National Forest land in southwestern Montana adjacent to the northern part of Yellowstone National Park. It includes southeastern parts of the Gallatin National Forest and western parts of the Custer National Forest. Most of the mineral resources of both Forests are within the ABSA.
- The ABSA contains essentially all of the identified resources of platinum-group elements (platinum, palladium, rhodium, ruthenium, osmium, and iridium) and 75 percent of the identified chromium resources in the U.S., as well as significant gold, silver, copper, lead, and zinc resources.
- Mines have operated in the area since the 1860's and have produced gold, silver, arsenic, tungsten, copper, lead, zinc, chromium, and platinum-group elements. Mines in production in 1992 are the Stillwater mine (platinum, palladium, gold, rhodium, copper, and nickel), the Mineral Hill mine (gold and silver), and the Livingston Marble and Granite Works (travertine).
- Recent (since 1970) exploration led to the discovery and development of the Stillwater mine and the discovery of gold-copper-silver deposits with geologic reserves of more than 2 million oz of gold in the New World district (see map on p. ii). Exploration for gold, platinum-group elements, and chromium deposits is ongoing in several parts of the ABSA. Two exploration wells for oil and gas were recently drilled near the eastern edge of the study area. Continued exploration is likely to result in new discoveries for some commodities.
- The mineral resource assessment of the ABSA is based on consideration of the types of mineral deposits that could be present. Classes of mineral deposits with shared geologic, commodity grade, and ore tonnage characteristics are associated with specific geologic environments. Nine geologic environments are recognized within the ABSA that are permissive for the occurrence of 20 different types of mineral deposits. Favorable areas for undiscovered deposits are delineated within some of these geologically permissive environments.
- Estimates of undiscovered resources are made for gold, silver, copper, molybdenum, iron, and phosphorous for four deposit types by combining estimated numbers of undiscovered deposits with statistical descriptions of grades and tonnages for each deposit type (table 1). Estimates of undiscovered resources by these methods for the other 16 deposit types are limited by availability of appropriate mineral deposit models.
- Estimates of resources of copper, nickel, chromium, and platinum-group elements for three other deposit types in a geologic formation known as the Stillwater Complex (shown on map on p. ii) are constrained by exploration data and geology (table 1).
- Estimates of resources of chromium in deposits near Red Lodge, Montana, are based on detailed geologic investigations conducted previously by the U.S. Geological Survey (table 1).
- Resource estimates represent in-place amounts of metal. The most economically important types of deposits are those that contain precious metals. Economic analysis must be applied to these estimates to determine any net value that may be associated with these undiscovered metals as minable commodities.
- Other types of mineral deposits in the ABSA are described qualitatively. Base- and precious-metals are likely to be present in vein deposits. Parts of the ABSA have low to moderate potential for placer gold deposits, uranium, oil and gas, coal and coal-bed methane.



Permissive tracts for selected deposit types

Table 1.--Estimated resources for selected commodities in selected mineral deposit types in the Absaroka-Beartooth study area reported as in-place amounts of metal

[Results are reported in metric tons; estimates are not additive]

Note: Metal tonnages reflect the size and grade of different types of mineral deposits and do not reflect the relative importance of different metals mined in the past or likely to be sought in the foreseeable future; for example, iron is less likely to be of interest than gold or platinum-group elements.

Commodity	Estimates of undiscovered resources based on computer simulation for 4 types of mineral deposits reported in terms of percent probabilities and mean expected values. For example, there is a 90% chance that undiscovered deposits contain 20 or more metric tons of gold.				Estimates of geologic resources in the Stillwater Complex based on evaluation of exploration data for 3 types of mineral deposits.		Estimates of geologic resources in Red Lodge chromite deposits from previous USGS studies.	
	90% (more likely)	50% (median)	10% (less likely)	Mean	Undiscovered	Extensions of identified resources	Undiscovered	Extensions of identified resources
Gold	20	90	400	200			43	
Silver	50	700	5,000	2,000				
Copper	500,000	3,100,000	17,000,000	6,500,000	220,000	1,200,000		
Molybdenum	0	35,000	300,000	130,000				
Iron	1,600,000	62,000,000	1,300,000,000	650,000,000				
Phosphorous	0	3,000	640,000	30,000				
Palladium						2,400		
Platinum							690	
Rhodium							24	
Chromium							6,500,000	4,000,000
Nickel							230,000	1,300,000

NONTECHNICAL SUMMARY FOR LAND AND RESOURCE MANAGERS

Mineral Resource Assessment of the Absaroka-Beartooth Study Area, Custer and Gallatin National Forests, Montana

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DESCRIPTION OF THE STUDY AREA

The Absaroka-Beartooth study area (ABSA) is a tract of approximately 1.4 million acres (5,700 km²) of National Forest land in southwestern Montana adjacent to the northern part of Yellowstone National Park. The ABSA includes southeastern parts of the Gallatin National Forest and western parts of the Custer National Forest. This report describes a mineral resource assessment of the ABSA that was conducted during 1990-1992 by the U.S. Geological Survey as part of a study of the mineral resources of the entire Gallatin and Custer National Forests. Most of the mines and prospects in both Forests are located within the ABSA. The remainders of both National Forests that lie outside of the ABSA will be studied during 1992-1994.

METHODOLOGY

This mineral assessment is based on several basic assumptions. First, mineral deposits can be grouped into classes or types that share essential features that result from fundamental geologic processes. Second, a class of mineral deposits is typically associated with a particular geologic environment in which ore-forming processes may operate. Third, the size (deposit tonnage) and grade (concentrations of various commodities) of a class of mineral deposits reflect the geologic environment and the mineralizing process.

Estimates of quantities of undiscovered resources are based on a three-part form of assessment. First, all available geologic information is compiled and used to identify areas in which one or more classes of mineral deposits may occur. These areas are called permissive tracts and are drawn such that the possibility of a mineral deposit belonging to the class occurring outside of the tract is negligible. For example, chromium deposits do not form in limestone. Therefore, areas within the ABSA where limestone

occurs are excluded from permissive tracts for chromium deposits. Some types of copper, gold, and silver deposits do form in limestone if certain geologic processes operated. Thus, limestone may be included in permissive tracts for some types of mineral deposits. Nine tracts that illustrate geologically permissive areas for 20 different types of mineral deposits are described in this report. Much of this report describes the different types of data that were considered in delineating permissive tracts. This data includes compilations of previous studies and new data acquired by the authors for this study. A new geologic map for the ABSA shows the spatial distribution of different rock types. Geophysical data are used to interpret the geology below the earth's surface. Sediments collected from streams are chemically analyzed to look for associations of elements that may indicate the presence of various types of mineral deposits. Mining and exploration history and locations and descriptions of mines, prospects, and mineral occurrences are examined to determine where the known resources are, what types of mineral deposits they represent, and how they relate to the geology.

As a second step in the assessment procedure, frequency distributions of grade and tonnage for the classes of mineral deposits under consideration are constructed or reviewed to determine if they are appropriate for the study area. Four of the 20 classes of deposits in the ABSA have appropriate grade and tonnage information that is used for estimating amounts of undiscovered resources.

Third, an estimate is made of the number of undiscovered mineral deposits of each type expected in a tract permissive for that deposit type. This subjective estimate is made by a team of scientists who consider all of the data described for the first part of the assessment, along with knowledge of the ore-forming processes, to arrive at a consensus opinion on the number of undiscovered deposits that may be expected at different levels of confidence.

Estimates of numbers of undiscovered deposits in the study area were made for four deposit types. Grades, tonnages, and estimated numbers of deposits are combined in a numerical simulation to provide an estimate of the amount of undiscovered resources that may be present in a permissive tract.

Lack of appropriate grade and tonnage models precludes applying steps 2 and 3 to all of the mineral deposit types expected in the ABSA. Some deposit types are appraised by evaluating and synthesizing exploration data and applying geologic constraints to estimate resources. Other deposit types are simply described and evaluated qualitatively.

IMPORTANCE OF THE STUDY AREA

The ABSA contains essentially all of the identified platinum-palladium-rhodium resources in the U.S., 75 percent of the identified chromium resources of the U.S., and significant gold, silver, copper, lead, and zinc resources. Historically, mining districts in the ABSA produced gold from lode and placer deposits, as well as silver, arsenic, tungsten, copper, lead, zinc, and chromium from lode deposits. Mines in production in 1992 are the Stillwater mine (platinum, palladium, gold, rhodium, copper, and nickel), the Mineral Hill mine (gold and silver), and the Livingston Marble and Granite Works (travertine and other stone products). Applications have been submitted by mining companies to develop copper-gold-silver ore deposits in the New World district and to develop an additional platinum-palladium-rhodium mine in the Stillwater Complex. Several other properties are being evaluated for gold or for chromium potential. Two exploration wells for oil and gas were recently drilled near the eastern edge of the study area.

GEOLOGIC ENVIRONMENTS FOR MINERAL DEPOSITS

The remarkable scenery of the ABSA includes some of the highest mountain peaks in Montana. The high elevations are due to geologic processes that caused much of the area of the ABSA to be uplifted relative to surrounding areas to the west, north, and east. The result is a unique window through geologic time that exposes some of the most ancient rocks on earth (Archean¹ rocks) as well as rocks of almost

every geologic age. Mines and prospects in the area are associated with rocks of very different ages and types (igneous, sedimentary, and metamorphic) that reflect changing geologic environments through time. The diversity of the geologic environments preserved in the ABSA make it an especially intriguing area for those interested in geology.

Four geologic environments are important in determining the significant types of metallic mineral deposits that may be present in the ABSA. Two are associated with ancient rocks exposed by the uplift. One is associated with deeply eroded Cretaceous¹ and Tertiary¹ volcanoes. The last environment consists of young stream deposits in which ore minerals (especially gold) derived from older deposits may be concentrated.

Archean metamorphosed sedimentary rocks in the southwest and northern parts of the study areas may contain two types of mineral deposits: banded iron formation (concentrations of iron- and phosphorous-bearing minerals in bands) and Archean lode gold deposits (gold-arsenic-tungsten-bearing veins). The Mineral Hill mine exploits an Archean lode gold deposit.

In the northern part of the study area, a rare association of Archean layered igneous rocks, the Stillwater Complex, contains several important types of mineral deposits: Stillwater nickel-copper deposits (concentrations of nickel- and copper-bearing sulfide minerals in the lowermost layers of the complex); Bushveld chromium deposits (concentrations of chromium-bearing minerals in layers in the lower part of the complex); PGE-enriched stratiform chromitite deposits (layers of rock enriched in chromium-bearing minerals that are also enriched in platinum-group elements (PGE)); and Merensky Reef PGE deposits (layers in the middle part of the complex that contain small amounts of sulfide minerals that are extremely enriched in the platinum-group elements). The Stillwater mine is developed on part of a Merensky Reef PGE deposit.

Deeply eroded Cretaceous and Tertiary volcanoes (hereafter referred to as volcanic-plutonic complexes) occur in the study area. The plutonic part of a complex represents the solidified magma chamber beneath the former volcano that is now largely eroded away. Processes that formed these complexes also formed a variety of different types of ore deposits. A Cretaceous volcanic-plutonic complex occurs at Sliderock Mountain in the northern part of the ABSA. Younger (Eocene¹ age) volcanic-plutonic complexes form a linear belt that trends in a northwest direction across the southern part of the study area. These

¹A geologic time chart is shown on p. ix.

complexes represent part of a belt of Eocene volcanoes that extends beyond the study area to the west and south. The entire belt of volcanoes produced the largest amount of volcanic rock of Eocene age preserved today in the Northern Rocky Mountains. In the ABSA, identified resources of gold, silver, copper, molybdenum, lead, and zinc are associated with volcanic-plutonic complexes in the Independence, Emigrant, and New World mining districts. Mineral deposit types are zoned in a crudely concentric fashion around the center of a volcanic-plutonic complex. Porphyry copper deposits (concentrations of veinlets and disseminated grains of copper-bearing minerals in plutonic igneous rocks) may form in the center; copper-gold skarns and replacement deposits (concentrations of minerals that may contain copper, gold, silver, iron, or other commodities formed by reactions of cooling magma with limestone) in limestone adjacent to the complex; and lead-zinc-silver polymetallic vein deposits (veins of sulfide minerals that contain high concentrations of lead, zinc, silver, and sometimes gold or other commodities) are found farther away from the center along faults and shear zones in any rock type. The New World district is a good example of a mineralized volcanic-plutonic complex.

Placer gold deposits result from the weathering and erosion of gold-bearing rocks and deposits followed by the transportation and concentration of gold particles by streams. The most productive placer deposits are located along Emigrant Creek and Bear Creek in the southwestern part of the ABSA.

RESULTS

This mineral resource assessment indicates that undiscovered resources are likely to be present in the ABSA. Undiscovered resources are defined as unidentified resources or identified resources for which no reliable information about location, quantity, and quality is available. Most of the undiscovered resources in the ABSA are likely to be present in the Gallatin National Forest, with the notable exception of the Stillwater Complex and the New World district. These two areas include parts of the Custer National Forest.

Results of numerical simulation to estimate undiscovered resources (table 1) are reported for the following types of mineral deposits: (1) gold and silver in Archean lode gold deposits, (2) iron and phosphorous in banded iron formation deposits, (3) copper, gold, silver, and molybdenum in porphyry

copper deposits, and (4) copper, gold, and silver in skarn deposits. Other commodities may be present in these deposit types or in other types of deposits within the ABSA. Lack of available data for some byproduct metals (such as arsenic and tungsten which are present in some Archean lode gold deposits) and lack of appropriate grade and tonnage models for some deposit types precludes simulation of all of the commodities that may be present. Estimates of undiscovered deposits are likely to change as exploration continues and as methods of resource assessment evolve.

Estimates of geologic resources (table 1) in undiscovered deposits and in extensions of identified resources within the Stillwater Complex are based on detailed evaluation of exploration data and geologic constraints. Resource estimates are reported for (1) copper and nickel in Stillwater nickel-copper deposits, (2) chromium in Bushveld chromium deposits, and (3) platinum and palladium, along with byproduct rhodium, gold, copper, and nickel in Merensky Reef deposits.

Chromite deposits near Red Lodge, Montana, were evaluated in the 1940's and restudied in the 1970's by the U.S. Geological Survey and U.S. Bureau of Mines. Results of those studies are included in this report (table 1).

The estimates in table 1 represent in-place amounts of metal, reported in metric tons. Estimated in-place resources may or may not have any net value as minable commodities when economic filters, such as exploration and development costs, are considered. The relative amounts of metal reported (for example, millions of metric tons of iron versus tens to hundreds of metric tons of gold or silver) reflect the size and ore grades of the types of mineral deposits and do not indicate the relative importance of different metals mined in the past or likely to be sought in the foreseeable future. For example, all of the iron reported is based on an estimate of one undiscovered deposit of banded iron formation, a rock that may be composed of 50 weight percent iron. In contrast, the amount of gold reported represents estimates of the gold contained in two undiscovered porphyry copper deposits, four undiscovered skarn deposits, and one undiscovered Archean lode gold deposit. These types of deposits may contain as little as 0.0001 percent (1 part per million) gold and still be economic.

Other products of this study include new maps showing the geology; aeromagnetic and gravity data; stream-sediment geochemical anomalies; locations of mines, prospects, and mineral occurrences; and permissive tracts for various types of mineral deposits.

All of these data are shown at a map scale of 1:126,720.

OUTLOOK

The most significant deposit types present in the study area are the platinum- and chromium-bearing deposits associated with the Stillwater Complex, the gold-bearing copper skarn deposits in the New World district, and the Archean lode gold deposit in the Jardine district. Exploration for these deposit types is likely to continue, both in areas adjacent to identified resources and in other permissive or favorable areas that are open to mineral entry. Undiscovered deposits are likely to include additional deposits similar to those that are presently mined as well as deposit types that are actively sought (for example, exploration and development of copper-gold skarns in the New World district; porphyry-copper deposits), and (or) deposit types that have been mined in the past (placer gold deposits in the Emigrant district; polymetallic base metal vein deposits in the New World district).

Copper-nickel ores associated with the basal parts of the Stillwater Complex are low-grade relative to similar deposits being mined elsewhere. The Iron Mountain area of the Stillwater Complex is the most favorable area for undiscovered copper-nickel deposits within the ABSA. However, the low grade of the ores, the poor exposure and lack of continuity of appropriate host rocks, and the metallurgical complexity of the ores may negatively impact exploration and development.

Chromite was mined from two layers in the Stillwater Complex under U.S. Government contract during and after World War II to provide stockpiles of critical minerals. The deposits are subeconomic (using current conventional processing methods) relative to higher grade ores from South Africa. The eastern parts of the Stillwater Complex are most favorable for development of chromite deposits, especially the Mouat-Sampson (Mountain View) area, where the extensive faulting that disrupts layers in many parts of the Stillwater Complex is minimal.

The Stillwater mine exploits a 1- to 3-meter-thick PGE-enriched layer in the Stillwater Complex known as the J-M reef. The only other deposit of this type that is currently being mined is in the Bushveld Complex of South Africa. Detailed exploration in the southernmost, geologically favorable part of the Stillwater Complex has failed to identify additional laterally continuous reef-type mineralization. Exploration for such deposits requires very detailed drilling and sampling. The southernmost part of the complex

may contain laterally discontinuous reef-type mineralization. In addition to the reef-type deposits, PGE are present in the Stillwater Complex in other associations, including local concentrations in some chromite-rich layers and in local concentrations of disseminated sulfide minerals.

Red Lodge chromite deposits are inferior in grade and tonnage to the chromite deposits in the Stillwater Complex and are unlikely to be attractive for development in the reasonably foreseeable future.

Deposits mined or explored in the past for copper (such as the Copper King mine at Goose Lake) and copper-molybdenum (such as the Emigrant district) are likely to be reexamined for precious metal (gold, silver, PGE) potential. Reworking of old placers and reevaluation of previously delineated placer areas may be expected.

Some mineral deposit types present in the study area, such as Red Lodge chromite deposits, Stillwater nickel-copper deposits, iron ores in magnetite in copper skarn and banded iron formation deposits, and polymetallic base metal vein deposits are less prospective than others at the present time because of economic factors (below grade or tonnage levels considered economic). Porphyry copper deposits in the ABSA may be too low-grade to be mined for copper, but may be prospective for other elements and for related deposit types.

Favorable areas within permissive tracts delineate areas most likely for exploration and development in the reasonably foreseeable future. The relative importance of these areas to the minerals industry depends largely on economic, rather than geologic factors. Many of these areas have been intensively explored in the past, but have not been developed. Exploration efforts prior to the mid-1970's were focused on copper, molybdenum, and chromium. Many areas that were explored in the past were not thoroughly evaluated for their gold or platinum-group element potential. Gold and platinum-group elements are the only metal commodities actively mined at the present time. Other commodities (nickel, copper, molybdenum, lead, zinc, iron, arsenic, tungsten) are present in ore concentrations that are too small, too laterally discontinuous, metallurgically complex, too low-grade, or too inaccessible to be economic as ore deposits at the present time.

Energy resources have not been exploited in the ABSA; results of recent oil and gas exploration are unavailable. Based on regional considerations, there appears to be a moderate potential along the Nye Bowler fault zone in the Gallatin National Forest and a low to moderate potential for oil and gas along the

eastern edge of the Beartooth uplift near Red Lodge. Large coal fields are present north, east, and west of the ABSA. Some of the sedimentary rocks along the northern and eastern margins of the ABSA are permissive for coal and coal bed methane.

Nonmetallic or industrial mineral resources do not occur in significant amounts in the ABSA, with the exception of the travertine deposits near Gardiner that have been mined since the 1950's. Massive

Precambrian granitic gneisses and green quartzite are potential sources of building stone. Thick limestone units such as the Madison Group are potential sources of rock for cement. However, as previous studies have noted, equally acceptable or superior sources of nonmetallic or industrial mineral resources are available outside of the ABSA where they are more accessible and closer to potential markets.

GEOLOGIC TIME CHART
Terms and boundary ages used in this report

EON	ERA	PERIOD	EPOCH	BOUNDARY AGE IN MILLION YEARS
Phanerozoic	Cenozoic	Quaternary	Holocene	0.010
			Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene
				5
			Paleogene Subperiod	Miocene
				24
				Oligocene
				38
		Mesozoic	Eocene	55
				66
			Paleocene	96
	Paleozoic	Cretaceous	Late	138
			Early	
		Jurassic	Late	205
			Middle	
		Triassic	Early	
			Late	~ 240
		Permian	Middle	
			Early	290
	Proterozoic	Carboniferous Periods	Pennsylvanian	Late
				Middle
			Mississippian	Early
		Devonian	Late	~ 330
			Middle	
			Early	360
			Late	410
		Silurian	Middle	
			Early	435
			Late	
	Archean	Ordovician	Middle	500
			Early	
			Late	~ 570 ¹
	Proterozoic	Cambrian	Middle	900
			Early	
			Late	1600
	Archean	Late Proterozoic	Middle	2500
			Early	
			Late	3000
	Archean	Middle Archean	Middle	3400
			Early	
			Late	3800?
pre-Archean ²				4550

¹ Rocks older than 570 m.y. also called Precambrian, a time term without specific rank.

² Informal time term without specific rank.

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CHAPTER A

THE ABSAROKA-BEARTOOTH STUDY AREA

By Jane M. Hammarstrom, James E. Elliott, Bradley S. Van Gosen, and Michael L. Zientek

INTRODUCTION

The Absaroka-Beartooth study area (ABSA) is an informally designated area of about 1.4 million acres within the Gallatin and the Custer National Forests of southern Montana. The geology and mineral resources of the ABSA (fig. A1) were studied by the U.S. Geological Survey during 1990 to 1992. This study is the first phase of a 4-year project to assess the undiscovered mineral resources of the Gallatin and the Custer National Forests and to provide minerals information to the U.S. Forest Service for land-use planning in management of Federal lands. This study includes new geologic maps and compilations of new as well as pre-existing geochemical, geophysical, mineral occurrence, and exploration data. The ABSA was chosen for the initial phase of the study because it includes a number of historic mining districts, active exploration projects, and producing mines and therefore is considered by the U.S. Forest Service as an area of high priority for mineral resource assessment. Separate reports will be issued for the remaining parts of the Gallatin and Custer National Forests (fig. A1) at the conclusion of the study. Most of the mineral resources for both forests are located within the ABSA.

Note to reader: Measurement units in this report are generally given in the unit (English or metric) in which the measurement was made for this study or originally reported. Metal grades are typically reported in troy ounces (precious metals) per short ton or as percents (copper, iron, lead, zinc). Grade and tonnage models used in mineral resource assessment report grades as grams per metric ton or as percents; estimates of metals contained in undiscovered deposits are reported in metric tons of metal. The following conversion factors may be used to convert English to metric units: 1 foot (ft) = 0.3048 meters; 1 square mile (mi²) = 640 acres = 2.590 square kilometers (km²); 1 troy ounce = 31.1 grams; 1 short ton (st) = 0.9072 metric ton (= t); 1 troy ounce per short ton (opt) =

34.285 parts per million. The following conversions are also useful to keep in mind in reading this report: 1 part per million (ppm) = 1 gram per metric ton; 1 percent (%) = 10,000 ppm; and 1 metric ton = 32,154 troy ounces.

IMPORTANCE OF THE STUDY AREA

The ABSA contains the only identified lode platinum-group elements (PGE) resources in the U.S., 80 percent of the identified chromium resources of the U.S., and significant gold, silver, copper, lead, and zinc resources. Historically, mining districts in the ABSA produced gold from lode and placer deposits, as well as silver, arsenic, tungsten, copper, lead, zinc, and chromium. Mines in production in 1992 are the Stillwater mine (platinum, palladium, gold, rhodium, copper, and nickel), the Mineral Hill mine (gold and silver), and the Livingston Marble and Granite Quarry (travertine and other stone products). Nine exploration projects were active in the ABSA in 1991 (McCulloch, 1992). These include ongoing exploration and development of five copper-gold-silver deposits in the New World district, exploration for chromium and platinum group elements (PGE) in the Stillwater Complex, and other exploration projects for gold and (or) copper. Two exploration wells for oil and gas were recently drilled near the eastern edge of the study area.

Mineral deposits are associated with Precambrian as well as Phanerozoic rocks in the ABSA. Archean metasedimentary rocks host the lode gold deposit at the Mineral Hill mine and include discontinuous lenses of banded iron formation. The 2.7-billion-year-old Stillwater Complex, which hosts a stratiform PGE-enriched deposit called the J-M Reef, is one of a small number of unusual, ultramafic to mafic layered igneous intrusions known throughout the world that host magmatic ore deposits. Although their number is limited, they are the principal repositories of PGE and chromium. The Stillwater Complex contains

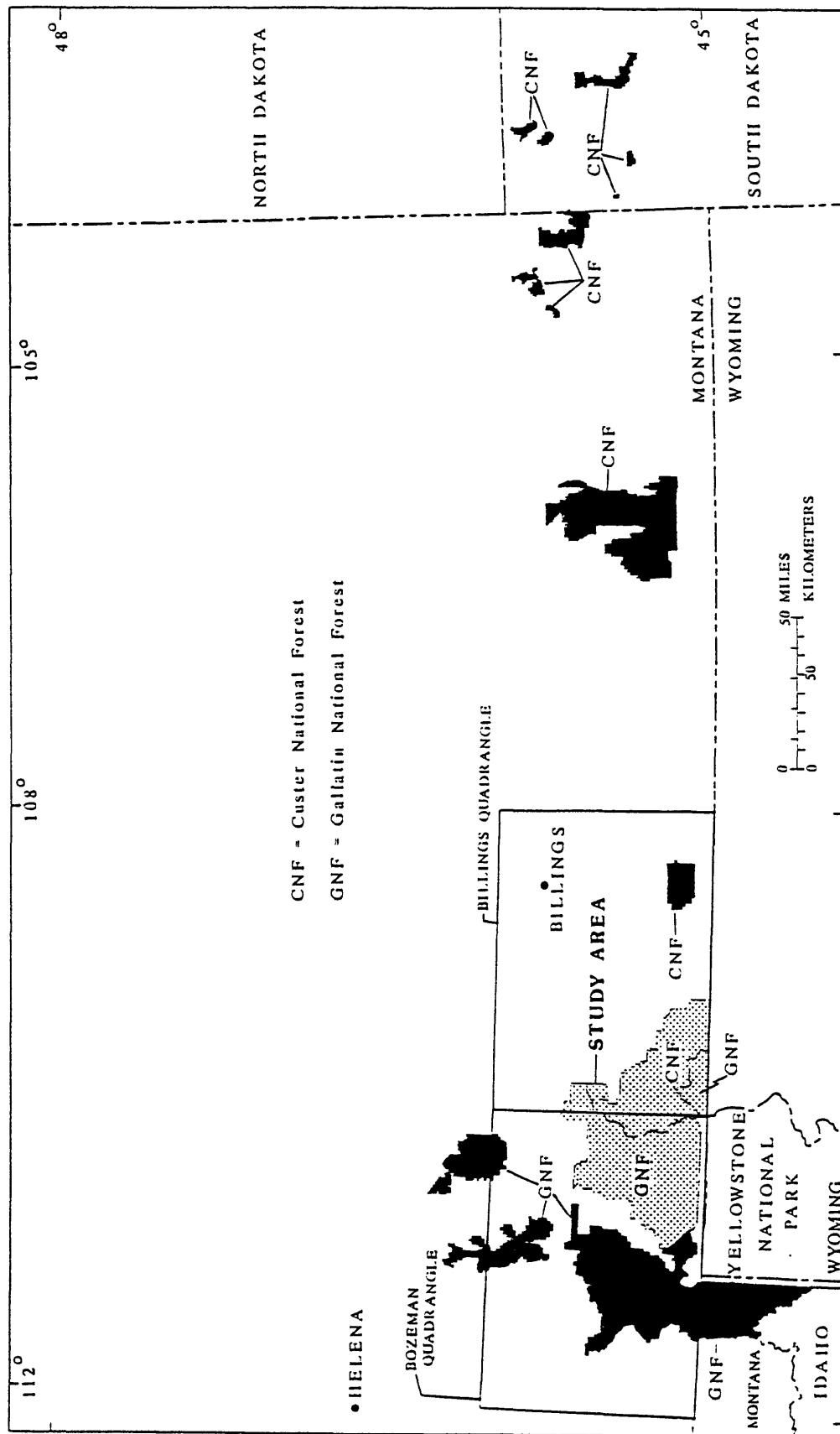


Figure A1.—Map showing locations of Absaroka-Beartooth study area and the Gallatin (GNF) and Custer (CNF) National Forests in southern Montana and northwestern South Dakota. Areas covered by the Bozeman and Billings $1^\circ \times 2^\circ$ quadrangles are also shown.

resources of chromium, copper, nickel, and gold as well as PGE resources. A belt of Tertiary intrusive centers that represents the deeply eroded roots of predominantly calc-alkaline stratovolcanoes crosses the ABSA. These centers probably represent some of the source volcanoes for the large volumes of volcanic rock that make up the Absaroka-Gallatin volcanic province (Chadwick, 1970) that extends to the north and west of the study area, and to the south into Wyoming. Late Cretaceous intrusive centers are also present near the center and in the northern part of the ABSA. Intrusive centers are an important geologic control on mineral deposits within the ABSA; many of these centers are spatially associated with porphyry deposits (copper, gold, molybdenum), skarns, and polymetallic veins. Weathering and erosion of gold-bearing deposits in both Precambrian and Phanerozoic rocks led to the formation of placer gold deposits.

LOCATION

The Gallatin National Forest (1.7 million acres or about 7,000 km²) covers the Gallatin and Bridger Ranges; parts of the Madison Range and Beartooth Mountains¹; and the southern part of the Crazy Mountains of south-central Montana. The Gallatin National Forest borders the northwestern and northern portions of Yellowstone National Park (fig. A1). The part of the Gallatin National Forest included in the ABSA (east and south of the Yellowstone River) adjoins the westernmost portions of the Custer National Forest and includes western and south-central parts of the Beartooth Mountains (fig. A2).

The Custer National Forest (2.5 million acres or about 10,000 km²) consists of a number of discontinuous tracts of land (fig. A1). The westernmost part of the Custer National Forest includes the eastern portion of the Beartooth Mountains in south-central

¹The Beartooth Mountains, as used here, includes the Absaroka and Granite Ranges, the Snow and Beartooth Mountains, and the Buffalo, West Boulder, East Boulder, Lake, Stillwater, Fishtail, Red Lodge Creek, Silver Run, Hellroaring, Beartooth, and Line Creek Plateaus (plate 1). Collectively, these geographic features form a continuous mountainous region in south-central Montana that is situated between the towns (clockwise from the west) Gardiner, Livingston, Columbus, and Red Lodge (fig. A2). This follows common usage, such as Foose and others (1961) and Mueller and Wooden (1982) even though on the Billings 1°×2° quadrangle map, the Beartooth Mountains are a smaller geographic feature and restricted to the eastern part of this large mountainous tract.

Montana. Other parts of the Custer National Forest extend eastward across the Montana state border into South Dakota (fig. A1).

The focus of this study is an area of high priority for mineral resource studies within parts of the two National Forests in south-central Montana, herein designated the Absaroka-Beartooth study area (ABSA) (figs. A2, A3). The study area covers the mountainous region between latitudes 45° to 45°45'N and longitudes 109°15' to 111°W in the southeastern Gallatin National Forest and westernmost Custer National Forest. The ABSA is bounded on the west and north by the Yellowstone River valley. Southwestern ABSA adjoins Yellowstone National Park; the southeastern boundary is the Montana-Wyoming state border. The study area lies within the eastern and western halves of the Bozeman and Billings 1°×2° quadrangles (scale 1:250,000), respectively. Parts of Park, Sweet Grass, Stillwater, and Carbon counties lie within the ABSA.

PREVIOUS AND CONCURRENT STUDIES

Most of the southern and central part of the ABSA is included in the Absaroka-Beartooth Wilderness. This study considers all National Forest lands within the ABSA, including the Absaroka-Beartooth Wilderness. Most of the new data acquired for this study are for peripheral areas of the ABSA that were not considered in previous studies related to wilderness.

Three previous mineral resource assessment studies were conducted in the Absaroka-Beartooth area during the period 1969 through 1974 as surveys of wilderness and primitive areas mandated by the provisions of the Wilderness Act (public Law 88-577, September 3, 1964). These studies delineated areas of high, moderate, and low potential for the occurrence of various mineral commodities. The boundaries for these studies are shown on figure A2. The earliest of these studies covered 365 mi² (235,000 acres) of the Beartooth Primitive Area (Simons and others, 1979) in the eastern half of the ABSA in parts of the Custer and Gallatin National Forests. The 105 mi² (62,874 acres) of the Absaroka Primitive Area (Wedow and others, 1975) and an additional 320 mi² (204,800 acres) included in the Absaroka Study Area lie entirely within the Gallatin National Forest in the southwestern part of the ABSA. The North Absaroka Wilderness Study Area (U.S. Geological Survey and U.S. Bureau of Mines, 1983), 540 mi² (346,681 acres)

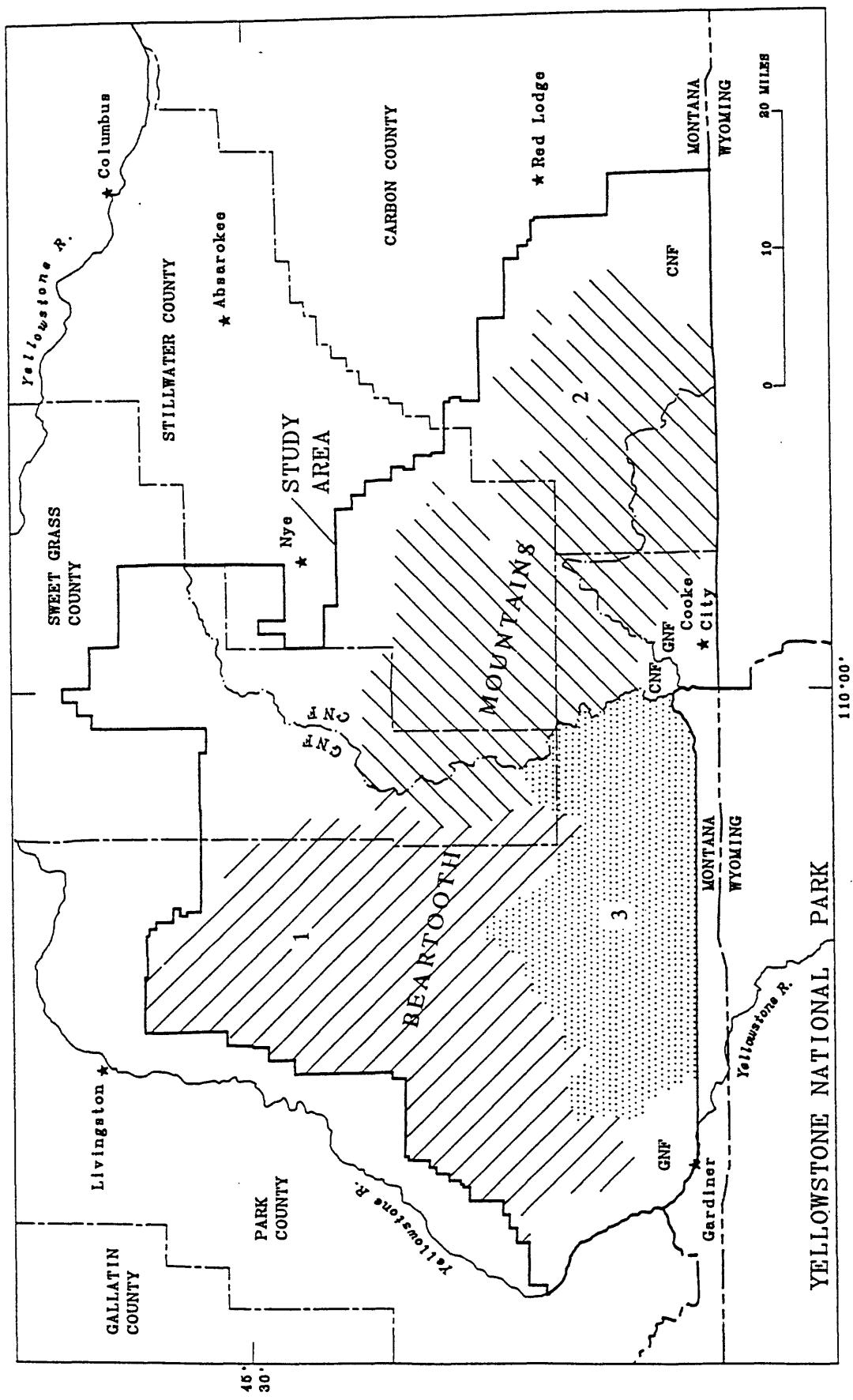


Figure A2.—Map showing the boundaries of the Absaroka-Beartooth study area. County boundaries and the location of towns within or near the study area are also shown. GNF = Gallatin National Forest; CNF = Custer National Forest. Areas covered by previous studies of wilderness areas are (1) U.S. Geological Survey and U.S. Bureau of Mines (1983), (2) Simons and others (1979), and (3) Wedow and others (1975).

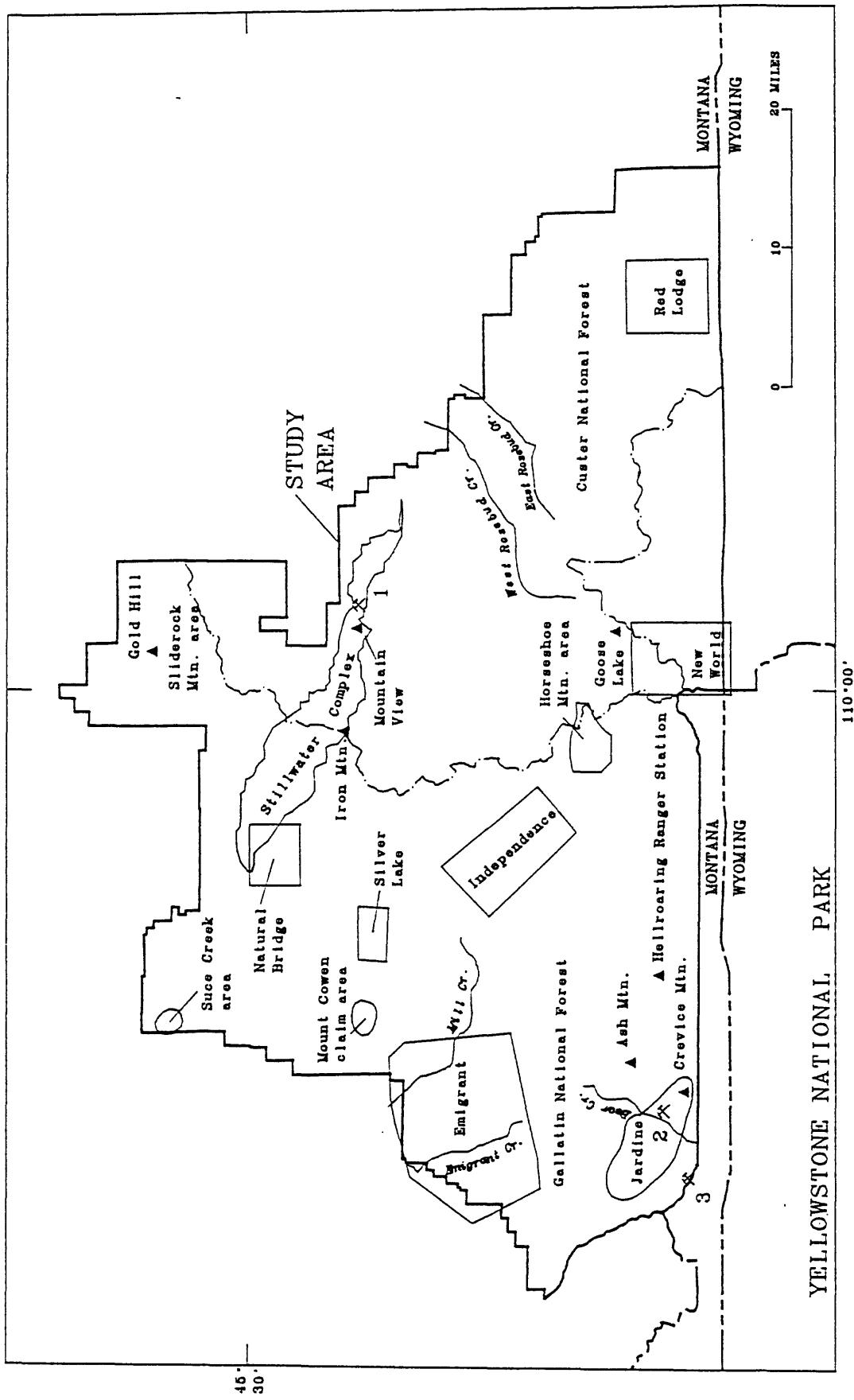


Figure A3.—Map showing locations of mining districts and areas of mining claims, active mines, and other localities within the Absaroka-Bearooth study area. Active mines are (1) Stillwater mine, (2) Mineral Hill mine, and (3) Livingston Marble and Granite quarry.

of the Gallatin National Forest that adjoins the Beartooth and Absaroka study areas, occupies most of the northwestern part of the ABSA. Results of these studies are incorporated into this study, along with new data collected by the authors of this report during 1990 and 1991 field seasons.

In addition to previous studies related to wilderness, a number of topical and areal studies by the U.S. Geological Survey contributed data to this report. Investigations conducted over a 60-year period focused on the Stillwater Complex are summarized in Czamanske and Zientek (1985). Other reports include a review of the petroleum potential of southwest Montana (Perry, 1988), a study of the geothermal resources near the southwest corner of the study area (Sorey, 1991), a geological map and report on the Gardiner area (Fraser and others, 1969), a report and geologic maps on the Cooke City area (Lovering, 1929; Elliott, 1979), a report on the Livingston area (Roberts, 1972), a report on the geology of Yellowstone National Park (Ruppel, 1972), a geologic map for the Stillwater Complex (Segerstrom and Carlson, 1982), a report on the Red Lodge chromite district (James, 1946), and a report on the Absaroka Volcanic Supergroup (Smedes and Prostka, 1972). The U.S. Forest Service made available their study on mineral input for the Stillwater Complex Integrated Resource Analysis (Curtiss and others, 1990) which covers 782 km² (193,243 acres) of the Gallatin and Custer National Forests within the ABSA.

FORMAT AND METHODOLOGY

All of the available data for the Absaroka-Beartooth study area were evaluated for the purpose of determining the mineral-deposit types known, or likely to be present, in the study area (table A1). The mineral deposit concept is the basis of the three-part form of mineral resource assessment (Singer, 1992) implemented in this study. A three-part assessment includes (1) delineation of areas according to the types of mineral deposits permitted by the geology, (2) use of mineral deposit models including descriptive as well as grade and tonnage models (frequency distributions) to help classify known deposits and provide quantitative information about the potential value of undiscovered deposits that may be present, and (3) subjective estimation of numbers of undiscovered deposits. A mineral deposit is defined as a mineral occurrence of sufficient size and grade such that under the most favorable of circumstances, it might be considered to have economic potential (Cox,

Barton, and Singer, 1986). For example, gold is present in the study area in a number of mineral-deposit types, including placer, skarn, porphyry copper, strata-bound, breccia pipe, replacement, and vein. The geologic characteristics, spatial distribution, tonnages, and commodity grades of the identified resources are examined and compared with published mineral deposit models in order to identify the mineral-deposit types and the potential for undiscovered mineral deposits within the study area. In this study, we use published mineral deposit models whenever possible, or modified published models. Zientek constructed new grade models to show the cumulative frequency of various metal grades in stratiform reef-type platinum-group-elements (PGE) deposits (Chapter F) and a new descriptive model for copper, gold, silver, and PGE associated with alkaline gabbro and syenite (Appendix to Chapter G).

Available geologic, geophysical, geochemical, mineral occurrence, past production, and exploration data are described in Chapters B through E of this report. The discussion of the geology of the ABSA (Chapter B) is based on a map compilation by Elliott and Van Gosen. During this study new geologic maps were prepared for several parts of the study area. The Sliderock Mountain area in the northern part of the ABSA was mapped during 1991 by du Bray, Elliott, Van Gosen, and LaRock. Elliott mapped areas near Jardine, in the southwestern part of the area, and near Red Lodge, in the southeastern part of the area during 1991. LaRock conducted geologic mapping and the examination of structures along the margins of the study area from south of Red Lodge to the vicinity of Nye in 1991. Carlson made modifications to the geologic map of the Stillwater Complex (Segerstrom and Carlson, 1982) in the area between the Stillwater River and the eastern end of the complex, and rectified structural and contact errors for the rest of the complex. Van Gosen and Carlson collaborated on transferring the Stillwater Complex geology from the plane-table-produced topography of the 1982 map to a digital format on the more recent photogrammetric topographic base. Zientek made further modifications to the Stillwater Complex geologic map and established tract boundaries. Van Gosen prepared a bibliography of geologic references for the study area, compiled index maps of previous studies, and did most of the geologic map compilation. Elliott assisted in the map compilation for parts of northwestern, southwestern, southern (New World district), and southeastern parts of the area. Geophysical data (Chapter C) described by Kulik include compilations of previous regional

Table A1.--Mineral deposit types known or suspected to occur within the Absaroka-Beartooth study area and expected commodities

[Bold type, deposit types that are currently mined or have been mined in the past]

Deposit type	Commodities expected
Deposit types associated with the Stillwater Complex	
Stillwater nickel-copper	Nickel, copper
Merensky Reef PGE	Platinum group elements
Picket Pin PGE	Platinum group elements
Stratiform chromite	Chromium, platinum group elements
Bushveld chromite	Chromium
Discordant PGE	Platinum group elements
Deposit types associated with other Archean rocks	
Archean lode gold	Gold, silver, tungsten, arsenic
Red Lodge chromite	Chromium
Algoma/Superior iron	Iron, phosphorous
Decorative stone	Dimension stone (granite, granitic gneiss, quartzite)
Contact or other uranium	Uranium
Pegmatites	Molybdenum
Serpentine-hosted asbestos	Asbestos
Deposit types associated with Phanerozoic rocks	
Polymetallic veins	Lead, zinc, silver, gold, copper
Skarns	Copper, gold, silver, iron, lead, zinc
Syenite-hosted copper	Copper, gold, platinum group elements
Placers	Gold, silver
Porphyry copper	Copper, gold, molybdenum, silver
Epithermal veins	Gold, silver, copper, lead, zinc
Oil and gas	Oil and gas
Coal	Coal

previous regional aeromagnetic and gravity surveys and new measurements and interpretations for this study. Lee and Carlson compiled geochemical data for stream-sediment and heavy-mineral-concentrate samples from previous studies by the U.S. Geological Survey (USGS) and collected additional samples in 1991 and 1992. Archived stream sediments, previously obtained in the study area as part of the National Uranium Resource Evaluation (NURE) program under the Department of Energy, were reanalyzed by the USGS. The results from each of these investigations were assembled and interpreted by Lee

and Carlson in Chapter D. Locations and descriptions of mines, prospects, and mineral occurrences and history of production (Chapter E) were compiled by Hammarstrom and Zientek. Mines, prospects, and occurrences are classified in terms of the types of mineral deposits that are present or likely to be present based on the available data. Hammarstrom examined the distribution of mining claims based on Bureau of Land Management records and researched the Anaconda Geological Document Collection of the International Archive of Economic Geology maintained by the American Heritage Center at the

University of Wyoming in Laramie. The mineral resources of the Stillwater Complex are described and appraised by Zientek in Chapter F. Carver and Mooney assisted with the compilation and preparation of maps for the Stillwater Complex. Mineral deposit models, grade and tonnage models, criteria for tract delineation, and estimates of undiscovered mineral deposits by tract for locatable minerals outside of the Stillwater Complex are discussed by Hammarstrom and others in Chapter G. Carlson, Elliott, Hammarstrom, Kulik, Lee, Van Gosen, and Zientek participated in delineation and definition of mineral resource tracts and the estimation of numbers of undiscovered deposits. Dennis Cox, U.S. Geological Survey, assisted in some phases of this process. Hammarstrom, with assistance from William Scott and David Root of the U.S. Geological Survey, performed the computer simulations and tabulated the results (Chapters G and J). Perry describes the hydrocarbon potential of the study area (Chapter H). Coal and coal bed methane resources are discussed by Weaver and Gruber (Chapter I). Estimates of undiscovered resources for the entire ABSA and for each National Forest within the ABSA are tabulated in Chapter J. The following types of data are plotted on maps at a scale of 1:126,720 (U.S. Forest Service map scale) on plates 1 through 19: geology, aeromagnetic and gravity data, stream-sediment geochemical data, locations of mines, prospects, and occurrences, spatial distribution of known or inferred mineral deposit types, and mineral resource assessment tracts.

Permissive Tracts

Mineral resource assessment tracts (Chapters F,G) are delineated as areas permissive for the occurrence of one or more mineral deposit types such that the probability of a deposit lying outside of the boundary is considered negligible. Tracts may or may not contain known deposits (Singer, 1992). A tract represents a synthesis of the current (1992) state of geologic knowledge about the area. Favorable subareas are delineated within some permissive tracts. Favorable areas represent areas for which available data, such as distribution of known deposits or mineral occurrences and (or) geochemical anomalies, suggest that deposits are most likely to be present within the permissive tract. New information acquired in future studies or mineral exploration could modify or change the boundaries of these tracts, the types of mineral deposits considered, and the estimates of undiscovered deposits. Nine mineral resource tracts

are delineated (table A2). The criteria for defining each tract are described in chapters F and G. Tracts are referred to by tract labels throughout this report. Labels are constructed as follows: Roman numerals (I through IX) for permissive tracts, lower case letters (a,b,c etc.) for geographically separated areas for a particular permissive tract, and Arabic numbers (1,2,3, etc.) for favorable subareas within permissive tracts. For example, tracts Ia and Ib both delineate Archean supracrustal rocks permissive for Archean lode gold deposits and Algoma or Superior banded iron formation deposits. Tract Ia refers to the Jardine area in the southwestern corner of the ABSA whereas tract Ib refers to an area in the north-central part of the ABSA. Subtract Ia1 represents a favorable area for undiscovered Archean lode gold deposits within tract Ia.

Undiscovered Resources

The U.S. Bureau of Mines and the U.S. Geological Survey (1980) jointly devised definitions for resource classification for minerals as follows:

Identified resources are defined as resources whose location, quality, and quantity are known or estimated from specific geologic evidence. Identified resources may be economic, marginally economic, or subeconomic. Identified resources include demonstrated (measured and indicated) and inferred resources.

Undiscovered resources are defined as resources whose existence is only postulated; these postulated resources may be in deposits that are economic, marginally economic, or subeconomic.

Estimates of Undiscovered Deposits

Estimates of numbers of undiscovered deposits are made for four types of mineral deposits: Archean (Homestake) lode gold, gold-bearing skarn, porphyry copper (-gold-molybdenum), and Algoma or Superior type banded iron formation. These estimates are combined with a computer simulation program that utilizes grade and tonnage data for well-characterized deposits worldwide to generate estimates of hypothetical amounts of metals in undiscovered deposits. Such estimates may be used in economic analyses to provide quantitative minerals information that can be compared with other types of subjective information (for example, assessment of scenic, recreational,

Table A2.--Mineral resource assessment tracts in the Absaroka-Beartooth study area

Tract	Description	Permitted deposit types
I	Archean supracrustal rocks	Archean lode gold Algoma/Superior iron
II	Archean gneiss and migmatite	Red Lodge chromite Pegmatite Uranium Algoma/Superior iron Serpentine-hosted asbestos
III	Archean gneiss, migmatite, amphibolite, and metasedimentary rocks	Algoma/Superior iron Pegmatite
IV	Stillwater Complex	Stillwater nickel-copper Merensky Reef PGE Picket Pin PGE Discordant PGE Stratiform chromite Bushveld chromite
V	Tertiary or Cretaceous intrusive centers and associated volcanic rocks	Porphyry copper-gold-molybdenum Epithermal veins
VI	Cretaceous syenite at Goose Lake	Alkaline gabbro-syenite-hosted copper-gold-PGE
VII	Paleozoic carbonate rocks within and adjoining tract V	Skarns
VIII	Precambrian and Paleozoic metamorphic and sedimentary rocks within and adjoining Tertiary or Cretaceous intrusive centers of tracts V and VI	Polymetallic veins Gold-silver-tellurium veins
IX	Quaternary alluvium along streams	Placer gold

timber, or wildlife value) for land-use planning. For some deposit types, such as polymetallic veins, data indicate that existing descriptive or grade and tonnage models are inappropriate for the study area and therefore no computer simulation is performed. Mineral deposit types associated with the Stillwater Complex are not amenable to computer simulation for estimating undiscovered resources because grade and tonnage models are nonexistent or inadequate. Other methods (Chapter F) are used to assess these deposit types. The likelihood of occurrence and potential impact of exploration and development for all types of

undiscovered deposits are discussed qualitatively (Chapters F,G).

Caveats

Quantitative mineral resource assessment is a relatively new and evolving field. Ideally, an area of active exploration should be re-evaluated on a recurring basis. Ludington and others (1991) noted that only the passage of time and exhaustive exploration can test the accuracy of quantitative estimates of

undiscovered resources. Lack of availability of appropriate mineral deposit models can limit the extent to which a 3-part assessment can be used to describe all of the undiscovered mineral resources in a study area. Favorable tracts indicate those parts of the ABSA that are most likely for exploration and development in the reasonably foreseeable future based on our current understanding of the geology of the study area. Estimates of numbers of undiscovered deposits combined with grade and tonnage models provide a probability distribution of amounts of in-place metals in undiscovered deposits that may be used by land-use and economic planners as they see fit. In-place estimates of undiscovered resources may have no value as removable (minable) resources once appropriate economic factors (e.g., metal prices, costs of exploration and development, metallurgical complexity of ores) are considered. Such economic analyses are beyond the scope of this study. Types of mineral deposits that are unknown or uneconomic today may be important in the future. Active exploration projects may result in development of mines in the near future that are considered in our estimates of undiscovered deposits.

MINING AND EXPLORATION HISTORY

MINING HISTORY

The study area encompasses 16 mining districts and areas of known mineral deposits (fig. A3). Mining began with the discovery of placer gold deposits in the 1860's. Many streams were placer-mined and the most significant production came from Bear Creek, Emigrant Creek, and the Boulder River (fig. A4).

Gold-bearing quartz veins were discovered in 1870 in the southwestern part of the ABSA at Jardine. The Jardine (Sheepeater) district became the largest producer of gold in the study area and a significant producer of arsenic and tungsten as well. Through 1974, the district produced more than 200,000 oz of gold (table A3). Gold is currently being produced from the Mineral Hill mine at Jardine (McCullough, 1992).

Lode silver-lead deposits were discovered in 1870 in the south-central part of the ABSA in the New World district. This district became a small but consistent producer of copper, gold, silver, lead, and zinc. The most important mine, the McLaren, was active during 1933-53. The total reported production for the New World district is about 62,000 ounces of gold; 692,000 ounces of silver; 1.9 million pounds of

copper; 3.4 million pounds of lead; and 920,000 pounds of zinc. Nearly all of the gold and copper came from the McLaren Gold mine (Elliott and others, 1992).

Mineralization within the Stillwater Complex is of particular interest because the metals present are those that have important technological uses and for which the United States must import most of what it needs (DeYoung and others, 1984; DeYoung and others, 1985; Sutphin and Page, 1986). The Stillwater Complex contains at least 75 percent of the identified chromium (Wetzel, 1986; Jackson, 1968) and essentially all the PGE resources (Sutphin and Page, 1986) in the United States. Deposits containing nickel and copper were discovered in 1883 in the Stillwater Complex and deposits of chromite likely were recognized as early as 1890 (Page and others, 1985). Limited mining of chromite occurred during both World Wars I and II. Large-scale mining of chromite was conducted at the Mouat mine during 1953 to 1961 when 900,000 short tons of chromite concentrate with greater than 39 weight percent Cr_2O_3 were produced under government contract (Page and others, 1985). Although the occurrence of PGE in the Stillwater Complex was noted by Howland and others (1936), exploration for PGE deposits did not begin until the 1960's. One of the great exploration successes of the 20th century was the discovery and delineation of economic deposits of PGE (the J-M Reef) during the 1970's by the John-Mansville Corporation (Conn, 1979; Todd and others, 1982). Platinum, palladium, rhodium, gold, copper, and nickel are currently being produced from this deposit at the Stillwater mine.

Lode deposits of gold, silver, copper, lead, and zinc have also been discovered and exploited in the Crevice Mountain, Emigrant (includes Mill Creek and Sixmile Creek subdistricts), Independence (Boulder), Natural Bridge districts and chromium deposits in the Red Lodge district were discovered and mined (fig. A3; Stotelmeyer and others, 1983; James, 1946).

Other areas of significant mineral occurrences include the Hellroaring Ranger Station area, Mount Cowen area, Suce Creek district, Silver Lake district, Horseshoe Mountain area, Goose Lake area, and Gold Hill-Iron Mountain (Sliderock) area (Stotelmeyer and others, 1983; Wedow and others, 1975; M.B. Jones and C.M. Swift, unpub. data, 1974).

ACTIVE MINES

There are three mines currently in operation in the study area. The Mineral Hill mine (fig. A3),

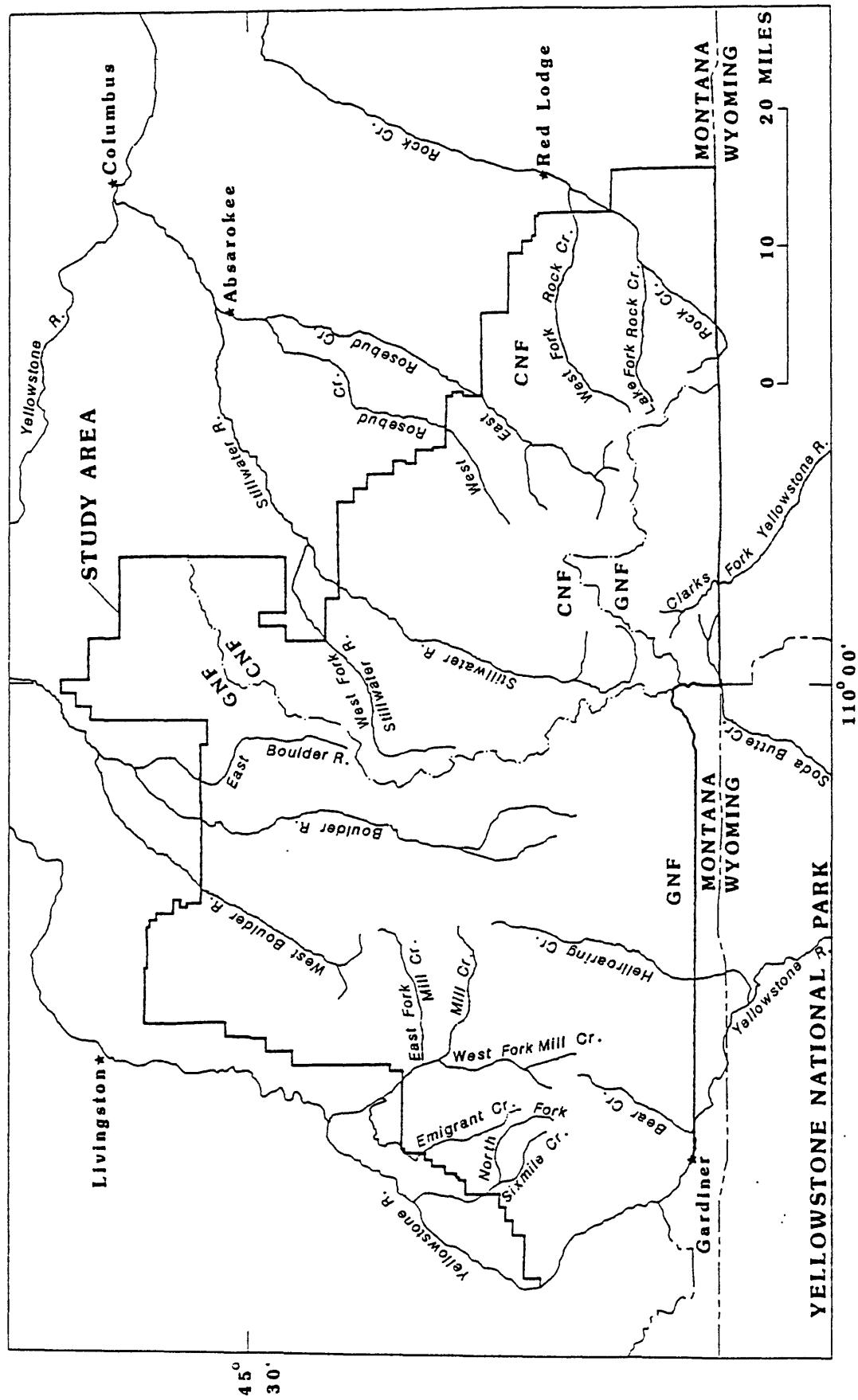


Figure A4.—Map showing major drainages within and near the Absaroka-Bearooth study area. GNF = Gallatin National Forest; CNF = Custer National Forest.

Table A3.-Mining districts in the Absaroka-Bearooth study area

Mining district or area (synonyms)	Active mines (1992)	Exploration (recent or significant)	Principal past producers	Past production and announced reserves	References
Jardine (Sheepeater)	Mineral Hill mine	Placer gold discovered in 1862 led to discovery and development of lode gold mines.	Jardine mine	District production for 1901 to 1947: Gold: > 200,000 oz (> 6 t) [Includes about 400 oz placer gold] Silver: 33,000 oz (1 t) Copper: 4,400 lb (4.1 t) Lead: 1,300 lb (0.6 t) Arsenic trioxide: 13,000,000 lb (5,900 t) Tungsten trioxide: 770,000 lb (350 t) Ore: 930,000 st (840,000 t). Announced reserves: 1 million st of ore averaging 0.03 opt gold (0.9 million t averaging 10.3 g/t gold). This ore contains 9.3 t of gold and 1.5 t of silver (using a 6:1 gold:silver ratio).	Reed, 1950 Wedow and others, 1975 Seager, 1944 McCulloch, 1991, 1992 D. Oliver, oral commun., 1991
Crevice Mountain (Crevasse)	None	Crevasse Project - 1991 exploration drilling for gold conducted by American Copper & Nickel Corp. and Jardine Joint Venture.	Conrad Hulse group	District production for 1901 to 1947: Gold: 2,800 oz (0.09 t) [Includes 1 oz placer gold] Silver: 500 oz (0.02 t) Ore: 13,000 st (12,000 t).	Reed, 1950 McCulloch, 1991, 1992 Seager, 1944
Unorganized - near Jardine	Livingston Marble and Granite Quarry	None	Gardiner travertine deposits	Present mine started in 1955; produces 2,000 st per year of travertine for ashlar, cut stone, and rubble. Production for 1932 to 1942: 8,450 st (7,700 t) of decorative stone.	Reed, 1950 McCulloch, 1991, 1992
Hellroaring Ranger Station area	None	Claims located prior to 1900.	None	None	Wedow and others, 1975

Table A3.--Mining districts in the Absaroka-Beartooth study area--Continued

Mining district or area (synonyms)	Active mines (1992)	Exploration (recent or significant)	Principal past producers	Past production and announced reserves	References
Emigrant (Includes Sixmile Creek and Mill Creek subdistricts)	None	Emigrant Placer - 1989 placer and lode exploration by Sandhurst/Montana Mining and Reclamation Co.; 1991 sonic drill holes (10) by Harrison Western/Montana Mining and Reclamation. Extensive exploration (drilling, etc.) for copper and molybdenum deposits in the 1970's and 1980's by a number of mining companies. Emigrant Project - 1990 drilling by Pegasus Gold Corp. in Duv Zone (gold, copper, silver) 1991 and 1992 ongoing drilling for gold deposits.	Emigrant Creek placers St. Julian mine Barbara Ann	District production for 1901 to 1947: Lode gold: 395 oz (0.012 t) Placer gold: 15,592 oz (0.5 t) Silver: 2,592 oz (0.08 t) Ore: incomplete data. Much of the production was in the 1880's to early 1900's before records were kept by the U.S. Bureau of Mines.	Reed, 1950 McCulloch, 1991, 1992 Stotelmeyer and others, 1983 The Mining Record, 1991
Mount Cowen area	None	Claims for molybdenum and uranium were located here in the 1940's; no identified resources were found by the U.S. Bureau of Mines as a result of sampling in 1974 (molybdenum and uranium do occur here).	None	None	Stotelmeyer and others, 1983
Silver Lake	None	Lode and placer claims, some pre-1900; no recent activity.	None	None	Stotelmeyer and others, 1983
Suce Creek	None	Placer and lode claims, mostly pre-1900; no recent activity.	None	None	Stotelmeyer and others, 1983

Table A3.--Mining districts in the Absaroka-Beartooth study area--Continued

Mining district or area (synonyms)	Active mines (1992)	Exploration (recent or significant)	Principal past producers	Past production and announced reserves	References
Natural Bridge	None	Big Group iron claims were explored in the 1950's by U.S. Steel Corp. Basal zone of Stillwater Complex was explored by Anaconda Co. for nickel and copper deposits.	Standard mine Nicon Group Milwaukee and Montana mine	Production for 1901 to 1937: Gold: 213 oz (0.007 t) Silver: 895 oz (0.028 t) Copper: 1,154 lb (0.523 t).	Stotelmeyer and others, 1983 Page and others, 1985
Independence (Boulder, Cowles, Haystack)	None	Independence project - 1991 exploration by Pathfinder Gold Corp. and Pegasus Gold Corp. (geophysics).	Independence mine Daisy mine Tramway (Mountain View, Ski Line)	Most mining activity before 1900, so few accurate records are available. Estimated production of about 10,000 oz (0.3 t) gold, mostly placer to 1907. Minor silver and lead production. Intermittent production from 1930's to 1950: Gold: 30 oz (0.001 t) Silver: 157 oz (0.005 t) Copper: 569 lb (0.3 t) Lead: 924 lb (0.4 t) Zinc: 893 lb (0.4 t).	Reed, 1950 Moyle and others, 1989 Stotelmeyer and others, 1983
New World (Cooke City)	Permitting in progress for mine and mill (New World project)	New World project - 1987-1992 exploration by Plexus, Crown Butte Mines, and Noranda Exploration for gold-copper-silver deposits.	McLaren mine Homestake mine Irma-Republic mines	District production for 1886 to 1933: Gold: 46,224 oz (1,44 t) Silver: 692,386 oz (21.5 t) Copper: 1,963,800 lbs (891 t) Lead: 3,242,615 lbs (1,471 t) Zinc: 920,200 lb (417 t) Ore: 371,043 st (336,610 t). Announced reserves for 5 deposits: Ore: 12 million st (11 million t) Gold: avg. grade 0.22 opt (82.1 t) Silver: avg. grade 0.87 opt (325 t) Copper: avg. grade 0.75% (82,500 t).	Reed, 1950 Johnson, 1991 Krohn and Weist, 1977 Elliott and others, 1992 The Northern Miner, 1992

Table A3--Mining districts in the Absaroka-Beartooth study area--Continued

Mining district or area (synonyms)	Active mines (1992)	Exploration (recent or significant)	Principal past producers	Past production and announced reserves	References
Goose Lake	None	The Copper King property was explored by a number of mining companies in the 1960's; recent interest in exploration for PGE.	Copper King mine	Small amount of ore mined and stockpiled during initial exploration in 1904 to 1907; no ore shipped.	Reed, 1950 Miller and Thompson, 1965
Iron Mountain-Gold Hill area (Siderock Mountain)	None	Gold Hill area explored in the 1970's by Anaconda and Bear Creek Mining Co. (Kennecott) for a porphyry copper deposit. Gold Hill project: 1989-1990, 8 rotary drill holes completed by Cominco American, Inc. (leased from ECM, Inc.) for a shallow gold target.	None	Several mines in the area reportedly developed for copper-iron or gold-silver; no record of production.	P. Cavanaugh, written commun., 1992 Curtiss and others, 1990
Stillwater (Nye)	Stillwater Mine	Jack Pine project - 1989 exploration for PGE by Chevron Resources/Manville Sales Corp.	Benbow mine Gish mine Mouat mine	Chromite was only mined in wartime when higher grade foreign ores were unavailable and as part of a government-subsidized program to create stockpile of chromite concentrate. Benbow and Mouat mines	Page and others, 1985 Rice and others, 1988 McCulloch, 1991, 1992 Minarik and McCulloch, 1989 Coombes, 1991 Randol, 1990
		Benbow project - 1991 Chrome Corp. of America completed 1 diamond drill hole for PGE in chromite.		Production for 1941 to 1943: Ore: 364,196 long tons (370,000 t) mined; 23,771 long tons (241,575 t) milled to produce 91,164 long tons (92,622 t) of chromium concentrates containing 38.5 weight percent Cr ₂ O ₃ . This concentrate was stockpiled.	
		Mountain View project - 1990 exploration (drilling) by Chrome Corp. of America with Phelps Dodge Mining Co.		Mouat mine Production for 1953-1961: Ore: 2.1 million st (1.9 million t) of ore produced 920,000 st (834,624 t) of concentrates that averaged 38.5 weight percent Cr ₂ O ₃ . This concentrate was stockpiled.	
		Chrome Corporation of America project - 1989 drilling at the Mouat mine.		Announced reserves of the Mouat mine are 19.2 million st averaging 23.0 wt. percent Cr ₂ O ₃ .	
		Picket Pin project - 1989 drilling by International Platinum.			

Table A3.--Mining districts in the Absaroka-Beartooth study area--Continued

Mining district or area (synonyms)	Active mines (1992)	Exploration (recent or significant)	Principal past producers	Past production and announced reserves	References
Stillwater (continued)		<p>Stillwater PGM Resources - ongoing. File application for mining permit for East Boulder Project, 1990. J-M Reef delineation in areas of structural or stratigraphic complexity. Submit patent applications.</p> <p>International Platinum - mapping, ground geophysics, trenching, and drilling 14 holes on Picket Pin zone.</p> <p>Chrome Corporation of America and Boulder Gold - In Mouat mine area from 1989 to present: rehabilitation of No. 5 level of mine, underground bulk sampling, underground drilling program, submit patent applications, submit application for mining permit. Exploration of PGE-enriched stratiform chromites: 1986-1989 - surface sampling and drilling in Crescent Creek-West Fork (11 holes) and Mountain View areas (2 holes). With Phelps-Dodge, drilled two holes, one each in the Crescent Creek-West Fork and Mountain View areas. Trenching in Benbow area in 1990. One hole drilled in Benbow area - 1990-1991.</p>		<p><u>Stillwater mine</u></p> <p>Production 1988:</p> <p>Platinum: 40,000 oz (1.2 t)</p> <p>Palladium: 120,000 oz (3.7 t)</p> <p>Production 1990:</p> <p>Platinum: 50,000 oz (1.6 t)</p> <p>Palladium: 187,000 oz (5.8 t)</p> <p>In 1990, ore production since opening of mine in 1987 estimated at 2,058,000 st (1,867,000 t).</p>	

Table A3.--Mining districts in the Absaroka-Beartooth study area--Continued

Mining district or area (synonyms)	Active mines (1992)	Exploration (recent or significant)	Principal past producers	Past production and announced reserves	References
Red Lodge area	None	<p>Oil and gas exploration: 1987 dry hole drilled by Amoco. 1991 drillhole by Phillips Petroleum (no results available). Exploration for uranium (Western Nuclear) and for uranium and base metals (Anaconda) in the 1960's.</p>	<p>Helroaring group Highline group</p>	<p>Production 1940's: Ore: 61,600 t of chromite ore averaged 24 to 40 weight percent Cr_2O_3.</p>	<p>Simons and others, 1979 Adler, 1969</p>

ACTIVE MINES

There are three mines currently in operation in the study area. The Mineral Hill mine (fig. A3), which opened in 1989 in the Jardine district, is a joint venture of American Copper and Nickel (ACNC) and Homestake Mining companies. The mine is producing 575 short tons/day at an average grade of 0.281 ounces per ton (opt) gold. The ore reserves are about 1 million short tons with an average grade of 0.30 opt gold and a cutoff of 0.15 opt gold. The gold mineralization is associated with iron formation in complexly folded Archean metasedimentary rocks.

The Stillwater mine (fig. A3), a joint venture of the Pittsburg & Midway Coal Mining Co. (a subsidiary of Chevron) and Manville Corporation, is the only mine outside of South Africa exploited solely for its PGE content. The J-M reef, the PGE-bearing zone currently being mined, is generally 3 to 10 feet thick but can be traced for 28 miles (42 km) along strike (Engineering and Mining Journal, 1990). The mine is permitted to operate at 1,000 st/day; the mine is currently seeking to increase this to 2,000 st/day. Average grade is approximately 0.8 opt platinum (Pt) plus palladium (Pd) with Pd to Pt ratios of approximately 3.5 to 1. In 1990, the Stillwater mine produced 55,000 oz of Pt and 187,000 oz of Pd (Coombes, 1991). The flotation concentrates produced at the mine are processed to converter matte at a smelter in Columbus and then the matte is shipped to Belgium for refining. Mining started in 1986 with an estimated mine life of 30 years. Geologic reserves are estimated to be 12,262,000 st (Randol Mining Directory, 1990).

The Livingston Marble and Granite quarry (fig. A3), operated by the Livingston Granite and Marble Works, produces ashlar, cut stone, and rubble from travertine deposits near Gardiner. This deposit, mined since 1955, produces about 2,000 tons per year.

RECENT EXPLORATION

Exploration activity has been intensive in some parts of the Absaroka-Beartooth area in recent years and is expected to continue for the foreseeable future. The Montana mining directory for 1991 (McCulloch, 1992) lists nine active exploration projects within the ABSA.

In Park County, American Copper and Nickel Corporation/Jardine Joint Venture conducted helicopter-supported drilling for gold on the Crevasse project in the Jardine district in sections 9, 16, and 17

of T9S, R9E. Pegasus Gold Inc. (in joint venture with Fischer-Watt Gold Company) is actively (1992) exploring in the Emigrant district. Drilling for a shallow gold target (Emigrant project) was conducted in 1991 and 1992. In 1990, the Duv Zone of the Emigrant Gulch property was explored by six diamond drill holes. All six holes (drilled to a maximum depth of 578 ft) explored a gold-copper-bearing breccia pipe and all holes were mineralized. Intercepts for two holes were reported as 260 ft of 0.033 opt gold and 0.31 percent copper; and 100 ft of 0.063 opt gold and 0.26 percent copper (The Mining Record, 1991). The Duv Zone is one of a number of targets within a 10 mi² altered area. The altered area is crudely zoned with respect to gold, silver, copper, molybdenum, lead, and zinc within an intrusive complex. Harrison Western Mining Corporation and Montana Mining and Reclamation completed 10 sonic drill holes to evaluate placer gold potential at the Emigrant Placer project in sections 5 and 6 of T7S, R9E along Emigrant Creek. Pegasus Gold Corporation and Pathfinder Exploration Corporation completed geophysical studies related to gold exploration at Independence. Crown Butte Mines completed surface and underground drilling at the New World Project in 1992 and is now in the process of applying for a permit to develop a mine. At the Republic mine, also in the New World district, recent exploration has been conducted for lead, silver, and zinc.

In the Stillwater area, Stillwater PGM resources is continuing a program of reef delineation, principally in areas of structural complexity, and has submitted patent applications for a large number of claims in both the Custer and Gallatin National Forests. Exploration activity on the area of the proposed East Boulder mine (Jack Pine project) is on hold pending acquisition of necessary permits. Chrome Corporation of America continues to do assessment work on their chromite holdings and continues negotiations on technologies and funding necessary to develop a mine (Mining Journal, 1992); patent applications were submitted for the Mouat mine property in 1991. Boulder Gold continues to do assessment work on holdings of the PGE-enriched chromitites near the base of the complex; two holes were drilled in 1990 with joint-venture partner Phelps-Dodge in the Mountain View and Crescent Creek areas. Based on the drill results, Phelps-Dodge subsequently dropped out of the project. An additional hole was drilled in the Benbow area in 1990 and 1991. International Platinum conducted an exploration program on the Picket Pin zone in 1989. The work consisted of mapping, ground geophysics, trenching, and drilling 14

(Sliderock) area was explored (surface sampling and geophysical studies) as a porphyry copper target by Anaconda and subsequently by Bear Creek Mining Company (Kennebott) in the early 1970's. Exploration ceased in 1975 due to low copper prices. In 1989, interest in a shallow gold target at Gold Hill prompted another round of exploration, including drilling and geophysical studies by Cominco and ECM Inc. A shallow, buried porphyry copper-gold-molybdenum deposit has been postulated to occur at Gold Hill (P. Cavanaugh, unpub. data, 1990; M.B. Jones and C.M. Swift, unpub. data, 1974).

Phillips Petroleum (1991) and Amoco (1987) drilled near Red Lodge to assess oil and gas potential. Results from these exploratory wells have not been released.

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Many individuals in private industry, in other government agencies, and within the U.S. Geological Survey provided essential information for this study or assisted the authors in various aspects of data compilation and mineral resource assessment.

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Much information vital to the mineral resource assessment of the ABSA was gained through discussions with industry geologists and visits to important mines and exploration projects in the study area. Allan Kirk and Todd Johnson, of Crown Butte Mines, provided important information on results of exploration for the New World project near Cooke City. They provided tours of the mining property, discussed the results and important implications of exploration, and permitted the examination of drill core. In the Emigrant district, Robert Thomason, Pegasus Gold, and John Childs led informative tours

of the district, permitted the examination of drill core, and discussed results of exploration by Pegasus. David Oliver, mine geologist for American Copper and Nickel Co. Inc. (Mineral Hill mine), led a tour of the Jardine area, displayed drill core from exploration drilling, and discussed the results of exploration in the Jardine and Crevice Mountain areas. Pat Cavanaugh, of ECM Inc., provided information on the Gold Hill district including copies of unpublished company reports.

The mineral resource assessment of the Stillwater Complex would not have been possible without the assistance provided by many people. For this study, Stillwater Mining Company and Stillwater PGM Resources shared information about their exploration programs and mining activity in the Stillwater Complex; without this information, it would have been impossible to provide an analysis for the potential for PGE deposits in the complex that reflects the knowledge gained by years of exploration activity. In particular we would like to acknowledge Sam Corson, Doug Keith, and Lynn LeRoy with Stillwater PGM Resources for assembling the material and for discussing the results of their exploration activities. R.W. Vian assembled information for the Stillwater mine and discussed geologic developments in the mine. E.L. Mann, Manville Corporation, read the assessment for the Stillwater Complex and provided many useful comments. In addition to information provided specifically for this study, unpublished results from previous and on-going cooperative projects between the U.S. Geological Survey and AMAX, Anaconda Minerals Company, Boulder Gold, Chrome Corporation of America, Cyprus Mines, Manville Corporation, Stillwater Mining Company, and Stillwater PGM Resources were incorporated into the assessment.

A number of individuals made significant contributions that were incorporated into the Stillwater assessment. Alan E. Boudreau, Duke University, provided information about work done on the Picket Pin deposit. Roger W. Cooper, Lamar University, shared a substantial amount of unpublished information and reviewed a manuscript version of the assessment. Bruce R. Lipin, U.S. Geological Survey, provided unpublished information on the PGE concentrations for some Stillwater chromitites and reviewed a manuscript version of the assessment. Alistair R. Turner provided some summary literature describing exploration results for Chrome Corporation of America and Boulder Gold. Craig Bow and Norman J Page both reviewed a manuscript version of the report for the Stillwater.

summary literature describing exploration results for Chrome Corporation of America and Boulder Gold. Craig Bow and Norman J Page both reviewed a manuscript version of the report for the Stillwater. Ed McHugh, U.S. Bureau of Mines, discussed mineral resource estimates for the complex.

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Rick Johnson, project leader for the U.S. Bureau of Mines' study of the Gallatin National Forest, and his coworkers at the Spokane office of the U.S. Bureau of Mines discussed the results of their work and provided data on mines, prospects, and occurrences for the Gallatin National Forest.

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CHAPTER B

GEOLOGY OF THE ABSAROKA-BEARTOOTH STUDY AREA

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GEOLOGIC MAPPING

At the beginning of this study, no geologic map was available that covered the entire Absaroka-Beartooth study area (ABSA) with the appropriate geological detail although most of the study area was covered by a map compiled at a scale of 1:126,720 on a planimetric base by Foose and others (1961). However, geologic mapping subsequent to that of Foose and others (1961) has indicated a need for changes to their compilation, and, some parts of the ABSA, such as the Sliderock Mountain area (fig. B1), were inadequately mapped at any scale.

For this study, we compiled a geologic map, showing 58 map units, at a scale of 1:126,720 (1 in. equals 2 miles). The geologic map of the ABSA is the product of compilation of previously published maps and geologic mapping during 1991 and 1992 by J.E. Elliott, E.A. du Bray, B.S. Van Gosen, and E.J. LaRock. Three maps were recompiled to provide coverage for a large part of the ABSA; these resulted from studies of proposed National Forest Wilderness areas by the U.S. Geological Survey and the U.S. Bureau of Mines. These areas (shown in fig. A2) are the (1) North Absaroka Wilderness Study Area (U.S. Geological Survey and U.S. Bureau of Mines, 1983), (2) Beartooth Primitive Area and vicinity (Simons and others, 1979), and (3) Absaroka Primitive Area and vicinity (Wedow and others, 1975). Geologic mapping as part of the present study was conducted in three areas not covered by previous studies; these are (1) the Sliderock Mountain area in the northern part of the ABSA (fig. B1), (2) northwest of Gardiner in the southwestern part of the ABSA (fig. A2), and (3) south, southwest, and west of Red Lodge (fig. A2). In addition to geologic mapping, chemical analyses and petrographic examinations were done on selected samples for the purpose of classifying and correlating igneous rocks. Several new $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations were made by Steve Harlan of the U.S. Geological Survey, Denver, Colorado, in order to

establish ages of igneous map units. Geologic reconnaissance in areas other than those listed above—such as the New World, Independence, and Emigrant mining districts (fig. A3)—aided in the correlation of map units and interpretations of geologic structures, genesis of intrusive rocks, and metallogenesis.

In addition to the compilation shown in plate 1, a new geologic map of the Stillwater Complex (plate 14; modified and revised from Segerstrom and Carlson, 1982) was compiled and prepared to incorporate recent exploration data and detailed geologic mapping.

REGIONAL GEOLOGIC AND STRUCTURAL SETTING

Most of the ABSA is coincident with the Beartooth uplift (fig. B1), a broad fault-bounded Laramide uplift in south-central Montana and northwestern Wyoming. This uplift includes all of the Beartooth Mountains and merges with the Absaroka Range of Wyoming along the south-central part of the uplift. The Beartooth uplift is one of many basement-cored ranges that make up the Rocky Mountain Foreland of south-central Montana, Wyoming, Colorado, and north-central New Mexico (Kulik and Schmidt, 1988). The northwest-trending Beartooth uplift or block (Foose and others, 1961) rises abruptly 4,000 to 5,000 ft from lower areas to the northwest, northeast, and east. Many of the peaks, ridges, and plateaus within the Beartooth uplift are above 10,000 ft in elevation and the highest peak in Montana, Granite Peak with an elevation of 12,799 ft, is located in the central part of the uplift. The uplift, which is about 70 by 40 mi and roughly rectangular in shape, extends south beyond the ABSA into Wyoming. The uplift is bounded on the north by the Crazy Mountain Basin (fig. B1), a northwesterly trending structural basin that is filled with sedimentary, intrusive,

volcanic, and volcaniclastic rocks, and on the west by Paradise Valley (fig. B1), the alluvium-filled valley of the Yellowstone River (fig. A2). The Gardiner thrust fault (fig. B1) and the Yellowstone River form the southwest boundary of the uplift. The uplift is bounded on its northeastern and eastern sides by the Beartooth thrust, on the eastern and southeastern sides by the Bighorn Basin, and southern side by the Clarks Fork Yellowstone River. Much of the southern boundary of the uplift is covered and overlapped by igneous and volcaniclastic rocks of the Absaroka-Gallatin volcanic province (Chadwick, 1970).

The Beartooth uplift is divided into three blocks—the North Snowy, South Snowy, and Beartooth Plateau—by two major structural zones. The east-west-trending Mill Creek-Stillwater fault (fig. B1) separates the North Snowy block, in the northwestern part of the ABSA, from the Beartooth Plateau block to the southeast and the South Snowy block to the southwest. A northwest-trending structural low, the Cooke City zone (fig. B1), separates the South Snowy block, to the west, from the Beartooth Plateau block, to the east. Several Tertiary intrusive centers, including Cooke City, Horseshoe Mountain, and Independence (fig. B1), and their associated mineralized and altered areas, are aligned along the Cooke City zone, indicating this zone may have been a major control on the emplacement of Eocene intrusive centers and associated mineral deposits. Along this zone, the Precambrian-Cambrian contact and overlying Paleozoic sedimentary rocks dip to the southwest. Exposures of Paleozoic sedimentary rocks and Eocene volcanic and volcaniclastic rocks are present along the Cooke City zone, to the west of that zone, and south of the Mill Creek-Stillwater fault. Throughout most of the rest of the Beartooth uplift, these rocks have been removed by erosion and only Archean rocks are exposed.

The northernmost part of the ABSA extends beyond the Beartooth uplift, to the west and northwest of Nye (fig. A2), and includes an area (Sliderock Mountain area) of mainly intrusive, volcanic, and volcaniclastic rocks of Late Cretaceous age (fig. B1). These rocks have been called the Livingston igneous rocks and have been correlated with the Upper Cretaceous Livingston Group to the north and northwest of the study area (Parsons, 1942).

STRATIGRAPHY

Rocks exposed in the study area include Precambrian metamorphic and igneous rocks, Paleo-

zoic sedimentary rocks, Mesozoic sedimentary and igneous rocks, and Cenozoic sedimentary and igneous rocks. Precambrian crystalline rocks predominate throughout most of the study area; they are exposed throughout the North Snowy and Beartooth Plateau blocks and in the southern and western parts of the South Snowy block. Sedimentary rocks of Paleozoic age are located mainly around the margins of the ABSA but are also exposed: (1) in a discontinuous band across the southwestern part of the study area (South Snowy block) and (2) in the Sliderock Mountain area, along the margin and to the north of the Beartooth uplift. They occur either in fault contact with Precambrian rocks or unconformably overlying these older rocks. Mesozoic sedimentary rocks are found around the margins of the Beartooth uplift, near Red Lodge, Gardiner, and Livingston (figs. A2 and B1), and in the Sliderock Mountain area where they overlie Paleozoic sedimentary rocks. Igneous rocks of Late Cretaceous age include a syenite stock and associated dikes and sills in the Goose Lake area of the Beartooth Plateau block (fig. B1) and intrusive and volcanic rocks of the Sliderock Mountain area. Cenozoic sedimentary units include a small area of the Paleocene Fort Union Formation near the southeastern corner of the study area and a variety of surficial deposits of Quaternary age throughout the study area. A large part of the South Snowy block is occupied by Tertiary volcanic, volcaniclastic, and intrusive rocks that are part of the Eocene Absaroka-Gallatin volcanic province (Chadwick, 1970). A small area near Gardiner has exposures of Quaternary basalt, tuff, and travertine.

Precambrian rocks are nearly all Archean (more than 2,500 Ma) and consist of intrusive, and metamorphosed sedimentary (metasedimentary) and igneous (metaigneous) types. Proterozoic rocks include some of the mafic dikes that are common throughout the Precambrian terrane. Metasedimentary rocks include schist, marble, quartzite, banded iron formation, hornfels, and probably some paragneiss and para-amphibolite (map units Am, Ash, Aqa, Anc, and As in plate 1). Meta-igneous rocks are trondhjemite gneiss, tonalitic gneiss, hornblende gneiss, ortho-amphibolite, metadolerite, metanorite, metagabbro, granitic gneiss, and minor serpentinite (map units Aga, Aag, Au, An, Agn, Au, most of mi, and part of Am in plate 1). Most amphibolite and gneiss is probably igneous in origin. Unmetamorphosed to slightly metamorphosed intrusive rocks include the Stillwater Igneous Complex, granitic intrusive rocks, and some mafic dikes (map units Asw1 to Asw7, Agr, and part of mi in plate 1).

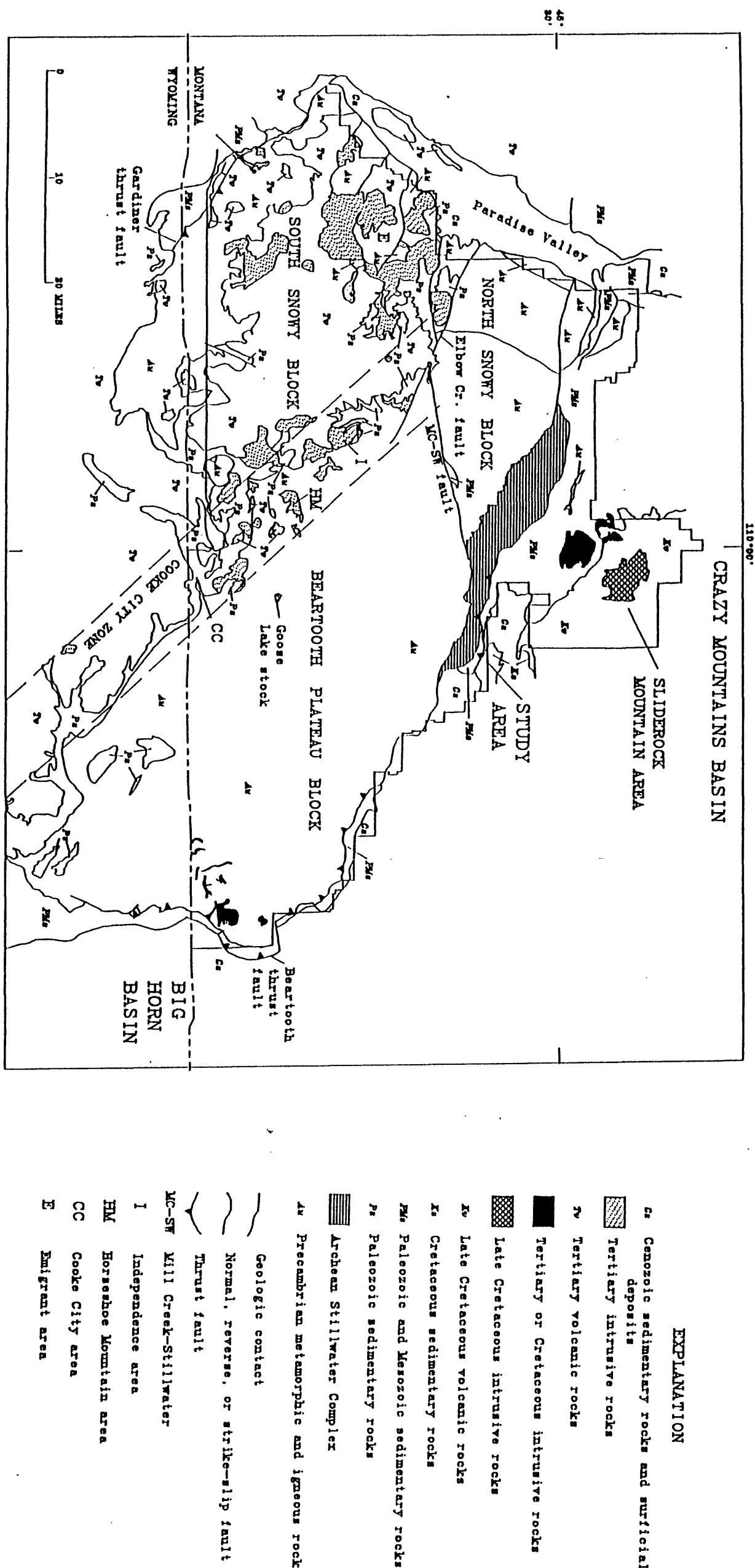


Figure B1.—Generalized geologic map for the Beartooth uplift and vicinity, Montana and Wyoming.

Paleozoic rocks in the study area range from Middle Cambrian to Permian and every system except the Silurian is represented (map units Pz, Cs, OCs, DOs, and PMs on plate 1). Rock units are typically separated by unconformities at system boundaries. Mapping and measurements near the southwestern (Ruppel, 1972), southeastern (Pierce, 1965), and northwestern (Richards, 1957) margins of the ABSA, indicate that Paleozoic rocks have a total thickness of about 2,800-3,500 ft. More than two-thirds of the total rock thickness consists of limestone or dolomite; the remainder consists of shale, siltstone, and sandstone.

Mesozoic rocks include a thick sequence of Triassic to Late Cretaceous sedimentary rocks (map units JTRs, Ku, Kls, and Kus in plate 1), consisting mainly of sandstone, siltstone, and shale with minor conglomerate and limestone, and Late Cretaceous volcanic and volcaniclastic rocks of the Sliderock Mountain area (map units Kad, Klc, Kll, and Kal in plate 1). The thickness of the Mesozoic sequence within the study area probably does not exceed 5,000 ft; however, in the Livingston area the total thickness of the Mesozoic sequence within and adjacent to the study area is about 12,800 ft (Richards, 1957). Intrusive rocks of known Late Cretaceous age occur in two areas; the Goose Lake area (map units Kgl and Ki in plate 1) and the Sliderock Mountain area (map units Kd and Ka in plate 1). There are numerous bodies of intermediate to felsic intrusive rocks within the study area whose ages are unknown (map unit TKi in plate 1). Some or all of these bodies could be Late Cretaceous in age; however, many could also be Tertiary.

Cenozoic rocks and deposits include Tertiary sedimentary, intrusive, volcanic, and volcaniclastic rocks (map units Tmz, Tdi, Tdp, Tgr, Ta, Tsb, Tfm, Th, Thm, Tba, Tbh, Tlp, Ti, Tf, and Tv on plate 1) and Quaternary volcanic, hot spring, and surficial deposits (map units Qb, Qy, Qt, and Qs on plate 1). The Tertiary intrusive, volcanic, and volcaniclastic rocks are part of the Absaroka-Gallatin volcanic province of middle Eocene age. Intrusive centers such as Emigrant, Independence, and Cooke City (fig. B1) indicate the sites of probable eroded stratovolcanoes, which were the sources of much of the material that formed the surrounding volcanic and volcaniclastic sequences. Quaternary surficial deposits (map unit Qs in plate 1) are widespread in the ABSA, and include alluvium in channel, flood plain, and terrace deposits; talus; colluvium; landslide deposits; rock glaciers; and glacial deposits (till, outwash, and glacial lake deposits). Other Quaternary units present in the

vicinity of Gardiner, near the southwest corner of the study area, are Pleistocene basalt flows, rhyolitic ash-flow tuff, and travertine (map units Qb, Qy, and Qt in plate 1). Extensive Pleistocene glaciation occurred in the study area forming U-shaped valleys, glacial striations and polish, moraine and till deposits, high level erratics, cirques, and hanging valleys. During maximum stages of glaciation, all of the study area lay under ice except the high peaks, ridges, and plateaus (Elliott and others, 1983).

STRUCTURE

The principal structures of ABSA are faults, fault zones, and a zone of downwarping that (1) form structural boundaries of the Beartooth uplift, (2) transect the uplift, and (3) occur as basement structures in adjacent areas. The major tectonic features of the Beartooth Mountains and adjacent areas are shown in figures B1 and B2. Additional structures of the interior of the uplift are shown in plate 1.

Faults Bounding the Beartooth Uplift

Faults and fault zones within and adjacent to the study area form boundaries along the southwest, northwest, north, northeast, and east sides of the Beartooth uplift. These bounding structures show large amounts of structural relief (10,000-20,000 ft) that developed during the Laramide orogeny, but it is possible that these structures are older fractures, possibly Precambrian. Their common alignment in two major directions, about N10°-20°E and N60°-70°W, is similar to that of many Precambrian mafic dikes that occupy fractures in older Archean rocks (Foose and others, 1961).

The southwest side of the Beartooth uplift (South Snowy block) is bounded by the Gardiner fault that forms the boundary between Precambrian rocks of the uplift to the north and Paleozoic and Mesozoic sedimentary rocks to southwest. The fault probably extends northwest across the Gallatin and Madison Ranges and may extend southeast across the Absaroka Range of Wyoming for a total length of about 140 mi, but throughout most of its postulated length, it is covered by Tertiary volcanic rocks (Fraser and others, 1969). A structural relief of at least 11,000 ft developed before Eocene time; this is the thickness of Paleozoic and Mesozoic sedimentary rocks that were stripped from the South Snowy block prior to the

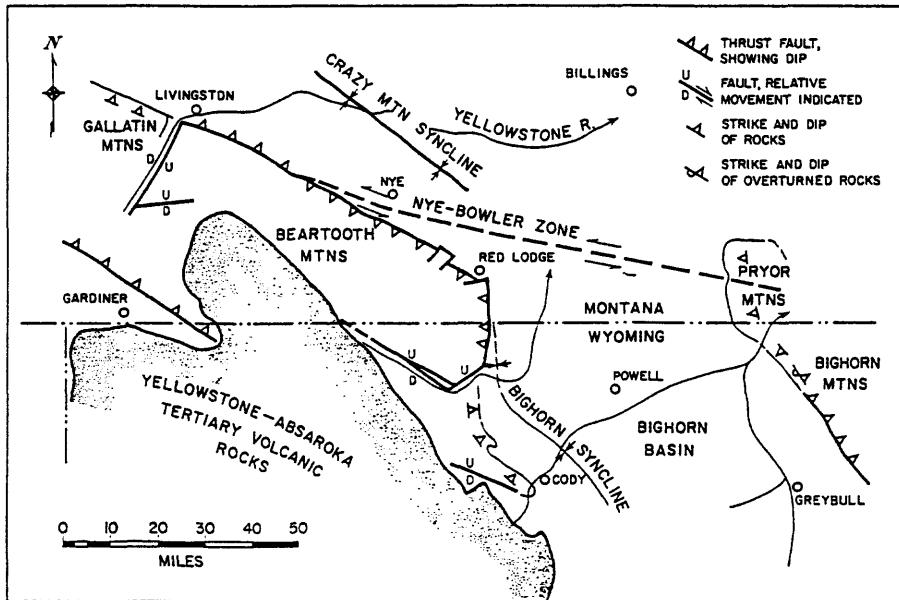


Figure B2.—Major tectonic features of the Beartooth Mountains and adjacent areas (from Foose and others, 1961).

deposition of Eocene volcanic rocks. At the level now exposed by erosion, the Gardiner fault appears to be a high-angle reverse fault or thrust. Some low-angle thrusts are present in sedimentary rocks within the drag zone of the downthrown block on the southwest side of the fault (Fraser and others, 1961).

The northwest corner of the North Snowy block near Livingston is a complex structural area formed by the intersection of north-northeast-trending structures like the Deep Creek fault and the northwest-trending structures that are present in the northeast-facing frontal zone of the Beartooth uplift. Much of the northwest side of the uplift (North Snowy block) is bounded by a normal fault, the Deep Creek fault, which separates the Precambrian rocks to the east from the alluvium-filled valley of the Yellowstone River (Paradise Valley) to the west. The northern end of the uplift consists of a double corner. A true corner of the uplift consists only of Precambrian crystalline rocks and a second corner is a tilted fault block, the Livingston Peak block, that is separated from the true corner by the Suce Creek fault and consists of Archean rocks overlain by Paleozoic and

Mesozoic sedimentary rocks (Foose and others, 1961). The Suce Creek fault is a high-angle reverse fault with 3,000-5,000 ft of vertical displacement (Foose and others, 1961). Foose and others (1961) proposed that the movement at the northern end of the uplift was predominantly vertical with less than 1 mi of horizontal displacement. Robbins and Erslev (1986), however, proposed a model of thin-skinned deformation for the north end of the uplift in which basement wedges are back-thrust to the south over the main Beartooth block due to motion on a master thrust fault that dips to the southwest. These authors propose crustal shortening in this area of approximately 8 mi.

The structure of the northern part of the uplift near Nye differs from other parts of the uplift by having a smaller amount of structural relief in the frontal zone. The structural relief between the Beartooth uplift and the Crazy Mountain Basin to the north is not as great as that along the eastern part of the uplift and this relief is spread over a greater horizontal distance (Foose and others, 1961). A number of faults, tilted fault blocks, and folds are

associated with this more gentle rise of the basement toward the south. Several of these faults, such as the East Boulder fault, have Phanerozoic sedimentary rocks preserved on their downthrown south side, which is the opposite sense of displacement from the uplift of the main mountain mass on the south. The structure of this part of the uplift is complicated by the proximity to the Nye-Bowler zone. A number of Laramide laccoliths and sill complexes of felsic and intermediate igneous rocks located near the juncture of the Nye-Bowler zone with the mountain front probably result from the intrusion of magmas along a zone of crustal weakness associated with this fractured area (Foos and others, 1961). Thrust faults such as the Horseman thrust, Bluebird thrust, and Lake fault have been mapped along the mountain front and within the Stillwater Complex near the mountain front (Page and others, 1973a, 1973b), but the displacement on these structures has not been determined.

Along the northeast and east sides of the Beartooth Plateau block, Precambrian crystalline rocks and Paleozoic and Mesozoic sedimentary rocks override Paleozoic and younger sedimentary rocks along one or more thrust planes that dip 30°-90° towards the mountains. The principal fault in this area is the Beartooth thrust (fig. B1 and plate 1). In several places along the mountain front, such as near Red Lodge, there are tear faults, with displacements of up to 10,000 ft, which offset the Beartooth thrust fault (Foos and others, 1961). Along the steep east and northeast sides of the uplift, the structural relief, as measured on the Cambrian-Precambrian contact, is approximately 10,000-20,000 ft. Based on gravity modeling and profiling of the eastern margin of the Beartooth uplift near Red Lodge, Bonini and Kinard (1983) postulate a southwest-dipping thrust fault with approximately 7.5 mi of overhang of Precambrian over Phanerozoic rocks.

Structures Within the Beartooth Uplift

The core of the Beartooth uplift is transected by several major structures and many lesser structures that divide the block into the North Snowy, South Snowy, and Beartooth Plateau blocks and many smaller units. The two principal structures within the uplift are the Mill Creek-Stillwater fault and the Cooke City zone (fig. B1). The Mill Creek-Stillwater fault is the southern boundary of the North Snowy block and separates this block from the South Snowy block to the southwest and the Beartooth Plateau

block to the southeast. The Cooke City zone separates the South Snowy block in the southwest from the Beartooth Plateau block in the southeast of the study area. The Mill Creek-Stillwater fault was first described by Wilson (1936) and, later by Foos and others (1961). The Cooke City zone is described by Foos and others (1961).

Mill Creek-Stillwater fault.--The Mill Creek-Stillwater fault extends east-northeast from near the mouth of Mill Creek, along the west side of the ABSA, to the north-central part of the study area, where it appears to merge with a zone of thrust-faulting in the lower part of the Stillwater Complex (fig. B1 and plate 1). Along the western part of the fault, Paleozoic rocks as young as Mississippian are down-faulted on the south side of the fault. However, near the eastern end of the fault, Phanerozoic rocks from Cambrian to Jurassic in age are preserved in a downdropped block on the north side of the fault. The fault forms the boundary between the North Snowy and Beartooth Plateau blocks where it marks the boundary between two contrasting terranes. On the north side of the fault there is a thick sequence of metasedimentary rocks consisting of schist, quartzite, hornfels, and iron formation that apparently is terminated by the fault. On the south side of the fault, the terrane consists almost entirely of granitic gneiss and migmatite with only thin septa and inclusions of amphibolite and schist. In the western part of the study area, the Mill Creek-Stillwater fault appears to cut Eocene intrusive rocks but is covered, in part, by younger Eocene volcanic rocks. Thus, much of the apparent movement along the fault is Eocene in age. However, the fault was probably active earlier in the Laramide Orogeny and likely originated during the Precambrian. Mogk (1988) suggests that the eastern part of the fault, in the vicinity of the Stillwater Complex, has a vertical offset of approximately 9 mi that occurred principally prior to 2,700 Ma.

Cooke City zone.--The Cooke City zone is a prominent northwest-trending structural zone that transects the Beartooth uplift from the Clarks Fork Canyon in Wyoming to its intersection with the Mill Creek-Stillwater and Elbow Creek faults in the north-central part of the study area (fig. B1). Many fractures are aligned along this zone including northwest-trending faults in the Clarks Fork Canyon with displacements up to 3,000 ft that form the southeastern corner of the Beartooth uplift. Many Precambrian mafic dikes along this zone with northwest trends probably were intruded along

fractures (plate 1). Several faults in the Cooke City area have this same trend (Lovering, 1929; Elliott, 1979).

All along the southwest margin of the Beartooth Plateau block, the Precambrian-Cambrian contact slopes to the southwest. In the southern part of the South Snowy block, the attitude of the Precambrian surface is reversed and it slopes to the northeast. Thus, a structurally downwarped zone is defined which coincides with the Cooke City zone. Along this zone the thickest sections of Paleozoic rocks are preserved whereas they were stripped from other parts of the Beartooth uplift, mainly during pre-Eocene uplift and erosion.

Several Eocene intrusive centers are aligned along the Cooke City zone; these include the Sunlight Mining Region and Hurricane Mesa intrusive areas in Wyoming (Nelson and others, 1980) and the Cooke City, Horseshoe Mountain, and Independence centers in the ABSA (fig. B1). Thus, the Cooke City zone may have been a zone of crustal weakness along which these intrusive centers were emplaced during the Eocene. Since many of the mineral deposits in the study area are closely associated with these intrusive centers, the Cooke City zone is also a primary metallogenic control of the location of these deposits.

Basement Structures in Adjacent Areas

The Nye-Bowler zone (fig. B2) generally parallels the northeast flank of the Beartooth Mountains, crosses the northern part of the study area, and may merge with the northwest end of the Beartooth uplift. This zone is defined by an alignment of a group of asymmetric domes and anticlines with a trend of N75W and a length of about 60 mi (Foose and others, 1961). The Nye-Bowler zone has a prevalent left-lateral sense of movement, but in northern part of ABSA, the East Boulder fault, a possible continuation of this zone, shows a south-side down sense of movement. The Nye-Bowler zone appears to cut Precambrian rocks, deforms the overlying Paleozoic and Mesozoic sedimentary rocks, and shows evidence, based on the thicknesses of sedimentary rocks, of movement from Late Cretaceous through Paleocene time (Foose and others, 1961). At the northwest end of the Beartooth uplift, near Livingston, the zone may be incorporated into the frontal structure of the uplift. The significance of the Nye-Bowler zone to the potential for oil and gas accumulations is discussed in Chapter H.

SUMMARY OF GEOLOGIC HISTORY

The region has had a complex geologic history from early Precambrian through Recent time. During the Precambrian, there is evidence of volcanism, plutonism, sedimentation, and metamorphism spanning a period of about 2,700 my from 3,400 to 700 Ma (Mueller and others, 1985). Early Archean sedimentary rocks were subjected to granulite facies metamorphism at about 3,400 Ma possibly during continental collision (Mueller and others, 1985). A major episode of crustal growth that included magmatism, metamorphism, and deformation occurred during the period of 3,000 to 2,800 Ma possibly as a result of subduction along converging plates (Mueller and others, 1985). At 2,705 Ma, the Stillwater Complex was emplaced and, somewhat later, quartz monzonite plutons were intruded (Page and Zientek, 1985a; Premo and others, 1990). During the Late Archean and Proterozoic a wide variety of mafic dikes were intruded along fractures of several different orientations. The ages of these are (1) 2,500-2,800 Ma, (2) 1,370 Ma, and (3) 740 Ma (Baadsgaard and Mueller, 1973). A long period of crustal stability began in the Cambrian and continued through all of the Paleozoic and most of the Mesozoic eras. During the Paleozoic, sedimentary rocks (about 2,800 ft thick in the Livingston area; Richards, 1957) were deposited in shallow seas that covered the region. During the Mesozoic, the deposition of sedimentary rocks (about 12,800 ft thick in the Livingston area; Richards, 1957) continued and the conditions of deposition shifted from mostly marine in Triassic and Jurassic time to mostly continental during the Cretaceous. The entire region of the Rocky Mountain foreland was affected by the Laramide orogeny; a period of deformation and igneous activity from about 75 Ma (Late Cretaceous) to about 37 Ma (the end of the Eocene epoch). During the Late Cretaceous to Paleocene, the major structures bounding the Beartooth uplift were formed, a major period of uplift commenced, and several igneous centers were active, which resulted in the intrusion of stocks, dikes, and other bodies and the deposition of volcanic and volcaniclastic rocks. The Eocene was a period of major igneous activity resulting in the formation of the Absaroka-Gallatin volcanic province, which consists of intrusive, volcanic, and volcaniclastic rocks. This volcanic province covers much of the southwestern part of the ABSA (South Snowy block), extends to the northwest where it constitutes most of the Gallatin Range, and to the south where it makes

up most of the Absaroka Range of Wyoming. Uplift of the region continued during the middle Tertiary and, by late Tertiary time, the region attained approximately its present elevation. Weathering and erosion due mainly to glaciation and streams during Quaternary time developed the present topography.

NORTH SNOWY BLOCK

The North Snowy block, in the northwestern part of the study area, is bordered on the west by normal faults that form the east side of Paradise Valley, on the north by the steep, north-sloping front of the Beartooth Mountains, and on the south by the Mill Creek-Stillwater fault zone (fig. B1). Precambrian rocks are exposed throughout most of this area. These include the mafic and ultramafic rocks of the Stillwater Complex, metasedimentary rocks adjacent to the Stillwater Complex, and metasedimentary and meta-igneous rocks in the western part of the block. Paleozoic and Mesozoic rocks are exposed in steeply dipping sequences along the northern part of the area, in a tilted fault block in the northern part of the area, along the Mill Creek-Stillwater fault, and in the southern part of the area, between the Elbow Creek fault and a portion of the Mill Creek-Stillwater fault. Tertiary intrusive rocks are exposed only in the southern part of the area, between the Elbow Creek and Mill Creek-Stillwater faults.

STRATIGRAPHY

Precambrian Metamorphic and Igneous Rocks

Metasedimentary and meta-igneous rocks west of the Boulder River.--The portion of the North Snowy block that is mainly west of the Boulder River is underlain mostly by an assemblage of diverse metasedimentary and meta-igneous units, including schist, gneiss; interlayered amphibolite and gneiss; interlayered quartzite and amphibolite, and a complex of amphibolite, marble, and quartzite (plate 1). This area has been mapped and described by Reid, McMannis, and Palmquist (1975), Elliott and others (1983), and Mogk (1984, 1988). Rocks of this area are mostly foliated or schistose with a northeasterly trend. Many of the lithologic units are distinct and are not found in other parts of the Beartooth Range. For example, the nappe core complex (Anc), consisting of amphibolite, marble, and quartzite, forms a northeast-trending fragmented band with a strike

length of about 27 mi. Other units such as trondhjemitic gneiss and amphibolite (Aga) and quartzite and amphibolite (Aqa) sequences are found only in this area. Studies of this area by Mogk (1988) and Mogk and others (1988) demonstrate that differing metamorphic grades and histories of deformation are present in adjacent units; they concluded that the rocks of the North Snowy block formed by tectonic amalgamation of numerous diverse lithologic suites during late Archean time. Mogk (1988) concluded that this area lies along a fundamental discontinuity between two distinct terranes in the Archean rocks of the Wyoming province. The North Snowy block is part of a western terrane that consists dominantly of medium- to high-grade metasupracrustal rocks as exposed in the Gallatin Range, Madison Range, and Tobacco Root Mountains, and Ruby Range to the west of the Beartooth Mountains. The Beartooth Plateau block is part of an eastern terrane that consists predominantly of plutonic rocks, similar to those exposed in the Bighorn Mountains to the southeast of the Beartooth Mountains.

Stillwater area.--The Stillwater area includes the Stillwater Igneous Complex and an area of metasedimentary rocks between the base of the complex and the Mill Creek-Stillwater fault. The metasedimentary rocks also extend to the west of the Boulder River, to the West Boulder Plateau (plate 1). Most of the metasedimentary rocks are hornfels as a result of contact metamorphism caused by the intrusion of the Stillwater Complex. An excellent compilation of the geology of the Stillwater area is provided by Czamanske and Zientek (1985).

The metamorphic rocks beneath the Stillwater Complex include massive hornfels and a sequence of fine-grained metasedimentary rocks, quartzite, diamictite, and banded iron formation (Page and Zientek, 1985b). Fine-scale sedimentary structures such as crossbedding and cut-and-fill structures can be seen in some of the metamorphic rocks but most of the metamorphic rocks are massive hornfels without discernible layering. The major- and minor-element chemistry of these rocks indicate they are similar to Archean graywacke. However, some of the hornfelses, particularly the quartz-bearing hornfels, are highly mafic with concentrations of chromium, cobalt, and nickel that are higher than typical graywacke or shale (Page and Zientek, 1985b). A proposed source for these metamorphic rocks is an Archean mafic to ultramafic protolith (Page and Zientek, 1985b).

The Stillwater Complex is a Late Archean (2,705 Ma; Premo and others, 1990) mafic to ultramafic

layered intrusion along the north flank of the Beartooth uplift (fig B1). As a result of northward tilting of the rocks near the front of the uplift during the Laramide orogeny, an 18,000-ft thick section of layered igneous rocks is exposed over a strike distance of 30 mi (plate 14). The base of the complex is exposed but the top is missing and the uppermost exposures are unconformably overlain by Cambrian sedimentary rocks. The layered igneous rocks that form the complex have been subdivided into four series (Basal and Ultramafic, Lower Banded, Middle Banded, and Upper Banded) and 10 zones based largely on the presence or absence of cumulus minerals (plate 14; Zientek and others, 1985). Because of limitations of map scale (plate 1), the 10 zones have been reduced to 7 map units by combining the norite and lower gabbro zones, the lower mixed-middle gabbro and middle mixed zones, and the upper mixed-upper gabbro and upper anorthosite zones of plate 14. The cumulus minerals which are present in various proportions are orthopyroxene, olivine, bronzite, chromite, augite, inverted pigeonite, and plagioclase. The geology and mineral resources of the Stillwater Complex are described in detail in Chapter F.

Paleozoic and Mesozoic Sedimentary Rocks

Paleozoic and Mesozoic sedimentary rocks are present mainly as a northwest-trending and northeast-dipping sequence along the northeast margin of the North Snowy block (plate 1). Paleozoic and Mesozoic rocks are also present along the Mill Creek-Stillwater fault, as part of a tilted fault block between Suce and Deep Creeks, and between segments of the Elbow Creek and Mill Creek-Stillwater faults in the southeast, the northwest, and the southwest parts of the North Snowy block respectively. The most complete sequence is along the northern margin of the North Snowy block where sedimentary rocks ranging in age from Middle Cambrian to Late Cretaceous are present.

Paleozoic rocks in the northwestern part of the study area have a total thickness of about 2,800 ft (Richards, 1957). Cambrian rocks, which consist of sandstone, limestone, shale, and conglomerate and have a total thickness of about 1,000 ft, consist of Middle Cambrian Flathead Sandstone, Wolsey Shale, Meagher Limestone, and Park Shale and Upper Cambrian Pilgrim Limestone, Snowy Range Formation, and Grove Creek Formation. The Upper Ordovician Bighorn Dolomite (200 ft thick)

unconformably overlies the Grove Creek Formation. The Bighorn is unconformably overlain by Upper Devonian Jefferson Limestone and Three Forks Shale with a combined thickness of 470 ft. The Mississippian Madison Group (860 ft of limestone and dolomite) is conformable with and overlies the Three Forks. In other parts of the study area, the Madison group is commonly subdivided into the Lodgepole and Mission Canyon Limestones. The Madison is unconformably overlain by the Amsden Formation (140 ft of limestone, dolomite, and siltstone). Although the precise age of the Amsden is not known in this area, it is considered to be mainly Pennsylvanian in age (Richards, 1957). The Pennsylvanian Quadrant Sandstone (100 ft) conformably overlies the Amsden and is the uppermost Paleozoic unit exposed in this part of the study area.

In the North Snowy block, Mesozoic sedimentary rocks are located mainly along the northern part of the block where they overlie Paleozoic rocks and dip generally to the northeast. Within the study area, the Mesozoic rocks have a total maximum thickness of about 6,500 ft (Richards, 1957); however, in the surrounding region the total thickness of the Mesozoic sequence is about 13,000 ft, including approximately 7,000 ft of beds assigned to the Upper Cretaceous Livingston Group (Roberts, 1972). Only the lower part of the Livingston Group is exposed in the study area.

Jurassic and Cretaceous formations are present but Triassic formations are not present in the North Snowy block, although they have been identified in the Sliderock Mountain area (Vhay, 1934; Garbarini, 1957) and along the eastern margin of the Beartooth Plateau block (Pierce, 1965). Jurassic units consist of the Middle and Upper Jurassic Ellis Group (415 ft of limestone, sandstone, and shale) and the Upper Jurassic Morrison Formation (400 ft of siltstone and sandstone). The Ellis Group consists of the Piper (240 ft), Rierdon (95 ft), and Swift (80 ft) Formations. Lower Cretaceous rocks described by Richards (1957) include the Kootenai Formation (320 ft of conglomerate, mudstone, and shale) and the lower part of the Colorado Shale (about 800 ft of mostly shale with minor sandstone). Beds assigned to the Upper Cretaceous by Richards are the upper part of the Colorado Shale (about 1,200 ft of sandstone and shale), the Virgelle Sandstone and undivided strata (about 1,430 ft of mostly sandstone), and the lower part of the Livingston Formation (about 500 ft of siltstone, sandstone, and conglomerate; called the Cokedale Formation of the Livingston Group by

Roberts, 1972). Roberts (1972) assigns beds described as Colorado Shale by Richards to the Lower Cretaceous Thermopolis Shale (515 ft) and Mowry Shale (465 ft) and the Upper Cretaceous Frontier Formation (415 ft), Cody Shale (1,285 ft), and Telegraph Creek Formation (285 ft). Roberts also assigns the Virgelle Sandstone to the Eagle Sandstone (645 ft).

Tertiary Intrusive Rocks

Tertiary or Cretaceous igneous rocks are rare in the North Snowy block unlike other parts of the study area where they are abundant. The only significant occurrence of Tertiary igneous rocks in this block is in the southwestern part of the area where a thick dacite porphyry sill (Ti), or possibly an unroofed laccolith, is exposed. This body intruded Cambrian sedimentary rocks and is related to other intrusives in the Mill Creek and Emigrant areas of the South Snowy block.

SOUTH SNOWY BLOCK

The South Snowy block is located in the southwestern part of the study area (fig. B1). It is bordered to the north by the North Snowy block and to the northeast and east by the Beartooth Plateau block. The geology of the South Snowy block consists mainly of Precambrian metamorphic and igneous rocks, Paleozoic and Mesozoic sedimentary rocks, and Eocene volcanic and intrusive rocks. Quaternary volcanic rocks and travertine are exposed near Gardiner (plate 1). Much of the South Snowy block is a structural low where the Archean basement rocks are covered by Paleozoic and Eocene rocks. Nearly all of the Eocene volcanic and intrusive rocks of the Absaroka-Gallatin volcanic province are restricted to this block.

STRATIGRAPHY

Precambrian Metamorphic and Igneous Rocks

In the South Snowy block, Precambrian rocks consist of medium- to high-grade metasedimentary rocks, high-grade gneiss and migmatite, granite stocks, and mafic dikes. Nearly all are Archean although a few of the slightly metamorphosed or unmetamorphosed mafic dikes may be Proterozoic. Precambrian rocks outcrop in a nearly continuous band across the

southwestern part of the study area. They also occur in the Sixmile Creek, Emigrant Creek, and lower parts of Mill Creek valleys.

Jardine area--Metasedimentary rocks predominate in Jardine area where they form a thick sequence that includes quartz-biotite schist, biotite schist, biotite-garnet-staurolite-andalusite schist, banded iron formation (hornblende-cummingtonite-garnet schist), and felsic metavolcanic rocks (Thurston, 1986). A U-Pb age of approximately 3.2 Ga has been determined for detrital zircon from these rocks. The metasedimentary rocks are metamorphosed to upper greenschist to lower amphibolite facies (Thurston, 1986) and have experienced three periods of folding (Jablinski, 1990). The Jardine rocks are lower in metamorphic grade (greenschist to amphibolite facies versus granulite facies) and are structurally distinct from other Archean rocks in the study area. Mogk (1988) proposed that the Jardine rocks are allochthonous and were tectonically emplaced with their metamorphic and structural signature established at some time before 2.6 Ga.

The protoliths for the Jardine rocks have been interpreted as graywackes and mudstones with interbedded dacitic volcanics that were deposited along an active continental margin (Thurston, 1986). A variety of preserved sedimentary structures indicate deposition by turbidity currents. Relatively high chromium, nickel, magnesium, and iron concentrations and low alkali content of the schists suggest a mafic or ultramafic (possibly volcanic) detrital component to the metasedimentary sequence. The rocks are chemically unique for the Wyoming Province (Thurston, 1986). Thin muscovite schist layers may represent a felsic volcanic component. The area has not been interpreted as an Archean greenstone terrane, although many authors have noted similarities to the metasedimentary parts of greenstone belts.

In a study of Archean banded iron formations of south-central and southwestern Montana, Stanley (1988) suggested that elevated concentrations of elements such as Hf, Ti, Al, Th, Sc, and rare-earth elements in iron formation from the Jardine area indicate contamination of chemical sediments with clastic material, compatible with a deep water, turbidite model of deposition near an active continental margin such as was suggested by Thurston (1986). Thurston (1986) proposed two sediment sources for the Jardine iron formations, one felsic and one mafic, and postulated that thin beds of plagioclase- and lithic fragment-bearing rocks of trondhjemite composition may represent tuffs. Hallager (1980) noted an ultramafic signature in his

factor analysis of the chemistry of the Jardine iron formation and suggested that quartz-poor beds may reflect an ultramafic component to the sedimentary sequence.

The Jardine rocks, which host the gold deposits of the Jardine and Crevice districts (fig. A3), are unlike other Archean rocks of the Beartooth uplift in their unusual whole-rock chemistry, anomalously low metamorphic grade, and distinct structural history (Mogk, 1988). To the west, the Jardine rocks are bounded by the higher grade gneisses and migmatites of Yankee Jim Canyon. To the east, these metasedimentary rocks are separated by a structural discontinuity from higher grade gneisses and migmatites similar to those of Yankee Jim Canyon.

In the Jardine area, several biotite-muscovite granite stocks have been mapped where they intrude metasedimentary rocks (Seager, 1944; Fraser and others, 1969; plate 1). Rb-Sr model ages for two of the stocks range from 2.62 to 2.74 Ga (Brookins, 1968; Wooden and others, 1979). The metasedimentary rocks are also intruded by Precambrian mafic dikes and by intermediate to felsic Tertiary or Cretaceous dikes and plugs.

Yankee Jim Canyon.--Quartzofeldspathic gneisses and migmatites are well exposed in Yankee Jim Canyon (Yellowstone River) to the northwest of Gardiner. The main lithologies are quartzofeldspathic gneiss, hornblende amphibolite, garnet-biotite-plagioclase gneiss, and pegmatite (Guy and Sinha, 1988). Similar gneissic rocks are also present in the Sixmile Creek area to the northeast of Yankee Jim Canyon. The gneisses show evidence of mylonization. Mylonite zones of the Yankee Jim Canyon and Sixmile Creek areas have also been described by Burnham (1982). Mineral chemistries and the presence of cordierite, garnet, sillimanite, and kyanite indicate temperature and pressure estimates of 775-800 °C and 4.5-6 Kb for metamorphism (Guy and Sinha, 1988). These conditions indicate granulite facies metamorphism (Philpotts, 1990) and a much higher grade of metamorphism than that indicated for the nearby Jardine metasedimentary rocks. The ages derived for Yankee Jim Canyon rocks from whole-rock Pb isotope data center around 2,625-2,650 Ma and zircon U-Pb data indicate a discordant age of 2,850 Ma (Guy and Sinha, 1988).

Sixmile Creek and Emigrant-Mill Creek areas.--Rocks similar to those in the Jardine area also occur in the lower parts of the Sixmile, Emigrant, and Mill Creek drainages. Higher grade gneiss and migmatite, perhaps continuous with the Yankee Jim Canyon sequence, are present in the upper parts of the

Sixmile Creek drainage. Relatively thick mafic intrusions, principally metagabbro, are present in the Emigrant-Mill Creek area.

Paleozoic and Mesozoic Sedimentary Rocks

Paleozoic sedimentary rocks are common throughout most of the South Snowy block and are thickest in the Emigrant-Mill Creek area and along the Cooke City structural zone. Mesozoic sedimentary rocks are present only in the lower plate of the Gardiner Thrust near the southwest corner of the study area. Paleozoic rocks have been mapped and described in the Cooke City area by Lovering (1929) and Elliott (1979), in the Absaroka Primitive Area (an area bounded by Gardiner, Independence, Cooke City, and Yellowstone National Park; fig. A2) by Wedow and others (1975), in the Emigrant-Mill Creek area by Elliott and others (1983), in the Gardiner area by Fraser and others (1969), and in the northern part of Yellowstone National Park by Ruppel (1972).

Throughout the South Snowy block, Paleozoic rocks lie unconformably on the Archean crystalline basement rocks. Erosion prior to the deposition of Tertiary volcanic rocks has stripped Paleozoic rocks from much of the uplifted block and removed all of the Mesozoic sedimentary rocks, which may have been as thick as 8,000 ft (Fraser and others, 1969). The Paleozoic section in the central and southeastern parts of the South Snowy block has a maximum thickness of about 2,100 ft (Wedow and others, 1975). This section includes Cambrian, Ordovician, Devonian, and Mississippian strata. Rocks of Pennsylvanian and Permian age are not present in the South Snowy block because of pre-Eocene erosion but are present near Gardiner in the lower plate of the Gardiner Thrust and in the northern part of Yellowstone Park. The pre-Eocene erosion removed a minimum of approximately 1,500 ft of Upper Paleozoic rocks from the entire South Snowy block. Cambrian rocks in the South Snowy block include the Flathead Sandstone (about 100 ft), Wolsey Shale (150 ft), Meagher Limestone (125 ft), Park Shale (400 ft), Pilgrim Limestone (125 ft), and Grove Creek and Snowy Range Formations (undivided; 250 ft). The single Ordovician unit is the Bighorn Dolomite (250 ft). Devonian units are the Three Forks Formation and Jefferson Limestone (undivided; about 300 ft). About 400 ft of the lower part of the Mississippian Madison Limestone (Madison Group) forms the top of the thickest sections. In the northern part of Yellowstone

Park where the Paleozoic section is complete, the Madison Group is about 1,300 ft thick and the Pennsylvanian rocks (Amsden Formation and Quadrant Sandstone) and Permian rocks (Shedhorn Sandstone) have a maximum combined thickness of 500 ft.

Along the southwestern boundary of the ABSA near Gardiner, partial, faulted sections of Mesozoic sedimentary rocks are present in the lower plate of the Gardiner Thrust. These include Triassic Chugwater and Dinwoody Formations, Jurassic Ellis Group (Sawtooth, Swift, and Rierdon Formations) and Morrison Formation, and Lower Cretaceous Cloverly Formation, Thermopolis Shale, and Mowry Shale. Upper Cretaceous units present along the study area border and in the adjacent parts of Yellowstone Park are Frontier Formation, Cody Shale, Telegraph Creek Formation, Eagle Sandstone, Everts Formation, and Landslide Creek Formation (Fraser and others, 1969).

Eocene Volcanic Rocks

Tertiary volcanic rocks of the Absaroka volcanic field or the Absaroka-Gallatin volcanic province of Chadwick (1970) are widespread in the South Snowy block. This volcanic field covers about 9,000 mi² from the south end of the Absaroka Range in northwestern Wyoming to the vicinity of the Tobacco Root Mountains in southwestern Montana, has a maximum thickness of about 4,900 ft, and is the largest volcanic pile of Eocene age in the Northern Rocky Mountains (Smedes and Prostka, 1972). The bulk of the volcanic activity probably lasted 5 to 10 m.y., approximately 45 to 55 m.y. ago and concurrent with major uplift of the region (Elliott and others, 1983). Throughout the field, the volcanic rocks are mostly andesite and dacite, and consist of pyroclastic and epiclastic volcanic material, lava flows, and genetically related intrusive rocks. Eruptive centers of the volcanic field are aligned along two northwest-trending structural zones that extend for at least 150 mi from northwestern Wyoming to southwestern Montana. One of these zones coincides with the Cooke City structural zone. Some of the intrusive centers are the eroded roots of volcanic cone complexes. Mineralization associated with the Eocene igneous activity was concentrated in and around the intrusive centers and occurred late in the intrusive cycle or subsequent to the emplacement of intrusives.

Within the study area the volcanic rocks have an aggregate thickness of about 4,700 ft (Elliott and others, 1983) and unconformably overlie Precambrian

and Paleozoic rocks. They form most of the high peaks and ridges in the South Snowy block (see Wedow and others, 1975). According to Smedes and Prostka (1972), volcanic rocks of this area are part of the Washburn and Sunlight Groups of the Eocene Absaroka Volcanic Supergroup. The volcanic rocks include deposits derived from several separate, but nearly contemporaneous, volcanic centers. The volcanic units are deeply eroded, display considerable lateral variation, and many unconformities. Volcanic strata from one center commonly interfinger with those of similar lithology from other volcanic centers. The volcanic rocks are chiefly near-source deposits and consist of interlayered basaltic to rhyodacitic tuff breccia and ash, basaltic to latitic lava flows, and volcaniclastic rocks (lahars, conglomerates, sandstones, siltstone, and shales). Volcanic rocks of the South Snowy block have been mapped and described by Wedow and others (1975) and Elliott and others (1983).

According to Rubel (1964, 1971) and Courtis (1965), a large stratovolcano was centered over the Eocene stock of the Independence area (fig. B1). Another major volcanic center is probably represented by the Emigrant stock and surrounding Eocene intrusive rocks of the Emigrant-Mill Creek area. These two centers appear to be the source of most of the volcanic material in the study area (Elliott and others, 1983). Ash Mountain, near Jardine, is also thought to be an eruptive center (Fraser and others, 1969) and a possible source for the extensive Slough Creek Tuff Member (welded and non-welded ashflow tuffs) of the southern part of the South Snowy block (Wedow and others, 1975).

Eocene Intrusive Rocks

Eocene intrusive rocks are widespread in the South Snowy block where they are associated with volcanic and volcaniclastic rocks of the Absaroka Volcanic Supergroup (Smedes and Prostka, 1972; Wedow and others, 1979). These intrusive rocks include stocks, plugs, laccoliths, sills, and dikes. Their compositions are predominantly intermediate to felsic and calc-alkaline, although mafic dikes (basalt or basaltic andesite) are common in the Absaroka volcanics. The largest intrusive bodies, mainly stocks and laccoliths, are located in the principal eruptive centers in the Emigrant, Independence, Horseshoe Mountain, and Cooke City areas (fig. A3). Nearly all of the intrusive rocks were emplaced at shallow depths and generally have porphyritic textures and aphanitic

groundmasses; only the Independence, Emigrant, and Scotch Bonnet Mountain stocks and a small plug near the head of Mill Creek have phaneritic textures (plate 1). The rocks range from basaltic andesite to rhyolite in composition, but dacitic rocks are volumetrically the most important. Porphyritic rocks include dacite porphyry, rhyolite porphyry, quartz latite, and andesite porphyry. Phaneritic rocks include granodiorite porphyry, quartz monzonite, quartz monzodiorite, monzodiorite, diorite, and diorite porphyry.

Emigrant-Mill Creek area.--Many intrusive bodies are exposed in the Emigrant-Mill Creek area, in the northern part of the South Snowy block. These include sills, dikes, laccoliths, a stock, and irregular-shaped bodies. Many of these were probably emplaced along faults (Wilson, 1936), and are commonly located at the contact between Precambrian and Cambrian rocks.

The Emigrant stock (fig. B1), in the western part of the ABSA, is located in the upper drainage basin of Emigrant Creek and is well exposed on the steep eastern slopes of Emigrant Peak and many ridges near the head of Emigrant Creek and its tributaries. This area has been mapped and described by Basler (1965) and Elliott and others (1983). The stock is an intrusive complex and consists of at least three phases (Elliott and others, 1983). Most of the stock consists of an older dacite porphyry and dacite that is, in part, intrusive tuff breccia or possibly a welded tuff. A younger dacite porphyry forms dikes and irregular-shaped bodies within the stock and dikes that cut andesitic volcanic rocks that border the stock. The younger dacite porphyry typically contains more phenocrysts, including abundant quartz "eyes," than the older dacite and dacite porphyry. The youngest major phase of the Emigrant stock is granodiorite porphyry that forms a small pluton in the core of the stock and is exposed in upper Emigrant Creek. This rock is light gray and consists of 50-75 percent phenocrysts in a fine-grained groundmass. The rock is weakly altered and cut by veinlets of quartz and sulfide minerals, principally chalcopyrite. A $^{40}\text{Ar}/^{39}\text{Ar}$ age of 48.7 ± 0.15 Ma has been determined on a biotite separate from the granodiorite porphyry (Stephen S. Harlan, U.S. Geological Survey, 1992, unpublished data).

Much of the Emigrant stock is moderately to intensely altered, and pyritic alteration is widespread and locally intense (Elliott and others, 1983). Several altered and mineralized breccia bodies are present within the stock. The alteration and mineralization of this area has been described by Pfau (1981).

Independence area.--In the Independence area (fig. B1), a compositionally zoned stock is exposed in the core of a partially eroded stratovolcano (Emmons, 1908; Rubel, 1964, 1971). The Independence volcano was a major eruptive center and a source of the volcanic flows and breccias that cover the surrounding terrane. The core of the volcano consists of, from oldest to youngest, andesitic intrusive breccia, monzodiorite, quartz monzodiorite, quartz monzonite, and granite dikes. Most of the core is fine- to medium-grained quartz monzodiorite. The Independence intrusive rocks are inferred to be Eocene in age, based on the association with surrounding Eocene volcanic rocks and on $^{40}\text{Ar}/^{39}\text{Ar}$ ages determined on biotite of 48.6 ± 0.13 Ma (Harlan and others, 1991) and 48.4 ± 0.14 Ma (Stephen S. Harlan, U.S. Geological Survey, 1992, unpublished data). The northern part of the Independence stock is altered and mineralized and several mineral occurrences are hosted by Precambrian and Paleozoic rocks surrounding the Independence volcano (U.S. Geological Survey and U.S. Bureau of Mines, 1983).

Cooke City area.--Intrusive rocks of the Cooke City area, which includes the New World mining district (fig. A3), consist of a suite of intermediate to felsic calc-alkaline rocks that include diorite, andesite, trachyandesite, dacite, quartz latite, and rhyolite (Elliott, 1979). The intrusions form stocks, laccoliths, and numerous sills, dikes, and irregular-shaped bodies. A shallow emplacement level is suggested by fine-grained textures of intrusive rocks. All of the intrusions are probably of Eocene age, although geochronologic data are sparse. The age of the Scotch Bonnet stock is 55.3 ± 0.7 Ma (Elliott, 1979, K-Ar from biotite). An age of 45.2 ± 4.6 m.y. was determined for the Henderson Mountain stock (Marvin and others, 1989, fission track data from zircons). Areas of altered rocks, several important gold-silver-copper deposits, and mineralized breccia pipes are closely associated with the intrusions (Elliott and others, 1992). The principal plutons of the Cooke City area are the Scotch Bonnet diorite stock, Fisher Mountain intrusive complex, Homestake rhyolite porphyry stock or intrusive complex, Henderson Mountain rhyolite porphyry stock, and Lulu Pass rhyolite porphyry laccolith (Elliott and others, 1992). Mineralized breccia pipes or breccia complexes are associated with the Homestake intrusive complex (Homestake breccia complex), Henderson Mountain stock (breccia of the Alice E. mine area), and Fisher Mountain intrusive complex.

The Fisher Mountain and Homestake intrusive complexes both show concentrically zoned alteration

typical of many porphyry copper deposits, which are characterized by silicic and potassic alteration assemblages in the cores of the plutons that grade outward into phyllitic and propylitic alteration zones (Elliott and others, 1992). Both of these intrusive complexes have been explored for porphyry-copper and (or) molybdenum deposits. The emplacement and hydrothermal alteration of these two intrusions are spatially, temporally, and probably genetically related to five identified gold-copper-silver deposits, which have total geologic reserves of more than 12 million tons of ore that contains more than 2.6 million ounces of gold, 179 million pounds of copper, and 10 million ounces of silver (Elliott and others, 1992).

The oldest of the major intrusives in the Cooke City area is the Scotch Bonnet diorite stock. This rock is fine grained and equigranular. It cuts slightly older andesite porphyry sills but is intruded by the younger Fisher Mountain complex and the Lulu Pass rhyolite porphyry. This stock is slightly older than or contemporaneous with the surrounding volcanic rocks. It has a composition similar to most of the volcanic breccias and lava flows and may represent the roots of an eroded stratovolcano.

The Fisher Mountain intrusive complex consists of a variety of aplianitic and fine-grained porphyritic felsic intrusive rocks, which include dacite, rhyolite, and quartz latite porphyry. Most of the complex is intensely sericitized and pyritized. The complex has breccia and stockwork zones. Stockwork veinlets consist of quartz-sericite-pyrite-chalcopyrite, quartz-sericite-molybdenite, and potassium feldspar-quartz-chalcopyrite-molybdenite-pyrite. The Como, Fisher Mountain, and McLaren gold-copper-silver deposits are hosted by limestone of the Middle Cambrian Meagher and Upper Cambrian Pilgrim Limestones in the contact zone of the Fisher Mountain intrusive complex (Elliott and others, 1992).

The Homestake intrusive complex consists dominantly of rhyolite porphyry that is moderately to strongly altered and locally brecciated. The rhyolite porphyry generally contains distinctive rounded to strongly embayed quartz phenocrysts. Similar quartz "eye" rhyolite porphyry in sills, dikes, and irregular-shaped bodies are abundant throughout the New World district. The Miller Creek gold-copper-silver deposit is a skarn and replacement deposit in the contact zone of the Homestake intrusive complex and the Homestake deposit is hosted by a breccia complex within the Homestake intrusive complex. The Henderson Mountain stock consists of rhyolite porphyry that is weak to moderately altered and strongly porphyritic.

The rhyolite porphyry of Lulu Pass is the youngest of the major intrusive bodies in the Cooke City area. It appears to have a relatively flat floor based on the northernmost exposures of this body where it intruded along the contact of Precambrian and Cambrian rocks. The Lulu Pass rhyolite porphyry is weakly to moderately altered to propylitic and sericitic assemblages. The laccolith contains numerous xenoliths and roof pendants of Cambrian sedimentary rocks. However, these rocks are little altered and mineralized, in contrast to other parts of the New World district where such Cambrian rocks are strongly altered and mineralized at contacts with intrusive rocks.

Miscellaneous intrusive rocks.--Other Eocene intrusive rocks, which may indicate the location of additional intrusive centers to those discussed above, are (1) a small plug of diorite porphyry near the headwaters of Mill Creek (Elliott and others, 1983), (2) a possible rhyolite stock at Ash Mountain (Wedow and others, 1975), and (3) a complex laccolithic body of intermediate to felsic composition at Horseshoe Mountain (Wedow and others, 1975).

Near the headwaters of Mill Creek, a small circular plug of diorite porphyry intrudes volcanic rocks (plate 1). This plug is central to a radiating group of dark-colored dikes that cut the volcanic rocks. Rhyodacitic intrusives are exposed over a large area at and near Ash Mountain, in the southwestern part of the South Snowy block. Southeast of Ash Mountain, a thick laccolith consisting of mostly porphyritic latite to rhyodacite, with trachytic texture and flow-banding, has been described by Wedow and others (1975). A large dike-like body or plug of trachyrhyolite "welded tuff" also occurs at Ash Mountain (Wedow and others, 1975). This intrusive is porphyritic, has vertical flow-banding, and may be the source of the Slough Creek Tuff Member ash-flow sheet. Intrusive rocks of a complex laccolith at Horseshoe Mountain intruded and domed Precambrian and Cambrian rocks. These rocks are variably altered to sericite and kaolin. Similar, but less altered, intrusives also cut Precambrian gneiss and Tertiary volcanic rocks northwest of Horseshoe Mountain (Wedow and others, 1975).

Quaternary Volcanic Rocks and Travertine Deposits

Near Gardiner, along the southwest margin of the study area, benchies northeast of the Yellowstone River are mantled by Quaternary basalt flows, rhyolitic ash-flow tuff (Lava Creek Tuff), and

travertine (Fraser and others, 1969; Pierce and others, 1991). The volcanic units are outliers of the extensive Quaternary basalt and rhyolite that cover much of the Yellowstone Park region to the south of the study area. The travertine deposits have been deposited from hot springs that have been active in the Gardiner-Mammoth area for at least the last 400,000 yr (Pierce and others, 1991). Active deposition of travertine is occurring at the La Duke and Bear Creek hot springs, on the border of the study area. These hot springs are apparently controlled by the northwest-trending Gardiner Thrust or intersections of that fault with north- and northeast-trending normal faults (Pierce and others, 1991).

BEARTOOTH PLATEAU BLOCK

The Beartooth Plateau block, in the eastern part of the study area (fig. B1), is bounded on the northwest by the Mill Creek-Stillwater fault and the Stillwater Complex, on the west by the Cooke City structural zone, and on the east and northeast by the Beartooth thrust fault, which forms the front of the Beartooth Mountains. Archean rocks, mainly granitic gneisses and migmatites, predominate throughout the block (plate 1). Prior to uplift, the area was covered by a thick sequence of Paleozoic and Mesozoic sedimentary rocks and Tertiary volcanic rocks, but these have been stripped away by post-Laramide erosion following uplift of the region. Paleozoic and Mesozoic rocks occur only around the margins of the northeastern and eastern parts of the Beartooth Plateau block where they are exposed in steeply dipping sequences along the Beartooth thrust. Sedimentary rocks of the Paleocene Fort Union Formation underlie a small part of the study area near the southeast corner of the ABSA (plate 1). A Cretaceous intrusive center is located at Goose Lake that consists of a syenite stock and related rhyolite and quartz latite porphyry sills and dikes. Intrusive rocks of Cretaceous or Tertiary age, mainly dikes, are abundant in the eastern part of the Beartooth Plateau block, particularly on the Line Creek Plateau, and in the vicinity of Granite Peak in the central part of the block (plate 1).

Most of the Beartooth Plateau block was mapped and described by Simons and others (1979) in a study of the mineral resources of the Beartooth Primitive Area and vicinity (now part of the Absaroka-Beartooth Wilderness). In addition, the southeastern part of the block has been the focus of many studies.

An excellent summary of pre-1968 studies is presented by Casella (1969). Many more recent studies are compiled in a volume on the Beartooth Mountains by Mueller and Wooden (1982).

STRATIGRAPHY

Precambrian Metamorphic and Igneous Rocks

Metamorphic and igneous rocks of Precambrian age underlie probably more than 95 percent of the Beartooth Plateau block. Most of the rocks are granitic gneiss, hornblende gneiss, and amphibolite; mafic intrusive rocks, mainly as dikes (dolerite, metadolerite, metanorite, and metagabbro), are abundant but constitute only a small proportion of the Precambrian terrane (Simons and others, 1979). Other units of small areal extent include quartz monzonite, aplite, and hornblende quartz diorite in the Stillwater area and supracrustal rocks including quartzite, biotite schist, iron formation, amphibolite, and ultramafic rocks (mainly serpentinite). The supracrustal rocks occur as inclusions and septa (up to kin-size) in granitic gneiss and migmatite.

Granitic gneiss, migmatite, pegmatite, microgranite or aplite, and orbicular rocks, commonly grouped under the title of granitic gneiss, probably constitute over 90 percent of the bedrock of the Beartooth Plateau block. Of these, pegmatite, aplite, and orbicular rocks make up less than 1 percent of the Precambrian terrane (Simons and others, 1979). Migmatites occur throughout the gneiss terrane and are distinguished by conspicuous layering, usually of alternating layers of biotite-rich and biotite-poor gneiss. Their relative abundance varies from place to place but no systematic variation has been recognized (Simons and others, 1979). Although the granitic gneiss represents a major crust-forming event and widespread granitic magmatism (Mueller and others, 1985), large bodies of granitic intrusive rock with clear crosscutting relations were not seen by Simons and others (1979) and have been reported from only one place in the study area. In the Stillwater area, along the northwestern side of the Beartooth Plateau block, plutons of quartz monzonite and associated hornblende quartz diorite and aplite intrude both granitic gneiss and the basal zone of the Stillwater Complex. An age of approximately 2,700 Ma has been assigned to these intrusive rocks (Page and Nokleberg, 1972; Nunes and Tilton, 1971).

To the south of the study area but still within the Beartooth uplift, detailed mapping near Long Lake

has located intrusive relationships between amphibolite (oldest), granodiorite, and granite (youngest) (Warner and others, 1982). A composite Rb-Sr isochron, defined by samples of granite, granodiorite, and amphibolite has an age of 2,790 Ma (Wooden and others, 1982). This age is interpreted as the age of intrusion of the granite and the resetting of the Rb-Sr systematics of the other two units, which are probably no more than 200 million years older than the granite. The acquisition of U-Pb zircon data permitted new interpretation of ages of these rocks (Wooden and others, 1988). Based on these data, the granitic rocks are thought to be about 2,740 Ma and are interpreted as mainly intrusive and representative of a single, major, crust-forming cycle. These Late Archean granitoids intruded slightly older 2,790 Ma amphibolites of andesitic composition and foliated granitoids of granodioritic composition (Wooden and others, 1988).

The supracrustal rocks of the Beartooth Plateau block, although small in areal extent, offer important evidence to the geologic history of the region. Structural studies of these rocks (Rowan, 1968) indicate two periods of folding; one isoclinal and the second non-isoclinal. These rocks show evidence of both a granulite-grade metamorphism at about 3,350 Ma (Mueller and others, 1985) and a Late Archean (approximately 2,800 Ma) amphibolite-grade metamorphism. The supracrustal rocks, have compositions equivalent to those of ironstones, basalts, andesites, ultramafic rocks, pelites, wackes, quartzites and felsic volcanic rocks. The ages of these supracrustal rocks are problematical and will remain so until new U-Pb zircon studies are completed (Wooden and others, 1988). Based on available data a maximum age of 3,300-3,500 Ma is indicated by uranium-lead (U-Pb) in zircon, and rubidium-strontium (Rb-Sr), samarium-neodymium (Sm-Nd), and common Pb data from some rocks (Wooden and others, 1988; Mueller and others, 1992).

Mafic intrusive rocks are common throughout the Beartooth Plateau block, generally occurring as dikes of metadolerite and dolerite. Other mafic intrusive rocks include sills, a stock, and irregular-shaped bodies of metanorite and metagabbro. Isotopic ages of a large number of mafic dikes from the Beartooth Plateau block were determined by Mueller (1971) and Baadsgaard and Mueller (1973), who concluded that the dikes were emplaced during at least three intrusive episodes, at about 2,550, 1,300, and 740 Ma.

Paleozoic, Mesozoic, and Tertiary Sedimentary Rocks

Paleozoic, Mesozoic, and Tertiary sedimentary rocks are exposed along the northeastern and eastern edges of the Beartooth Plateau block, mainly in the lower plate of the Beartooth thrust fault. They commonly form palisades along the mountain front, especially near Red Lodge. The most complete and best exposures of the Paleozoic and Mesozoic sequence are about 10 mi south of the southeast corner of the study area at the mouth of Clarks Fork Canyon. This area has been mapped and described by Pierce (1965).

In the Clark Fork Canyon section, Paleozoic rocks have a total thickness of about 3,500 ft. Cambrian rocks include the Flathead Sandstone (100 ft), Gros Ventre Formation (625 to 700 ft; equivalent to the combined Wolsey Shale, Meagher Limestone, and Park Shale to north and northwest in the study area), Pilgrim Limestone (100 to 125 ft), Snowy Range Formation (300 ft), and Grove Creek Formation (50 ft). The Ordovician Bighorn Dolomite is 400 to 475 ft thick. Devonian units include the Beartooth Butte Formation (0 to 75 ft), Jefferson Formation (300 ft), and Three Forks Formation (90 ft). Mississippian and Pennsylvanian rocks include the Madison Limestone (950 ft), Amsden Formation (150 ft), and Tensleep Sandstone (200 to 240 ft; equivalent to the Quadrant Sandstone in the study area). The Permian Park City Formation is 40 to 110 ft thick.

Mesozoic rocks in the Clark Fork Canyon section have a total thickness of about 7,100 ft. Triassic rocks include the Dinwoody (35 to 50 ft) and Chugwater (600 to 700 ft) Formations. Jurassic rocks include the Sundance and Gypsum Spring Formations (combined thickness of 425 to 500 ft; equivalent to the Ellis Group in the study area) and the Cloverly and Morrison Formations (combined thickness of 550 ft). Cretaceous rocks include the Thermopolis Shale (550 ft), Mowry Shale (450 ft), Frontier Formation (450 ft), Cody Shale (1,800 ft), Mesaverde Formation (about 1,200 ft), and Meeteetse Formation (about 1,000 ft).

Part of the Paleocene Fort Union Formation is present within the study area adjacent to the mountain front near the Montana-Wyoming border. In this area, the Fort Union consists of conglomerates and sandstones formed during the uplift of the Beartooth Mountains. See Chapter J of this report for details of the Fort Union Formation in the Red Lodge and Bear Creek areas.

Cretaceous and Tertiary or Cretaceous Intrusive Rocks

Goose Lake area.--The Goose Lake area, located about 8 mi north of Cooke City in the south-central part of the study area (fig. B1), consists of a syenite stock and numerous rhyolite to quartz latite porphyry sills and dikes (plate 1; Elliott, 1979). This alkalic intrusive center differs from the Cooke City Eocene intrusive center to the southwest in age, composition, mineralogy, texture, and style and types of mineralization and alteration. The age of the syenite stock is Late Cretaceous as indicated by fission track data from sphene (87.0 ± 12 Ma; Marvin and others, 1989) and $^{40}\text{Ar}/^{39}\text{Ar}$ data for adularia (74.5 ± 0.2 Ma; Stephen S. Harlan, U.S. Geological Survey, 1992, unpublished data).

The stock at Goose Lake (plate 1) is nearly circular in plan with a diameter of about 1 mi. The stock is multi-phase; the main phase is syenite but monzonite and quartz monzonite are also present. Most of the stock is fine to medium grained and equigranular to porphyritic. Many dikes and sills of rhyolite and latite porphyry are exposed in the ridges and peaks surrounding the area of the stock. These show compositional similarities to the Goose Lake stock and have been affected by both propylitic and pyritic alteration. Several features, such as miarolitic cavities, outward-dipping contacts, the shape of an associated aeromagnetic high, association with dikes and sills, and surface exposures of altered and mineralized rocks, suggest that only the top of the stock is exposed and the intrusive body may be much larger in the subsurface.

In the central and northern parts of the stock, copper minerals are associated with potassic alteration and with pods and masses of adularia, quartz, and chalcedony. Copper-rich samples also contain anomalously high contents of platinum and palladium (Lovering, 1929; Simons and others, 1979). Lovering (1929) concluded that the copper-platinum deposit at the Copper King property, near the north end of the Goose Lake stock, is a magmatic segregation deposit.

Miscellaneous intrusive rocks.--Intrusive rocks of unknown but probable Tertiary or Cretaceous age are common in parts of the Beartooth Plateau block. These occur as dikes, small plugs, and a stock and are generally of dacitic or latitic composition. They are generally light colored, fine grained, and porphyritic. These rocks are found mainly in the central (Granite Peak area) and southeastern parts of the Beartooth

Plateau block. The greatest abundance of these intrusive rocks is in the area of Line Creek Plateau where they occur as dikes, plugs, and a small stock. Simons and others (1979) described four general lithologic types for the Beartooth Primitive Area; these are (1) pale-red or brown sparsely porphyritic latite, (2) gray to red coarsely porphyritic latite, (3) light-gray or red corasely porphyritic hornblende latite, and (4) light- to dark-gray porphyritic dacite or andesite.

SLIDEROCK MOUNTAIN AREA

The Sliderock Mountain area is located in the northernmost part of the study area (fig. B1). It includes all of the National Forest lands north of the northern front of the Beartooth Mountains and east of the Boulder River. This area is mountainous with moderate to high local relief but has lower elevations than most of the Beartooth Mountains to the south; the highest peaks are between 7,500 and about 9,000, much lower than many of the peaks and plateaus of the Beartooth uplift, which are 10,000 ft and higher. Although topographically lower, the bedrock of this area is generally higher in the stratigraphic sequence due to structural offset along faults that form the mountain front. Archean rocks are exposed only in a relatively small area along the East Boulder River. The bedrock for approximately one-half of the Sliderock Mountain area is a sequence of Paleozoic and Mesozoic sedimentary rocks. Most of the remainder of the area consists of Late Cretaceous volcanic, volcanioclastic, and intrusive rocks. Some parts of the area are also underlain by intrusive rocks of uncertain age; these consist of dikes, sills, laccoliths, and stocks that may be Tertiary or Cretaceous in age.

Much of the Sliderock Mountain area has been previously mapped and described and much of this previous work has been compiled on plate 1. However, in the northern part of this area, the Late Cretaceous igneous rocks were inadequately mapped and described; therefore, additional mapping, petrography, geochemical sampling, and geochronologic studies were done in 1991 and 1992 to portray and describe the geology of this area and to collect data for the resource assessment of the ABSA. Previous work in the area includes theses by Vhay (1934), Garbarini (1957), and Brozdowski (1983). Published reports and maps used in this study include those by Parsons (1942), Foose and others (1961), and Page and others (1973a, 1973b).

STRATIGRAPHY

Paleozoic and Mesozoic Sedimentary Rocks

Paleozoic and Mesozoic sedimentary rocks are exposed in the southern and western parts of the Sliderock Mountain area where they generally strike east-west to west-northwest and dip to the north or northeast. They are folded and faulted; the trends of folds generally parallel the mountain front (Foose and others, 1961). The largest of the faults is the East Boulder fault which has a south-side-down sense of movement and may be a continuation of the Nye-Bowler zone to the east (Foose and others, 1961).

Paleozoic and Mesozoic rocks of the area have been mapped by Vhay (1934) and Garbarini (1957). The sequence is similar to that of the Livingston area (Richards, 1957; Roberts, 1972) except that (1) a thin zone of Permian Phosphoria Formation is present, (2) up to 110 ft of Triassic Chugwater Formation is present, and (3) the Livingston Group is not present but is correlated with the volcanic and volcaniclastic rocks of the northern part of the area. The following description is based on mapping by Garbarini (1957) as shown by Foose and others (1961, table 1).

The total thickness of the Paleozoic rocks in the Sliderock Mountain area is about 2,870 ft. Cambrian rocks (about 1,100 ft thick) consist of Flathead Sandstone, Wolsey Shale, Meagher Limestone, Park Shale, Maurice Formation (equivalent to Pilgrim Limestone), Snowy Range Formation, and Grove Creek Formation. The Ordovician Bighorn Dolomite is about 120 ft thick. Devonian rocks (about 455 ft thick) consist of the Jefferson and Threeforks Formations. The Mississippian Madison Group and Amsden Formation have a combined thickness of about 1,100 ft. The Pennsylvanian Quadrant Sandstone is 40 to 100 ft thick and the Permian Phosphoria Formation is 10 to 40 ft thick.

The total thickness of Mesozoic sedimentary rocks from the base of the Triassic Chugwater Formation to the top of the Upper Cretaceous Eagle Sandstone is about 5,550 ft. The Chugwater is about 110 ft thick. Jurassic rocks consisting of the Piper, Rierdon, and Swift Formations (Ellis Group) total about 965 ft of thickness. The total thickness of the pre-Livingston Group Cretaceous rocks is about 4,475 ft consisting of the Kootenai Formation, Thermopolis Shale, Mowry Shale, Frontier Formation, Cody Shale, Telegraph Creek Formation, and Eagle Sandstone.

Cretaceous Volcanic, Volcaniclastic, and Intrusive Rocks

The geology of the northern part of the Sliderock Mountain area is dominated by the remains of a deeply eroded Upper Cretaceous stratovolcano centered near Sliderock Mountain (plate 1). Lahars (previously described as agglomerates by Vhay, 1934) compose the majority of the volcano, although andesite lava flows are also present. The total thickness of this sequence of volcanic and volcaniclastic rocks may be as much as 3,500 ft. Extensive erosion has exposed a weakly mineralized hypabyssal intrusive complex inferred to represent the volcano's solidified magma chamber. Cretaceous sandstones and shales and Paleozoic sedimentary rocks, principally the Madison Limestone, host the stratovolcano; remnants of these rocks are preserved as large xenoliths and roof pendants.

The oldest rocks exposed in the Sliderock Mountain area are Paleozoic rocks that occur as isolated roof pendants, large xenoliths, or as host rocks to the intrusive phase of the Sliderock Mountain stratovolcano. Lower Cretaceous rocks, well exposed in Lower Deer Creek where they are intruded by the stock of Sliderock Mountain, include massive to thin-bedded black shale and siltstone containing intervals of fine-grained micaceous or quartzose sandstone. The lower part of this section includes massive chert pebble conglomerate and sandstone. In the Sliderock Mountain area, this Lower Cretaceous section includes the Kootenai Formation and the Thermopolis and Mowry Shales. Upper Cretaceous rocks, composed of the Frontier Formation, Cody Shale, Telegraph Creek Formation, and the Eagle Sandstone, are also present in northern part of the Sliderock Mountain area. The largest exposed mass of Upper Cretaceous sedimentary rocks is located in Upper Deer Creek.

The earliest manifestation of volcanic activity associated with the Sliderock stratovolcano is represented by the Upper Cretaceous andesite of Derby Ridge (map unit Kad, plate 1). These rocks are interpreted as lava flows, and include minor pyroclastic flows, block and ash flows, welded tuff, and interbedded lahars, erupted from the Sliderock Mountain stratovolcano and unconformably deposited on Mesozoic sedimentary rocks. This unit is at least 1,300 ft thick.

The andesite of Derby Ridge is overlain by texturally and compositionally immature volcanic

sedimentary rocks (Klc, plate 1) well exposed about 2 mi northwest of Black Butte in the northwest part of the Sliderock Mountain area, in West Bridger Creek north of Derby Mountain, and in Derby Gulch. This unit, approximately 150 ft thick, consists of pale-olive, interbedded sandstone, siltstone, and shale and probably forms the base of the Livingston Group rocks in this area.

The immature sedimentary rocks described above are overlain by at least 1,000 ft of clast-supported lahar deposits (Kll) composed of poorly sorted, bouldery mudflows (Parsons, 1942). The lahars are correlative with sedimentary rocks of the Livingston Group and unconformably overlie andesite of Derby Ridge and Upper Cretaceous arkosic sandstones. The lahars are inferred to be derived from disaggregation of lavas erupted from the Sliderock Mountain stratovolcano. Individual mudflows form prominent rubbly cliffs, are massive, and tens of feet thick; bedding is absent or poorly developed in most places. Clasts are 0.2- to 10-ft-diameter, subangular to angular blocks dominantly composed of disaggregated andesite lava, although some dacite porphyry clasts in the basal part of unit may be derived from the Lodgepole laccolith of Brozdowski (1983). The matrix for the lahar deposits is composed of ash and finely comminuted, altered andesite lava. A few thin andesite lava flows are enclosed within lahars. The lahar unit contains thin interbeds of more well sorted epiclastic volcanic sandstone, siltstone, and shale that contain carbonized plant remains and may also contain minor pyroclastic flow deposits.

Three rock units, including the diorite stock of Sliderock Mountain (Kd), a diorite sill, and a sequence of andesite lavas (Kal), are demonstrably younger than the lahar deposits but relative age relations between these three units have not been determined.

A stock of diorite intrudes the older lahars, andesite lavas, and sedimentary rocks at Sliderock Mountain. Between Gold Hill and Fire Ridge the diorite is moderately to pervasively altered. Preliminary age determinations suggest the diorite stock of Sliderock Mountain is Late Cretaceous in age. Sericite, separated from an altered part of the stock, yielded a Late Cretaceous age of about 74.5 Ma (Stephen S. Harlan, U.S. Geological Survey, 1992, unpublished data). Since the stock was emplaced prior to formation of the secondary sericite in an altered zone, the minimum age of the stock is also 74.5 Ma. The diorite is texturally inhomogeneous and characterized by pronounced grain size variation; it may represent multiple intrusive phases or stocks that

have coalesced to form an intrusive complex. The intrusive complex is inferred to represent the stratovolcano's solidified, residual magma chamber. In the area around Evergreen Mountain, the diorite includes either a finer grained border phase or andesitic lava flows similar to the andesite of Derby Ridge; poor exposure and the altered nature of these rocks preclude definitive identification.

A 650-ft-thick diorite sill crops out about 3 mi west of Sliderock Mountain. It is petrographically similar and possibly genetically related to a sill exposed nearby at Enos Mountain (to the west) and to the Lodgepole laccolith (to the south) (Brozdowski, 1983). This sill may be the same age as the stock of Sliderock Mountain, but its age has not been determined.

Porphyritic, light- to dark-gray andesite lava flows form three large masses, about 1,000 ft thick, located (1) around the Red Mountain area, (2) atop the ridge that extends east northeast from Hicks Mountain, and (3) atop the ridge that extends southeast from Sugarloaf Mountain, and numerous, small erosional outliers. The relationship of these lava flows to the inferred Sliderock Mountain stratovolcano is unknown though they may represent a terminal, post-lahar, phase of eruptive activity.

Porphyritic, light-gray andesite dikes, 1 to 3 mi long and 3 to 30 ft thick, form prominent, linear ridges, especially north of Sliderock Mountain, and intrude components of the Sliderock Mountain stratovolcano. The dikes contain 15-30 percent phenocrysts, including laths of clay-altered plagioclase and subequal amounts of clinopyroxene, and hornblende in an aphanitic turbid, devitrified groundmass. These rocks are compositionally and petrographically similar to other igneous rocks of the Sliderock Mountain area and probably represent the terminal phase of igneous activity associated with the inferred stratovolcano. An age of about 75 Ma has been determined by the $^{40}\text{Ar}/^{39}\text{Ar}$ method on hornblende from one dike (Stephen S. Harlan, U.S. Geological Survey, 1992, unpublished data).

Tertiary or Cretaceous Intrusive Rocks

A number of hypabyssal intrusive bodies occur in the central part of the Sliderock Mountain area. These are predominately composed of dacite porphyry but also consist of diorite porphyry and andesite (Brozdowski, 1983; Rouse and others, 1937). These intrusives occur as sills, laccoliths, and plugs and intrude Paleozoic and Mesozoic sedimentary rocks.

They have been mapped and described by Vhay (1934), Brozdowski (1983), and Rouse and others (1937). The ages of these intrusives have not been determined by isotopic methods; stratigraphic evidence suggests they are Late Cretaceous (Rouse and others, 1937; Brozdowski, 1983). The largest of these intrusives, the Lodgepole, is a laccolith with an early dacite porphyry border phase and late diorite porphyry core. It contains xenoliths of amphibolite, gneiss, Paleozoic sedimentary rocks, and mafic rocks with cumulate textures (Brozdowski, 1983). A fine-grained andesite pipe on Enos Mountain also has plagioclase-cumulate-textured xenoliths. The occurrence of the mafic rocks with cumulate textures is of particular interest to the mineral resource assessment of the ABSA because they indicate that a portion of the Stillwater Complex may be present in the subsurface of the southern and central part of the Sliderock Mountain area. A study of these cumulate-textured xenoliths by Brozdowski (1983) showed that they are compositionally and texturally similar to mafic rocks of the Stillwater Complex. Some xenoliths indicate a potential for undiscovered deposits of chromium and PGE in the postulated subsurface portion of the Stillwater Complex. These xenoliths include the occurrence of (1) a chromitite xenolith, (2) mafic lithologies such as anorthosite and troctolite similar to those in the Stillwater Complex that host PGE minerals of JM Reef, and (3) the presence of disseminated, magmatic-appearing sulfide minerals in two troctolite and anorthosite xenoliths.

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CHAPTER C

GEOPHYSICS OF THE ABSAROKA-BEARTOOTH AREA

By Dolores M. Kulik

GEOPHYSICAL DATA

GRAVITY

Approximately 1,000 gravity measurements were obtained from files maintained by the Defense Mapping Agency of the U.S. Department of Defense. These data were supplemented by 41 measurements made by the author in 1991. The 1991 data were tied to the International Gravity Standardization Net 1971 (U.S. Defense Mapping Agency, Aerospace Center, 1974) at base station ACIC 0545-1 at Lamar Ranger Station, Wyoming and ACIC 1203-0 at Big Timber, Montana. Elevations were obtained from benchmarks, spot elevations, and interpolated estimates from topographic maps at 1:24,000 and 1:62,500 scales. Elevations are accurate to \pm 20-40 ft. The error in the Bouguer anomaly is less than 2.5 mGal (milligals) for errors in elevation control. Bouguer values were computed using the 1967 gravity formula (International Association of Geodesy, 1967) and a reduction density of 2.67 g/cm^3 (grams per cubic centimeter). Mathematical formulas are given in Cordell and others (1982). Terrain corrections were made by computer for a distance of 167 km (kilometers) from each station using the method of Plouff (1977). The combined gravity data are shown on plate 2 as a complete Bouguer gravity anomaly map with a contour interval of 2 mGal.

AEROMAGNETIC

Residual total intensity aeromagnetic data are shown on plate 3 with a contour interval of 20 nT (nanoteslas). Plate 3 is a composite map with data in the western part (west of longitude 110° west) from McCafferty (1991), and data in the eastern part from the National Uranium Resource Evaluation (NURE) program. Individual surveys of the western part shown in plate 3 were projected to Cartesian coordinates using a Lambert projection. The data

from each survey were interpolated to a $1 \text{ km} \times 1 \text{ km}$ square grid and the regional field was mathematically removed. Data were continued upward or downward and draped at 1,000 ft (305 m) above terrain. Each survey was then regridded and merged to adjoining surveys. Details of the processing are given in McCafferty (1991). These data were then plotted on a UTM projection with a $2 \text{ km} \times 2 \text{ km}$ square grid for this report. The survey in the eastern part was flown at 400 ft above terrain and is compatible with the western surveys at this scale of 1:126,720. The digital data were plotted on a UTM projection using a $1 \text{ km} \times 1 \text{ km}$ grid and the regional field removed. A constant value of 145 nT was added to correct for a datum shift between surveys. The data were then regridded at a 2 km interval, and the eastern and western parts of the data merged.

GEOPHYSICAL INTERPRETATIONS

Gravity anomalies (plate 2) are caused by differences in density of igneous, metamorphic, and sedimentary rocks and their distribution, while magnetic anomalies usually reflect differences in magnetization only of igneous rocks and some metamorphic rocks. Except for banded iron formation, sedimentary rocks usually are considered non-magnetic. Interpretations are based on the measured physical properties of rock samples obtained from localities within the Absaroka-Beartooth study area (ABSA). Data for measurements of the density and magnetic properties are not yet available for this report.

Gravity data are interpreted in terms of the average bulk density of bodies of rock and are measured in g/cm^3 . The density of any particular rock is determined by the densities of the individual minerals that make up the rock, their proportions, and the porosity (amount of empty space between grains or crystals). Bulk density is the combination of grain densities of the minerals and the amount of open pore

space with density of 0.0 gm/cm^3 (the porosity); the higher the porosity, the lower the bulk density. The higher the density, the more the rock weighs per measured unit, and the greater is the attraction of gravity on it. As a simplification, a gravity map can be thought of as a pattern of weight distribution of the rocks.

Metamorphic rocks (gneiss, schist, quartzite, etc.) usually have relatively high densities ($2.6\text{-}3.0 \text{ gm/cm}^3$) because the metamorphic processes cause the compaction of the rocks (thus decreasing the porosity) and the growth of higher density minerals at the expense of lower density ones. Sedimentary rocks (sandstone, siltstone, conglomerate, etc.) usually have lower relative densities ($2.2\text{-}2.6 \text{ gm/cm}^3$), and unconsolidated fill materials (sand, gravel, etc.) in valleys have densities lower still. Limestone is a notable exception as it generally has a high density ($2.6\text{-}2.8 \text{ gm/cm}^3$); it has very low porosity and is comprised mostly of calcite which has a higher density than quartz (the major constituent of most common sedimentary rocks).

The gravity anomaly associated with a rock body is also influenced by the rocks adjacent to the body. A granitic intrusion with an average bulk density of 2.62 gm/cm^3 will produce a high gravity anomaly, if it is intruded, for example, into a terrane of sandstone and siltstone with average bulk density of 2.57 gm/cm^3 . The same granitic intrusion, however, will produce a gravity low anomaly if it intrudes a terrane of metamorphic rocks with average bulk density of 2.70 gm/cm^3 . The character of the anomaly depends on the neighborhood.

As the gravity map shows the distribution of density, the aeromagnetic map shows the distribution of magnetic intensity (the degree of rock magnetization). Magnetic intensity depends on the magnetic susceptibility of the rock (mainly its magnetite content) and the distance of the rock from the sensor of the magnetometer. Minerals other than magnetite such as hematite, ilmenite, pyrrhotite contribute to the susceptibility. Magnetic anomalies may be caused by differences in lithology (hence differences in magnetic susceptibility) or differences in depth of burial of the magnetic sources in the crystalline basement rocks. The measured intensity decreases rapidly with the distance of the magnetic source from the sensor, thus a deeply buried rock will have a lower measured intensity than the same rock at the surface.

Most magnetic surveys are measured from aircraft, and distance to the magnetic source becomes

an important influence on the measured intensity. If the survey aircraft flies at a constant elevation, magnetic sources in peaks and ridges will be closer to the sensor than similar rocks in the valleys and flat-lying country. Magnetic surveys are often "draped," that is the pilot attempts to maintain a constant elevation above the topography (i.e., 400 ft). Obviously the degree of relief of the topography and the placement and size of its features determine how accurate the pilot can be. Computer programs may be used to compare constant flight elevation to topography and the measured intensity is mathematically corrected for the differences in elevation. Computer programs are also used to "continue" survey values upward or downward. This means that the measured values are changed by mathematical computation to the values that would have been measured if the survey had been flown at a different elevation. These techniques allow a survey flown at one elevation to be compared directly to another flown at a different elevation, or an undraped survey to be compared to a draped one. If many surveys are all mathematically converted in this way to a single style and elevation, they may be merged into one data set and plotted as a single map. This process has been used to produce the map on plate 3.

The gradients of the magnetic anomalies are caused by the degree of contrast in magnetic susceptibility between adjacent rock sources and by the depth at which the bodies lie. The interpretation, then, of both gravity and magnetic maps is a matter of integrating all information available from geologic mapping, structural interpretation, and physical property measurements of the rocks themselves. The interpreter also must consider the spacing, elevation, and method of the aeromagnetic surveys used and the spacing and elevation accuracy of the gravity data.

PREVIOUS WORK

Detailed geophysical interpretations were made in parts of the ABSA by Wedow and others (1975) for the Absaroka Primitive Area, by Simons and others (1979) for the Beartooth Primitive Area, and by the U.S. Geological Survey and U.S. Bureau of Mines (1983) for the North Absaroka Wilderness Study Area (fig. A2). Geophysical studies of the Stillwater Complex in the north-central part of the ABSA (fig. B1) were made by Kleinkopf (1985) and Blakely and Zientek (1985).

GRAVITY DATA

A northwest-trending belt of low gravity values (A) is associated with volcanic rocks in a structural trough extending from the Emigrant stock in the northwest to the Cooke City area in the southeast (plate 2). A gravity high (B) in the Hellroaring Creek drainage occurs over relatively high-density, west-dipping Cambrian rocks where Peterson (in Wedow and others, 1975) also interpreted a north-plunging structural high. A smaller high (C) probably reflects a similar structural high and metasedimentary rocks in a drainage to the southeast. A plateau (D) in the gravity values extending northeast of this anomaly was attributed to a core of Precambrian metamorphic rocks uplifted by Tertiary intrusive rocks in the subsurface (Rubel and Romberg, 1971). A series of east-west trending highs and lows (E) with magnitudes of less than 5 mGals occurs over layered Precambrian metasedimentary rocks near Jardine, Montana. Poorly constrained anomalies of similar trend and magnitude (E₁) occur over metasedimentary rocks in the Sixmile Creek area. There are no data in the intervening area and correlation of the two areas is therefore speculative. However, as the rocks in the Jardine area are host to strata-bound gold-arsenic-tungsten ores, the possible correlation warrants consideration, particularly in that the aeromagnetic data suggest that an extension of the Emigrant stock underlies the area that lacks gravity control. Another east-west trending relative gravity high (E₂) is associated with metasedimentary supracrustal rocks north of the Emigrant stock. A gravity gradient appears to separate the anomalies associated with rocks in the Sixmile Creek area from a major gravity high (F) that extends west of the study area to an adjacent basement block of metasedimentary rocks. The high anomaly (F) is associated with gneissic and migmatitic rocks in the Yankee Jim Canyon area, and suggests that the rocks there may be similar to those in the western area and different from those in the Sixmile Creek area. Density measurements of eighteen rock samples from the Yankee Jim Canyon area cluster in two distinct populations. One population centers about an average of 2.64 g/in/cm³ and a smaller population centers about an average of 2.81 g/in/cm³. Two samples fall outside both groups at 2.92 and 3.01 g/in/cm³. Densities of eight Archean gneiss samples from nearby areas in Wyoming and Montana average only 2.62 g/in/cm³.

A northwest-trending gravity gradient is associated with the transition from Precambrian rocks of the Beartooth uplift to younger sedimentary rocks

that crop out in the valley of the Yellowstone River to the southwest. The gradient is the expression of the Gardiner fault which bounds the Beartooth uplift on the southwest. Segments of the fault are exposed near the town of Gardiner, Montana, but in this area the gravity gradient is deflected by a low anomaly which extends north of the trace of the fault and is probably caused by a low density intrusive body which is the source of the volcanic rocks that outcrop here. Alternatively, the low may be caused by the extension of a graben feature identified to the south. Northwest of the Emigrant stock a northeast-trending low anomaly (G), 12 mGal in amplitude, is associated with Quaternary sediments in the valley of the Yellowstone River and may indicate a down-dropped fault segment.

In the northwest corner of the study area a broad gravity high (H) is mostly surrounded by a series of local high and low anomalies. To the southeast, and aligned with the trend of the apex of anomaly H, is a linear, composite high (I) associated with ultramafic rocks of the Stillwater Complex. Anomaly H may be the expression of a down-dropped segment of the Stillwater Complex buried beneath back thrusts of metasedimentary rocks of the North Snowy block. However, structural reconstructions, the shape and breadth of the anomaly, and the coincidence of a magnetic high (plate 3) surrounded by smaller lows coincident with the highs and lows surrounding the gravity high strongly suggest that the area is underlain by a large intrusive complex and possible associated ring structure. A small gravity high (J) may be caused by a buried extension of the Stillwater Complex ultramafic rocks. A gravity high (K) occurs over the stock at Independence in contrast to the lows associated with other volcanic centers. Two elongate gravity lows (L) are caused by Quaternary sediments in the valleys where the measurements were obtained.

Between the gravity lows associated with the volcanic centers and the highs associated with the Stillwater Complex, a gravity gradient of approximately 30 mGals occurs over a granite and gneiss terrane which would presumably have densities intermediate between those of the volcanic rocks and ultramafic rocks. Relatively high gravity values with a similar range (-190 to -170 mGals) characterize the gneiss terrane in the eastern half of the study area. A north-trending gradient east of longitude 110° west, with a magnitude of 15 to 20 mGals separates the eastern gneiss terrane (tract IIb in plate 16) from the western half of the area (tract IIa) and continues at least 35 miles farther south. The gradient is not coincident with the boundary of the volcanic terrane

as the gneiss continues west of the gradient to the Independence area. In the area between the gradient and the Independence anomaly, gravity data are sparse, but several widely spaced values are lower than -200 mGal. The low values and scattered outcrops of Tertiary volcanic rocks within the gneiss terrane suggest that this area of gneiss may be shallowly underlain by low-density intrusive rocks and that the gradient may represent a structural boundary which confined the intrusive centers to the west of the gradient. Alternatively, and perhaps more likely, the north-south gradient may be associated with structural offset of the gneiss terrane with higher density gneissic rocks from deeper basement levels exposed in the eastern terrane. Geochemical anomalies from stream-sediment samples differ between the eastern and western gneiss terranes (see Lee and Carlson, Chapter D, this report). In the western terrane, widely scattered tin and numerous gold anomalies are present in stream-sediment samples. In the eastern terrane, stream-sediment anomalies in tungsten, iron, nickel, chromium, and thorium are more common than in the western terrane.

High gravity anomalies (M , M_1 , M_2) are discussed in the interpretation of magnetic data which follows. A low gravity anomaly (N) occurs over sedimentary rocks of the adjacent basin.

A strong gravity gradient separates the uplifted Beartooth Plateau block from the adjacent basin rocks on the eastern and northeastern margins of the Beartooth uplift. A narrow, steep gradient coincides with the north-trending mapped segment of the fault on the eastern boundary of the block from Clarks Fork Canyon, south of the area of plate 2, to Rock Creek (fig. A4). From Rock Creek to the northwest corner of the block the gradient broadens and extends westward across the Precambrian block indicating that the upper plate is thrust over low-density rocks of the basin in this area. Along the northeastern margin of the Beartooth Plateau block it is difficult to determine the location or attitude of the bounding fault. Here, the gradient also represents the transition from moderately dense rocks of the Beartooth Plateau block to more dense ultramafic rocks of the Stillwater Complex and the transition along the Nye-Bowler zone (fig. B1) from moderately dense rocks of the Beartooth Plateau block to the area north of the Nye-Bowler zone where gravity values increase steadily for at least 100 mi to the north over presumably more dense basement.

Low gravity values occur at the north edge of the map over low-density sedimentary rocks. No gravity anomaly is associated with the stock of Sliderock

Mountain suggesting either that it is thin or that it has an insufficient density contrast to cause an anomaly.

MAGNETIC DATA

Characteristic high amplitude, short wavelength magnetic anomalies (plate 3) occur over Tertiary volcanic rocks and their associated intrusive centers in the western half of the Beartooth uplift (plate 1). The topographic relief and high intensity of the anomalies makes interpretation of individual anomalies difficult. A large, composite anomaly (1) is associated with the Emigrant stock and north-trending elongate extensions of the anomaly (1a, 1b) suggest subsurface extensions of the intrusive source. Other magnetic highs (2) are probably caused by intrusive centers or near-surface portions of more widespread intrusives at depth. Two additional magnetic highs (3) occur in the Mill Creek area, another high (4) over 500 nT in amplitude is associated with the Independence stock, and several smaller high anomalies (5) occur near the Cooke City area. A magnetic low (6) is associated with volcanic rocks at the surface west of the New World (Cooke City) mining district. The New World district itself lies east of the low anomaly on a magnetic gradient which may be caused by the fault system in that location. Rocks with high magnetic susceptibilities occur within the New World district (Allan Kirk, Noranda Exploration, Inc., personal communication), and may be expressed in the magnetic high nose extending east of the district.

Several high anomalies (7) also occur within the gneiss terrane northeast of the area of volcanic cover and are discussed in detail by Peterson (USGS and USBM, 1983). He infers that the anomalies are caused by a combination of topography and areas of differentially high magnetic susceptibility of stocklike bodies within the gneiss. There is a possibility that the anomalies are caused by younger intrusives in the shallow subsurface similar to those of the Emigrant, Mill Creek, Independence, and Cooke City areas, but there are no surface indications of younger intrusive rocks.

A linear magnetic high (8) is associated with banded iron formation in the metasedimentary rocks immediately below the Stillwater Complex and is discussed in detail by Kleinkopf (1985) and Blakely and Zientek (1985). The highs are associated with scattered outcrops of the iron formation south of the Bluebird thrust between the Boulder River and the West Fork Stillwater River (fig. A4). A magnetic high

of lesser magnitude (9) is located to the northwest of anomaly 8 and is possibly caused by a buried extension of the iron formation. A composite high anomaly (10a, 10b) could also be caused by similar rocks, but it is coincident with a gravity high (H) discussed earlier, and, along with the low anomalies surrounding it, is more likely caused by a large intrusive complex in the subsurface. The decrease in magnitude of the part of the anomaly at 10b and the narrow low separating the two highs suggest that the body may be offset by a fault. A magnetic saddle between anomalies 10b and 9, a gradient west of anomaly 9 and a saddle that continues southward between anomalies of group 7 are associated with the West Boulder River fault (plate 1).

Southwest of the Emigrant area anomalies (1), an area of lower magnetic intensity (11) is associated with the Precambrian metasedimentary rocks (plate 1). Low magnetic values also occur over similar rocks in the Sixmile Creek area (11a) and north of the Emigrant stock (11b).

A composite magnetic high (12) is associated with the stock of Sliderock Mountain and a high of similar magnitude (13) to the southeast may indicate the presence of a similar body in the subsurface there. Major high magnetic anomalies (14) northeast of the study area are probably caused by extensive iron formation in the basement rocks.

The eastern part of the ABSA exhibits a complex pattern of broad, complexly ovoid magnetic highs (15) 5 to 10 miles across. These anomalies have magnitudes of 500 to 1,000 nT and are bounded by steep gradients usually associated with shallow causative bodies and (or) high susceptibility contrasts. The eastern part of the ABSA is underlain by Precambrian crystalline rocks, predominantly granitic gneiss and amphibolites (plate 1). Mafic dikes, iron formation, small ultramafic bodies, and some schist units are minor constituents. Anderson (in Simons and others, 1979) discusses the anomalies in detail and reports on the results of two-dimensional models used to determine the likely cause of the anomalies. He concludes that, except for local irregularities on the flanks of the anomalies, topography does not play a significant role in their configuration or magnitude. Measurements of magnetic susceptibility suggest that no single average susceptibility of any rock type can account for the intensity of the anomalies, but the maximum susceptibility of each type is greater than necessary to produce the anomalies. Anderson also points out that the steep gradients require sharp susceptibility contrasts rather than the gradational changes usually observed in compositionally varying

gneiss bodies. Numerous small Tertiary dikes occur in the area, and near-surface Tertiary or Cretaceous intrusive bodies cannot be ruled out as a cause of the anomalies. Close examination, although speculative, suggests that the source of the major anomalies probably lies within the Archean rocks, and the lower magnitude flanking noses and extensions of the anomalies arise from Cretaceous/Tertiary sources. The apices of magnetic anomaly 15 coincide with apices of a composite gravity high (M) indicating that the causative body (or bodies) is both more magnetic and more dense than the surrounding rocks.

The area of anomaly 15a and a broader gravity anomaly M₁ (extensions of the main anomalies 15 and M), is located roughly in an area of several Cretaceous or Tertiary dikes (Tract Vd in plate 17). The elongate high anomaly may be enhanced by a topographic ridge and the relative low (15a₁) to the east enhanced by basin topography. Thus the entire 15a-15a₁ area probably represents a moderate magnetic high. The southeastern extensions of magnetic anomaly 15 (magnetic noses 15b₁ and 15b₂, and high magnetic saddle 15b₃) are also located in areas of Cretaceous or Tertiary dikes (Tract Vc). Only the magnetic nose 15b₁ has an associated gravity high (M₂). The gravity field at the locations of magnetic anomalies 15b₂ and 15b₃ is overwhelmed by the expression of sedimentary rocks of the adjacent basin beneath the thin overthrust edge of the Bear-tooth uplift. Magnetic high 15c extends beyond the uplift and the gravity expression in this area is part of the flank of the low associated with sedimentary rocks in the basin. The source of the magnetic anomaly may be deeply buried rocks similar to those responsible for the major magnetic highs (15) or to a Cretaceous or Tertiary intrusive at shallower depth similar to those responsible for the lower magnitude flanking anomalies (15b). Another extension of the high magnetic values (15d) is spatially associated with a syenite stock at Goose Lake (Kg1, plate 1). No gravity anomaly is associated with the magnetic anomaly as they are at the other locations just discussed, although two measurements in the immediate area should have defined such an anomaly if it were present. If the Goose Lake stock is the source of anomaly 15d, the size of the anomaly suggests that the body is somewhat more extensive in the subsurface than in outcrop.

A broad magnetic high (16) of moderate magnitude and moderate gradient is located within the gneiss terrane just northeast of Independence. Cretaceous or Tertiary dikes are concentrated also in an area northeast of Independence, and may be

associated with the western end of magnetic anomaly 16. However, the association is tenuous at best; anomaly 16 appears, from its breadth and gradients, to arise from a deep source, possibly in the lower plate beneath the uplift. There is no association of the Cretaceous or Tertiary dikes with gravity anomalies at Goose Lake or northeast of Independence, suggesting that these dikes may be of different composition than the dikes to the east associated with anomalies 15a and 15b.

Archean mafic dikes are widespread in the gneissic terrane of the Beartooth uplift, but appear to have no clear associations with magnetic or gravity anomalies in the western half of the uplift. In the eastern half of the uplift, the Archean dikes are continuous for longer distances and most are associated with magnetic gradients. This provides some support for the speculation that the major magnetic anomalies (15) are caused by unrecognized Archean intrusive bodies within the gneiss. The emplacement of the intrusives and the Archean mafic dikes appears to have been fault-controlled.

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CHAPTER D

GEOCHEMISTRY OF THE ABSAROKA-BEARTOOTH AREA

By Gregory K. Lee and Robert R. Carlson

GEOCHEMICAL SURVEYS

The geochemical contributions to the mineral resource assessment of the Absaroka-Beartooth portion of the Custer and Gallatin National Forests, the "study area," were derived from data that include analyses of 2,599 stream-sediment and 139 heavy-mineral-concentrate samples from the USGS geochemical databases. Of these, 2,149 samples were collected by USGS personnel and 589 stream sediments had been obtained in 1976 as part of the National Uranium Resource Evaluation (NURE) program under the Department of Energy. Archived NURE samples were reanalyzed by the USGS to provide analytical consistency and to obtain information for concentrations of elements which were not included in the Los Alamos Scientific Laboratory (LASL) reports (Bolivar, 1980; Broxton, 1979). Included in the geochemical information produced by the USGS were data generated for mineral resource appraisals of the North Absaroka Wilderness (Elliott and others, 1983), the Absaroka (Wedow and others, 1975) and Beartooth (Simons and others, 1973) Primitive Areas, and unpublished data from 1991 sampling of the Sliderock Mountain area and of the Custer and Gallatin National Forests.

METHODS OF STUDY

ANALYTICAL TECHNIQUES

Stream-sediment samples collected for the Absaroka, North Absaroka, and Beartooth studies, and heavy-mineral concentrates collected for the North Absaroka study, were analyzed for 35 elements using a semiquantitative, direct-current arc emission spectrographic (E-Spec) method (Grimes and Marranzino, 1968). These samples were also analyzed for gold content using a flame atomic absorption (F-AA) method described by Thompson and others (1968).

The heavy-mineral-concentrate samples collected in 1991 were spectrographically analyzed for 37 elements by the method described by Grimes and Marranzino (1968). In addition, these samples were analyzed for low-level gold and platinum group elements (PGE) content using a fire assay-inductively coupled plasma-mass spectrometry (ICP-MS) technique (Meier and others, 1991).

Samples collected in 1991, together with archived stream sediments previously obtained for the NURE program were analyzed by inductively coupled argon plasma-atomic emission spectroscopy (ICP-AES) for 40 elements using a method described by Crock and others (1983), and for 10 elements using the method described by Motoooka (1988). Low-level gold determinations were also performed on these samples using the graphite furnace atomic absorption (GF-AA) method described by O'Leary and Meier (1986). LASL data are not evaluated in this report, except those obtained by delayed neutron counting, neutron activation, and X-ray fluorescence determinations of uranium, thorium, and tungsten concentrations, respectively (Bolivar, 1980; Broxton, 1979).

METHODS OF GEOCHEMICAL INTERPRETATION

Although 33 elements were considered in calculating associations among the variables, the following 13 elements determined by the analyses were considered to be of primary geochemical importance in the assessment of resource potential in the study area: silver (Ag), arsenic (As), gold (Au), bismuth (Bi), chromium (Cr), copper (Cu), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), uranium (U), tungsten (W), and zinc (Zn).

Except for interpretation of the distribution of gold, platinum (Pt), and palladium (Pd), only stream-sediment sample data were considered in the geochemical appraisal of the study area. The stream-sediment sample locations were much more densely

and evenly distributed throughout the study area than were the heavy-mineral concentrates and were therefore felt to provide a more consistent and comprehensive basis for evaluation. The heavy-mineral-concentrate data, however, were used to supply additional information regarding the distribution of gold, platinum, and palladium, and served to aid the interpretation of anomalous concentrations of elements found in stream sediments. In addition, selected concentrates were microscopically examined to provide mineralogical information.

Statistical Methods

The data produced from the E-Spec, ICP-AES, F-AA, GF-AA, and selected LASL analyses were treated separately in terms of statistical reduction and the determination of anomaly thresholds. In each case, thresholds (highest background concentrations) were determined by calculating the highest reportable value below 2 deviations above the geometric mean for each selected element. Locations of samples containing concentrations above these thresholds are plotted in plates 4-10. The symbols are plotted with 3 possible sizes indicating ranked levels beginning at 2, 3, and 5 deviations above geometric mean. In the

ensuing discussions, these three levels are termed slightly, moderately, and highly anomalous, respectively. The values which correspond to these levels are listed in table D1.

Gold was considered anomalous in heavy-mineral concentrates at F-AA and ICP-MS determinations of 0.1 ppm and greater. Platinum was regarded as anomalous in these samples at ICP-MS values greater than 10 ppb.

Factor Analysis

R-mode factor analysis (Koch and Link, 1971) was used to identify geochemical associations in the stream sediment data. The objective of performing factor analysis was to reduce the data to several groups of elements that geochemically characterize dominant lithologic and ore-related associations in the study area. This mathematical treatment places elements which vary similarly into factors (groups) based on their correlation coefficients.

Factor analysis cannot be performed on data which contains non-numeric data, e.g., values qualified with "N"—not detected, "L"—detected but below the analytical limit of determination, or "G"—greater than the upper limit of analytical determination.

Table D1.--Anomaly thresholds for selected elements in stream sediments

[Values left of "/" calculated as nearest reportable value less than 2 standard deviations above mean; percentages of samples with background values shown in parentheses; lower determination limit in {brackets}. Values in parts per million. NA, not applicable. Blanks, not used. Leaders (—), all qualified; L, less than the determination limit shown; N, not detected at the determination limit shown.]

Element	ICP-AES	E-Spec	F-AA	GF-AA	LASL
Ag	.23(96.7)/{0.067}	.5(98.5)/{0.5}	NA	NA	
As	19(96.7)/{0.67}	200N(99.6)/{200}	NA	NA	NA
Au	/{0.1}	—/{10}	.05L(94.3)/{0.05}	.02(94.7)/{0.002}	
Bi	.51(96.1)/{0.67}	10N(99.3)/{10}	NA	NA	
Cr	660(97.0)/{1}	500(98.7)/{10}	NA	NA	
Cu	80(96.9)/{0.05}	100(97.7)/{5}	NA	NA	
Mo	2.4(96.9)/{0.09}	5L(96.7)/{5}	NA	NA	NA
Ni	150(96.9)/{2}	150(99.5)/{5}	NA	NA	
Pb	65(97.9)/{0.60}	70(97.1)/{10}	NA	NA	
Sb	.98(97.4)/{0.67}	—/{100}	NA	NA	NA
U	/{100}	NA	NA	NA	29.9(97.1)/{0.01}
W	NA	50N(99.0)/{50}	NA	NA	15L(96.1)/{15}
Zn	170(96.6)/{.02}	200L(98.6)/{200}	NA	NA	

Therefore, prior to factor analysis, censored values were replaced by the following:

N—All values of an element qualified with an "N" were replaced with 0.3 times the lower limit of determination for that element.

L—All values of an element qualified with an "L" were changed to 0.7 times the lower limit of determination for that element.

G—All values of an element qualified with a "G" were replaced with 1.5 times the upper limit of analytical determination for that element. For the emission spectrographic data, these replacement values correspond to approximately 3 reporting steps lower than the lower determination limit, 1 step below the lower limit, and 1 step above the higher determination limit, respectively.

Because of statistical uncertainty in performing computations with highly censored data, most elements which were detected in less than 60 percent of the samples were removed from the datasets prior to the calculations. Exceptions were several elements (Ag, As, Au, Mo, and Sb) considered to be important as potential resources or as pathfinder elements for various mineral resource types. A series of factor analyses, both with and without these highly censored elements, showed that inclusion of these elements caused no significant change in the statistical relationships among the other elements. Therefore, in order to provide a means of identifying correlations within the upper ends of their distributions, these elements were retained in the data matrix in spite of their low detection ratios (number of samples with determined values divided by total number of samples). The elements that were included in the factor analysis computations are listed in tables D2 and D3.

The computed factor loadings, which measure the influence of each element on a factor, are listed for the E-Spec/F-AA and ICP-AES/GF-AA stream-sediment data in tables D2 and D3, respectively. The numbers of factors that were chosen from the data matrices were based upon consideration of the eigenvalues associated with the factors along with examination of the slopes of factor number versus total variance curves.

RESULTS

FACTOR-ANALYSIS ASSOCIATIONS

A five-factor model was chosen to characterize the E-Spec/F-AA data. These five factors all have

eigenvalues greater than one and they explain 67 percent of the total variance in the data. The elements which have significantly high loadings (absolute value greater than or equal to 0.40) are shown in table D2. Elements with marginally high loadings (less than 0.40 and greater than 0.30) are shown in parentheses. In the E-Spec/F-AA data, two factors emerged from the varimax calculations that are suggestive of mineralization. Factor Spec-1 (table D2) represents a suite of elements, {Mg, Ni, Cr, Co, Fe, Sc, V, Ca, Mn, Ti, Cu}, which is likely associated with Cr- and Ni-bearing mafic and (or) ultramafic rocks such as those of the Red Lodge chromite deposits. Factor Spec-4 represents a suite of elements, {Au, Ag, Mo, Pb, Cu}, that may be associated with polymetallic and (or) porphyry types of mineralization.

Similarly, a six-factor model was chosen to characterize the ICP-AES/GF-AA data. These factors are listed in table D3 and account for 77 percent of the total variance in the data. Two significant factors were calculated that are thought to be associated with mineralization. Factor ICP-2, {Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As}, appears to be correlative with factor Spec-4 and is probably related to similar types of mineralization. Factor ICP-3, {Ni, Cr, -P, Mg, Sc, Co, (-K), (As)}, is an association of elements that probably reflects the presence of Cr- and Ni-bearing ultramafic rocks, such as those found in the Stillwater Complex. Factor ICP-3 probably correlates to factor Spec-1 in parts of the study area.

Factor scores depict the contributions of factors to each sample and are useful in analysis of the spatial distributions of the factors. Plates 11 and 12 are maps of the locations of samples which have high scores (at least 1.5 standard deviations above mean) in factors considered most likely to be associated with mineralization, ICP-2/Spec-4 and ICP-3/Spec-1, respectively.

GEOCHEMICALLY ANOMALOUS AREAS

Following is a description of geochemical anomalies found in stream sediments within and proximal to the study area. The spatial context of the samples is provided, when applicable, in terms of mining districts and other areas of known deposits; otherwise, the anomalies are geographically referenced. The general locations of the districts and known deposits are shown in figure A3 and the major drainages are shown in figure A4.

Table D2.--Factor loadings for the first five factors after Varimax rotation of log-transformed E-spec/F-AA stream sediment data (marginally significant values in parentheses)

[Total variance explained by five factors equals 67 percent. Leaders (—), loadings less than |0.30| that have been omitted. F-AA, determined by flame atomic absorption spectrophotometry]

Element	Factor Spec-1	Factor Spec-2	Factor Spec-3	Factor Spec-4	Factor Spec-5
Ag	—	—	—	.67	—
Au (F-AA)	—	—	—	.73	—
B	—	.56	—	—	—
Ba	—	—	.89	—	—
Be	—	—	—	—	.76
Ca%	.65	—	—	—	.40
Co	.77	—	—	—	—
Cr	.83	—	—	—	—
Cu	.50	—	(-.36)	.48	—
Fe%	.76	(.31)	—	—	—
La	—	.61	—	—	(.34)
Mg%	.86	—	—	—	—
Mn	.55	.57	—	—	—
Mo	—	—	—	.60	—
Ni	.85	—	—	—	—
Pb	—	.57	—	.49	—
Sc	.72	.45	—	—	—
Sr	—	—	.87	—	—
Ti%	.55	.53	—	—	—
V	.69	.47	—	—	—
Y	—	.83	—	—	—
Zr	—	.74	—	—	—
Percent of total variance explained by factor	33	13	9	7	7

**Emigrant District-Sixmile Creek-Mill Creek Area,
Tracts Va1 and VIIIa1 (Plate 17)**

Many samples collected in this area were found to contain anomalous concentrations of one or more of a considerable variety of elements (plates 4-10). Moreover, samples with high scores in factors Spec-4 (table D2 and plate 11) and ICP-2 (table D3 and plate 11), indicating polymetallic and (or) Cu-Mo porphyry type mineralization, were collected in the vicinities of Emigrant Creek, upper Sixmile Creek, and Arrastral Creek and upper West Fork Mill Creek to the east. The Emigrant Creek drainage contains anomalous Ag, As, Au, Bi, Cu, Mo, Pb, Sb, W, and Zn. Samples from the Sixmile Creek watershed were found to be elevated in Ag, As, Au, Bi, Cu, Mo, Pb, and Sb, and

anomalous Ag, As, Au, Bi, Pb, and Zn were determined in West Fork Mill Creek. Moderately and highly anomalous values of Zn were also found 5 and 7 kilometers farther east in the drainage of Wicked Creek and in a short southern tributary of the middle reaches of Mill Creek east of Passage Creek.

The spatial distribution of the anomalous elements suggests polymetallic mineralization (tract VIIIa1) around the periphery of a Cu-Mo porphyry system (tract Va1) centered approximately 2 km east of Emigrant Peak. The associated geochemical anomalies indicate that the system occupies an area extending 6 to 7 km outward from this center, and possibly as much as another 7 km eastward, if the Zn anomalies in the middle reaches of Mill Creek are due to this system.

Table D3.--Factor loadings for the first six factors after Varimax rotation of the log-transformed ICP-AES/GF-AA stream-sediment data (marginally significant values in parentheses)

[Total variance explained by six factors equals 77 percent. Leaders (—), loadings less than |0.30| that have been omitted]

Element	Factor ICP-1	Factor ICP-2	Factor ICP-3	Factor ICP-4	Factor ICP-5	Factor ICP-6
Ag	—	.78	—	—	—	—
Au (GF-AA)	—	.61	—	—	—	—
As	—	.42	(.30)	—	.61	—
Ba	—	—	—	—	—	.85
Be	—	—	—	—	.61	(.38)
Bi	—	.80	—	—	—	—
Cd	—	.63	—	—	.54	—
Co	.85	—	.45	—	—	—
Cr	—	—	.90	—	—	—
Cu	(.33)	.70	—	—	—	—
Fe%	.95	—	—	—	—	—
Ga	.51	—	—	(.38)	—	.60
K%	—	—	(-.34)	—	.44	.61
La	—	—	—	.90	—	—
Li	—	—	—	—	.71	—
Mg%	.62	—	.52	—	—	—
Mn	.89	—	—	—	—	—
Mo	—	.64	—	—	.43	—
Na	—	—	—	(.35)	-.43	.60
Nb	—	—	—	—	.53	.49
Nd	—	—	—	.88	—	—
Ni	—	—	.91	—	—	—
P%	.45	—	-.61	—	—	(.33)
Pb	—	.69	—	—	—	(.35)
Sb	—	.74	—	—	—	—
Sc	.77	—	.51	—	—	—
Sr	.45	—	—	—	—	.74
Th	—	—	—	.89	—	—
Ti%	.80	—	—	—	—	(.32)
V	.92	—	—	—	—	—
Y	(.32)	—	—	.54	.65	—
Yb	.46	—	—	—	.58	—
Zn	.65	.55	—	—	—	—
Percent of total variance explained by factor	25	18	14	8	7	4

Jardine-Crevise Mountain-Hellroaring Creek Area, Tract Ia (Plate 16)

Gold was found in samples from the Bear, Palmer, Hellroaring, Specimen, Horse, and Grizzly Creek drainages (plate 4). Anomalous arsenic (plate 5) and tungsten (plate 9) were also determined in samples from lower Bear Creek, upper Hellroaring Creek, and Specimen Creek, and elevated As was found in Grizzly Creek. Samples with high scores in factor Spec-4 (Au, Ag, Mo, Pb, Cu) were found in lower Bear Creek, Specimen Creek, and Grizzly Creek (plate 11).

The locations of the geochemically anomalous samples in this area are fairly scattered and isolated. In addition to the anomalous Au-As-W suite of elements found at the Jardine deposit and in Specimen Creek near similar "Homestake-style" occurrences, there appears to be geochemical exposure of this type of mineralization in Grizzly Creek. Samples with slightly anomalous gold from streams draining the flanks of Ash Mountain, approximately centered in tract Ia, may represent the Homestake style mineralization, but could also indicate possible gold mineralization associated with the Ash Mountain stock.

Other low-level gold and arsenic anomalies were found in samples collected outside the volcanic cover from the east side of the upper and lower reaches of the Hellroaring Creek drainage basin. The general association of Au, As, and W anomalies, although scattered by Tertiary volcanic and Quaternary cover in this area, indicates potential for stratiform gold type mineralization in the area from Jardine to the Hellroaring Creek-Buffalo Creek drainage divide.

Independence District, Tracts Va2 and VIIIa2 (Plate 17)

Gold anomalies (plate 4) were found in East Fork Boulder River, upper Boulder River, and in Bridge Creek, all of which drain parts of the Independence area. Moderately anomalous levels of Zn, Cr, and Ni (plates 8 and 7) were also determined in samples from the East Fork Boulder River and moderately anomalous Mo (plate 6) was found in samples from Bridge Creek. High scores in factor Spec-4 (plate 11) were also seen for these three drainages. Skarn mineralization has been found in the Bridge Creek basin. However, it can be seen from plates 4-12 that geochemical expression of mineralization in the area is not suggestive of intense

or widespread ore formation. Although mineralization in the Independence District has been characterized as Cu porphyry type (Wedow and others, 1975), the geochemical data does not provide strong supporting evidence of a significant deposit of this type. Elliott and others (1983) refer to mineralization in this area as vein, replacement, and disseminated base metals, precious metals, and molybdenum.

Cooke City (New World) District, Tracts Va4 and VIIIa4 (Plate 17)

Numerous geochemical anomalies were found in samples collected from this area. Highly anomalous Au, Ag, Cu, Mo, Bi, and Zn (plates 4, 6, 9, and 8) and moderately elevated Pb concentrations (plate 8) were determined in samples collected from the uppermost reaches of the Stillwater River, above its confluence with Goose Creek. Samples from these locations also scored high in factor Spec-4 (Au, Ag, Mo, Pb, Cu) (plate 11). These anomalies and factor scores are undoubtedly related to the mineralization and mining activity on the north and west sides of Crown Butte and Fisher Mountain.

Moderately anomalous Au, Ag, Cu, Mo, Bi, Pb, and Sb (plate 5) concentrations were determined in samples collected from Miller Creek and the west fork of the Clarks Fork Yellowstone River. Samples from these locations also scored high in factor ICP-2 (Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As) (plate 11). These anomalies and factor scores reflect the presence of mining activity on the south and east sides of Henderson Mountain and Fisher Mountain.

The distributions of the factors and geochemical anomalies suggest polymetallic mineralization (tract VIIIa4) distal to Cu-Mo porphyry type mineralization (tract Va4) in the upper Stillwater River, Miller Creek, and Fisher Creek basins.

Horseshoe Mountain Area, Tracts Va3 and VIIIa3 (Plate 17)

Geochemical anomalies in the Rock Creek and Wounded Man Creek drainages that flank Horseshoe Mountain on the south and north consist of moderately anomalous levels for Mo and W (plates 6 and 9), and slightly anomalous concentrations for Au, Ag, and Cu (plates 4 and 6). A moderate Au anomaly was located near the drainage divide between Rock Creek and the Stillwater River. High scores for factor Spec-4 (plate 11) were seen for streams

draining the north and south flanks of Horseshoe Mountain, indicating the likelihood of Cu-Mo porphyry type mineralization (tract Va3) as described by Wedow and others (1975).

Goose Lake Area, Tracts Ve, VI, and VIIIe (Plate 17)

Highly anomalous Mo and slightly anomalous Cu concentrations (plate 6) were found in samples collected from upper Goose Creek and in the vicinity of the Copper King mine. The headwaters of West Rosebud Creek to the northeast and East Rosebud Creek to the east also contain elevated Mo and Pb values which may indicate an extension of the mineralization around Goose Lake. High scores for factor Spec-4 (Au, Ag, Mo, Pb, Cu) (plate 11) were seen for the same areas in upper West and East Rosebud Creeks and the Copper King mine vicinity. These anomalies and factor scores are consistent with an alkaline gabbro-syenite environment, containing fracture fillings, sulfide breccias, and carbonate replacement mineralization, as reported by Simons and others (1973), and also correspond to geochemical indicators associated with Cu-Mo porphyry and polymetallic vein type mineralization.

These data suggest that the mineralization associated with the Copper King mine extends not only upstream in the Goose Creek basin, but may also reach northeastward across the drainage divide into the upper West Rosebud Creek watershed, and possibly eastward into upper East Rosebud Creek.

Red Lodge Chromite Area, Tract IIb (Plate 16)

The Red Lodge chromite deposits in the Rock Creek drainage basin are geochemically expressed in stream-sediment samples as slightly anomalous concentrations of Cr and Ni (plate 7) in upper Rock, Lake Fork, and Hellroaring Creeks. Slightly high scores in factor Spec-1 (plate 12), indicating the presence of mafic rocks containing chromium and nickel minerals, were found in samples collected from streams draining the Hellroaring Plateau and other upper Rock Creek tributaries. The zone of indicative geochemistry appears to be confined to edges of the Hellroaring Plateau and Line Creek Plateau overlooking Rock Creek and does not appear to extend into upper Lake Fork or West Fork Rock Creek. However, very similar geochemical anomalies

occur in samples collected in the East and West Rosebud Creek drainages (see description under that heading).

Hellroaring Plateau-Line Creek Plateau Area, Tracts Vc and VIIIc (Plate 17)

Various samples in tract VIIIc, from the area of the Hellroaring Plateau south to Hellroaring Creek (southwest of Red Lodge), contained moderately anomalous Ag and Mo (plates 4 and 6), slightly anomalous Au, Pb, and Zn (plates 4 and 8), and a moderately high value for factor Spec-4 (Au, Ag, Mo, Pb, Cu) (plate 11). In addition, a heavy-mineral concentrate collected from Spring Creek (a Rock Creek tributary that drains the northern flank of the Line Creek Plateau in tract Vc) showed a Au value of 0.94 ppm. Although these anomalously concentrated elements fit expected geochemical signatures for porphyry and (or) polymetallic vein type deposits, the spatial distribution does not strongly indicate favorability for significant mineralization in these tracts.

Stillwater Complex, Tract IVa (Plate 16)

Anomalous concentrations of metals expected to be associated with the Stillwater Complex were found in stream-sediment samples in an area extending from Little Rocky Creek on the east to Contact Creek, a western tributary of the Boulder River, on the west. In addition to slightly to moderately anomalous Cr, Ni, and Cu values (plates 7 and 6), many slightly to highly anomalous Zn concentrations (plate 8) were determined in streams draining the complex. Numerous samples also exhibited high scores in factor ICP-3 (Ni, Cr) (table D3 and plate 12).

Anomalous Au, As, Cu, Mo, Cr, Ni, and Zn values were found in Flume Creek, which is south and topographically outside of the exposures of the Stillwater Complex rocks; however, some of these anomalous elements likely result from Stillwater Complex basal zone xenoliths in the upstream quartz monzonite which cuts the ultramafic rocks (Page and Nokleberg, 1974) or from glacial transport of rocks of the Stillwater Complex.

Although the distribution of heavy-mineral concentrate samples was quite scattered in the study area, low-level PGE analyses of these samples showed anomalous Pt and Pd to be found at or near the study

area boundary in the Boulder River (96 ppb Pt), East Boulder River (55 ppb Pt, 18 ppb Pd), West Fork Stillwater River (450 ppb Pt, 13 ppb Pd), Stillwater River (72 ppb Pt, 230 ppb Pd), and between Fishtail Creek and the Stillwater River in Little Rocky Creek (17 ppb Pt, 4.4 ppb Pd). Each of these occurrences of Pt and Pd is thought to be associated with the upstream presence of Stillwater Complex rocks.

Sliderock Mountain (Iron Mountain) Area, Tract Vb and Vb1 (Plate 17)

The Sliderock Mountain vicinity, at the northeast corner of the study area had not been extensively discussed in earlier publications. Geochemical sampling, however, revealed that several drainages in the area contain numerous geochemical anomalies. Slightly to highly anomalous Ag, Au, As, Bi, Cu, Mo, Pb, and Sb (plates 4, 5, 6, 8, and 9) were found in the Gold Hill-Iron Mountain vicinity. The most strongly anomalous samples were collected from Placer Gulch (Bi, Ag, Sb, Pb, Mo, Au, As), with lower levels occurring in Fire Gulch (Ag, Sb, Cu), West Fork Lower Deer Creek (Bi, Sb), Davis Gulch (As), and Bear Gulch (Ag). High scores for factor ICP-2 (Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As) (plate 11) were seen in samples from Placer Gulch, Fire Gulch and West Fork Lower Deer Creek. Previous mining and prospecting activity is mapped in these drainages except for West Fork Lower Deer Creek and Davis Gulch, indicating a probable, undiscovered, southerly extension of the known mineralization occupying Placer Gulch.

Suce Creek-Pine Creek Area, Tract III (Plate 16)

Samples collected near the northwest corner of the study area (in the area from Suce Creek south to Pine Creek and east into the western tributaries of the West Boulder River) were found to weakly indicate the presence of mineralization. A sample scoring slightly high in factor Spec-4 (table D2 and plate 11) was collected in North Fork Deep Creek, and contained moderately anomalous Au (plate 4). Moderately anomalous Cu (plate 6) and highly anomalous W (plate 9) were found in samples from Suce Creek and Pine Creek, respectively, and Cu shows slightly anomalous values in many other drainages in the area. Other elements determined at slightly to moderately anomalous levels were Bi, Pb, and Zn, but the

locations are scattered widely about the area, providing no pattern indicative of cohesive mineralization.

Other Anomalous Areas

Pinnacle Mountain area, tracts VIIa2 and VIIa3 (plate 17).--Slightly, moderately, and highly anomalous Au values (plate 4) were found in samples collected from the upper reaches of Slough Creek in the cirque on the western side of Pinnacle Mountain and from upper Wounded Man Creek in the southern part of the study area. A sample from this area also had a slightly high score for factor Spec-4 (plate 11). This area lies between the previously discussed Horseshoe Mountain and Independence anomalous areas and may indicate an extension of the mineralization found in one or both of these areas.

East and West Rosebud Creek drainages, tracts IIb, Vd, and VIIId (plates 16 and 17).--Upper East Rosebud Creek, tracts Vd and VIIId. Moderately to highly anomalous values for Mo (plate 6) and slightly to moderately anomalous values for Pb (plate 8) were found in samples from the upper reaches of East Rosebud Creek. While the source(s) for these anomalies is unknown, their areal extent corresponds well with the concentration of mapped Cretaceous or Tertiary latite porphyry dikes in this area (plate 1).

East and West Rosebud Creeks, tract IIb. A strong trend of anomalous W values extends from the upper reaches of East Rosebud Creek northeast across the eastern flank of the basin to the National Forest boundary (plate 9). Microscopic mineralogical examination of heavy-mineral concentrates collected in this area showed the presence of tungsten minerals from the scheelite-powellite isomorphous series. Slightly to moderately anomalous values for Au, Mo, Zn, and Bi were determined in samples from the middle reaches of East and West Rosebud Creeks (plates 4, 6, 8, and 9); the source(s) for these and the W anomalies is speculative. A pattern of slightly anomalous values for Cr and Ni (plate 7) crosses the middle reaches of the two Rosebud Creeks in a northwesterly trend, and an even stronger pattern for slightly high scores in factor Spec-1 (Cr- and Ni-bearing mafic, ultramafic rocks) (plate 12) is seen from the eastern divide of East Rosebud Creek to the western divide of West Rosebud Creek. The areal trends and chemical similarities of these anomalies to those seen for the Red Lodge chromite area are strong indications that similar, but unmapped, chromitite may occur in the East and West Rosebud Creek drainages.

Hawley Mountain to West Boulder River area, northern tract IIa.--This northwest-southeast trending zone shows numerous moderately to highly anomalous values for molybdenum from the middle reaches of the West Boulder River to the drainages of Hawley Mountain (plate 6). Elliott and others (1983) suggested that the anomalies are related to a concentration of Mo in the subsurface Falls Creek Gneiss along its northern flank.

Other anomalies.--**Silver (Ag, plate 4).** Anomalous values for Ag that are not obviously associated with the previously discussed areas are scattered about the study area, occurring in tract IIb in Basin Creek southwest of Red Lodge and in a stream on the northwest side of Mystic Lake; and in tract IIa in a stream feeding Roosevelt Lake (in the middle reaches of the Stillwater River), in Divide Creek (in the middle reaches of the West Fork Stillwater River), and in Speculator Creek and the stream draining the cirque of Hawley Mountain (both in the middle reaches of the Boulder River). The sources for these isolated anomalies are unknown.

Arsenic (As, plate 5). Anomalous As not associated with previously discussed areas occurs in Farley Creek (east of Cooke City), in Trail Creek and Tumble Creek (middle reaches of the West Fork Stillwater River), in Miller Creek (middle reaches of the Boulder River), in Davis Creek (lower reaches of the West Boulder River), and in a northern tributary of East Fork Mill Creek. The sources for these isolated anomalies are unknown.

Gold (Au, plate 4). Anomalous Au values that do not coincide with historically placer-mined areas were used to produce the Geochemical Anomalies Subtract of tract IX, on plate 18.

Chromium (Cr, plate 7). Scattered, slightly anomalous values of Cr occur in the drainages of Buffalo Creek, Slough Creek, and the upper reaches of the Stillwater River (all in the south-central region of the study area), and at a single site north of Meatrack Creek (central region of the study area). These sites do not appear to represent any confined mineralizing system and may simply be indicative of the upper ranges of background values for individual lithological units.

Copper (Cu, plate 6). A scattering of decreasingly anomalous values of Cu was found in the Stillwater River downstream of the Cooke City District and Goose Lake area, and probably represents a geochemical trail from these areas.

Molybdenum (Mo, plate 6). Widely scattered, isolated occurrences of samples with slightly to moderately anomalous values of Mo were found at a

stream feeding Roosevelt Lake (middle reaches of the Stillwater River), at Divide Creek (middle reaches of the West Fork Stillwater River), and from two small tributaries of the Yellowstone River in the southwest corner of the study area. Sources for these isolated anomalies are unknown.

Nickel (Ni, plate 7). Two moderately anomalous Ni values occur in samples from the upper reaches of the Stillwater River. The source for these anomalies is unknown.

Lead (Pb, plate 8). Several slightly to moderately anomalous Pb values were found in drainages east of Tumble Creek (middle reaches of the West Fork Stillwater River). Although the source for these anomalies is unknown, their areal concentration is of interest.

Antimony (Sb, plate 5). Moderately anomalous Sb was found at Divide Creek (middle reaches of the West Fork Stillwater River) and highly anomalous Sb was found in a northern tributary of East Fork Mill Creek. Sources for these isolated anomalies are unknown.

Uranium (U, plate 10). A cluster of slightly to moderately anomalous uranium values were found in the area around Mt. Cowen, southwest of the head of the West Boulder River, and moderately to highly anomalous values were found in samples from the Boulder River, Stillwater River, West Fork and Lake Fork Rock Creek, and Sedge Creek (8 km east of Cooke City) drainages. Isolated, slightly anomalous U values were found in Sixmile and Emigrant Creeks, Davis and Pine Creeks (northwest part of study area), Falls Creek and Bridge Creek (tributaries of the Boulder River), West and East Rosebud Creeks, and upper Gold Creek (east edge of study area). Sandstone-hosted uranium has been mined in the West Fork Rock Creek watershed, and prospecting and minor mining activity in vein type U occurrences has taken place in the Boulder River drainage. A more detailed study conducted by the USGS in part of the North Absaroka Wilderness Area (Suits and Wenrich, 1980) suggested that the uranium in stream sediments from the area is likely derived not only from gneisses which contain high background uranium in resistate minerals such as xenotime, but also from weathering of mineralized rocks. The anomalies found in other drainage basins of the Absaroka-Beartooth Study area are probably related to similar occurrences of high background rocks and (or) scattered, vein type occurrences.

Tungsten (W, plate 9). Slightly to highly anomalous W values form a roughly semi-circular pattern around Iron Mountain (northern region of the

study area). A speculative source of the W is possible epithermal veins in the volcanic rocks of this area. Isolated W anomalies occur in the drainages of East Fork Mill Creek, Buffalo Creek, Slough Creek, the Boulder River, the West Fork Stillwater River, and the Stillwater River. Sources for these isolated occurrences are unknown.

Zinc (Zn, plate 8). Two moderately anomalous values for zinc were found in samples from the upper reaches of the Stillwater River below the Goose Creek confluence. They probably represent a geochemical trail of the mineralization in the Cooke City District.

CONCLUSIONS

The spatial distributions of anomalous ore-related elements, as seen on the geochemical anomaly maps (plates 4-10), and of high R-mode factor analysis scores, as seen on plates 11 and 12, indicate that the study area includes a diverse and widespread group of mineral occurrences. Most of the geochemical anomalies reflect the known areas of mineralization in the study area, but also suggested are six areas with potential for undiscovered deposits. These six areas include: (1) the area around East Fork Mill Creek to Meatrack Creek, containing an abundance of slightly to moderately high Au anomalies that may indicate lode and placer gold occurrences or deposits across the west-central part of the study area, particularly in the proximity of the Mill Creek-Stillwater fault; (2) the area from Specimen Creek to Grizzly Creek has Spec-4 factor scores and scattered Au, As, and W anomalies that may indicate Homestake-style mineralization similar to the Jardine area; (3) the cirque area on the west side of Pinnacle Mountain, containing a concentration of Au anomalies and a Spec-4 factor score that may indicate an extension of one or both of the mineralizing systems of Horseshoe Mountain and the Independence District; (4) the area northeast and east of Goose Lake (including the uppermost reaches of East and West Rosebud Creeks), containing Spec-4 factor scores and Mo, Cu, and Pb anomalies that may indicate an extension of the known Goose Lake deposit and (or) the presence of unexposed Cu-Mo porphyry mineralization; (5) the upper East Rosebud Creek watershed, with its concentration of Mo and Pb anomalies that may be associated with mapped latite porphyry dikes or may be peripheral to unexposed mineralization; and (6) the Line Creek Plateau area, containing Ag, Mo, Au, Pb, Zn, and Spec-4 factor

score anomalies that may indicate unexposed porphyry and (or) polymetallic vein type mineralization.

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CHAPTER E

MINERAL OCCURRENCES AND LEVEL OF EXPLORATION

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DATA SOURCES

A number of sources were used to compile data on site locations, commodity information, local geologic setting, and production history for mines, prospects, and occurrences within the ABSA. These include the U.S. Geological Survey Mineral Resources Data System (MRDS, 1992), the U.S. Bureau of Mines MILS database (Babitzke and others, 1982), the Anaconda Geological Documents Collection maintained by the American Heritage Center at the University of Wyoming, Laramie, Wyo., data from previous mineral resource assessment studies, county and topical reports, theses, data supplied by private industry, and site visits conducted for this study. U.S. Forest Service geologists provided updates on exploration activity within the ABSA. A number of mining companies generously allowed us access to their properties and mine geologists conducted tours for the assessment team and provided information on geology, exploration, and mine development (see Acknowledgments section of Chapter A). In addition, the U.S. Bureau of Mines provided a preliminary listing of their updated occurrence file for the Gallatin National Forest (R. Johnson, written commun., 1992).

MINES, PROSPECTS, AND OCCURRENCES

Examination and analysis of the nature and spatial distribution of identified resources is an essential part of the process of assessing undiscovered mineral resources because identified resources provide clues to the types and sizes of mineral deposits that may be present. Mines, prospects, and occurrences in the ABSA are listed in table form in the appendix to this chapter. The appendix lists sites (grouped by mining district), production status, commodities present, location information, MRDS record number,

and a brief description of the development status or geologic characteristics of the site. Site locations are plotted at a scale of 1:126,720 (plate 13). Updated and new site locations will be entered into the MRDS database to be released separately. Individual sites may represent a number of closely spaced workings. Many sites and mining districts historically have been referred to by various names.

Where sufficient geologic information is available, entries in the appendix are classified in terms of the mineral deposit type that appears to be most compatible with the geology, mineralogy, commodities present, structure, alteration, and geochemistry at the site (plate 18). Only a few of the more than 500 sites listed in the appendix represent currently economically viable mineral deposits. Patterns of spatial distributions of occurrences show where mineralizing processes have operated and help define permissive tracts for the occurrence of undiscovered mineral deposits. In many cases, geological information is insufficient to establish an association between an occurrence and mineral deposit type.

District production data are described in Chapter A of this report. Publicly available tonnage and grade data for production, reserves, and identified resources for individual mines and prospects exclusive of the Stillwater Complex are compiled in table E1; data for mines, prospects and mineral occurrences in the Stillwater Complex are given in Chapter F. U.S. Bureau of Mines estimates (submarginal, paramarginal, etc.) are included for some sites (table E1); these represent partially delineated resources based on assay data and engineering calculations to estimate tonnages rather than thoroughly delineated (i.e., discovered) mineral resources whose quantity and quality are known from drilling and (or) underground workings. Past production and reserve data provide a basis for comparing grades and tonnages of identified resources in the ABSA with worldwide grade and tonnage models to determine the applicability of such models in the study area. Data for

partially delineated resources help define the types of mineral deposits that may be present in the study area.

EXPLORATION

Recent exploration projects (Stillwater, New World, Emigrant, Independence, and Sliderock areas) are described in Chapter A. The overall level of historic exploration throughout the ABSA is indicated by the number of mining claims staked. Mining claims data for Montana were obtained from the Bureau of Land Management (November, 1991, release), sorted by township and range for the study area, tabulated in terms of numbers of mining claims per section (Public Lands Survey System coordinates), and plotted schematically (fig. E1). These data have not been sorted for categories of mining claims (i.e., active vs. inactive; valid vs invalid; lode, placer, or mill site). These data show the extent of exploration in and away from known centers of mineralization within permissive tracts, although the nature of the exploration (commodity or deposit type sought) that led to the staking of a claim is unknown. In a general way, these data indicate the location and size of target areas within permissive tracts provided that an area has been well explored. In the Sliderock area in the northeastern part of the ABSA, for example, the mining claims are centered on the section that encompasses the altered stock at Gold Hill. All of the other exposed intrusive rocks in the Sliderock area (map unit TKi on plate 1), such as the Lodgepole laccolith which lies about 6 miles to the southwest of Gold Hill, lack associated altered rocks and mineral occurrences. Mining claim data cannot be used reliably to omit areas from permissive tracts unless it can be demonstrated that an area has been thoroughly evaluated. High claim density areas (e.g., 51 or more claims per section on fig. E1) are a good indication of areas that have been mined or well explored in the past and are likely to be important in the future. Many of the isolated sections that have low mining claim densities (e.g., 20 or less claims per section on fig. E1) represent small-scale exploration for placer gold deposits.

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Table E1.--Grade and tonnage data for identified resources in the Absaroka-Beartooth study area

[g/t, grams per metric ton; X, commodity present in unknown quantity]

A. Jardine (Sheepeater) and Crevice (Crevasse) districts

Site name (key to plate 13) <i>Probable deposit type</i>	Tonnage (Millions of metric tons)	Au g/t	Ag g/t	Cu %	Pb %	Zn %	Fe %	Comments	References
Mineral Hill mine (1) <i>Archean lode gold</i>	0.90720	10.3	1.7					Announced reserves; gold to silver ratios average 6:1	D. Oliver, oral commun., 1990
Jardine mine (2) <i>Archean lode gold</i>	0.86139	6.9	1.4	X	X			Production 1899 to 1948 included 800,000 lbs of tungsten and 14,000 lbs of arsenic.	Seager, 1944 Reed, 1940
Watson mine (16) <i>Archean lode gold</i>	<0.00001		X					Single 800 lb shipment of scheelite. Quartz lenses (1 to 4 ft thick) reported to contain up to 10 g/t Au.	Reed, 1950, p. 34
First Chance (20) <i>Archean lode gold</i>	Unknown		X					A few small lots of ore were produced in 1939.	Reed, 1950, p. 32
Medona mine (24) <i>Archean lode gold</i>	Unknown							Small amounts of scheelite were produced during World War I.	Reed, 1950, p. 32
Snowshoe mine (27) <i>Archean lode gold</i>	0.00544							Production 1934 to 1940.	Reed, 1950, p. 33-34

B. Emigrant, Mill Creek, and Sixmile Creek districts and vicinity

Magnetic claim group (44) <i>Algoma/ Superior iron?</i>	0.15876					27.5	Inferred submarginal resource based on average vein widths of 7.5 ft and 22.6 ft.	Stotelmeyer and others, 1983, p. 135
Great Eastern mine (53) <i>Basic Metals breccia pipe Breccia pipe</i>	1.54224		27.7	0.4		0.39	Ore shipped for smelter tests in 1895; explored by drilling in the late 1960's and 1970's. Within the area of 1992 exploration by Pegasus. Calculated reserves by Exxon based on drilling of breccia pipe.	Stotelmeyer and others, 1983 Ahrens, 1968 (source of Exxon data)

Table E1.--Grade and tonnage data for identified resources in the Absaroka-Bearooth study area (continued)

B. Emigrant, Mill Creek, and Sixmile Creek districts and vicinity (continued)

Site name (key to plate 13)	Tonnage (Millions of metric tons)	Au g/t	Ag g/t	Cu %	Pb %	Zn %	Fe %	Comments	References
<i>Probable deposit type</i>									
Allison tunnel (55) <i>Breccia pipe</i>	0.06804	X	X					Submarginal resource Assays 0.3% Mo	Stotelmeyer and others, 1983, p. 134
Ku Klux claim (63) <i>Polymetallic vein</i>	0.00052 0.00169			32.9 8.9	0.24	1.79 0.15	3.08 0.15	Indicated submarginal resources based on average vein widths of 1.4 ft (smaller tonnage) and 2.0 ft (larger tonnage)	Stotelmeyer and others, 1983, p. 135
Alaska claim (65) <i>Polymetallic vein</i>	0.02041			17.8	1.44	2.67		Indferred paramarginal resource based on 2.1 ft average vein width	Stotelmeyer and others, 1983, p. 134
McAdow No. 2 (73) <i>Polymetallic vein</i>	<0.001	0.7	52.4	1.54				Indicated submarginal resource; a few hundred short tons of ore	Stotelmeyer and others, 1983, p. 134
St. Julian mine (77) <i>Breccia pipe</i>	0.22680	17.1	34.3					Paramarginal hypothetical resources based on 1 ft average vein width. Last record of production was a small amount of gold in 1903.	Stotelmeyer and others, 1983, p. 134
Grand View claim (79) <i>Grand View-Dixie</i> <i>Polymetallic vein</i>	<0.001 0.06441	25.7 1.7	88.5 18.9	7.76 1.48				Indferred submarginal resources based on average vein widths of 0.6 ft (a few hundred short tons) and 1 ft	Stotelmeyer and others, 1983, p. 134
Corbett and Montana Queen (89) <i>Precious metal vein</i>	0.32360	1.7	8.9					Indicated and inferred submarginal resources based on 0.8 ft average vein length	Stotelmeyer and others, 1983, p. 135
Midnight deposit (138) <i>Bog deposit</i>	0.20866						10.7	Indferred submarginal resource; 3.5% Mn	Stotelmeyer and others, 1983, p. 135

Table E1--Grade and tonnage data for identified resources in the Absaroka-Beartooth study area (continued)

B. Emigrant, Mill Creek, and Sixmile Creek districts and vicinity (continued)

Site name (key to plate 13)	Tonnage (Millions of metric tons)	Au g/t	Ag g/t	Cu %	Pb %	Zn %	Fe %	Comments	References
<i>Probable deposit type</i>									
Copper Queen (139) <i>Unknown</i>	0.00635			6.8	0.56			Inferred submarginal resource; includes 0.15% Ni	Stotelmeyer and others, 1983, p. 135
Lost Cabin claim (143) <i>Unknown</i>	0.07040			5.1	0.48			Inferred subeconomic resources between Lost Cabin and Copper Queen workings; assumes vertical depth equal to half of strike length and 2.3 ft average vein width; includes 0.08% Ni	Stotelmeyer and others, 1983, p. 135
Alice C claim (142) <i>Polymetallic vein</i>	0.00209	0.3	62.4	0.1	2.29	0.55		Indicated submarginal resources	Stotelmeyer and others, 1983, p. 135
McAdow claim group (145) <i>Polymetallic vein</i>	0.03765	9.3	479	0.03	4.10	0.18		Indicated and inferred paramarginal resource based on 1.7 ft average vein width; estimate projected to 295 ft beyond adit level; failed vein system; includes 0.05% Bi.	Stotelmeyer and others, 1983, p. 135; also pp. 183-188
Spring claim (154) Virginia claim (157) <i>Polymetallic vein</i>	0.08346			8.6		0.66		Note: Sites 154, 157, 158, and 160 all lie, or project along, the same mineralized structure. Inferred submarginal resource based on 3.6 ft average vein width	Stotelmeyer and others, 1983, p. 135
Pilgrim and St. Croix (158) <i>Polymetallic vein</i>	<0.00009			3.8	1.8	1.3		Pre-1948 production.	Stotelmeyer and others, 1983, p. 135
Barbara Ann (160) <i>Polymetallic vein</i>	0.00009	27.4	415	0.3	0.9	0.3		Production 1947 to 1968: grades are based on average smelter returns for 53 short tons of ore; 1 lot of ore contained 0.26% Bi.	Stotelmeyer and others, 1983, p. 177

Table E1.--Grade and tonnage data for identified resources in the Absaroka-Beartooth study area (continued)

B. Emigrant, Mill Creek, and Sixmile Creek districts and vicinity (continued)

Site name (key to plate 13)	Tonnage (Millions of metric tons)	Ag g/t	Cu %	Pb %	Zn %	Fe %	Comments	References
Area between Barbara Ann and St. Croix	0.61100	2.1	118	0.6			Indicated and inferred paramarginal resource listed for the area between Barbara Ann and St. Croix.	Stotelmeyer and others, 1983, p. 135

C. New World district and Goose Lake area

Alice E (233) <i>Unknown</i>	0.00227						1892-1895 production \$14 gold/short ton	Reed, 1950, p. 65
McLaren mine (245) <i>Copper-gold skarn</i>	1.90512 0.29938	3.1 6.2	13.1 17.7	0.70 0.6	0.05 0.02		Crown Butte Resources Ltd. announced reserves as of 4/4/92; bottom line - Cumulative production 1933-1952. Note: The New World project includes entries 245, 246, 247, 248, and 251.	Elliott and others, 1992 MRDS W014716
Miller Creek (246) <i>Copper-gold skarn</i>	2.0125		13.3	52.8	0.87		Crown Butte Resources Ltd. announced reserves as of 4/4/92	Elliott and others, 1992
Fisher Mountain (247) <i>Fault-controlled vein and replacement</i>	0.30319		6.5	38.7	0.28		Crown Butte Resources Ltd. announced reserves as of 4/4/92	Elliott and others, 1992
Como (248) <i>Copper-gold skarn</i>	0.64168		3.8	18.7	1.03		Crown Butte Resources Ltd. announced reserves as of 4/4/92	Elliott and others, 1992
Homestake (251) <i>Breccia</i>	5.98840		7.7	28.4	0.71		Crown Butte Resources Ltd. announced reserves as of 4/4/92	Elliott and others, 1992
Morning Star (259) <i>Polymetallic vein</i>	<0.00001		X	X	X		40 short tons of lead-silver ore shipped in 1922	Reed, 1950, p. 45
Black Warrior mine (260) <i>Polymetallic vein</i>	<0.00001	21.9	480	0.11	17.1	3.6<	41 short tons of ore shipped in 1945	Reed, 1950, p. 39

Table E1--Grade and tonnage data for identified resources in the Absaroka-Beartooth study area (continued)

C. New World district and Goose Lake area (continued)

Site name (key to plate 13)	Tonnage (Millions of metric tons)	Au g/t	Ag g/t	Cu %	Pb %	Zn %	Fe %	Comments	References
Duke (262) <i>Polymetallic vein</i>	Unknown		X	X				Reportedly produced high grade lead-silver ores pre-1885.	Reed, 1950, p. 40
Big Blue (264) <i>Polymetallic vein</i>	0.00052		308	20 to 30				Cumulative production to 1947	Reed, 1950, p. 67
Carlton (267) <i>Polymetallic vein</i>	<0.00001		X	X				20 short tons of crude ore mined in 1906; 700 lbs ore netted \$375	Reed, 1950, p. 67
Irma-Republic (268) <i>Polymetallic vein</i>	>0.270				564	10	5	Production 1901 to 1949; 1956 No reliable tonnages available.	MRDS W014715 Reed 1950, p. 42-43
Stemwinder (272) <i>Polymetallic vein</i>	Unknown	5.5	960.0	49.0				Small shipment of ore; idle since 1929; grades listed are indicated metal content	Reed 1950, p. 67
Copper King mine (357) <i>Alkaline gabbro-syenite hosted CuAu-PGE</i>	Unknown	Trace to 1	Nil to 15	0.03 to 0.7				Drill core assay values reported by Bear Creek Mining Co., 1970; PGE locally present. Explored early 1900's; small amount of ore mined and stockpiled.	Reed, 1950, p. 48-49 Simons and others, 1979, p. F87; F98-F100

D. Independence (Boulder, Cowles) district, Natural Bridge district, Stillwater area (see Chapter F for resources in the Stillwater Complex)

Black Diamond/Lori Kay/War Eagle (361) <i>Iron-copper skarn</i>	10	1.03 0.03	44.6 1.7	2.38 0.02		58.5 10.3	Assay grades (highest) Assay grades (lowest) Mo present	Stotelmeyer and others, 1983, p. 216 Reed, 1950, p. 67
Red Fox mine (371) <i>Unknown</i>	0.01905	3.4					Inferred submarginal resources assuming average thickness of 2 ft, depth 250 ft, and length 500 ft. Minor production around 1900.	Stotelmeyer and others, 1983, p. 210 Reed, 1950, p. 66

Table E1.--Grade and tonnage data for identified resources in the Absaroka-Beartooth study area (continued)

D. Independence (Boulder, Cowles) district, Natural Bridge district, Stillwater area (see Chapter F for resources in the Stillwater Complex)
(continued)

Site name (key to plate 13) <i>Probable deposit type</i>	Tonnage (Millions of metric tons)	Au g/t	Ag g/t	Cu %	Pb %	Zn %	Fe %	Comments	References
Independence mine (379) <i>Precious metal vein</i>	0.00025 0.00002	14.4	114.6 23.9	0.04				Production 1930-1939 Production 1933 Small production 1894-1904	MRDS DC08173 Reed, 1950, p. 66 Stotelmeyer and others, 1983, p. 212
Ski Line Mine (383) <i>Polymetallic vein</i>	<0.00014	X	233.0	10.00				Production pre-1950; minor gold produced 1941	Stotelmeyer and others, 1983, p. 212 Reed, 1950, p. 67
Daisy mine (386) <i>Precious metal vein</i>	0.000148	13.9	61.6	1.2	X			Minor pre-1900 gold production, reported figures are production for 1939	Stotelmeyer and others, 1983, p. 212 Moyle and others, 1989, p. 20
Hidden Treasure mine (391) <i>Precious metal vein</i>	0.000093	30	250					Minor production 1901, 1904	Moyle and others, 1989, p. 20
Skillman mine (410) <i>Polymetallic vein</i>	0.00018	3.5	1.4					Production 1901	Stotelmeyer and others, 1983, p. 209
Standard mine (411) <i>Unknown</i>	0.00091 0.00009	5.6 3.7	3.9 6.7	0.6				Production 1902 Production 1912-1917	Stotelmeyer and others, 1983, p. 206ff

E. Red Lodge district

Site name (key to plate 13) <i>Probable deposit type</i>	Tonnage (Millions of metric tons)	Cr ₂ O ₃ %	Comments	References
Gallon Jug No. 1 (484) <i>Red Lodge chromite</i>	0.03629	14	Estimated resource potential	Simons and others, 1973, p. F105
Gallon Jug No. 4 (485) <i>Red Lodge chromite</i>	0.00048 0.00354	X 16	Production for 1943 Estimated reserves	Simons and others, 1973, p. F105
Gallon Jug No. 2 (486) <i>Red Lodge chromite</i>	0.00101 0.02059	11.3	Production 1942 Estimate for zone	Simons and others, 1973, p. F105
Bluebird No. 2 claim (487) <i>Red Lodge chromite</i>	Unknown	X		Simons and others, 1973, p. F105

Table E1.--Grade and tonnage data for identified resources in the Absaroka-Beartooth study area (continued)

E. Red Lodge district (continued)

Site name (key to plate 13)	Tonnage (Millions of metric tons)	Cr ₂ O ₃ %	Comments	References
<i>Probable deposit type</i>				
Drill and Gallon Jug (488) <i>Red Lodge chromite</i>	0.00153 0.00454	5.5	Production Resource estimate	Simons and others, 1973, p. F103- F104
Shovel (490) <i>Red Lodge chromite</i>	Unknown	X	Mined out	Simons and others, 1973, p. F105
Pick (491) <i>Red Lodge chromite</i>	0.00485	X	Production; mined out	Simons and others, 1973, p. F105
North Star No. 1 claim (493) <i>Red Lodge chromite</i>	0.03157	X	Production	James, 1946
Little Nell deposit (494) <i>Red Lodge chromite</i>	0.00018	X	Remaining reserves	James, 1946
Highline Group (496) <i>Red Lodge chromite</i>	0.02186 0.00454	X	Production Remaining reserves	James, 1946
Four Chromes Group (497) <i>Red Lodge chromite</i>	0.00027	X	Remaining reserves	James, 1946
Edsel claim (500) <i>Red Lodge chromite</i>	0.00009	X	Remaining reserves	James, 1946

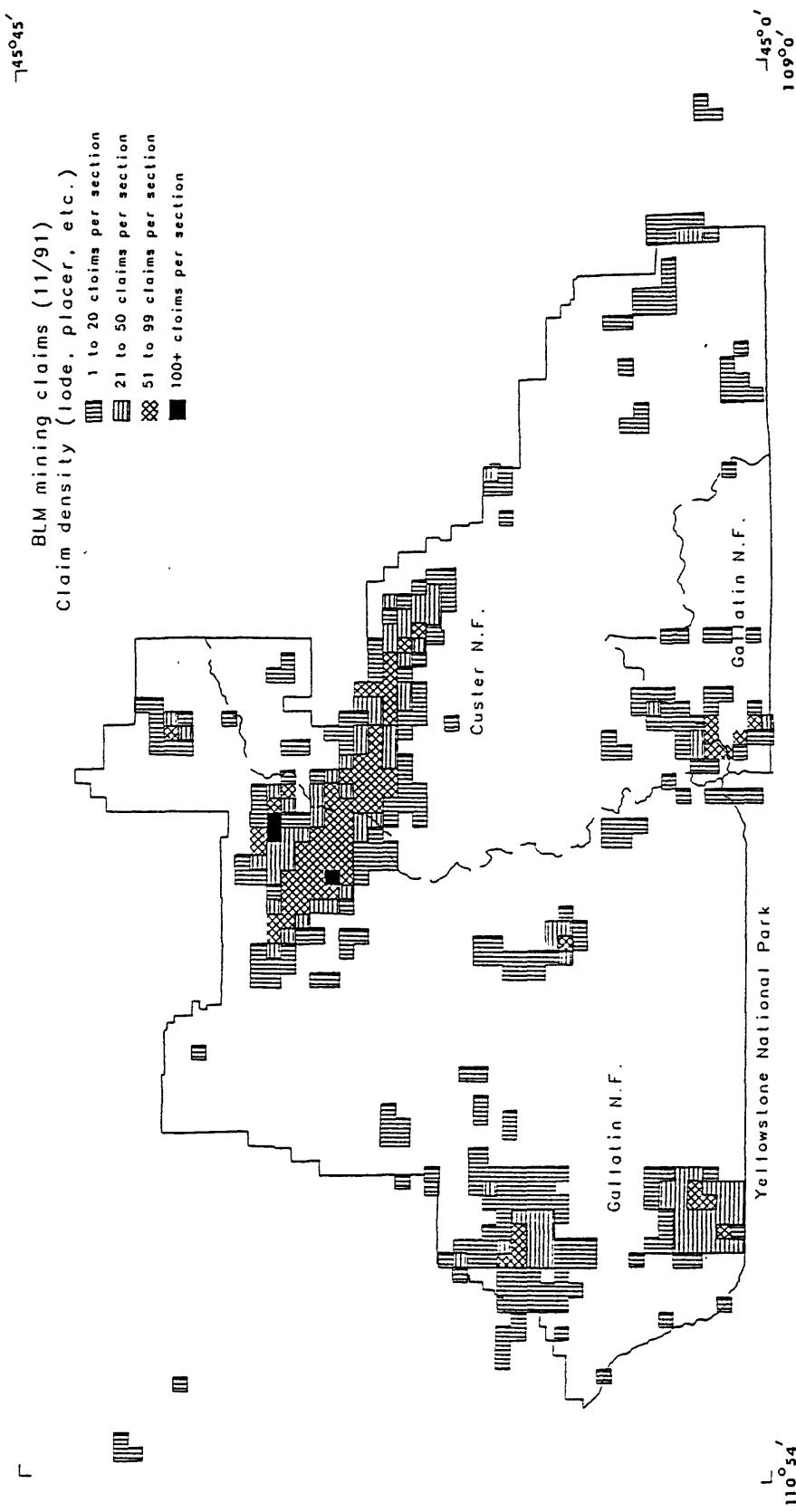


Figure E1.-Map of mining claim densities in the Absaroka-Beartooth study area (outlined). Based on November 1991 Bureau of Land Management Mining Claims Recordation System data for Montana. All types of claims (placer, lode, mill site, active, inactive) are included in the count of numbers of claims per section (Public Lands Survey System grid).

APPENDIX

The following table is a compilation of data on mines, prospects, and mineral occurrences within the Absaroka-Beartooth study area. Data sources include the MRDS (U.S. Geological Survey) and MILS (U.S. Bureau of Mines) databases as well as county reports, site visits by the authors, and previous mineral resource assessment studies referenced in chapter E.

Map numbers

Site numbers refer to localities plotted on plate 13 of this report.

Site names

A number of sites have had different names at different times. Many of the sites represent circa 1900 claims and prospects that may have been included in later claims or claim groups with different names. Many of the sites are unnamed sites that were sampled during previous assessments and found to have anomalous metal concentrations.

Mining districts

Mining district names are used in a broad sense and include sites in areas adjacent to organized districts. These areas are shown on plate 13. The Crevice area is referred to as "Crevasse" in the older literature. The Natural Bridge district is grouped with the Stillwater district. The Goose Lake area is included with the New World district in some reports. The following names refer to geographic areas that lie outside of organized mining districts: Hellroaring, for the Hellroaring plateau area; Horseshoe, for the Horseshoe Mountain area; Mt. Cowen; Suce Creek; Sliderock, for the Sliderock Mountain-Gold Hill-Iron Mountain area; and Plateau, for the area near East and West Rosebud Creeks in the eastern part of the study area.

Deposit types

Mines, prospects, and mineral occurrences are classified in terms of the mineral deposit type believed (by the authors of this report) to be represented by, or associated with, a particular site. In most cases, classification is tentative and can be expected to change if more data become available. Descriptive models for the types of mineral deposits considered are given in Chapters F and G. Deposit type abbreviations that require explanation are as follows:

Archean lode gold: Archean lode (Homestake) gold veins.

Algoma/Superior iron: Algoma or Superior type banded iron formation.

Polymetallic veins: Base-metal vein and replacement deposits in any host rock.

PM vein/dissemination: Precious metal veins or disseminations in Tertiary or Cretaceous igneous rocks. These may represent polymetallic veins that are enriched in precious metals relative to base metals, or epithermal veins, or disseminated mineralization related to porphyry copper-gold-molybdenum deposits.

Syenite-hosted segregations: Magmatic segregation copper-gold-silver-platinum-group element deposits in alkaline gabbros or syenites.

Skarn: Copper, gold-bearing copper, or magnetite skarn replacement deposits in carbonate rocks adjacent to igneous rocks.

Breccia pipes: Mineralized breccia pipes associated with porphyry copper-gold-molybdenum deposits.

Porphyry copper-gold-molybdenum: Porphyry copper deposits that may contain significant gold or molybdenum resources. Gold-rich porphyry copper-gold deposits may be shallower level deposits than porphyry copper-molybdenum.

Merensky Reef PGE: Reef type platinum-group element mineralization in the J-M reef of the Stillwater Complex in the study area.

Bushveld chromitite: Stratiform chromitite deposits associated with the Stillwater Complex in the study area.

Red Lodge chromite: Chromite pods in serpentinite and other metamorphosed rocks in Archean gneiss near Red Lodge.

Uranium occurrence: Many of these are poorly described reports of anomalous radioactivity, some of which were disproved by follow-up studies (indicated by NRD [no radioactivity detected] in comments column of table).

Serpentine-hosted asbestos: No geologic descriptions are available for most of the reported asbestos

occurrences in the study area; because asbestos is reported from serpentinite associated with the Red Lodge chromite deposits, they are tentatively assigned to this deposit type.

Production (P)

A, active mine

P, past production reported

D, active (1992) development

E, recently explored

blank, no production or unknown

Commodities

Commodities listed are those reported as present at the site, either in minerals or in assays of rock samples. Chemical symbols for the elements are used. In addition, the following abbreviations are used: PGE, platinum-group elements; trv, travertine; asb, asbestos.

Latitude and longitude

Site locations are reported in degrees (D), minutes (M), and seconds (S). Locations are taken from

previous reports or were digitized from maps included in previous reports. Locations reported for a given site are generalized because sites are not point localities and some sites include several adits, pits, or other workings. Sites are probably accurate to within no more than 10 seconds.

Description and comments

A brief description is given of the geology of the site, if available. Some entries were taken from MILS files which include only location and commodity data. Some MILS sites correspond to sites examined in previous mineral resource assessments where no significant assays [NSA] were determined. These localities are included for completeness, but the source and validity for some of these sites has not been verified.

Reference

MRDS record numbers are listed. These records contain more complete descriptions and references for each site.

No.	Site name(s)	District	Probable deposit type	P	Commodities present				Latitude, north (D M S)	Longitude, west (D M S)	Description/Comments on location	Reference (MRDS record)
1	Mineral Hill mine	Jardine	Archean lode gold	A	Au	Ag			45° 4' 9"	110° 37' 14"	Stratabound gold in Archean iron formation and associated quartz veins.	KAR0001
2	Jardine mine	Jardine	Archean lode gold	P	Au	W	As	Cu	45° 4' 6"	110° 37' 10"	Quartz & arsenopyrite veins associated with Precambrian schist, quartzite, and granite stock	W014722
3	Iron King	Jardine	Archean lode gold	Ag					45° 4' 59"	110° 37' 35"	Quartz & arsenopyrite veins in folded, sheared quartz-cummingonite schist	KAR0112
4	Lower Pine Creek	Jardine	Archean lode gold	Au	W	Ag			45° 4' 39"	110° 37' 16"	Past producer	J000035
5	Standard group	Jardine	Archean lode gold	Au	Ag	W			45° 5' 25"	110° 37' 51"	Quartz veins in schist, quartzite, and gneiss	KAR0282
6	Frank prospect	Jardine	Archean lode gold	Au	As	W			45° 2' 59"	110° 35' 5"	Quartz vein	DC08842
7	Hazel	Jardine	Algoma/Superior iron	Ag	Fe	W			45° 5' 21"	110° 38' 27"	Metasedimentary rocks (quartzite, biotite schist)	KAR0223
8	Hy Grade Placer	Jardine	Gold placer	Au					45° 5' 32"	110° 47' 2"	Placer	FS00252
9	Bear Creek	Jardine	Gold placer	Au					45° 3' 21"	110° 38' 46"	Placer	J000055
10	Jumbo placer	Jardine	Gold placer	Au					45° 4' 4"	110° 38' 31"	Placer	J000098
11	Moonlight Mine	Jardine	Unknown	Au	Cu	Ag			45° 2' 12"	110° 42' 23"	Mineral location	J000068
12	Occurrence	Jardine	Unknown	Au					45° 4' 34"	110° 37' 4"		J000099
13	Apex Ole	Jardine	Unknown	Pb					45° 5' 38"	110° 35' 6"	Anomalous lead in dacite porphyry	J000100
14	Livingston Marble and Granite	Jardine	Travertine	A	Trv				45° 2' 33"	110° 43' 5"	Hot spring travertine deposit mined for decorative stone	J000101
15	Last Chance lode	Crevice	Archean lode gold	Au	Ag				45° 4' 26"	110° 37' 54"	Veins	FS00300
16	Watson mine	Crevice	Archean lode gold	P	Au	As	W		45° 2' 33"	110° 36' 6"	Vein	DC08181
17	McCauley Group	Crevice	Archean lode gold	Au	As	W	Zn		45° 3' 9"	110° 36' 10"	Quartz veins	DC08847
18	Si Nombra mine	Crevice	Archean lode gold	Au	W				45° 3' 9"	110° 36' 19"	Vein, replacement	DC08848
19	Dryden	Crevice	Archean lode gold	Au					45° 1' 55"	110° 34' 50"	Quartz veins	DC08849

20	First Chance	Crevice	Archean lode gold	P	Au	As	W			45	2	20	110	36	22	Gold-bearing quartz veins and lenses in Archean schist	DC08180
21	Conrad mine	Crevice	Archean lode gold	Au						45	2	6	110	36	0	Quartz lenses in Precambrian quartz-biotite schist	W014717
22	Crevice Mn. Mine	Crevice	Archean lode gold	W	Au	Ag				45	2	44	110	35	49	Quartz veins in laterized Precambrian schist	J000102
23	Tiny Jack	Crevice	Archean lode gold	W	Au					45	2	46	110	34	31	Quartz stringers in diorite and schist near gabbro contact	J000045
24	Medona mine	Crevice	Archean lode gold	P	Au	W	As			45	2	42	110	36	0	Vein	DC08178
25	Kennebec claim	Crevice	Archean lode gold	As	Au	Cr				45	2	52	110	35	43	Vein	DC08843
26	Pop incline	Crevice	Archean lode gold	As	Au					45	2	45	110	35	52	Vein	DC08844
27	Snowshoe mine	Crevice	Archean lode gold	P	Au	W	Ag			45	2	45	110	35	57	Quartz lenses in Precambrian schist	W014714
28	Palmer Mountain	Crevice	Archean lode gold	Au						45	2	59	110	35	5	Surface-underground workings	J000034
29	Empire	Crevice	Archean lode gold	Au	As					45	3	45	110	34	50	Quartz vein	DC08841
30	Nebraska Nos. 1&2 Place	Crevice	Gold placer	Au						45	3	15	110	36	11	Placer	J000069
31	Crevasse Creek	Crevice	Gold placer	Au						45	2	27	110	35	6	Placer	J000052
32	Whitewood Girl	Hellroaring	Archean lode gold	Au	Ag					45	4	43	110	26	33	Anomalous gold in quartz veinlets in Archean cummingtonite schist	J000038
33	Hellroaring Ranger	Hellroaring	Archean lode gold	Au						45	4	36	110	25	6	Gold in garnetiferous quartz-cummingtonite schist and interlayered quartzite	KAR0293
34	Goldbug claim	Sixmile	PM vein/ dissemination	Au	Ag	Bi				45	14	37	110	43	25	Fault zone in siliceous dacite; assays 3.4 g/t Au, 34 g/t Ag, 0.07% Bi	KAR0304
35	Goldmed	Sixmile	PM vein/ dissemination	Ag						45	14	30	110	42	58	Stained dacite porphyry with disseminated pyrite	KAR0101
36	Crevis	Sixmile	Polymetallic vein	Au	Ag	Pb				45	14	6	110	40	12	Galena vein in shear zone in dacite	KAR0090
37	Overlap	Sixmile	Polymetallic vein	Au	Ag	Pb	Zn			45	13	46	110	40	12	Pyrite, galena, and sphalerite in quartz-calcite gangue in silicified dacite	KAR0315
38	Si claim	Sixmile	PM vein/ dissemination	Ag						45	12	57	110	40	14	Fe- and Mn-stained dacite, porphyry, breccia	KAR0079

39	Bar No. 6,7	Sixmile	Polymetallic vein	Ag	Pb	Au			45	14	30	110	40	38	Fe-stained shear zone in dacite with disseminated sulfides; assays 2.35gPb, 1.6 opt Ag, .3 o	KAR0046
40	Pot	Sixmile	PM vein/ dissemination	Ag					45	13	29	110	39	17	Fractured, Fe-,Mn-stained dacite	KAR0013
41	Barb No. 2	Sixmile	PM vein/ dissemination	Pb	Zn				45	13	59	110	39	54	Silicified dacite with disseminated pyrite cements	KAR0057
42	Pedestal	Sixmile	PM vein/ dissemination	Ag					45	13	15	110	39	26	Fault zone in silicified dacite	KAR0035
43	Iron group	Sixmile	Algoma/ Superior iron	Fe	Ag				45	12	4	110	43	36	Dacite, Fe-bearing schist, and quartzite	KAR0124
44	Magnetic claim group	Sixmile	Algoma/ Superior iron	Fe	Au	Ag			45	13	12	110	41	12	Magnetite in shears in Precambrian silicicous schist	KAR0037
45	Alta	Sixmile	Unknown	Cu					45	15	37	110	46	28	Ch-stained fractured quartz	KAR0002
46	Madgierre	Sixmile	Unknown	Ag					45	16	21	110	45	3	Stockpile of silicicous schist	KAR0068
47	Marve	Sixmile	Unknown	Ag					45	16	14	110	45	20	Brecciated dacite porphyry and schist	KAR0326
48	Harve No. 1 claim	Sixmile	Unknown	Ag	Cu				45	17	1	110	44	59	Quartz lens in schist	KAR0024
49	Occurrence	Emigrant	Bog	Mn	Cu	Mo			45	15	15	110	40	6		J000103
50	N - nr Allison Tunnel	Emigrant	Bog	Fe	Au	Ag			45	15	39	110	40	20	Limonic-cemented gravel	J000104
51	Unnamed bog iron de posit	Emigrant	Bog	Fe	Zn				45	15	34	110	40	20	Bog iron deposit	J000105
52	Min Gp & Orschell	Emigrant	Unknown	Ag	Au				45	15	32	110	40	18	MILS Pe-Cu-Mo mineral locality; also reported as a silver and gold occurrence in argillized dacite	J000106
53	Great Eastern mine	Emigrant	Breccia pipe	Ag	Cu	Pb	Zn		45	15	55	110	41	29	Polymetallic mineralization in breccia adjacent to copper porphyry target area	KAR0308
54	Peter Pear mine	Emigrant	Breccia pipe	Ag	Pb	Cu	Au	Mo	45	16	5	110	40	10	Breccia pipe(?) at rhizolite porphyry/dacite porphyry contact (Dinal exploration)	KAR0296
55	Allison tunnel	Emigrant	Breccia Pipe	Mo	Au	Ag			45	15	36	110	40	13	Breccia pipe(?)/trachytic porphyry, rhizolite, dacite porphyry	KAR0268
56	Emigrant Gulch Molybdenum	Emigrant	Breccia pipe	Mo	Au	Ag			45	15	14	110	39	57	Fractured brecciated trachyte porphyry pipe	KAR0283
57	Emigrant Gold Mining/Emigrant Creek	Emigrant	Gold placer	A	Au				45	17	29	110	40	50	Placer	J000107

58	Gold Bug placer	Emigrant	Gold placer	Au				45	17	41	110	40	56	Placer	J000108			
59	W.M.Clayton placer	Emigrant	Gold placer	Au				45	16	49	110	39	12	Placer	J000109			
60	Nancy prospect	Emigrant	Pegmatitic	Au	Ag			45	18	0	110	34	0	Pegmatitic lenses in Precambrian schist and quartzite	DC08767			
61	Wisconsin	Emigrant	Unknown	Ag				45	18	54	110	41	43	Adit along shear zone in graphite schist in chloritic schist	J000110			
62	Burlesque claim	Emigrant	Polymetallic vein	Zn				45	19	27	110	41	34	Nos. 62-68 are prospects that explored mineralized shear zones in schist and along an unconformity between schist and Cambrian Flakstad Sandstone.	KAR0314			
63	Ku Klux claim	Emigrant	Polymetallic vein	Ag	Pb	Zn		45	19	16	110	41	7		KAR0317			
64	Bank claim	Emigrant	Polymetallic vein	Ag	Zn			45	19	22	110	41	24		KAR0319			
65	Alaska claim	Emigrant	Polymetallic vein	Ag	Pb	Zn		45	19	31	110	41	47		KAR0310			
66	Occurrence	Emigrant	Polymetallic vein	Ag	Cu	Pb		45	18	49	110	41	33		J000111			
67	N-projected structure	Emigrant	Polymetallic vein	Ag	Cu	Pb		45	18	49	110	41	33		J000112			
68	Mountain Lion claim	Emigrant	Polymetallic vein	Ag	Zn			45	19	10	110	41	23		KAR0312			
69	Balm of Gilead Creek	Emigrant	Polymetallic vein	Au				45	18	59	110	40	43	Mineralization at Precambrian-Cambrian contact; similar to Alaska, Kukluk geology	KAR0307			
70	Elvin Clayton	Emigrant	Polymetallic vein	Pb				45	17	53	110	40	56	Explored prospect	J000113			
71	N-pit NE Gold Leaf	Emigrant	Polymetallic vein	Ag				45	16	18	110	39	22		J000114			
72	Winona F	Emigrant	PM vein/ dissemination	Au	Ag	Bi		45	14	38	110	38	2	Disseminated pyrite in fractured dacite porphyry	KAR0157			
73	Meadow No. 2	Emigrant	Polymetallic vein	Au	Ag	Pb		45	15	30	110	38	32	Quartz vein - projection of St. Julian structure	KAR0212			
74	Huckleberry Ridge	Emigrant	PM vein/ dissemination	Au	Ag	Pb		45	14	47	110	38	21	Pyrite in argillized, silicified dacite and ryolite	KAR0277			
75	Little Ax	Emigrant	PM vein/ dissemination	Au				45	14	52	110	38	26	Altered dacite, ryolite	KAR0284			
76	Margaret	Emigrant	PM vein/ dissemination	Ag				45	15	9	110	38	18	Fe-, Mn-stained dacite breccia	KAR0135			
77	St. Julian mine	Emigrant	Breccia pipe	P	Au	Ag	Cu	Pb	Zn	Fe	45	15	15	110	38	55	NE-trending shear zone in dacite	DC08782
78	Broken Glasses	Emigrant	PM vein/ dissemination	Au				45	15	20	110	38	17	Shear at gradational rhyolite-dacite contact	KAR0146			

79	Grand View claim	Emigrant	Polymetallic vein	Au	Ag	Pb			45	15	17	110	38	10	Galena in quartz vein in shear in altered dacite	KAR0306	
80	Crow Chief	Emigrant	PM vein/ dissemination	Au					45	16	11	110	38	46	Altered dacite	KAR0292	
81	Janette claim	Emigrant	Polymetallic vein	Au	Ag	Pb			45	15	19	110	37	54	Breccia vein with sulfides	KAR0289	
82	Mackay claim group	Emigrant	Polymetallic vein	E	Ag	Pb	Zn	Ch		45	13	15	110	37	1	Galena veins in dacite; fault zone explored by drilling & geochemical sampling	KAR0290
83	Seismoneit mine	Emigrant	Polymetallic vein	Au	Ag	Pb	Cu		Bi	45	17	7	110	36	24	Sphalerite in vein in andesite flows near intrusives	DC08769
84	Occurrence	Emigrant	Unknown	Au						45	15	38	110	35	17		J000115
85	Min group	Emigrant	PM vein/ dissemination	Au	Ag					45	15	27	110	40	25	Augillized dacitic volcanics	KAR0299
86	Great Western adit	Emigrant	Porphyry Cu (Au,Mn)	E	Ag	Ch	Pb	Zn		45	16	14	110	40	50	Drilled 1974; may be part of Emigrant stock	KAR0287
87	Queen Bee	Emigrant	PM vein/disseminatio n	Au	Ag					45	14	54	110	39	39	Disseminated pyrite in fractured dacite	KAR0235
88	E Fork Emigrant prospects	Emigrant	PM vein/ dissemination		Ag					45	15	17	110	39	49	Disseminated sulfides Emigrant stock	KAR0313
89	Corbett & Montana Queen	Emigrant	PM vein/ dissemination		Ag	Au				45	14	31	110	39	19	Shear zone- Emigrant stock	KAR0279
90	E Fork Emigrant prospects	Emigrant	PM vein/ dissemination	Au	Ag	Pb	Bi			45	15	41	110	39	34	Hematite-stained felsic rock	KAR0311
91	E Fork Emigrant prospects	Emigrant	PM vein/ dissemination		Ag	Mo				45	15	17	110	39	60	Disseminated sulfides associated with Emigrant stock	KAR0291
92	Iron King claim	Emigrant	Porphyry Cu (Au,Mn)		Au	Ag	Bi	Cu		45	15	40	110	39	22	Ch-bearing fractures in pyritized felsic rock	KAR0298
93	E Fork Emigrant prospects	Emigrant	Porphyry Cu (Au,Mn)		Cu					45	15	7	110	39	8	Disseminated sulfides associated with Emigrant stock	KAR0309
94	Sheila claim group	Emigrant	PM vein/ dissemination		Au	Ag	As	Ba	Mo	45	14	23	110	39	59	Shear zone between Emigrant stock dacite & younger dacite flows	KAR0224
95	E Fork Emigrant prospects	Emigrant	PM vein/ dissemination		Au	Ag	Mo			45	15	9	110	39	44	Disseminated sulfides associated with Emigrant stock	KAR0294

96	Occurrence	Emigrant	PM vein/ dissemination	Ag				45	16	18	110	39	22	Shear zone at contact of Emigrant stock dacite porphyry with older dacite	J000116
97	Montana Queen	Emigrant	PM vein/ dissemination	P	Au	Ag		45	14	24	110	39	15	Gold-bearing hematite gouge vein in Emigrant stock	KAR0257
98	E Fork Emigrant prospects	Emigrant	PM vein/ dissemination	Ag				45	15	25	110	39	15	Disseminated sulfides in Emigrant stock dacite	KAR0321
99	Little Chief	Emigrant	Unknown	Ag				45	17	59	110	44	10	Shear zone in limonitic quartz schist	J000117
100	Alpha	Emigrant	Unknown	Au	Ag			45	18	41	110	43	46	Graphite schist lenses in chalcopyrite-biotite schist; shear zones	KAR0302
101	Silver Star	Emigrant	Unknown	Ag				45	18	17	110	43	54	Underground workings	J000084
102	Copper Group	Emigrant	Unknown	Cu	Fe	Ni		45	15	25	110	42	20		J000049
103	Lucky Allen	Emigrant	Unknown	Cu	Ni			45	18	6	110	41	26	Surface workings	J000118
104	Duval 12	Emigrant	Unknown	Cu				45	15	53	110	40	18		J000094
105	Lower Falls No. ore	Emigrant	Unknown	Ag				45	17	37	110	40	55	Mineral location	J000119
106	Hope Group	Emigrant	Unknown	Cu	Ag			45	16	29	110	40	14		J000120
107	Esparranza	Emigrant	Unknown	Ag				45	15	42	110	40	0		J000091
108	Adelle	Emigrant	PM vein/ dissemination	Bi				45	15	1	110	40	3	Limonite-stained fault zone with pyrite in silicified dacite	KAR0285
109	Virginia Dare claim	Emigrant	Unknown	Cu	Be			45	17	60	110	39	29	Shear zone at E end pyritized molybrite porphyry dike	KAR0300
110	Little Bonanza group	Emigrant	PM vein/ dissemination								110	39	55	Altered dacite talus	KAR0281
111	Gold Leaf No. 2 claim	Emigrant	PM vein/ dissemination	Au	Ag			45	16	12	110	39	29	Altered zone with quartz veins in dacite porphyry	KAR0318
112	Crown Point	Emigrant	Unknown	Au	Ag	Pb		45	16	11	110	39	28		J000086
113	E Fork Emigrant prospects	Emigrant	Unknown	Ag	Cu	Mo		45	15	12	110	39	50	Quartz monzonite in talus	KAR0320
114	Lea No. 34	Emigrant	Unknown	Au	Pb			45	13	50	110	39	10	Underground workings	J000095
115	E Fork Emigrant prospects	Emigrant	Unknown	Ag	Cu	Mo		45	15	17	110	39	58	Quartz monzonite in talus	KAR0301
116	Duv 19 Group	Emigrant	Unknown	Ag	Mo	Mn		45	15	22	110	39	13		J000085

117	Old Bill Gray mine	Emigrant	Unknown		Ag				45	15	34	110	39	8	Dump of caved adit	KAR0303
118	Occurrence	Emigrant	Unknown	Cu					45	17	54	110	39	38	Frost near Virginia Dale	J000121
119	Dav Minnie Bell No. 2	Emigrant	Unknown	Ag	Au				45	15	39	110	39	39		J000093
120	Gold Leaf	Emigrant	PM vein/ dissemination	Au	Ag				45	15	53	110	39	36	Silicified dacite on dump	KAR0280
121	Helen(?)	Emigrant	PM vein/ dissemination	Ag	Bi				45	14	59	110	38	40	Gossan stockpile; gossan-cemented brecciated dacite	KAR0179
122	Mackay #17	Emigrant	Unknown	Ag					45	13	28	110	38	14	Glacial rubble includes limonite-stained dacite porphyry	KAR0288
123	Garland Comus	Emigrant	Unknown	Au	Ag				45	15	16	110	38	8	Shear zones in altered dacite; basalt dike	KAR0246
124	Minn #41	Emigrant	Unknown	Ag					45	13	30	110	38	20	Dacite in glacial alluvium	KAR0286
125	Annie No. 2	Emigrant	PM vein/ dissemination	Ag					45	14	58	110	38	55	Pyrite in fractured dacite	KAR0201
126	Dixie claim	Emigrant	Polymetallic vein	Ag	Pb	Zn			45	15	17	110	37	54	Dixie shear zone: along contact between porphyry and pyritized rhyolite; assays 8.6% Zn, 3.2% Pb;	KAR0190
127	Jewell	Emigrant	Unknown	Ag					45	15	45	110	37	19	Shear zone in argillized mylonite; limonite, manganese oxides [NSA]	J000122
128	Nabob	Emigrant	Unknown	Ag	Pb	Au	Zn		45	15	14	110	37	47		J000089
129	Crystal	Emigrant	Unknown	Cu	Ag	Au			45	15	43	110	37	23	Calcite in shear zone in argillized dacite [NSA]	J000123
130	Julie Ellen	Emigrant	Unknown	Ag	Pb	Au			45	15	40	110	37	58	Flow-banded, bleached, aphanitic rock	J000124
131	Falls	Emigrant	Unknown	Cu					45	15	50	110	36	53	Rhölite in talus or moraine [NSA]	J000125
132	Upper Hellroaring prospect	Emigrant	Unknown	Au					45	13	33	110	22	13	Surface workings	J000037
133	Magnetic Group	Emigrant	Unknown	Au	Ag	Pb	Re		45	14	26	110	43	45		J000126
134	Forgotten Mine	Emigrant	Unknown	Au					45	19	22	110	42	16		J000096
135	Chico Hot Springs	Emigrant	Travertine	Trv					45	20	2	110	41	32	Travertine at hot springs	J000127
136	Back Pay	Emigrant	Travertine	Trv	Ag				45	17	46	110	37	59	Travertine hot spring deposit, calcite and aragonite crystals; silicified dacite	J000128
137	Hot Shot	Mill Creek	Travertine	Trv					45	17	29	110	31	12	Travertine at Montanapolis Springs	J000129

138	Midnight deposit	Mill Creek	Bog	Fe	Mn	Zn		45	15	23	110	37	5	Low-grade Mn wad and bog iron deposit	KAR0008		
139	Copper Queen	Mill Creek	Unknown	Cu	Au	Ag	Pt	Ni	45	17	15	110	34	56	Mineralized shear in diorite	KAR0007	
140	Copper Duke	Mill Creek	Unknown	Cu					45	17	42	110	34	8	Mineralized shears in schist and quartzite; assay 0.68% Cu	KAR0335	
141	Peacock claim	Mill Creek	Unknown	Cu					45	17	22	110	34	8	Altered Precambrian schist near Precambrian metadiorite and younger dacitic rocks	KAR0011	
142	Alice C claim	Mill Creek	Polymetallic vein	Pb	Ag	Zn	Cu	Au	45	17	48	110	34	35	Galena, sphalerite, and pyrite in quartz stringers in fractured Precambrian schist	KAR0014	
143	Lost Cabin claim	Mill Creek	Unknown	Cu	Ag	Ni	As		45	17	22	110	34	43	Projection of Copper Queen mineralized structure	KAR0340	
144	Arrow Peak claim	Mill Creek	Polymetallic vein	Pb	Ag	Au			45	20	14	110	31	56	Galena veins in Precambrian gneiss at schist contact	KAR0327	
145	McDowell claim group	Mill Creek	Polymetallic vein	Au	Ag	Pb	Zn	Cu	Bi	45	15	28	110	38	1	NW and NE-trending mineralized shear zone in volcanic rocks and brecias	KAR0339
146	David claim	Mill Creek	PM vein/ dissemination	Au	Ag	Bi				45	15	33	110	37	4	Highly brecciated shear zone	KAR0332
147	Dodge	Mill Creek	Unknown	Pb	Mo	Bi				45	15	23	110	37	42	Altered zone (fault?), in dacite with specular hematite	KAR0336
148	Galena Queen	Mill Creek	Polymetallic vein	Au	Pb	Ag	Mn			45	15	20	110	37	15	Vein	D004315
149	Vivienne claim	Mill Creek	Polymetallic vein	Au	Ag	Pb	Mo			45	15	34	110	37	52	Siliceous shear zone	KAR0330
150	High Point	Mill Creek	PM vein/ dissemination	Ba	Au	Ag				45	14	41	110	37	18	Barite veins in fractured porphyritic dacite	KAR0342
151	Floyd Combs	Mill Creek	PM vein/ dissemination	Au	Ag	Cu	Pb	Bi	W	45	15	39	110	36	48	Replacement in shear zones at contact between intrusive and mafic extrusive rocks	KAR0334
152	Montana	Mill Creek	PM vein/ dissemination	Au	Ag	Cu	Bi	W		45	15	38	110	36	37	Limonite boxwork at shear zone intersection	KAR0012
153	Shirley	Mill Creek	Unknown	Cu	Ag	Bi	Au	Sb	Pb	45	15	38	110	36	42	Copper minerals in shear zone	KAR0006
154	Spring claim	Mill Creek	Polymetallic vein	Ag	Pb					45	16	7	110	36	21	SW projection of Barbara Ann shear	KAR0346
155	Arastra Quartz	Mill Creek	PM vein/ dissemination	Au	Ag					45	15	18	110	36	60	Fractured, pyritized dacite breccia	KAR0010
156	Cathy claim	Mill Creek	Polymetallic vein	Ag	Pb					45	16	15	110	36	18	SW projection of Barbara Ann shear	KAR0009
157	Virginia claim	Mill Creek	Polymetallic vein	Pb	Ag	Cu	Zn	W	Au	45	16	4	110	36	29	Galena at fracture intersections in NW-trending shear in volcanic rocks	KAR0325

158	Pilgrim & St. Croix	Mill Creek	Polymetallic vein	Au	Cr	Ag			45	16	29	110	35	44	Stained breccia near contact between Precambrian metadiorite and younger volcanic rocks	KAR0328		
159	Lightning No. 3	Mill Creek	Unknown	Cu					45	16	13	110	35	38	Shear zone intersections in porphyritic basal	KAR0324		
160	Barbara Ann mine	Mill Creek	Polymetallic vein	P	Au	Ag	Pb	Cu	Zn	Bi	45	16	39	110	35	34	Replacement along brecciated shear zone in basal	DC08768
161	Occurrence	Mill Creek	Polymetallic vein	Pb	Ag				45	17	14	110	35	30	Prospect pit near the Sharon Sue adit	KAR0341		
162	Contact No. 2 claim	Mill Creek	Unknown	Cu	Au	Ag			45	17	4	110	35	17	Copper-bearing shear zone in hornblende diorite	KAR0331		
163	Sharon Sue	Mill Creek	Polymetallic vein	Pb	Ag	Ba			45	17	17	110	35	25	Vuggy sandstone with sulfides in fractures	KAR0333		
164	Alice	Mill Creek	Polymetallic vein	Au	Ag	Cu	Pb	Zn	Mo	45	15	57	110	34	43	Replacement & vein in shear zone in basal dike	KAR0347	
165	Big Pine claim	Mill Creek	Polymetallic vein	Au	Ag	Pb				45	17	54	110	34	59	Sulfidized shear in biotite schist	KAR0338	
166	Camel claim	Mill Creek	Unknown	Au	Ag					45	15	9	110	37	8	Pyritized area - Cr-Mo porphyry at depth?	KAR0345	
167	Copper Queen claim	Mill Creek	Polymetallic vein	Cu	Ag					45	16	57	110	27	9	Chalcocite in limestone replacement at contact with porphyritic andesite	J000130	
168	Twilight	Mill Creek	Unknown	Fe	Mn					45	15	13	110	37	18	Surface workings	J000092	
169	Pyrite claim	Mill Creek	Unknown	Au	Ag	Bi	Cu			45	15	33	110	37	5	Talus cover - pit in altered rock	KAR0004	
170	Occurrence	Mill Creek	Unknown	Au	Ag	Cu				45	16	35	110	35	27	Roadcut near Barbara Ann mine	J000131	
171	Bornite	Mill Creek	Unknown	Au	Pb	Cu				45	17	24	110	35	6	Disseminated pyrite in quartz veins, hornblende schist in talus; assay 1.52% Pb, .98% Cu, .01 ozy Au	KAR003	
172	Robert E. Lee	Mill Creek	Unknown	Cu	Ag	Sb				45	20	43	110	35	55	Malachite, azurite, and chalcopyrite in shear zone in schist near Precambrian-Cambrian contact	KAR0015	
173	Burnt Creek	Mill Creek	Unknown	Ni	Cr					45	17	4	110	34	32	Three aplite dikes [NSA]	J000132	
174	Hope	Mill Creek	Unknown	Ni						45	17	29	110	34	41	Quartz vein or lens in biotite-muscovite schist [NSA]	J000133	
175	Platinum Ridge claim	Mill Creek	Unknown	As						45	17	36	110	34	44	Arsenopyrite vein in shear in mafic rock; no PGE detected in assays	KAR0005	
176	Mill Creek	Gold placer		Au						45	15	38	110	25	5	Placer	J000054	
177	Oregon Lodge claim	Mount Cowen	Unknown	Au						45	26	55	110	28	55	Free gold in quartz vein; patented claim	KAR0019	

178	Mt. Cowen Mo	Mount Cowen	Pegmatite	Mo	Au	Ag			45	23	17	110	21	12	Scattered molybdenite in pegmatites and enclosing gneiss	KAR0020
179	Granite Mountain claim	Silver Lake	Unknown	Cu	Ag	Au			45	22	11	110	21	21	Quartz float, fault breccia	KAR0017
180	Jumbo	Silver Lake	Unknown	Ag	Au	Cu			45	22	30	110	20	7	Pyrite in brecciated quartzite [NSA]	J000134
181	Monarch claim	Silver Lake	Unknown	Ag					45	22	24	110	20	25	Quartz vein	KAR0016
182	Montana claim	Silver Lake	Unknown	Cu	Ag				45	22	43	110	19	25	Shear zone in granitic gneiss and quartzite	KAR0018
183	First Out	Suce Creek	Unknown	Ag					45	30	39	110	31	51	Adit in orthoclase gneissic schist	KAR0021
184	Honolulu	Suce Creek	Unknown	Ag	Cu				45	32	6	110	31	1	Shear zone in quartz mica schist	KAR0025
185	King Philip	Suce Creek	Unknown	Cu					45	31	56	110	31	1	Quartz lens in biotite-amphibolite schist	KAR0026
186	Big Chief	Suce Creek	Unknown	Au					45	35	16	110	30	2	Jointed milky quartz	KAR0029
187	Sixty Five	Suce Creek	Unknown	Ag	Ni	Cr	Co		45	31	39	110	30	42	Biotite-amphibolite schist [NSA]	J000135
188	First Chance	Suce Creek	Unknown	Ag					45	34	37	110	29	42	Massive Madison Limestone	KAR0027
189	Oro-Y-Place	Suce Creek	Unknown	Co	Cr	Ni			45	34	57	110	29	50	Micaeous quartzite and hematite schist [NSA]	J000136
190	Ruby	Suce Creek	Unknown	Cr					45	35	10	110	29	55	Micaeous schist	KAR0028
191	Northern Pacific	Suce Creek	Pegmatite	Cu					45	35	18	110	29	34	Granite pegmatite lens/amphibolite schist	KAR0022
192	Blue Manganese	Suce Creek	Unknown	Ag	Au	Cu			45	35	6	110	29	30	Hematite gneiss in shear zone in chlorite schist	KAR0023
193	Frozen Lake Group	Suce Creek	Unknown	Mo					45	23	2	110	29	31	Explored prospect	J000047
194	Gold Hill mine	Slidrock	PM vein/ dissemination	E	Au				45	35	59	109	56	33	Altered porphyry	J000019
195	Butte and Butte No. 1 claims	Slidrock	Unknown	Fe					45	37	0	109	56	14		J000010
196	Surprise mine	Slidrock	Unknown	Au	Ag				45	36	20	109	55	10	Topo map locality	KAR0049
197	Occurrence	Slidrock	Skarn	Fe					45	35	20	109	55	20	Magnetite streak at contact of porphyry with Madison Limestone	J000137
198	Silver King mine	Slidrock	Unknown	Ag	Au				45	35	58	109	55	29		KAR0044
199	Deer Creek prospect	Slidrock	Unknown	Fe					45	36	11	109	55	11		KAR0047

200	Knapp mine	Slidrock	Unknown	Fe			45	36	39	109	55	48		KAR045			
201	Occurrence	Slidrock	Skarn	Fe	Au			45	35	54	109	54	50	Magnetite and pyrite at prospect pit; 0.066 ppm Au	J000138		
202	Ross mine	Slidrock	Unknown	Au	Ag			45	36	29	109	54	57		KAR051		
203	Unnamed copper mine	Slidrock	Unknown	Cu				45	35	25	110	6	53		KAR055		
204	Bar D	Horseshoe	Unknown	Au				45	9	13	110	7	36	Explored prospect	J000063		
205	Horseshoe Mountain claim	Horseshoe	Polymetallic vein	Au	Ag	Cu	Pb	Zn	Mo	45	9	5	110	5	4 Quartz veins and fracture zones in Precambrian gneiss, Cambrian sandstone, and Tertiary porphyries	D004304	
206	Beavertrail	New World	Unknown	Ag	Cu	Au				45	6	15	109	59	52		KAR0207
207	Hudson Mine	New World	Polymetallic vein	Ag	Pb					45	3	49	109	58	13		J000067
208	Great Rift Claim	New World	Polymetallic vein	Ag	Pb					45	3	49	109	58	15		J000066
209	Acme Group	New World	Polymetallic vein	Ag	Pb					45	5	22	109	58	12	Developed deposit	J000139
210	Wally Jr.	New World	Polymetallic vein	Ag	Cu	Pb				45	5	31	109	57	23	Quartz in shear in granitic gneiss; assays 9 g/t Ag, 0.73% Cu and Pb	KAR0196
211	Polar Star Iode	New World	Polymetallic vein	Ag	Cu	Pb				45	3	38	109	57	17	Ven's and disseminations	FS00330
212	C.C. and Acme claims	New World	Unknown	Ag	Au					45	5	29	109	57	47	Shear zone in granitic	KAR0195
213	Lazy Beele	New World	Polymetallic vein	Ag	Zn	Pb	Cu			45	6	42	109	54	25	Fracture in Archean granite; copper, lead, and zinc sulfide minerals in quartz-pyrite gneiss	KAR0193
214	Sky Top Creek	New World	Unknown	Ag	Au					45	5	24	109	52	4	Sulfide-bearing shear zone in granite	KAR0197
215	Greenback prospect	New World	Pegmatitic	Ag	Au					45	5	45	110	0	7	Pyrite-bearing pegmatitic dike cut by diabase dikes	D004280
216	Unnamed	New World	Unknown	Ag	Au					45	6	33	110	0	34		KAR0216
217	North End Mt. Abundance	New World	Unknown	Ag						45	4	48	110	0	51	Prospect in brecciated Pilgrim Limestone	J000044
218	Occurrence	New World	Unknown	Ag						45	4	58	110	0	51		J000140
219	Days of 49 placer	New World	Gold placer	Au						45	1	21	109	59	7	Placer	FS00261
220	Lulu Mine	New World	Skarn	Au	Cu					45	3	48	109	57	2	Mineral location	J000141
221	Glenarry Mine	New World	Skarn	Au	Ag	Cu				45	4	16	109	57	21	Contact metamorphic pyritic gold-copper ores in limestone	W014660

222	Happy Thought placer	New World	Gold placer	Au				45	1	37	109	57	37	Placer	FS00249	
223	Crown Butte and Melisa Mine	New World	Unknown	Au	Ag	Cu	Pb		45	2	57	109	57	5		J000051
224	Golden Grizzly	New World	Unknown	Au				45	4	6	109	57	33	Explored prospect	J000060	
225	Adit claim	New World	Unknown	Au	Cu			45	3	48	109	57	2		J000064	
226	Viola lode	New World	Unknown	Au	Ag			45	3	18	109	56	27	Veins (stringers)	FS003333	
227	Henderson Group	New World	Unknown	Au	Ag	Cu		45	3	20	109	56	27	Developed deposit	J000087	
228	Arrowhead lode	New World	Unknown	Au	Ag			45	3	18	109	56	27	Vein	FS003332	
229	Parkment Mining Co.	New World	Unknown	Au	Cu			45	4	2	109	56	50	Underground workings	J000033	
230	DMH Group	New World	Unknown	Au	Ag	Cu		45	3	48	109	55	47		J000050	
231	Schiller lode	New World	Unknown	Au	Ag	Cu		45	2	45	109	55	42	Fracture zone	FS003331	
232	Mohawk Mine	New World	Polymetallic vein	Au	Ag	Pb	Zn	45	0	47	109	55	30		J000142	
233	Alice E.	New World	Unknown	P	Au	Cu		45	2	22	109	55	52	Gold-bearing pyrite in quartzite adjacent to gabbro	KAR0210	
234	Trednick	New World	Unknown	Au	Cu			45	4	13	109	55	48	Sheeted zone in Precambrian granite along gabbro contact	KAR0199	
235	Early Vacation group	New World	Unknown	Au	Ag			45	3	4	109	50	25	Uranium claims in biotite-hornblende granite and pegmatitic dikes [NRD]	KAR0203	
236	Slough Creek drainage	New World	Gold placer	P	Au	Fe	Ti	Zr	45	4	35	110	8	31	Placer	D004303
237	Rock Creek Placer	New World	Gold placer	Au				45	7	25	110	4	37	Placer	J000040	
238	Grand Central claim	New World	Unknown	Au	Ag	Pb		45	7	10	110	2	5	Intrusive body	D004302	
239	Pig's Eye Placer	New World	Gold placer	Au				45	3	38	110	1	57	Explored prospect along Wolverine Creek	J000041	
240	Occurrence	New World	Unknown	Au	Ag			45	6	32	110	0	33		D004300	
241	Long Tom placer	New World	Gold placer	Au				45	5	13	110	0	18	Explored placer at SE end of Lake Abundance	J000039	
242	Occurrence	New World	Unknown	Au	Ag			45	4	59	110	0	59		D004301	
243	Grace lode	New World	Porphyry Cu (Au,Mo)	Cu				45	2	4	109	57	35	Disseminated and massive concentrations of sulfide minerals	FS003351	

244	Elizabeth	New World	Unknown	Cu				45	5	54	109	57	4	Chalcopyrite, argentite, and pyrite filling fractures in Archean granite	KAR0205		
245	McLaren Mine	New World	Skarn	D	Cu	Ag	Au			45	3	43	109	57	29	Stratabound/replacement/skarn deposit	W014716
246	Miller Creek	New World	Skarn	D	Cu	Ag	Au			45	3	14	109	57	13	Stratabound	J000143
247	Fisher Mountain	New World	Skarn	D	Cu	Ag	Au			45	3	58	109	57	32	Fault replacement	J000144
248	Como	New World	Skarn	D	Cu	Ag	Au			45	4	10	109	57	27	Skarn and replacement	J000145
249	Silver Zone lode	New World	Unknown	Cu						45	2	4	109	57	35	Disseminated and massive concentrations of sulfide minerals	FS00335
250	Lulu extension lode	New World	Unknown	Cu	Ag		Au			45	4	4	109	57	26	Vein	FS00322
251	Homestake Mine P	New World	Breccia pipe	D	Cu	Au	Ag			45	3	22	109	56	41	Mineralized breccia; includes contact metamorphic limestone replacement	W014659
252	Commonwealth	New World	Unknown	Cu	Ag		Au			45	4	56	109	55	12	Pyrite and chalcopyrite in fracture filling in quartzite	KAR0211
253	Longstreet	New World	Polymetallic vein	Cu						45	2	23	109	55	8	Disseminated chalcopyrite and pyrite in ls	KAR0215
254	Rearguard	New World	Unknown	Cu	Au	Ag				45	1	28	109	29	56	Quartz pods along diabase-trachyte dike contact	KAR0198
255	Josephine lode	New World	Polymetallic vein	Pb	Ag		Au			45	3	13	109	59	3	Replacement	FS00350
256	Occurrence	New World	Unknown	Pb	Au	Ag				45	5	45	109	57	21		KAR0214
257	Shoo Fly	New World	Polymetallic vein	Pb		Ag				45	2	25	109	57	13	Replacement pipe in limestone next to monzonite porphyry dikes	KAR0194
258	U.S. Treasury	New World	Polymetallic vein	Pb	Cu	Ag	As			45	4	56	109	57	1	Shear in Archean granite	KAR0204
259	Morning Star	New World	Polymetallic vein	P	Ag	Cu				45	2	25	109	57	13	Sulfide minerals in siliceous gangue in fractured dolomitic	KAR0219
260	Black Warrior mine	New World	Polymetallic vein	P	Pb	Ag	Au			45	2	58	109	57	48	Galena and other sulfide minerals in limestone replacement deposit	KAR0217
261	Bull Elk lode	New World	Polymetallic vein	P	Pb	Au	Ag	Zn	Cu	45	3	18	109	56	27	Vein	FS00334
262	Duke	New World	Polymetallic vein	P	Pb		Zn			45	1	38	109	56	58	Galena, sphalerite, and pyrite in silicified veins in limestone	KAR0202
263	Early Day	New World	Polymetallic vein	Pb		Zn				45	1	30	109	56	45		J000042
264	Big Blue	New World	Polymetallic vein	P	Pb	Ag	Au	Cu	Zn	45	1	38	109	56	58	Galena, cerussite, and pyrite lenses and stringers in siliceous gangue along fault	KAR0208

265	Mutt Lake	New World	Polymetallic vein	Pb	Cu	Au	Ag		45	5	31	109	56	23	Sulfides minerals in basalt dike in granitic gneiss	KAR0221
266	Sump	New World	Polymetallic vein	Pb	Zn	Cu			45	1	38	109	56	58	Flat-lying sulfidized lenses in limestone	FS00349
267	Carlton	New World	Polymetallic vein	P	Pb				45	2	22	109	56	0	Galena, tetrahedrite, and other sulfide minerals in fracture zone in gabbro	KAR0206
268	Irma-Republic	New World	Polymetallic vein	P	Pb	Zn	Ag	Mn	45	0	41	109	56	28	Fracture fillings and replacements in limestone; complex ore with manganese carbonates	W014715
269	Mohawk Warrior	New World	Polymetallic vein	Pb	Ag				45	1	40	109	55	31	Galena seams in tight fractures in quartzite	KAR0218
270	Chippunk	New World	Unknown	Pb	Cu	Zn			45	5	4	109	55	51	Galena and other sulfide minerals in fracture zone in gabbro	KAR0222
271	Lost Chance	New World	Polymetallic vein	Pb	Zn				45	2	22	109	55	49	Underground workings	J000043
272	Stewnwinder	New World	Polymetallic vein	Pb	Ag	Au			46	3	4	110	17	34	Galena, anglesite, and bornite in quartz-pyrite gangue in fracture zone in diorite	KAR0225
273	Unnamed shear zone sample	Goose Lake	Unknown	Ag	Au				45	6	15	109	55	19	Shear zone	KAR0139
274	Unnamed	Goose Lake	Unknown	Ag	Au				45	7	19	109	55	2		KAR0121
275	Ontario claim	Goose Lake	Unknown	Ag	Au				45	5	42	109	55	20	Shear zone in granitic rock; basalt dike	KAR0107
276	Occurrence	Goose Lake	Unknown	Ag	Au				45	5	42	109	55	38		KAR0178
277	Hiball Uranium	Goose Lake	Unknown	Ag	Au				45	7	15	109	55	16	Re-, Mn-stained rhyolite; [NRD]	KAR0189
278	Occurrence	Goose Lake	Unknown	Ag	Au	W	Cu		45	5	8	109	55	11	Shear zone in granitic gneiss	KAR0151
279	Copper Glance claim	Goose Lake	Unknown	Au	Ag	Pb	Cu		45	6	46	109	55	4	Disseminated sulfide minerals in quartz gangue in fracture in Archaen Granite	KAR0145
280	Mercer group	Goose Lake	Unknown	Ag	Au				45	7	20	109	55	6	Shears in altered granite and latite; basalt dike	KAR0123
281	Occurrence	Goose Lake	Unknown	Ag	Au				45	5	15	109	55	51		KAR0187
282	Unnamed shear zone sample	Goose Lake	Unknown	Ag	Au				45	6	7	109	55	6		KAR0154
283	Occurrence	Goose Lake	Unknown	Ag	Au				45	5	37	109	55	31		KAR0185
284	Comet-Lone Star	Goose Lake	Polymetallic vein	Ag	Pb	Au			45	7	4	109	55	4	Sulfides in silicified shear zone	KAR0129

285	Unnamed occurrence	Goose Lake	Unknown	Ag	Au			45	7	11	109	55	4		KAR0120
286	Unnamed occurrence	Goose Lake	Unknown	Ag	Au			45	7	12	109	55	1		KAR0133
287	Uranium Acre	Goose Lake	Unknown	Ag	Au			45	6	29	109	55	5	Shear zone in granite gneiss	KAR0159
288	Uranium Glance	Goose Lake	Polymeric vein	Ag	Au			45	6	58	109	55	6	Sulfide-bearing pegmatite in granite	KAR0152
289	George Extension	Goose Lake	Syenite-hosted segregation	Ag	Au			45	7	34	109	54	15	Disseminated sulfide minerals in NE-trending shear zone in syenite	KAR0149
290	Unnamed occurrence	Goose Lake	Unknown	Ag	Cu			45	7	26	109	54	40		KAR0105
291	Unnamed trench	Goose Lake	Unknown	Ag	Au			45	7	24	109	54	14		KAR0127
292	Unnamed occurrence	Goose Lake	Unknown	Cu	Ag	Au		45	5	28	109	54	21	Sulfide minerals in quartz lens xenolith in granite	J000146
293	Unnamed occurrence	Goose Lake	Unknown	Ag	Au			45	7	22	109	54	54		KAR0131
294	Little Iomie	Goose Lake	Unknown	Ag	Au			45	7	16	109	54	44	Basalt dike	KAR0177
295	Green Lake prospect	Goose Lake	Unknown	Ag	Au			45	5	43	109	54	7	Shear zone in mica schist	KAR0183
296	Lake View	Goose Lake	Unknown	Au	Ag			45	7	30	109	54	34		KAR0122
297	Georgia	Goose Lake	Syenite-hosted segregation	Ag	Au			45	7	3	109	54	8	Fe-stained syenite porphyry float	KAR0188
298	Unnamed trench	Goose Lake	Unknown	Ag	Cu			45	7	20	109	54	33		KAR0162
299	Unnamed trenches (2)	Goose Lake	Unknown	Ag	Au			45	7	23	109	54	39		KAR0119
300	Lonesome Pine	Goose Lake	Unknown	Ag	Au			45	7	54	109	54	57	Brecciated quartz body with yellow ochre	KAR0175
301	Unnamed pit/trench	Goose Lake	Unknown	Ag	Cu	Au		45	5	40	109	54	41		KAR0192
302	Unnamed occurrence	Goose Lake	Unknown	Ag	Au			45	7	43	109	54	22		KAR0191
303	Copper Idol	Goose Lake	Unknown	Ag	Au			45	6	41	109	54	34	Sulfidized shear in granite	KAR0143
304	Unnamed pit	Goose Lake	Unknown	Au	Ag			45	5	39	109	54	50		KAR0172
305	Copper Index	Goose Lake	Syenite-hosted segregation	Cu				45	8	11	109	54	37	Chalcopyrite in feldspar gangue in syenite	KAR0111
306	Unnamed trench	Goose Lake	Unknown	Ag	Au			45	7	16	109	54	40		KAR0114

307	Unnamed trench	Goose Lake	Unknown	Ag	Au			45	6	44	109	54	24		KAR0150		
308	Unnamed	Goose Lake	Unknown	Ag	Au			45	7	37	109	54	4		KAR0158		
309	Urns	Goose Lake	Syenite-hosted segregation	Ag	Au			45	7	16	109	54	12	Shear in syenite porphyry	KAR0136		
310	Unnamed trench	Goose Lake	Unknown	Ag	Au			45	7	16	109	54	35		KAR0126		
311	Unnamed caved shaft	Goose Lake	Unknown	Ag	Au			45	7	22	109	54	33		KAR0160		
312	Dora Quartz	Goose Lake	Unknown	Ag	Au			45	6	38	109	54	14	Shear zone along contact between granite and mafic rock	KAR0134		
313	Black Rock	Goose Lake	Syenite-hosted segregation	Ag	Au			45	7	4	109	54	13	Shear zone in syenite porphyry	KAR0118		
314	Unnamed trench	Goose Lake	Unknown	Ag	Au			45	6	21	109	54	23		KAR0148		
315	Unnamed adit	Goose Lake	Unknown	Ag	Au			45	7	8	109	54	1		KAR0116		
316	Unnamed pit	Goose Lake	Unknown	Ag	Au			45	5	52	109	54	33		KAR0176		
317	Kerr-McGee Pot Nos. 4-8	Goose Lake	Unknown	Ag	Au			45	7	10	109	54	56		KAR0142		
318	Unnamed trenches (2)	Goose Lake	Unknown	Ag	Au			45	7	27	109	54	7		KAR0166		
319	Unnamed trench	Goose Lake	Unknown	Ag	Au			45	7	20	109	54	36		KAR0186		
320	Jupiter-Talisman	Goose Lake	Syenite-hosted segregation	Ag	Au			45	7	20	109	54	18	Shear zones in syenite; quartz breccia	J000149		
321	Unnamed caved adit	Goose Lake	Unknown	Ag	Au			45	6	35	109	54	45		KAR0130		
322	White Quartz	Goose Lake	Unknown	Ag	Au			45	6	56	109	54	14	Trace gold and silver in syenite with amphibolite xenoliths	KAR0128		
323	Unnamed pit	Goose Lake	Unknown	Ag	Au			45	6	46	109	54	22		KAR0167		
324	Unnamed trench	Goose Lake	Unknown	Ag	Ch	Au		45	5	40	109	54	39		KAR0174		
325	Unnamed	Goose Lake	Unknown	Ag	Au			45	7	31	109	54	29		KAR0140		
326	Copper King claim	Goose Lake	Syenite-hosted segregation	Cu	Au	Ag	Pt	Pd	Rh	45	7	23	109	54	23	Vein associated with Precambrian hornblende gabbro dike	M045434
327	Copper Queen	Goose Lake	Syenite-hosted segregation	Cu	Ag	Au				45	7	20	109	54	30	Quartz veinlets in iron-stained syenite	KAR0180
328	McBride	Goose Lake	Syenite-hosted segregation	Ag	Ch	Au				45	7	37	109	54	41	Shear zone in syenite	KAR0138

329	Heceta-Flora	Goose Lake	Syenite-hosted segregation	Cu				45	8	11	109	\$4	37	Chalcopyrite, galena and limonite in sheared zone in syenite and granodiorite	KAR0173	
330	Unnamed	Goose Lake	Unknown	Ag	Au			45	7	11	109	\$4	47		KAR0164	
331	Occurrence	Goose Lake	Unknown	Ag	Au			45	5	27	109	\$4	48		KAR0181	
332	Unnamed	Goose Lake	Unknown	Ag	Au			45	6	32	109	\$4	47		KAR0141	
333	OBW	Goose Lake	Unknown	Ag	Au			45	6	37	109	\$4	35	Shear zone in granite	KAR0137	
334	Unnamed	Goose Lake	Unknown	Ag	Au	Cr		45	7	32	109	\$4	41		KAR0155	
335	Unnamed pit	Goose Lake	Unknown	Ag	Au			45	6	12	109	\$4	24		KAR0163	
336	Goose Lake area	Goose Lake	Unknown	Cu	Ag			45	8	11	109	\$4	37		J000032	
337	Unnamed	Goose Lake	Unknown	Ag	Au			45	7	28	109	\$4	44		KAR0117	
338	Cahuet	Goose Lake	Syenite-hosted segregation	Ag	Ch	Au		45	7	31	109	\$4	2	Sulfide in sheared syenite porphyry; gabro	KAR0169	
339	Unnamed	Goose Lake	Unknown	Ag	Ti	Au		45	7	50	109	\$4	2	Disseminated sulfide minerals in shear zone in gabro	KAR0110	
340	Copper Sentinel	Goose Lake	Syenite-hosted segregation	Ag	Au			45	6	56	109	\$4	31	Sulfides in syenite in stockpile	KAR0161	
341	Uranium Homestead	Goose Lake	Unknown	Ag	Au			45	6	29	109	\$4	53	Shear in quartz monzonite and amphibolite	KAR0156	
342	Unnamed	Goose Lake	Unknown	Ag	Au			45	6	60	109	\$4	18		KAR0165	
343	George	Goose Lake	Unknown	Ag	Ch	Au		45	7	37	109	\$4	13	Sulfide minerals at contact of a mafic dike	KAR0171	
344	Lorraine	Goose Lake	Syenite-hosted segregation	Ag	Au			45	6	48	109	\$4	7	Vertical shear in diabase in syenite	KAR0132	
345	Unnamed	Goose Lake	Unknown	Ag	Au			45	7	33	109	\$3	45		KAR0125	
346	Unnamed	Goose Lake	Unknown	Ag	Au			45	8	22	109	\$3	26		J000150	
347	Giant Extension	Goose Lake	Unknown	Ag	Ti	Au		45	7	31	109	\$3	57		KAR0184	
348	Unnamed	Goose Lake	Unknown	Ag	Ch	Au		45	7	48	109	\$3	59		KAR0115	
349	Unnamed	Goose Lake	Unknown	Ag	Au			45	8	5	109	\$3	28		KAR0109	
350	East Green Lake	Goose Lake	Unknown	Au	Ag	Ch	Pb	V	45	5	48	109	\$3	42	Shear zone in granitic gneiss	KAR0106

351	Unnamed	Goose Lake	Unknown	Ag	Au			45	7	36	109	53	41	Sulfide minerals in a shear that cuts granite	J000151		
352	Great Eastern Lake prospect	Goose Lake	Unknown	Au	Ag	Cu	Pb	V		45	5	48	109	53	42	Shear zone in granitic gneiss	KAR0170
353	Giant	Goose Lake	Unknown	Ag	Ti	Au			45	7	29	109	53	50		KAR0102	
354	Occurrence	Goose Lake	Unknown	Ag	Au				45	8	22	109	53	26		J000152	
355	Hercules	Goose Lake	Unknown	Ag	Au				45	7	22	109	53	51	Granitic gneiss and gabbro float; no mineralized structure apparent	KAR0144	
356	Hecta	Goose Lake	Unknown	Ag	Au				45	7	55	109	52	36	Quartz crystals in veins in iron-stained, sheared gabbro	KAR0182	
357	Copper King mine	Goose Lake	Syenite-hosted segregation	P	Cu	Ag	Au	Pt	45	7	26	109	54	26		KAR0108	
358	Jim Hawkes	Independence	Unknown	Ag	Cu				45	17	1	109	56	46	Shear zone in granitic gneiss; mafic rocks and pegmatite dikes	KAR0071	
359	Ray & Al Rudd property	Independence	Uranium occurrence	U					45	14	46	110	19	24		DC08784	
360	Falcon	Independence	Unknown	Au	Ag				45	14	6	110	16	8	Limonite-stained zones at contact of limestone overlying columnar basalt.	KAR0074	
361	Black Diamond	Independence	Skarn	Cu	Fe	Mo	P	Au	Ag	45	15	34	110	16	39	Gold-bearing pyrrhotite in quartz-magnetic garnet in limestone contact zone	DC08772
362	Charity	Independence	Unknown	Ag						45	15	3	110	16	25	Major strike fault between limestone-shale and argillized granite	KAR0089
363	Shawn Marie	Independence	Unknown	Au	Ag	Cu	Pb	Mo	45	17	7	110	16	9	Galena, pyrite, and chalcopyrite in quartz fissure between metasedimentary rocks and a mafic dike	KAR0086	
364	Raymond Rudd No. 2	Independence	Uranium occurrence	U						45	14	48	110	16	9	Uranium reported at contact between schist and silicified granite	KAR0083
365	Henke-Beer placer	Independence	Gold placer	Au						45	12	4	110	16	33	Reported gold placers deposit; no record of production	J000073
366	Arnit No. 5 claim	Independence	Unknown	Au	Ag					45	15	2	110	15	10	Gold-bearing carbonate gossan in fractures at contact between Precambrian schist and Tertiary or Cretaceous intrusive rock	KAR0094
367	Holy Terror	Independence	Unknown	Ag						45	14	31	110	15	39	Pyrite in shears in creek bank	KAR0073
368	Basin Creek	Independence	PM vein/ dissemination	Au						45	14	10	110	15	40	Sulfide minerals in dacite and porphyries of Independence stock	J000053

369	Cabin	Independence	Unknown	Ag				45	17	2	110	15	42	Quartz-cemented shear and veins in gneiss	KAR0084			
370	South Fork No. 1	Independence	Unknown	Ag				45	12	27	110	15	21	Disseminated pyrite in granite at granite-latite contact.	KAR0092			
371	Red Fox mine	Independence	Unknown	P	Au	Ag	Fe				45	27	52	110	15	12	Pyrite, pyrrhotite, and arsenopyrite in siliceous gneiss along shear zone in hornfels	DC08749
372	Blakely	Independence	Unknown	Ag							45	12	14	110	15	34	Prospect pit in argillized rock	KAR0093
373	Four Sevens claim	Independence	Polymeric vein	Pb	Ag	Zn					45	12	37	110	15	36	Vein	DC08788
374	Mansion No. 1 Lode	Independence	Gold placer	Au							45	22	8	110	14	2	Placer	FS00339
375	Bridge Placer	Independence	Gold placer	Au							45	17	16	110	14	15	Placer	FS00399
376	Gent No. 59	Independence	Unknown	Ag							45	14	35	110	14	36	Argillized dacite near contact with granitic gneiss	KAR0085
377	Skylark	Independence	Polymeric vein	Ag	Pb	Zn					45	13	3	110	13	15	Underground workings	J000027
378	Bench	Independence	Unknown	Ag							45	13	31	110	13	36	Prospect pits in iron stained quartz monzonite	KAR0087
379	Independence mine	Independence	PM vein/ dissemination	P	Au	Ag					45	13	15	110	13	5	Vein in andesite	DC08173
380	North Star	Independence	Unknown	Ag	Cr	Pb					45	13	4	110	13	21	Alteration along granodiorite-andesite contact	J000026
381	Tam and Zana	Independence	Unknown	Ag							45	13	36	110	13	11	Pyrite in quartz veins and gossan in altered quartz monzonite	KAR0088
382	Placer	Independence	Unknown	Au	Ag						45	13	11	110	13	3		J000025
383	Ski Line Mine	Independence	Polymeric vein	P	Au	Ag	Pb				45	14	29	110	13	24	Shear zone at shale/gneiss contact	KAR0075
384	Independence "A"	Independence	Unknown	Ag	Au						45	12	58	110	13	30		J000153
385	Midnight Bell	Independence	Unknown	Au	Ag						45	12	58	110	12	58	Underground workings	J000018
386	Daisy mine	Independence	PM vein/ dissemination	P	Au						45	13	0	110	12	30	Vein in granodiorite of Independence stock	DC08789
387	Liliput	Independence	Polymeric vein	Pb	Zn						45	12	34	110	12	26	Altered quartz monzonite	KAR0095
388	Major Pease	Independence	PM vein/ dissemination	Au	Ag						45	12	16	110	12	40	Magnetite and sulfide minerals in quartz monzonite	KAR0077
389	Brilliant	Independence	Unknown	Au	Pb						45	12	37	110	12	35		J000023
390	Springfield	Independence	Unknown	Ag							45	13	18	110	12	48	Underground workings	J000024

391	Hidden Treasure mine	Independence	PM vein/ dissemination	P	Au	Ag				45	13	0	110	12	30	Argillic and sericitic alteration in Independence stock	DC08790
392	King William	Independence	PM vein/ dissemination	Au	Ag					45	12	39	110	12	10	Sulfide minerals in fault zone in altered quartz monzonite	KAR0078
393	Harvey	Independence	PM vein/ dissemination	Ag	Au					45	12	46	110	12	31	Shear zone in quartz monzonite	KAR0076
394	Cody	Independence	Unknown	Au	Ag	As	Pb			45	12	26	110	12	26	Disseminated sulfide minerals in shear zones in altered monzonite	KAR0091
395	G.S.	Independence	PM vein/ dissemination	Au	Ag					45	12	42	110	12	21	Disseminated pyrite in joined quartz monzonite	KAR0096
396	Accident	Independence	Unknown	Au	Ag					45	12	51	110	12	58		J000014
397	Boulder River Ni-Cu (Riverside)	Independence	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	28	23	110	11	56	Pyrite-pyrrhotite vein in basal zone of Stillwater Complex P	M060099
398	Diadem	Independence	Unknown	Au						45	12	54	110	12	26	Iron oxides in monzonite	KAR0082
399	Half Moon mine	Independence	Polymeric vein	Au	Ag	Pb				45	12	58	110	11	55	Vein	DC08786
400	Ida B	Independence	Unknown	Ag						45	12	42	110	11	30	Fault zone in monzonite	KAR0080
401	Clara	Independence	PM vein/ dissemination	Ag						45	12	27	110	11	47	Disseminated sulfide minerals in altered quartz monzonite	KAR0098
402	Wheelon	Independence	Unknown	Au	Ag					45	12	39	110	11	37	NW-trending fault zone in monzonite	KAR0099
403	Cumberland	Independence	Unknown	Ag						45	12	56	110	11	40	Fault zone in monzonite	KAR0081
404	Dixie	Independence	Unknown	Ag						45	12	39	110	11	33	Fault zone in altered monzonite	KAR0100
405	Skyline prospect	Independence	Polymeric vein	Pb	Ag	Au				45	14	15	110	10	35	Contact fracture zone	DC08172
406	Rainbow	Independence	Unknown	Au	Ag					45	16	10	110	7	48	Pegmatite dikes in granite	D004299
407	East Rainbow	Independence	Unknown	Au	Ag					45	16	44	110	7	29	Vein/shear zone	D004317
408	Unnamed prospects	Independence	Unknown	Au	Ag					45	9	23	110	5	9		J000154
409	Occurrence	Stillwater	Unknown	Mo	Bi					45	25	22	110	17	21		J000155
410	Skillman mine	Stillwater	Unknown	P	Au	Ag				45	27	32	110	16	1		KAR0033
411	Standard mine	Stillwater	Unknown	P	Au	Ag	Cu			45	29	27	110	14	16	Quartz-filled fissure in hornfels	KAR0038
412	Niccon	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	29	9	110	13	21	Location near the collar of BR-1	KAR0032
413	Majestic & Flora B claims	Stillwater	Picket Pin	Pt	Pd	Cu	Ni			45	30	32	110	12	50		KAR0030

414	Iron Dike	Stillwater	Algoma/Superior iron	Fe				45	28	33	110	12	11	Deposit exposed in roadcut	J000099	
415	Grish mine	Stillwater	Bushveld Cr	P	Cr	PGE		45	28	39	110	12	8		M000988	
416	Sky Baby chains	Stillwater	Unknown	Au	Ag			45	27	53	110	11	30		KAR0037	
417	Coors 602	Stillwater	Discordant PGE	Pt	Pd	Cr	Ni	45	26	4	110	5	29		J000156	
418	laser 50	Stillwater	Discordant PGE	Pt	Pd	Cr	Ni	45	25	3	110	2	55		MP00096	
419	Alaskite	Stillwater	Other PGE	Pt	Pd	Cr	Cu	45	26	18	110	2	55		J000157	
420	Pine claim	Stillwater	Shear-zone Au	Au	Cr			45	26	26	110	8	54		J000158	
421	Boulder River Ni-Cu (east)	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	26	37	110	9	30	Location near the collar of BR-2
422	Boulder-Forge Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	26	2	110	7	18	Generalized location
423	Iron Mountain Ni-Cu (Iron Creek)	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	24	26	110	2	45	Generalized location
424	Crescent Peak Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	23	37	110	1	57	Generalized location
425	Crescent Creek Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	23	9	110	1	10	Generalized location
426	Bluebird Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	23	6	109	58	0	Generalized location
427	Monat Ni-Cu (Verdigrips Creek)	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	22	48	109	53	44	Generalized location in the exposures of mineralization N of Verdigrips Cr.
428	Monat Ni-Cu (south)	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	22	37	109	53	57	Generalized location
429	Nye Basin Ni-Cu (lip)	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	22	44	109	51	8	Generalized location
430	Nye Basin Ni-Cu (east)	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	22	27	109	50	5	Portal of Nye Basin adit
431	Bonbow Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	21	37	109	48	49	Generalized location
432	Chrome lake Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	21	6	109	47	48	Generalized location
433	Fishtail Creek Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cu	Co	PGE	Ag	Au	45	20	25	109	45	25	Approximate location of portal of Fishtail adit
434	Stillwater River	Stillwater	Gold placer							45	5	1	109	59	27	Placer

435	Bluebird	Stillwater	Bushveld Cr	Cr	PGE			45	23	19	109	57	41	Generalized location on G chromitite	M060093			
436	Mount-Sampson Mine	Stillwater	Bushveld Cr	P	Cr	PGE		45	23	15	109	54	21	No. 5 portal	M06000			
437	Initial Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni	45	23	12	109	56	44	Generalized location	M700432			
438	Unnamed copper mine	Stillwater	Unknown	Cr				45	29	13	109	56	29		KAR061			
439	Initial Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cr	Co	PGE	Ag	Au	45	23	9	109	56	53	Generalized location	M060098	
440	Hawkes lode	Stillwater	Unknown	Au	Ag					45	20	29	109	55	38	Sulfide minerals in quartz veins along shear zone in hornblende-biotite granite	KAR059	
441	Stillwater Mine	Stillwater	Merensky Reef PGE	A	Pt	Pd	Rh	Au	Cu	Ni	45	23	20	109	52	16	5000 portal of Stillwater mine on west side of Stillwater River	MP00087
442	Tecate	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	29	41	110	14	5	Generalized location		
443	Boulder west	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	29	14	110	12	3	Generalized location		
444	Boulder east	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	28	16	110	10	7	Generalized location		
445	Frog Pond west (~adit)	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	27	16	110	8	18	Generalized location	MP000101	
446	Frog Pond east	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	26	50	110	6	28	Generalized location		
447	Monkey west	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	25	55	110	4	34	Generalized location		
448	Monkey east (~Camp zone)	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	25	6	110	2	46	Generalized location	MP000103	
449	West Fork west	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	24	16	110	0	22	Generalized location		
450	West Fork east (adit)	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	23	56	109	58	5	West Fork adit	MP000102	
451	Dow	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	23	34	109	56	25	Generalized location		
452	Blitz	Stillwater	Merensky Reef PGE	Pt	Pd	Rh	Au	Cu	Ni	45	22	11	109	47	23	Generalized location		
453	Nye Basin (1ip)	Stillwater	Bushveld Cr	Cr	PGE						45	22	51	109	51	27	Generalized location	M060086
454	Nye Basin (Alice) Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni				45	22	54	109	50	50	Generalized location	M060095

455	Crescent Creek Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	23	15	110	1	24	Generalized location	MP00112	
456	West Fork Cr-Pt (Tuttle)	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	22	54	110	0	34	Generalized location		
457	Bluebird Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	23	9	109	57	52	Generalized location		
458	Mountain View Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	22	56	109	53	57	Generalized location		
459	Nye Basin Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	22	11	109	49	20	Generalized location		
460	Benbow Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	21	46	109	48	59	Generalized location		
461	Chrome Lake Cr-Pt	Stillwater	PGE chromitite	Pt	Cr	Cr	Ni		45	21	9	109	47	44	Generalized location		
462	Nye Basin (Big Seven)	Stillwater	Bushveld Cr	Cr	PGE				45	22	22	109	49	9	Generalized location	MO0096	
463	Benbow mine	Stillwater	Bushveld Cr	P	Cr	PGE			45	21	52	109	48	22	Benbow shaft	MO0101	
464	Little Rocky Creek Ni-Cu	Stillwater	Stillwater Ni-Cu	Ni	Cr	Co	PGE	Ag	Au	45	21	26	109	48	17	Generalized location of adit near Little Rocky Creek	MO0097
465	Blakely Cliffs	Stillwater	Bushveld Cr	Cr	PGE				45	27	24	110	10	3	Generalized location	M700434	
466	Montana Asbestos Co.	Stillwater	Serpentine-hosted asbestos	asb					45	21	29	110	10	25		KAR0070	
467	East Boulder Plateau	Stillwater	Bushveld Cr	Cr	PGE				45	26	27	110	7	41		MO0092	
468	Big Group (Chrome Mountain)	Stillwater	Algoma/Superior iron	Fe					45	25	36	110	7	44	Generalized location	J000012	
469	Big Group (Iron Mountain)	Stillwater	Algoma/Superior iron	Fe					45	24	12	110	3	44	Generalized location		
470	Big Group (East Boulder)	Stillwater	Algoma/Superior iron	Fe					45	25	1	110	4	55	Generalized location		
471	East Boulder River - Chrome Queen	Stillwater	Bushveld Cr	Cr	PGE				45	25	39	110	6	10	Generalized location for chromite on Chrome Queen No. 9 claim; near USBM trench	MO0091	
472	Iron Mountain Ni-Cu (Camp)	Stillwater	Stillwater Ni-Cu	Ni	Cr	Co	PGE	Ag	Au	45	24	30	110	4	29	Generalized location	MP00079
473	Picket Pin	Stillwater	Picket Pin	Pt	Pd	Cr	Ni		45	26	58	110	3	1	Generalized location	MP00090	
474	Iron Mountain - Chrome Group (W)	Stillwater	Bushveld Cr	Cr	PGE				45	24	28	110	3	2	Generalized location; near trench 275	M700423	

475	Iron Mountain - Chrome Group (E)	Stillwater	Bushy Cr	Cr	PGE			45	23	49	110	2	0	Generalized location for chromitite on Chrome D claim; near survey point "Carl"
476	West Fork G (Taylor-Fry)	Stillwater	Bushy Cr	Cr	PGE			45	22	57	110	0	16	Generalized location on G chromitite
477	Pyramid Mountain group	Plateau	Unknown	Au	Ag			45	16	1	109	45	57	Talus claims in granitic gneiss, serpentinite, chlorite asbestos
478	Rosebud, Tamm y, join	Plateau	Serpentine-hosted asbestos	asb				45	15	5	109	28	0	Shear zone, serpentinite
479	Fishtail Creek Mine	Plateau	Unknown	Cu				45	22	15	109	41	22	
480	Rosebud	Plateau	Pegmatite	Mo				45	15	57	109	39	13	Drilled molybdenum prospect in pegmatite in Archean schist
481	Penda asbestos pros.	Plateau	Serpentine-hosted asbestos	asb				45	12	9	109	37	57	Mineral locality
482	Lake Mary	Plateau	Unknown	Au	Ag			45	9	24	109	33	54	Iron-stained, chloritized brecciated granite in fault
483	Elk claims	Red Lodge	Polymetallic vein	Cu	Zn	Pb	U	45	4	57	109	14	16	Vents near granitic/Flathead Sandstone contact
484	Gallon Jug No. 1	Red Lodge	Red Lodge Cr	Cr				45	1	53	109	28	12	Serpentinized peridotite
485	Gallon Jug No. 4	Red Lodge	Red Lodge Cr	Cr				45	1	17	109	28	17	Serpentinized peridotite
486	Gallon Jug No. 2	Red Lodge	Red Lodge Cr	Cr				45	2	6	109	27	57	Serpentinized peridotite
487	Bluebird No. 2 claim	Red Lodge	Red Lodge Cr	Cr				45	2	34	109	27	7	
488	Drill and Gallow Jug	Red Lodge	Red Lodge Cr	Cr				45	2	24	109	27	12	Serpentinite
489	Occurrence	Red Lodge	Uranium occurrence	U				45	10	11	109	26	3	Stratabound
490	Shovel	Red Lodge	Red Lodge Cr	Cr	Cu			45	2	32	109	26	40	Chromite lens in serpentinite; quartz stars
491	Pick	Red Lodge	Red Lodge Cr	Cr				45	2	41	109	26	25	Chromite lens at serpentinite-porphphy dike contact
492	Uranium occurrence	Red Lodge	Uranium occurrence	U				45	10	11	109	26	3	
493	North Star No. 1 claim	Red Lodge	Red Lodge Cr	Cr				45	2	12	109	26	52	Chromite lenses in serpentinite

494	Little Nell deposit	Red Lodge	Red Lodge Cr	Cr				45	5	18	109	25	54	Chromite with talc, actinolite, and tremolite pods in serpentinite	KAR0239
495	Occurrence	Red Lodge	Uranium occurrence	U				45	10	25	109	25	55		J000186
496	Highline Group	Red Lodge	Red Lodge Cr	Cr				45	2	2	109	24	34		J000001
497	Four Chromes group	Red Lodge	Red Lodge Cr	Cr				45	5	45	109	23	46	Serpentinite in granite cut by faults & dikes	KAR0236
498	Vijak Quartz lode	Red Lodge	Unknown	Cr	Au	Ag		45	8	41	109	22	1		J000064
499	Silver Run	Red Lodge	Unknown	Au	Ag			45	7	26	109	22	34	Amphibolite on dump	KAR0227
500	Edsel claim	Red Lodge	Red Lodge Cr	Cr				45	5	31	109	22	34	Serpentized peridotite	KAR0229
501	Ingle Creek	Red Lodge	Unknown	Au	Ag			45	7	49	109	22	35	Diabase dike	KAR0232
502	Wapiti Mountain group	Red Lodge	Unknown	Ag	Au			45	6	38	109	21	3	Chlorite, magnetite, and malachite in quartz veins hornblende granite	KAR0233
503	Thom property	Red Lodge	Uranium occurrence	U	REE			45	11	9	109	19	0	Monazite and uranocircite in vein in gneissic layer near granite contact	DC08794
504	Occurrence	Red Lodge	Uranium occurrence	U				45	10	25	109	19	51		J000187
505	Occurrence	Red Lodge	Uranium occurrence	U				45	10	14	109	19	42	Stratabound	J000188
506	Unnamed occurrence	Red Lodge	Uranium occurrence	U				45	10	14	109	19	42		DC08793
507	Weaver property	Red Lodge	Uranium occurrence	U				45	9	21	109	17	13	Vein or related deposit	DC08820
508	Unnamed occurrence	Red Lodge	Uranium occurrence	U				45	5	11	109	15	56		J000189
509	Unnamed occurrence	Red Lodge	Uranium occurrence	U				45	5	7	109	15	55	Stratabound	DC08821
510	Royse claim	Red Lodge	Uranium occurrence	U				45	5	7	109	14	41	Vein	DC08822

CHAPTER F

MINERAL RESOURCE APPRAISAL FOR LOCATABLE MINERALS: THE STILLWATER COMPLEX

By Michael L. Zientek

SUMMARY

A mineral resource appraisal for locatable minerals in the Stillwater Complex, a mafic- to ultramafic layered igneous intrusion located along the northern margin of the Beartooth uplift, indicates significant resources are present in undefined and fault offset extensions of known prospects and deposits. Undiscovered deposits of copper, nickel, chromium, and platinum-group elements are likely to be present in the Stillwater Complex. The method for the assessment involved: (1) defining the types of mineralization (deposit types) appropriate for the Stillwater Complex and delineating terranes within the complex that are geologically permissive for their occurrence, (2) collecting and summarizing information about grade and tonnage for each deposit type for comparative purpose, (3) evaluating the results of exploration activity within each geologically permissive tract and indicating areas favorable for mineral occurrences and deposits, and (4) estimating the quantity of mineralized rock that may be present in extensions of identified mineral deposits and undiscovered deposits. Numerical simulation of undiscovered deposits (as used in Chapter G) was not done because there are no tonnage-grade distributions for the mineral deposit types found in the Stillwater Complex. The quantity of mineralized rock that may be present in some areas was limited by geologic constraints. The results are summarized below by deposit type.

STILLWATER NICKEL-COPPER

Disseminated to massive copper-nickel sulfide mineral deposits are found near the base of the Stillwater Complex. Exploration by a number of companies determined that sulfide mineralization is

widely distributed in rocks near the base of the complex and identified large tonnage, low-grade resources. Some of the deposits are found in the upper plate of thrust faults near the base of the complex. Sulfide mineralization in the Basal series was prospected along the strike length of the complex; sulfide mineralization in the Peridotite zone was sought intentionally in the Iron Mountain and Chrome Mountain areas. Favorable areas for mineral deposits include the Basal series in the eastern part of the complex and the Peridotite zone and Basal series from the East Boulder River to Crescent Creek. Only the Mouat nickel-copper and Camp deposits are explored adequately to allow estimates of contained resources; exploration work elsewhere incompletely determined the quantity and quality of mineral resources. Most undefined resources are in extensions of known prospects in the Basal series (1.2 million metric tons of nickel and 1.2 million metric tons of copper); potential for similar undiscovered mineral deposits exists in the lower plate of thrust faults in the Nye Basin and Mountain View areas (0.23 million metric tons of nickel and 0.23 million metric tons of copper). Undiscovered mineralization in the Peridotite zone similar to the Camp deposit may be present in the complexly faulted area near Iron Mountain but no estimate of the resource is possible.

The grade of nickel-copper mineralization in the Basal series and Peridotite zone is below what is currently considered to be economic; laterally continuous domains of higher-grade mineralization within these deposits were not identified. This mineralization also contains cobalt and platinum-group elements (PGE) but not in concentrations that substantially add to its value. The sulfide mineralization is pyrrhotite-rich and difficult to treat metallurgically.

No development beyond assessment work is anticipated in the foreseeable future; however, this mineralization represents a substantial resource that

may be of interest when higher grade ores elsewhere are depleted.

MERENSKY REEF PGE

For this mineral deposit type, there are only two examples of economic deposits: the Merensky Reef in the Republic of South Africa and the J-M Reef of the Stillwater Complex. The J-M Reef is a thin, laterally-persistent, stratigraphically-confined interval of PGE-enriched disseminated sulfide mineralization. The mineralization that comprises the reef is in the Lower Banded series and can be traced the length of the Stillwater Complex. The deposit is being mined near the Stillwater River valley (Stillwater mine) and a second mine (East Boulder project) is proposed. The mineralized interval is not defined over the vertical extent over which it will be technically feasible to mine the deposit; resource estimates for extensions of this deposit (2.4 million metric tons of palladium and 0.7 million metric tons of platinum) are much larger than published reserve data.

Based on geologic considerations alone, three tracts can be defined where the occurrence of Merensky Reef PGE-type deposits is permissive. Tract A, the stratigraphically lowest, includes rocks that are stratigraphically like those that host the Merensky Reef and prospects in Zimbabwe and Western Australia. Most of the PGE-related exploration activity focused on this tract and led to the discovery of the J-M Reef. The J-M Reef was found by geochemical surveys conducted both on contour traverses and on systematic grids that extended over the permissive tract. Although the reef is typically about three feet thick, soil geochemical anomalies that define the trace of the reef form linear clusters that can be dispersed several hundred feet away from it. Undiscovered reef-type deposits would be expected to produce anomalies similar to those for the J-M Reef. The soil sampling located several discontinuous zones of mineralization below the J-M Reef but did not show any linear clusters of anomalies that would give evidence for other undiscovered, laterally continuous reef-type deposits. Because the geochemical anomaly associated with the J-M Reef is spread over a large stratigraphic interval relative to the thickness of a typical reef-type deposit, additional, undiscovered reef-type deposits could possibly be found near the J-M Reef and not be resolved by soil geochemical anomalies. However, drilling to evaluate the J-M Reef covered the intervals close to the reef and did not locate continuous reef-type mineralization. The

probability that a reef-type deposit remains undiscovered in the tract that contains the J-M Reef is low (less than 1 in 1,000?).

Exploration activity in the two other tracts in which reef-type mineralization is permissive is limited and does not exclude or suggest the presence of undiscovered deposits. The geologic features of these tracts, the few analyses that are available, and the scarcity of this deposit type suggest that the probability of undiscovered deposits is still low (less than 1 in 100?).

SULFIDE AND PGE CONCENTRATIONS OCCURRING AT OR BELOW IMPERMEABLE LAYERS

Concentrations of disseminated, PGE-enriched sulfide minerals may be localized beneath layers that act as a barrier to the migration of interstitial liquids during consolidation of layered mafic and ultramafic rocks; however, no economic mineral deposits are known that formed as a result of this mineralizing process. The occurrence of this type of mineralization is possible anywhere in the complex. In particular, the intervals near the top of thick, massive sections of anorthosite in the Middle Banded series and intervals beneath chromite seams in the Peridotite zone have features expected in zones of impeded melt migration. The PGE-enriched sulfide mineralization of the Picket Pin "deposit" near the top of the complex is an example of this style of mineralization. Grades are too low and the distribution of sulfide minerals too discontinuous for this mineralization to be considered a deposit; no resource estimates were made. Higher metal prices may result in attempts to locate locally continuous volumes of sulfide mineralization in the Picket Pin zone and prompt exploration elsewhere.

PEGMATOIDAL LENSES, PIPES, AND OTHER DISCORDANT MINERALIZATION

PGE-enriched magmatic sulfide minerals have been found in lens-like to discordant mafic pegmatoids in the upper part of the Bronzitite zone and the lower part of Lower Banded series. Many examples of sulfide-bearing mafic pegmatoids are recognized in the complex but those that are PGE-enriched appear to be clustered in the area from Lost Mountain to north of Iron Mountain. Although grades similar to the J-M Reef have been reported for samples from some occurrences, known bodies are too

small and overall grade is too low to be of economic interest; no resource estimates were made. Changes in land position may stimulate new investigations of these bodies with the expectation of locating bodies large enough to warrant exploitation.

BUSHVELD CHROMIUM

Layers with high proportions of chromite are found in the Peridotite zone of the Ultramafic series, the Basal series, and locally within the Lower Banded series. Only the chromite-enriched layers in the Peridotite zone in the Mountain View, Nye Basin, Benbow, and Gish areas have the continuity, thickness, and grade to be of economic interest. Deposits in the Mountain View, Nye Basin, and Gish area are located in the upper plate of thrust faults near the base of the complex. Undefined resources may be found in extensions of known deposits, principally in the Benbow area (4 million metric tons Cr₂O₃); undiscovered resources that may exceed those in the Benbow area may be found in the lower plate of thrust faults in the Nye Basin and Mountain View areas (6.5 million metric tons Cr₂O₃). The chromite mineralization is similar to, but lower grade than, high-iron or chemical grade ores mined elsewhere. If a low cost method for ferrochrome production is devised, the chromite seams will become the focus for additional development activity. Otherwise, minimal exploration work is anticipated.

PGE-ENRICHED STRATIFORM CHROMITITES

Some of the chromite seams in the Peridotite zone are enriched in PGE. Exploration work has focused on chromite seams lowest in the Peridotite zone in the eastern part of the Stillwater Complex, particularly those in the exposures north of the West Fork of the Stillwater River and east of Crescent Creek. Although platinum, palladium, and rhodium are significantly enriched in these chromite seams, the grade is substantially less than deposits that are currently being mined in South Africa and less than other chromite seams that are currently considered to be uneconomic. No resource estimates for extensions to known prospects or undiscovered deposits was made. The potential to find other PGE-enriched chromite seams has not been eliminated by exploration work. Systematic geochemical surveys of all chromite seams have not been conducted; anomalous PGE concentrations determined for poorly located

chromite-enriched samples in the western part of the complex indicate PGE-enriched chromitites are not restricted to the eastern part of the complex. Samples selected in reconnaissance surveys typically were massive chromitite; subsequent investigations of mineralized seams show that elevated PGE concentrations are not simply related to any macroscopic feature observed in the field, not uniformly distributed in a seam, and not restricted to chromite-enriched rocks. Since few of the chromite seams in the Stillwater Complex have been adequately tested, changes in land position or an increase in metal prices could result in increased exploration activity.

INTRODUCTION

This section summarizes the mineral resources associated with the Stillwater Complex, places limits on extensions to identified resources and undiscovered resources, and indicates where future exploration and development activity may take place. Previously, the mineral resource potential of the Stillwater Complex and adjacent rocks was considered by Page and Dohrenwend (1973) and Curtiss and others (1990). This section focuses on the mineral resource potential of the Stillwater Complex, particularly for mineralization that may contain copper, nickel, chromium, PGE, and gold. Aluminum was not considered; interested readers are referred to the summary in Page and Dohrenwend (1973). Rocks adjacent to the complex are considered in Chapter G.

In Chapter G, quantitative estimates for undiscovered resources are determined utilizing a three-part form of assessment (Singer and Cox, 1988) which involves: (1) delineating tracts permissive for the occurrence of a one or more deposit types, (2) construction of grade-tonnage models for deposit types of interest, and (3) estimation of the number of undiscovered deposits. Grades, tonnages, and estimated numbers of undiscovered deposits are combined in a numerical simulation to estimate the amounts of undiscovered resources (Root and others, 1992). Numerical simulation of undiscovered resources is not possible for the complex because rigorous grade and tonnage curves are not available for the magmatic deposit types likely to be found in the Stillwater Complex. Nonetheless, this assessment follows the three-part form when applicable. The steps used in this assessment are to:

(1) *Define the types of mineralization appropriate for the Stillwater Complex and delineate terranes within the*

complex that are geologically permissive for their occurrence.

Rocks that comprise the Stillwater Complex can host mineral occurrences and deposits enriched in nickel, copper, chromium, and platinum-group elements (PGE) that form by segregation and accumulation of crystals of metallic oxides or immiscible sulfide liquids from silicate magma. These deposit types are generally referred to as magmatic ore deposits. Occurrences and deposits can be divided into types that have shared characteristics; these types can be described as models which allow geologists to link deposit types to geologic environments (Singer, in press a). Some magmatic ore deposits are formally described as mineral deposit models (Cox and Singer, 1986); appropriate to Stillwater are the models for Stillwater nickel-copper, Bushveld chromium, and Merensky Reef PGE. Three other types of mineralization formed by magmatic processes have not been formally described as models but are important to the mineral resource assessment: (1) PGE-enriched stratiform chromitites, (2) sulfide and PGE concentrations occurring at or below impermeable layers, and (3) pegmatoidal lenses, pipes, and other discordant mineralization.

Tracts permissive for these deposit types are illustrated on plates 14 and 15. Within the areas shown, the existence of deposits of the specified type is permitted; outside these areas, the probability of deposits of the specified type is negligible. Geologic criteria and mineral occurrence information were used to outline tracts on geologic maps. These tracts show the areal extent of permissive rocks at the surface; unlike the tract maps in Chapter G, the tracts do not illustrate the extent of permissive rocks within a kilometer of the surface. If the tracts were modified to show the areal extent of permissive rocks that are within a kilometer of the surface, only the northern boundary of the tracts would change, shifting less than a kilometer to the north. Permissive rocks will occur less than a kilometer to the north of the illustrated tract at depth because rocks in the complex dip to the north at moderate to steep angles. The location and results of geochemical surveys, bulk samples sites, and drill hole collars are illustrated against these tracts, but the results of the exploration activity were not used to modify the tract boundaries.

(2) *Collect information about grade and tonnage for deposits of each type of mineralization.*

Although Cox and Singer (1986) present descriptive models for several types of magmatic ore deposits appropriate for the Stillwater Complex (Models 1 - Stillwater nickel-copper, 2a - Bushveld chromium, and

2b - Merensky Reef PGE), grade and tonnage models were not included. Economically exploitable magmatic ore deposits within large stratiform layered intrusions, such as the Stillwater Complex, are uncommon. Singer (in press b) prefers at least twenty deposits in the tonnage-grade distribution so that estimates of the population parameters are stable. For magmatic deposits, information on more than six or seven deposits is difficult to find and commonly is only available for a single deposit. In order to put the Stillwater data into perspective, tonnage and grade of producing deposits and significant prospects are given for each deposit type. For two deposit types, grade data are summarized on cumulative frequency plots. Tonnage data were not provided in order to discourage their use in numerical modeling. The tonnage of the deposits is limited by the size of the intrusion; if numerical simulation for undiscovered deposits in the Stillwater Complex (with lateral continuity not exceeding 25 mi and an area of about 77 mi²) used tonnages reported for the Bushveld Complex, Republic of South Africa (with lateral continuity of layers measured in hundreds of miles and an area in excess of 23,000 mi²), the results would be meaningless.

(3) *Evaluate the results of exploration activity within each geologically permissive tract and indicate areas favorable for mineral occurrences and deposits.*

Although the exploration work done in the Stillwater Complex is extensive, the information derived from this work is not easy to find; the summaries presented here are derived from both published and unpublished sources that represent only part of the actual work done. Although different companies were involved, the exploration approach was similar. Work typically began with reconnaissance mapping, geochemical sampling, and geophysical investigations to identify areas to be tested by bulk sampling, trenching, drilling, or underground exploration. Rather than summarize the complete exploration process, activities that are representative of the latter stages of the exploration process or data critical to locating mineralization are emphasized. Location of bulk sample sites, trenches, and drill hole collars are shown on plates 14 and 15 to illustrate the level of exploration activity for different types of mineralization. The areal extent and results of pertinent geochemical surveys are shown if the information is available. Mineral occurrences and deposits and resource information are summarized in tables F1, F2, and F3. Geologic factors that contribute to the economic viability of mineral resources in the Stillwater Complex and areas favorable for undiscovered deposits are described.

(4) Estimate the quantity of mineralized rock that may be present in extensions of identified mineral deposits and undiscovered deposits.

Without the tonnage and grade models, numerical simulation of the amount of undiscovered resources based on probabilistic estimates of undiscovered deposits is not possible. To give some idea of the mineral endowment of the complex, the quantity of mineralized rock that may be present in extensions of identified mineral deposits and undiscovered deposits is estimated using geologic constraints to estimate the volume of rock that may be mineralized. Resources are projected to an elevation of 1,722 ft (525 m), which is a kilometer below the lowest surface exposure of the complex. The difference in elevation between the higher terrains in Stillwater area and 1,722 ft limit is close to 6,500 ft (2 km). These numbers are comparable to resource estimates available for the Bushveld Complex, Republic of South Africa (Sutphin and Page, 1986) which were calculated to a depth of 1.2 km.

GEOLOGIC SUMMARY

Layered, ultramafic to mafic intrusions, such as the Stillwater Complex, are uncommon in the geologic record but are economically important because they can host magmatic ore deposits containing economic concentrations of chromium, nickel, copper, titanium, and PGE. The Stillwater Complex is important because it contains most of the domestic supply of PGE and chromium, materials that are critical to a number of industrial applications and for which industries in the United States must import most of what they use.

The Stillwater Complex was emplaced in the Late Archean ($2,705 \pm 4$ Ma; U-Pb zircon, Premo and others, 1990), shortly after a major, regional crust-forming event which culminated in the emplacement of the 2.73-2.79 Ga Late Archean granitoid suite in the batholith exposed in the Beartooth uplift (Wooden and others, 1991). The original size and shape of the complex are not known inasmuch as only a portion of the complex is exposed in a fault-bounded block along the northern margin of the Beartooth uplift.

The complex was intruded by Archean quartz monzonite intrusions, Proterozoic mafic dikes, and Tertiary siliceous and intermediate composition sills and was affected by several episodes of deformation after consolidation. The Archean quartz monzonite suite intrudes the Basal series and the older

metasedimentary rocks adjacent to the complex; U-Pb zircon ages are indistinguishable from the complex (Nunes and Tilton, 1971). Archean and Proterozoic mafic dikes are found throughout the complex; some dikes are associated with faults. Ages determined for dikes that cut the Stillwater Complex include 2,650 Ma (Sm-Nd; Longhi and others, 1983) and 2,441 and 1,640 Ma (K-Ar; Baadsgaard and Mueller, 1973). The complex was penetratively deformed, subjected to low grade regional metamorphism, tilted, and unroofed prior to being unconformably overlain by middle-Cambrian sedimentary rocks (Page and Zientek, 1985). During the Laramide orogeny, the complex was intruded by intermediate composition sills and dikes and involved in fold-thrust foreland deformation during the formation of the Beartooth uplift. The complex was folded and cut by high-angle, south-dipping reverse faults and north-dipping bedding parallel faults. South-dipping reverse faults truncate and conceal the downdip extensions of rocks hosting nickel-copper, chromium, and PGE mineralization. Faults that are oriented almost normal to layering accommodate differential movement between the reverse faults and disrupt the continuity of some mineralization. Scarps developed in post-Pleistocene deposits suggest Holocene movement on some faults.

The complex is comprised almost entirely of layered cumulates. Cumulates are igneous rocks characterized by distinctive textural and compositional features. These rocks consist of high temperature minerals that crystallize from mafic silicate melts, but in proportions that are not appropriate for the bulk composition of naturally occurring mafic magma. In addition, the rocks are depleted in minerals that crystallize late from magmas and elements that behave incompatibly during crystallization. Textures of these rocks are characterized by hypidiomorphic granular fabrics that consist of a "framework" of anhedral to euhedral crystals (cumulus crystals) "cemented" by minerals interstitial to the cumulus grains. Post-cumulus, interstitial material may form crystallographically continuous grains that surround and include cumulus crystals (oikocrysts), fill intergranular interstices, or form overgrowths on existing cumulus crystals. Rock names for cumulates are formed by listing the cumulus minerals in decreasing order of abundance followed by the word "cumulate." For example, a rock composed principally of cumulus plagioclase, a smaller proportion of cumulus olivine, and postcumulus augite would be called a plagioclase-olivine cumulate.

Cumulates commonly show layering which can be defined by variations in cumulus minerals present as

Table F1.-Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Mouat Tunnel No.8 - FW zone Tunnel No. 8 - HW zone Tunnel A zone Red Bird zone	Custer National Forest (NF): west side of Stillwater Valley, between the Lake Fault and the Bluebird thrust	unknown	0.9 (0.8) 0.5 (0.4) 0.25 (0.23) 10.8 (9.8)	0.37 0.47 0.32 0.39	0.35 0.29 0.40 0.38	Higher grade zones within the northern part of the prospect area. Hart (1938).
Mouat			0.4 % Ni 0.3 % Ni 0.2 % Ni 0.1 % Ni not stated; assume 0.1% Ni	23.1 (21.0) 30.8 (28.0) 91.9 (83.4) 119.1 (108.1) 145 (131.6)	0.45 0.40 0.27 0.25 0.29	0.62 0.39 0.29 0.26 0.31
			0.8% Cu + Ni 0.6% Cu + Ni 0.4% Cu + Ni 0.2% Cu + Ni 0.8% Cu + Ni 0.6% Cu + Ni 0.4% Cu + Ni 0.2% Cu + Ni	0.98 (0.89) 3.96 (3.59) 13.15 (11.93) 24.34 (22.08) 0.20 (0.18) 0.49 (0.44) 2.87 (2.60) 8.14 (7.38)	0.43 0.35 0.27 0.22 0.56 0.43 0.26 0.18	Drill indicated resource to maximum depth of 1,900 ft (5,000 ft elev.); deposit was drilled on 200 ft centers and is open to the west. Adler (1972); R.N. Miller (written commun., 1978). Revised resource information based on fill-in drilling (two holes) in 1978. Turner (1979).
					0.56 0.41 0.30 0.24 0.47 0.40 0.27 0.20	Drill indicated resource. Tonnage estimates for two domains within the Mouat deposit. Tonnages calculated using inverse distance squared algorithm. Attanasi and Bawiec (1987).

Table F1.—Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Nye Basin	Custer NF: south side of Nye Basin between Nye Lip and the Big Seven fault	0.4 % Ni 0.3 % Ni 0.2 % Ni 0.1 % Ni	1.39 (1.26) 4.1 (3.72) 15.9 (14.4) 21.4 (19.4)	0.46 0.30 0.27 0.25	0.61 0.30 0.25 0.22	Drill indicated resource. Based on first 14 of the 21 holes drilled; resource numbers were not updated to include mineralization in last seven holes. Drill results projected 100 ft on strike either side of sections that were typically separated by more than 300 ft. Adler (1972); R.N. Miller (written commun., 1978).
	Intermediate grade material					Surface to 1,500 ft depth. W.C. Mouat (written commun., 1989).
Benbow	Custer NF: base of complex from Big Seven fault to Little Rocky Creek	0.4 % Ni 0.3 % Ni 0.2 % Ni 0.1 % Ni	1.34 (1.22) 2.5 (2.27) 7.7 (7.0) 10.2 (9.26)	0.42 0.33 0.28 0.26	0.57 0.34 0.28 0.25	Drill indicated resource. Drill results projected 100 ft on strike either side of sections that were typically separated by more than 300 ft. Adler (1972); R.N. Miller (written commun., 1978).
	Intermediate grade material					Surface to 1,500 ft depth. W.C. Mouat (written commun., 1989).

Table F1.-Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Nye Basin-Benbow	see above	unknown	10.2 ¹ (9.26) 60 ² (54.5) 120 ³ (109)	0.52 0.52 0.5	0.59 0.59 0.5	Correlate higher grade zones between adjacent drill sections and project down dip. Turner (1979). 1 Proven - 2 Probable - projected 1,500 ft below surface 3 Prospective - projected to 5,000 ft elevation
Crescent Creek	Custer NF: Basal series exposures near Crescent Creek	0.2 % Ni 0.1 % Ni	0.4 (0.36) 0.4 (0.36)	0.16 0.16	0.23 0.23	Does not include results of drilling after 1972. Adler (1972).
Rocky Claim group (Chrome Lake)	Custer NF: concealed beneath glacial deposits beneath Chrome Lake, between Little Rocky Creek and Fishtail Creek	higher grade 0.5% Cu + Ni 0.5% Cu + Ni	6.4 (5.8) 34 (30.9) 40.7 (37.0) ¹	0.874 Cu + Ni 0.523 Cu + Ni 0.527 Cu + Ni	Based on results of four drill holes (ST 3 to 6) defining mineralized zone 2,050 ft long and 40 to 430 ft wide. Projected to depth of 700 ft	¹ Project mineralized zone 300 ft either side of outermost holes. Geophysical data support extending mineralized zone one mile to the southeast; this would triple tonnage estimate. Reference: E.A. Schmidt (written commun., 1977). NOTE: Between 1971 and 1982, Cypress drilled 14 core holes in the deposit; resource numbers were not updated.
						Indicated resource. Reference: R.N. Miller (written commun., 1978).
	unknown	54 (49)		0.26	0.28	

Table F1. Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Iron Mountain - Camp deposit	Gallatin NF: southwest flank of Iron Mountain	0.30 % sulfide Ni	4.5 ¹ (4.1) 9.5 ² (8.6) 41 ³ (37.2)	.24 .23 –	.45 .40 –	¹ Proven, Iron Mountain west ² Probable, Iron Mountain west ³ Possible Iron Mountain and Chrome Mountain Reference: Ken Kuxhausen (written commun., 1973).
		0.30 % sulfide Ni	6.44 (5.85)	0.23	0.42	Drill indicated reserves based on intercepts in 9 drill holes (3, 5, 16, 22, 23, 31, 44, 46, and 48). Calculations based on cross sections spaced 350 to 400 ft. apart. Mineralization was correlated 1,500 ft between 4 adjacent sections; mineralization was projected half the section line spacing. Resource includes mineralization encountered 1,500 ft east of these sections; data was projected 187.5 ft either side of section to give 0.4 million tons at 0.097 Cu and 0.31 Ni. Reference: G.E. Walker (written commun., 1972) and R.B. Hoy (written commun., 1973 and 1974).
Iron Mountain - Iron Creek area	Iron Creek - Custer NF: east flank of Iron Mountain	–	0.7 (0.6)	0.32	0.93	Reserve estimate based on 100 ft intercept in hole 59. Parameters for calculation: true thickness of 85 ft, width assumed to be two times the thickness (170 ft), and arbitrary length of 500 ft. Reference: R.B. Hoy (written commun., 1975).

Table F1.-Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Iron Mountain area	Gallatin NF: permissive mineralized ground between West and Iron Creek No. 2 faults on Iron Mountain	unknown	170 (154)	—	—	Estimated potential for Ultramafic zone mineralization. Conditions assumed in calculations: average thickness of 75 ft; tonnage factor of 10 cubic ft/ton; tonnages arbitrarily reduced by 50%. NOTE: no information on depth. Reference: G.E. Walker (written commun., 1972). R.B. Hoy (written commun., 1973) comments that these calculations require block about 10,000 ft long and 4,000 ft down dip.
Chrome Mountain area - Hi claims	Gallatin NF	—	—	0.07 0.22 0.11 0.11 0.06 0.09 0.04 <0.01 0.02	0.21 0.41 0.16 0.18 0.15 0.15 0.13 0.13 0.14	Best drill intercepts (in feet): Hole from to 4 173.3 187.5 6 52.6 100 13 228.4 256.4 20 430 490 65 228.5 240 69 476 544 150 300 450 500 750 900 Holes 29, 30, 33, 46 - no intervals analyzed.

Table F1.-Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Chrome Mountain area	Gallatin NF: permissive mineralized ground	unknown	100 (90.8)	—	—	Estimated potential for Ultramafic series mineralization. Conditions assumed in calculations: average thickness of 75 ft; tonnage factor of 10 cubic ft/ton; tonnages arbitrarily reduced by 50%. NOTE: no information on depth Reference: G.E. Walker (written commun., 1972).
Boulder River	Gallatin NF	unknown	—	0.12 0.14 0.18 0.21 0.06 0.09 0.14 0.05 — — 0.13 0.12 — 0.3	0.12 0.17 0.20 0.20 0.14 0.26 0.20 0.21 — — 0.28 0.14 — 0.3	from to Hole (128 ft intercept) BR-1 879 883 BR-2 983 988 BR-3 138 141 251 252 334 335 410 411 BR-4 no significant assays BR-5 no data BR-6 30 40 BR-6A 175 208 BR-7 no significant assays grab samples - dump from adit on Boulder River

Table F1.--Resources associated with Ni-Cu sulfide deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Cutoff	Millions of short tons (millions of metric tons)	Cu %	Ni %	Comments
Boulder River	Gallatin NF: Basal series east of Boulder River in the Gish mine area	unknown	12 (10.9)	0.43	0.19	Hypothetical resource based on drill hole BR-2. No information on calculations. Reference: R.N. Miller (written commun., 1978).
Boulder River Nixon claim group	Gallatin NF: Basal series west of Boulder River	unknown	300 (272)	0.12	0.12	Grade and thickness based on Anaconda drill hole BR-1. Thickness 130 ft; length 9,500 ft (mapped extent of Basal series to the west); projected 4,700 ft below surface (half the strike length). Reference: Stotelmeyer and others (1983).

Table F2.--Resources associated with chromite deposits, prospects, and occurrences in the Stillwater Complex

Deposit, prospect, or occurrence name	Where	Millions of short tons (millions of metric tons)	Cr ₂ O ₃ content in percent	Thickness in feet	Comments
Benbow mine - G chromite seam	Custer NF: Big Seven fault to Fishtail Creek	1.2 (1.1) ¹ 1.1 (1.0) ² 1.1 (1.0) ³ 2.5 (2.3) ⁴ 7.9 (7.2) ⁵ 10 (9.1) ⁶ 19.7 (17.9) ⁷ 22.2	22.7 24.4 - 26.1 25.3 24.3 20.0 — —	5 — — — — — —	¹ E.S. Rugg (written commun., 1958) - proven, indicated, and inferred reserves in blocks bounded by underground workings. ² J.W. Peoples and W.R. Jones (written commun., 1950) - no information on boundary conditions. ³ U.S. Bureau of Mines (1945) - 100 to 140 ft below lowest workings or borehole intercept; no resources calculated for central Benbow. ⁴ Turner (1979) - developed, probable, and possible ore above 7,500 ft. ⁵ T.P. Thayer (written commun., 1957) - resources above 5,300 ft. ⁶ Turner (1979) - developed, probable, possible, and prospective ore above 5,000 ft. ⁷ Wetzel (1986) - resources to approx. 5,000 ft.
Nye Basin	Custer NF	0.01 (0.01) ¹ 0.03 (0.03) ² 0.05 (0.04) ¹ 9.5 (8.5) ²	26 19.6 16.8 22.2	5.3 2.9 4.4 —	¹ U.S. Bureau of Mines (1945h) - projected 100 ft downdip. ² Big Seven area. ² Alice Lode area.

Table F2.-Resources associated with chromite deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Millions of short tons (millions of metric tons)	Cr ₂ O ₃ content in percent	Thickness in feet	Comments
Mouat Sampson mine - G chromite seam	Custer NF: west side of Stillwater valley between the Lake fault and the Bluebird thrust	2.6 (2.4) ¹ 3.1 (2.8) ² 6.5 (5.9) ³ 6.4 (5.8) ⁴ 6.6 (6.0) ⁵	21.7 23.2 — 21.7 23.9	Mining width: 3.9 to 8 ft. Borehole below no. 5 up to 20 ft.	Resources indicated by underground workings and drilling: ¹ U.S. Bureau of Mines (1945e). ² Total ore reserves based on American Chrome Company estimates, Jan. 1, 1960. Price (1963). Resources above and below the number 5 level: ³ J.W. Peoples and W.R. Jones (written commun., 1950). ⁴ E.D. Jackson (written commun., 1957). ⁵ M.L. Zientek (unpub. data, 1979) - to Monte Alto Tunnel level (5,280 ft).
Mouat Sampson mine - H chromite seam		1.2 (1.1) ¹ 1.3 (1.2) ² 3.3 (3.0) ³ 3.6 (3.3) ⁴ 4.7 (4.3) ⁵	21.1 20.5 20.7 21	Mining width: 4.0 to 7.1 ft. Borehole below no. 5 up to 12 ft.	Resources indicated by underground workings and drilling: ¹ U.S. Bureau of Mines (1945e). ² Total ore reserves based on American Chrome Company estimates, Jan. 1, 1960. Price (1963). Resources above and below the number 5 level: ³ J.W. Peoples and W.R. Jones (written commun., 1950). ⁴ E.D. Jackson (written commun., 1957). ⁵ M.L. Zientek (unpub. data, 1979) - to Monte Alto Tunnel level (5,280 ft).
Mouat Sampson mine - G and H chromite seam combined		8.2 (7.4) ¹ 16.6 (15.1) ² 15 (13.6) ³ 19.2 (17.4) ⁴	21.5 22.6 23.2 23.0		¹ E.S. Rugg (written commun., 1958). ² Wetzel (1986). ³ Turner (1979). ⁴ Randol International Ltd. (1990). Wetzel (1986) and Turner (1979) estimates are to floor of Stillwater valley (approx. 5,000 ft).
Initial Creek - B chromite seam	Custer NF	0.03 (0.03) ¹ 0.03 (0.03) ²	13.2 14.9	6.8 4.6	¹ U.S. Bureau of Mines (1945b) - projected 100 ft below surface. ² E.S. Rugg (written commun., 1958).

Table F2.-Resources associated with chromite deposits, prospects, and occurrences in the Stillwater Complex (continued)

Deposit, prospect, or occurrence name	Where	Millions of short tons (millions of metric tons)	Cr ₂ O ₃ content in percent	Thickness in feet	Comments
Bluebird area - G chromite seam	Custer NF	0.03 (0.03) ¹ 0.06 (0.05) ²	19.4 16.9	5.3 4.3	¹ U.S. Bureau of Mines (1945d) - projected 100 ft below surface. ² E.S. Rugg (written commun., 1958).
Taylor-Fry	Custer NF: West Fork of the Stillwater	0.07 (0.06) ¹ 0.09 (0.08) ²	16.7 12.4	3.0 min. 4	¹ U.S. Bureau of Mines (1945g) - projected 100 ft below surface. ² E.S. Rugg (written commun., 1958).
Iron Mountain	Custer and Gallatin NF	0.04 (0.04)	10.8	4.0	E.S. Rugg (written commun., 1958).
East Boulder Plateau	Gallatin NF	---- 0.04 (0.04) ²	16.8 ¹ 12	2.8 4.0	¹ U.S. Bureau of Mines (1945f). ² E.S. Rugg (written commun., 1958).
East Boulder River	Gallatin NF	---	19.1	4.0	E.S. Rugg (written commun., 1958).
Gish Mine	Gallatin NF	0.20 (0.18) ¹ 0.52 (0.47) ² 0.85 (0.77) ³	17.2 16.3 15	4.5 4.8 —	¹ E.S. Rugg (written commun., 1958). ² U.S. Bureau of Mines (1945i) - projected to Brownlee Creek Fault. ³ Weitzel (1986).

Table F3.--Resources associated with PGE deposits, prospects, and occurrences in the Stillwater Complex

Deposit, prospect, or occurrence name	Where	Millions of short tons (millions of metric tons)	Width, ft	Pt, opt (ppm)	Pd, opt (ppm)	Pt + Pd, opt (ppm)	Comments
J-M Reef - entire complex	Custer and Gallatin NF	0.9 (0.8) ¹	—	0.18 (6.2)	0.62 (21.2)	0.8 (27.4)	¹ Reserves, Stillwater Mine, McCulloch (1992).
		12.36 (111.2) ²	—	0.18 (6.2)	0.62 (21.2)	0.8 (27.4)	² Geologic reserves, Stillwater Mine, Randol International Ltd. (1990).
		15.5 (14.1) ³	7.0	0.17 (5.82)	0.64 (21.9)	0.81 (27.8)	³ Higher grade reserve, East Boulder project area, Thompson (1987).
		31.0 (28.14) ⁴	5.9	—	—	0.59 (20.2)	⁴ Reserve, East Boulder project area, Thompson (1987).
		143 (130) ⁵	—	0.13 (4.4)	0.45 (15.6)	0.58 (20)	⁵ Resource estimate based on 42 km strike length, 1.83 m thickness, 600 m depth, and rock density of 2.87 g/cc. Suphlin and Page (1986).
		127.6 (115.8) ⁶	4.7	0.13 (4.4)	0.42 (14.4)	0.55 (18.8)	⁶ Surface to adit levels (5,000 ft - Stillwater mine, 5,300 ft - west of Boulder River, 6,450 ft - East Boulder project).
		185.6 (168.4) ⁷	4.7	0.13 (4.4)	0.42 (14.4)	0.55 (18.8)	⁷ Surface to 1,000 ft below proposed adit level.
		464.6 (421.4) ⁸	4.7	0.13 (4.4)	0.42 (14.4)	0.55 (18.8)	⁸ Surface to sea level.
							⁵ to ⁸ Stillwater PGM Resources (written commun., 1992). Grade reported as 0.55 opt Pt + Pd to Pt ratio of 3.38 to 1 used to calculate Pt and Pd.
							Loehr (1979): 5,750 ft strike length projected to elevation of West Fork of the Stillwater River, 9 cu ft per ton used to convert volumes reported by Loehr (1979) to tons. Contains 11.8 wt. percent Cr ₂ O ₃ .
B chromite seam	Custer NF: Peridotite zone exposures east of Crescent Creek on north side of West Fork of the Stillwater River	3.8 (3.4)	Nominal thickness of 4 ft	0.02 (0.685)	0.05 (1.714)	0.07 (2.4)	

Table F3.--Resources associated with PGE deposits, prospects, and occurrences in the Stillwater Complex

Deposit, prospect, or occurrence name	Where	Millions of short tons (millions of metric tons)	Width, ft	Pt, opt (ppm)	Pd, opt (ppm)	Pt+Pd, opt (ppm)	Comments
Picket Pin deposit	Custer and Gallatin NF; near top of the Anorthosite II zone			0.040 (1.37) ¹ 0.039 (1.34) ² 0.04 (1.37) ³ 0.11 (3.77) ⁴	0.026 (0.89) 0.024 (0.82)	-- --	730 kg bulk samples of Picket Pin mineralization (Williams, 1981): 1 West side of Contact Mountain. 2 West side of Picket Pin peak. Best results of surface and drill sampling; thickness is intercept or sampling interval (Marshall, 1992, and D.M. Marshall, oral commun., 1992). 3,4 Anaconda drill sample ³ and surface grab sample ⁴ . 5 KEM drill sample. 6 to 8 International Platinum surface grab sample ⁶ , trench grab sample ⁷ , and drill samples ⁸ .

well as their orientation, their proportions and size, and systematic variations in proportions and size. About 18,000 ft of layered igneous rocks are preserved between the intrusive lower contact of the complex and the pre-Middle Cambrian unconformity that truncates the top of the complex. Along strike, layering features can be traced for 26 mi, limited only by the present exposure of the complex.

This succession of layered rocks form a stratigraphic section that is divided into five series which are subdivided into 14 to 17 zones based largely on the occurrence and proportions of cumulus minerals (fig. F1). The five series divisions in stratigraphic order are: Basal, Ultramafic, Lower Banded, Middle Banded, and Upper Banded. Figure F1 illustrates the nomenclature proposed by different investigators for zones in the Lower Banded, Middle Banded, and Upper Banded series; despite the differences in names and detail, similar lithologic sequences were recognized. For sake of clarity, some units are grouped on the geologic map on plates 14 and 15. Names of zones in the Lower, Middle, and Upper Banded series are those proposed for units mapped by Segerstrom and Carlson (1982); correlative names used in the stratigraphic studies of McCallum and others (1980) are shown in parentheses in the explanation.

BASAL SERIES

The Basal series can be divided into two zones, an upper Basal bronzite cumulate zone and a lower Basal norite zone (Page, 1979). The Basal norite zone is characterized by locally variable textures and proportions of minerals; bronzite is the predominant cumulus mineral, but cumulus plagioclase, olivine, augite, inverted pigeonite, and chromite occur locally. The Basal bronzite cumulate zone consists predominantly of bronzite cumulates. Sulfide mineral accumulations are typical of the lower part of the Basal series; generally the proportion of sulfide minerals increases toward the base of the complex (Page, 1979).

The Basal norite zone as mapped by Page and Nokleberg (1974) includes a suite of sills and dikes that intrude metasedimentary rocks near the base of the complex (Zientek, 1983; Helz, 1985). Zientek and others (1985) and Helz (1985) refer to the sill and dike rocks as Stillwater-associated sills and dikes because they are spatially and compositionally distinct from the layered cumulates that make up the bulk of the complex. At least five distinct compositional types of sills and dikes are recognized: (1) gabbronoritic

diabase (group 1 of Helz, 1985), (2) olivine gabbroic diabase (group 6 of Helz, 1985), (3) high-Ti noritic diabase (group 4 of Helz, 1985), (4) high-Mg gabbronorite (group 2 of Helz, 1985), and (5) mafic norite (group 3 of Helz, 1985). Some of the diabasic-textured rocks are slightly older than the Stillwater Complex (Premo and others, 1990): group 1 gabbronorites ($2,711 \pm 1$ Ma) and group 4 high Ti norite ($2,712 \pm 3$ Ma). Sulfide-bearing, ultramafic sills and dikes (groups 2 and 3) are comprised of lithologies that range from cumulates to more liquid-like compositions that resemble siliceous high-magnesium basalts or boninites; the age of these rocks is indistinguishable from the age of the Stillwater Complex ($2,703 \pm 10$ Ma). The group 2 and 3 sills may be petrologically related to the cumulates in the overlying Basal series (Zientek, 1983). Disseminated sulfide minerals (less than 10 volume percent) are present in all the sills and dikes; however, matrix (10 to 60 volume percent) and massive (greater than 60 volume percent) accumulations of sulfide minerals are largely restricted to the group 3 mafic norite sills and dikes near mineralized Basal series cumulates (Zientek, 1983).

ULTRAMAFIC SERIES

The Ultramafic series is made up of rocks that contain cumulus olivine, bronzite, and chromite and is subdivided into a lower Peridotite zone and an upper Bronzitite zone (Jackson, 1961; Raedeke and McCallum, 1984). The Peridotite zone is made up of cyclic units, layered sequences of lithologies that occur repeatedly in the section. The number of cycles recognized in the Peridotite zone vary from as few as 8 in the West Fork area to 24 in the Mountain View area (R.W. Cooper, written commun., 1991). A typical sequence in a cyclic unit begins with olivine cumulate that may contain a chromite seam. Olivine cumulate is overlain by olivine-bronzite cumulate; within the olivine-bronzite cumulate, the ratio of olivine to bronzite decreases upward. The disappearance of olivine as a cumulus phase marks the lower contact of the bronzite cumulate at the top of a cycle. Contacts within cyclic units may be gradational whereas contacts between cyclic units are sharp. Cyclic units showing only a part of the lithologic sequence described above are common.

Disseminated sulfide minerals are common in cyclic units that characterize the Peridotite zone; however, accumulations of matrix and massive sulfide minerals are only known to occur in the Iron

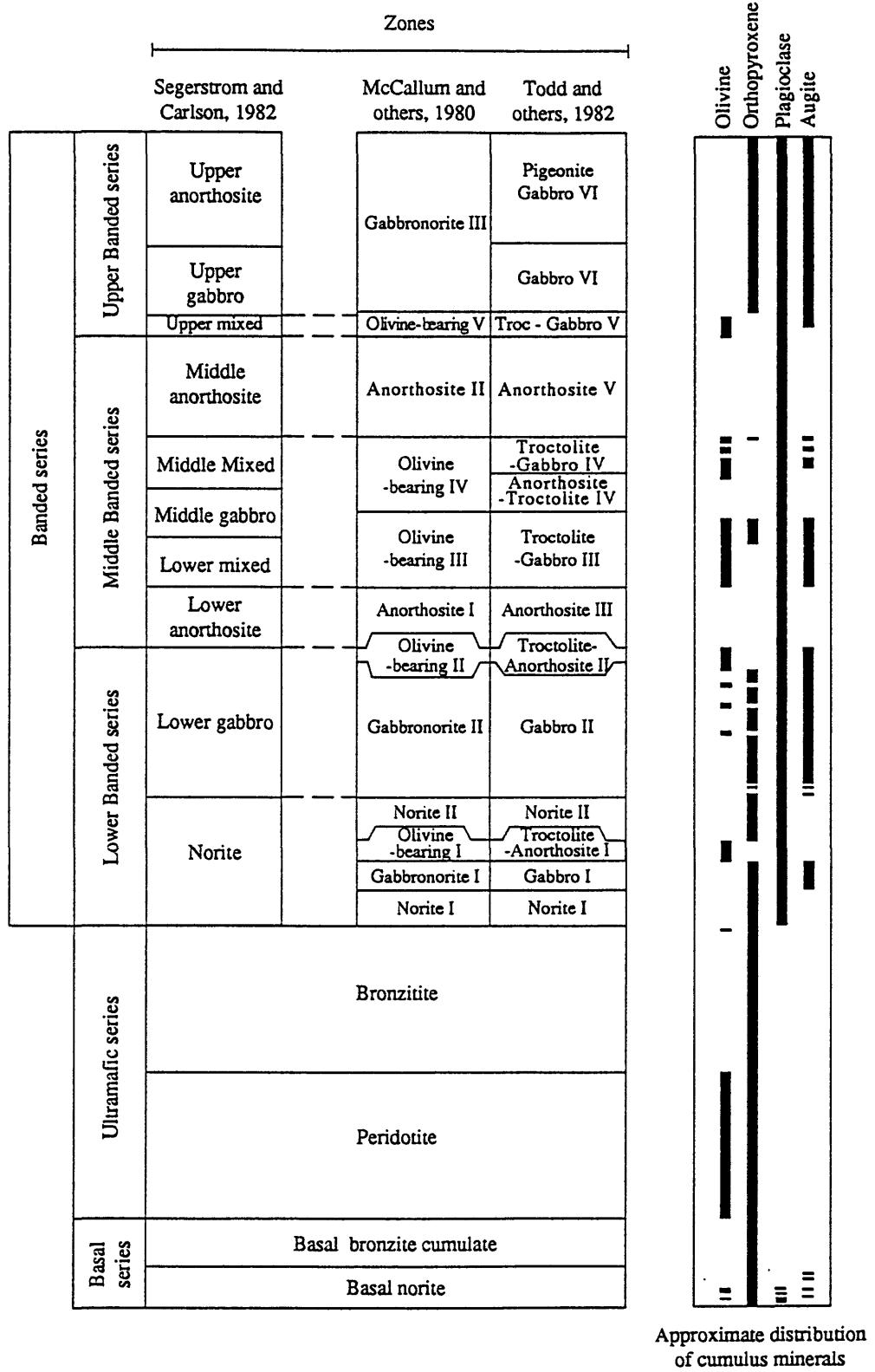


Figure F1.—Subdivisions of Stillwater Complex stratigraphy and approximate distribution of cumulus minerals.

Mountain area (Camp deposit and Iron Creek prospect) and at the Mouat-Sampson mine [also referred to as the Mouat mine or the Mountain View mine]. Massive sulfide within the Mouat-Sampson mine was found as small pods associated with the G chromite seam (Page and Jackson, 1967).

Intervals in which chromite is concentrated in layers (chromite seams) are most common in the olivine cumulates near the base of cyclic units in the Peridotite zone but are locally found in bronzite cumulates near the top of the Bronzitite zone. Up to 13 chromite seams are present within the Peridotite zone and are designated by the letters A to K from the base to the top of the section (Jackson, 1968). The discrepancy between the number of letters and chromite seams stems from the designation of chromite seams immediately above the G and H in the Mountain View area as the hanging wall G and H. These chromite seams are not present in the Benbow area where the A to K designation was first used. Disseminated sulfide minerals (0.01 volume percent or less) are associated with the chromite seams (Page, 1971; Mann and others, 1985).

The Bronzitite zone consists almost entirely of bronzite cumulates. Near the top of this zone, thin layers containing cumulus olivine or chromite are found locally. Pegmatoid pods near the top of the Bronzitite zone [Janet 50 zone] contain disseminated to matrix sulfide minerals enriched in PGE and graphite (Volborth and Housely, 1984).

LOWER BANDED SERIES

The Lower, Middle, and Upper Banded series are distinguished by the presence of cumulus plagioclase. The presence (or absence) and proportion of cumulus bronzite, augite, olivine, and inverted pigeonite, as well as changes in crystallization order, are the basis for subdivision of the Banded series (McCallum and others, 1980; Segerstrom and Carlson, 1982; Todd and others, 1982). Unfortunately, there is no consensus on how to subdivide these rocks (fig. F1). The discussion that follows will be largely based on the subdivision proposed by McCallum and others (1980).

The Lower Banded series comprises those rocks between the top of the Ultramafic series and the base of the Anorthosite I zone of the Middle Banded series. McCallum and others (1980) divide these rocks into five zones. The lowest is the Norite I zone which largely consists of plagioclase-bronzite cumulate. The Gabbronorite I zone overlies the

Norite I zone and consists of cyclically layered rocks that are made up of cumulus plagioclase, bronzite, and augite. The idealized upward lithologic sequence within a cyclic unit is: plagioclase-bronzite-augite cumulate, plagioclase-bronzite cumulate, plagioclase cumulate. This zone is overlain by the Olivine-bearing I zone, in which olivine reappears as a cumulus mineral. The upper part of this zone consists of cyclic units in which the ideal upward sequence is olivine cumulate, plagioclase-olivine cumulate, plagioclase cumulate. The J-M Reef is associated with rocks in this zone. A monotonous sequence of plagioclase-bronzite cumulates referred to as the Norite II zone overlies the Olivine-bearing I zone. The Norite II zone is overlain by the Gabbronorite II zone. In the western part of the complex, the Gabbronorite II zone consists of plagioclase-bronzite-augite cumulates that are separated from the base of the Anorthosite I zone by a thin sequence of olivine-bearing rocks (Olivine-bearing II zone). In the eastern part of the complex, rocks correlative with the Gabbronorite II zone include plagioclase-bronzite-augite cumulates with many sequences of olivine-bearing rocks (M.L. Zientek, J.A. Peterson, and R.W. Cooper, unpub. data, 1988).

MIDDLE BANDED SERIES

The Middle Banded series consists of rocks that are stratigraphically between the base of the Anorthosite I zone and the top of the Anorthosite II zone. The Anorthosite I and II zones are made up solely of massive, coarse-grained plagioclase cumulate with less than 20 percent postcumulus minerals. Mineralization that comprises the Picket Pin zone is near the top of the Anorthosite II zone. The rocks between these two zones have been divided into a lower Olivine-bearing III zone and an upper Olivine-bearing IV zone. Olivine-bearing zone III consists of a complexly layered sequence of cumulates that are comprised of various proportions of cumulus plagioclase, augite, and olivine. Olivine-bearing zone IV consists of cyclically layered rocks; the upward succession of lithologies in a cyclic unit is: plagioclase cumulate, plagioclase-olivine cumulate, plagioclase-olivine-augite cumulate.

UPPER BANDED SERIES

The Upper Banded series is made up of all rocks that overlie the top of the Anorthosite II zone.

Olivine-bearing zone V is the lowermost unit and consists of cyclically layered rocks at the base (plagioclase-olivine cumulate overlain by plagioclase cumulate) and complexly interlayered rocks composed of cumulus plagioclase, bronzite, and augite at the top. The Gabbronorite III zone is predominantly plagioclase-bronzite-augite cumulate with little variation in mineral proportions. The structural state of the high-temperature cumulus low-calcium pyroxene changed from orthorhombic to monoclinic partway through this unit; structural transformations of this cumulus mineral upon cooling caused it to form large oikocrysts. Thin plagioclase cumulate layers with minor postcumulus iron-titanium oxide minerals and intervals of fine-grained gabbronorite with phenocrysts of plagioclase occur near the top of the Gabbronorite III zone.

MINERALIZATION IN THE STILLWATER COMPLEX: ASSOCIATIONS AND DEPOSIT TYPES

Many schemes have been proposed for classifying mafic and ultramafic rocks and their associated ore deposits. Most are based on the tectonic setting and petrologic characteristics of the mafic and ultramafic rocks (Page and others, 1982; Naldrett, 1989). Cabri and Naldrett (1984) proposed a classification of PGE-bearing deposits that recognized two classes of occurrences: a sulfide-association and an oxide-silicate association. These two associations were then subdivided into deposit types based on differences in geochemistry, mineralogy, and tectonic setting. Hulbert and others (1988) proposed four subclasses of magmatic deposits (stratabound, discordant, marginal, and other) based on the spatial association of the mineralization to the enclosing ultramafic and mafic host rocks. The discussion of mineralization in the Stillwater Complex integrates these classifications into the scheme listed below in which deposit types based on specific geologic characteristics are grouped by association (sulfide versus oxide):

Sulfide-associated mineralization

- Magmatic sulfide minerals concentrated near the margins of intrusions (Stillwater nickel-copper: model 1 - Page, 1986a)
- Stratiform concentrations of disseminated sulfide minerals in layered intrusions (Merensky Reef PGE: model 2b - Page, 1986b)
- Sulfide and PGE concentrations occurring at or below impermeable layers

- Pegmatoidal lenses, pipes, and other discordant mineralization
- Oxide-associated mineralization
- Stratiform chromitite layers (Bushveld chromium - model 2a - Page, 1986c)
- Stratiform PGE-enriched chromitite layers

In the discussion that follows, features that are common to all deposit types in an association are discussed first, followed by summaries of the specific characteristics of each deposit type, and an assessment for each deposit type that may include:

- (1) examples of deposits and significant prospects,
- (2) a description of occurrences in the Stillwater Complex,
- (3) a description of permissive tracts,
- (4) a summary of factors that localize deposits,
- (5) a summary of exploration activity,
- (6) a summary of geologic factors affecting resource development, and
- (7) an analysis of resource potential.

SULFIDE-ASSOCIATED MINERALIZATION

The exsolution of immiscible sulfide liquid from a mafic silicate magma is the fundamental ore-forming process in the genesis of sulfide-associated mineralization in the Stillwater Complex. Once droplets of immiscible sulfide liquid form in a silicate magma, they act as "collectors" for cobalt, copper, nickel, and PGE because these elements will be preferentially concentrated into the sulfide liquid relative to the silicate liquid.

Texture and distribution.--When not modified by weathering or alteration, the textures between silicate and sulfide minerals record the distribution and abundance of the sulfide liquids and the interaction between solid silicate minerals and molten sulfide liquid. The nomenclature for mineralized rocks depends upon the proportions of sulfide minerals present; the nomenclature used here is similar to that used by Page (1979). Rocks with less than 10 volume percent sulfide minerals are called by their rock names and are said to contain disseminated sulfide minerals. The sulfide minerals form fine- to coarse-grained droplet-shaped aggregates that are molded around and are interstitial to the cumulus or earlier formed silicates or may be present as fine-grained, rounded aggregates enclosed in cumulus minerals. Rocks containing 10-60 volume percent sulfide minerals are also called by their rock name but are said to contain matrix sulfides. Aggregates of sulfide

minerals are interstitial to earlier formed silicates but are interconnected. Rocks with greater than 60 volume percent sulfide minerals are called massive sulfide rocks. In massive sulfide mineralization, the sulfide minerals form the matrix of the rock.

Ore mineralogy.--The textures and mineralogy of sulfide ores record a prolonged and complex process of solid state transformation and recrystallization starting with the solidification of the sulfide liquid at temperatures in excess of 900 °C and continuing to temperatures lower than 100 °C; these textures can be substantially modified by alteration and weathering. For the Stillwater Complex, the sulfide mineralogy resulting from the solid state recrystallization of high-temperature minerals is dominated by pyrrhotite, pentlandite, and chalcopyrite, with the proportions of minerals determined by the bulk composition of the immiscible sulfide liquid. Oxide minerals (magnetite and ilmenite) are commonly intergrown with the sulfide minerals. Minor phases include PGE minerals (sulfide, arsenides, tellurides, antimonides, and alloys), nickel- and cobalt-bearing arsenides (for example gersdorffsite), galena, sphalerite, and gold, silver, and lead tellurides. Minerals formed during alteration and weathering can include violarite, bornite, mackinawite, cubanite, pyrite, marcasite, troilite, vaesite, smythite, polydymite, millerite, hematite, and magnetite. In supergene environments, chalcocite, malachite, native copper, cuprite, nickel-iron carbonates, nickel- and nickel-iron hydroxycarbonates, and nickel-silicates may form. Gossans may form over sulfide-rich rocks.

Ore chemistry.--Primary compositional variations of magmatic sulfide ores are controlled by the composition of the silicate magma and the mass ratio of silicate to sulfide liquid (Naldrett, 1989). This relation is expressed in the following equation:

$$Y_i = \frac{D_i * C^o_i (R+1)}{(R+D_i)}$$

where R = mass ratio of silicate to sulfide liquid, C^o_i is the initial concentration of metal i in the silicate magma, D_i is the Nernst partition coefficient, and Y_i is the concentration of any metal i in the sulfide melt. For equilibria between sulfide melts and silicate magmas, the Nernst partition coefficient is defined as:

$$D_i = \frac{(\text{wt. percent of metal } i \text{ in sulfide melt})}{(\text{wt. percent of metal } i \text{ in silicate melt})}$$

For the Stillwater Complex, differences in the composition of sulfide mineralization in different horizons can be attributed to variations in R . The low

tenor of nickel-copper mineralization near the base of the complex can be attributed to values of R that are on the order of 100 or less and may reflect assimilation of crustally derived sulfur into a limited volume of magma (Zientek and Ripley, 1990). PGE-enriched sulfide liquids that formed the J-M Reef require R values that are 10,000 or higher, which is why models for reef sulfide genesis must incorporate physical processes such as magma mixing to allow a small volume of sulfide liquid to come in contact with a large volume of silicate liquid.

The composition of the immiscible sulfide liquid is also affected by fractional crystallization of the host magma, which affects the concentrations of metals in the magma (C^o_i), and variations in the oxygen fugacity, which affects the value of the partition coefficient (D_i), but these effects have not been demonstrated to be important for Stillwater mineralization. Fractional crystallization of sulfide melt may result in sulfide cumulates that are enriched in Fe, Co, Ir, Ru, and Rh and residua that is enriched in Cu, Pd, Pt, and Au (Naldrett, 1989). Chalcopyrite segregations or stringers observed in hand samples or thin sections of many mineralized samples probably are formed by this process. This residua is volumetrically insignificant and has not moved any significant distance from the material from which it separated. However, the pyrrhotite-rich, nickel-copper ores near the base of the complex may represent sulfide cumulates from which the residua has been removed, but the analytical data needed to test this idea are not available.

Subsolidus equilibration of sulfide minerals with the enclosing silicate-rich or oxide-rich rock may modify the bulk composition of the sulfide mineral assemblage (Naldrett, 1989). The greatest change would be expected for sulfide inclusion in silicate or oxide minerals where the sulfide grain size is small (tens of microns) and the abundance is low.

Structural setting.--Sulfide minerals may be concentrated in structurally low areas at the base of intrusions or in zones where silicate magma interacted with xenoliths. Sulfide concentrations in layered cumulate sequences may be related to major lithologic features such as cyclic units boundaries, unconformities, chromite seams, pegmatoids, or stratigraphic intervals characterized by major changes or discontinuities in fractionating minerals.

Deformation and alteration can remobilize sulfide minerals into breccia ores and segregate sulfide minerals into fractures, cleavage planes, and veins. Mineral assemblages of remobilized sulfides may be copper-rich relative to unaffected mineralization. Sulfide mineral assemblages that appear to have

precipitated from fluids moving through fault zones or along joint surfaces are dominated by pyrite.

Geophysical signatures--Concentrations of sulfide minerals may be characterized by magnetic, induced polarization (IP), and electromagnetic (EM) anomalies. However, these anomalies do not unambiguously indicate the presence of sulfide minerals. For the Stillwater Complex, variations in the magnetic field have been determined from regional aerial surveys that cover large areas and ground-based surveys that are restricted to smaller areas. Induced polarization and electromagnetic surveys conducted in the complex relied on ground-based measurements and were areally limited. Ground-based measurements of variations in the magnetic field have been successfully used to trace the location of units containing serpentinized olivine that are concealed by surficial deposits. IP anomalies in the complex were found to correspond to sulfide mineralization, fault zones, and unmineralized rock that contains serpentinized olivine, magnetite stringers, or disseminated graphite. EM surveys were conducted in areas of known mineralization to test the method; results were generally encouraging. Downhole geophysical surveys were not routinely performed. The results of exploration geophysical surveys are not illustrated in this report because there simply was not enough time to assemble all the information.

Ore controls/exploration guides--The solubility of sulfur in mafic magmas is affected by changes in the bulk composition of the magma, the fugacity of sulfur and oxygen, temperature, and pressure. Once a magma becomes saturated in sulfur, it can exsolve an immiscible sulfide liquid. Processes that change the solubility of sulfur and may cause an exsolution event include fractional crystallization of the silicate magma, mixing of magmas, assimilation of sulfur from sources external to the magma, and modification of magma composition by interaction with host rocks.

The best guide to ore is the presence of sulfide minerals and their alteration products. Sulfide mineralization may also be indicated by geochemical and geophysical anomalies. The equilibration and removal of sulfide liquid from the silicate magma may be indirectly recorded by nickel depletion in olivine.

Sulfide mineralization is commonly associated with: (1) abrupt variations in the cumulus mineral succession including major lithologic changes, reversals or changes in crystallization order, discontinuities in mineral fractionation patterns, and cyclic units, (2) rocks near the lower contact of the intrusion that may contain country rock xenoliths and may be characterized by irregular variations in grain size,

mineralogy, and texture, or (3) pegmatoids and rocks enriched in minerals that crystallize late from silicate magmas.

MAGMATIC SULFIDE MINERALS CONCENTRATED NEAR THE MARGINS OF INTRUSIONS (DEPOSIT TYPE-- STILLWATER NICKEL-COPPER)

Concentrations of disseminated to massive sulfide minerals are commonly found near the margins of mafic-ultramafic intrusions. Sulfide abundance is typically about 3 to 5 volume percent, but large tonnages of matrix and massive sulfide ores may be present. Erratic variation in the distribution of sulfide minerals is typical (sulfide minerals are not uniformly distributed), although, in a general sense, the concentration of sulfide minerals within the intrusion systematically increases towards its contact with its host rocks. Concentrations of sulfide minerals are commonly present in the country rocks adjacent to mineralized igneous rock. Commonly, igneous rocks hosting sulfide deposits are texturally and lithologically heterogeneous, exhibiting changes in texture and mineral proportions on a variety of scales (inches to tens of feet). Textures indicative of chilling or unidirectional growth may be present. Mineral fractionation patterns of ferromagnesian minerals commonly show magnesium enrichment trends up-section, away from the intrusive contact. Inclusions of country rock are commonly surrounded by igneous rocks that have textural, mineralogical, and isotopic features suggestive of reaction. Sulfur isotopic compositions of the sulfide deposits commonly indicate the presence of crustal sulfur. Concentrations of sulfide minerals and the tenor of the ores may be inconsistent with the volume of the silicate magma in the intrusion hosting the sulfide mineralization. In such cases, emplacement of magmas with large quantities of exsolved immiscible sulfide liquids may be indicated.

Deposits with Production

Platreef, Bushveld Complex, Republic of South Africa--PGE-enriched disseminated sulfide mineralization of the Platreef is found near the contact between the Bushveld Complex and its floor rocks in the Potgieterus area (Vermaak and von Gruenewaldt, 1981; Gain and Mostert, 1982). Economically exploitable resources are estimated at

329 million metric tons of ore averaging 5 ppm PGE, 0.3 wt. percent nickel and 0.2 wt. percent copper (Sutphin and Page, 1986). Projecting resources to a depth of 1,200 m (3,937 ft), Vermaak and von Gruenewaldt (1981) estimate the Platreef contains 4,080 million metric tons of ore with recovery grades of 3 ppm PGE, 0.36 wt. percent nickel and 0.18 wt. percent copper.

Other Significant Deposits or Occurrences

Copper-nickel-PGE mineralization, Duluth Complex, Minnesota.--Along a 31 mi distance at the base of the complex southeast of Ely, Minnesota, disseminated to massive sulfide mineralization occurs near the lower contact of Troctolite series intrusions. More than 4 billion metric tons of ore averaging 0.66 wt. percent copper and 0.2 wt. percent nickel have been identified, assuming a minimum thickness of 49 ft (15 m) and cutoff of 0.5 wt. percent copper plus nickel (Listerud and Meinike, 1977). Estimates for the overall platinum and palladium concentrations in various deposits are: Minnamax (Babbit)—0.140 to 1.446 ppm; Maturi (Duval)—0.200 to 2.01 ppm; Dunka Road—0.377 to 1.164 ppm; and Spruce Road—0.141 to 0.651 ppm (Barnes and others, 1985; Morton and Hauck, 1989; Schluter and Landstrom, 1976; Coombes, 1990; Listerud and Meinike, 1977).

Great Lakes nickel deposit, Crystal Lake Gabbro, Ontario, Canada.--Disseminated to massive sulfide mineralization is found at the base of the Crystal Lake Gabbro; 40.8 million metric tons of ore containing 0.34 wt. percent copper and 0.18 wt. percent nickel have been identified (Eckstrand and others, 1989). Average platinum plus palladium concentrations for 29 samples is 1.78 ppm (Hulbert and others, 1988).

Suhanko-Konttijärvi intrusion, Finland.--Disseminated to massive sulfide mineralization occurs in the marginal series of the Suhanko-Konttijärvi intrusion (Alapieti, Lalitinen, and others, 1989). Samples of disseminated sulfide mineralization in the Konttijärvi marginal series and the Suhanko marginal series have average concentrations of 4 ppm PGE, 0.22 wt. percent copper, and 0.10 wt. percent nickel and 1.8 ppm PGE, 0.18 wt. percent copper, and 0.16 wt. percent nickel, respectively. Pyrrhotite-dominant mineralization in the Suhanko intrusion forms numerous deposits, the largest of which, Vaaralampi, contains about 10 million metric tons of ore. Average PGE, copper, and nickel contents for samples of the massive sulfide mineralization are 1.7 ppm, 0.65 wt. percent, and 0.94 wt. percent, respectively.

Occurrence in the Stillwater Complex

Nickel-copper mineralization was discovered in the 1880's in the eastern part of the complex and occurs in the Basal series and lower part of the Peridotite zone of the Ultramafic series as well as in metasedimentary rocks adjacent to the complex. Extensive exploration work outlined subeconomic large-tonnage, low-grade deposits, prospects, and occurrences (table F1). From east to west, prospects and deposits (and companies that conducted most of the exploration) include: Fishtail Creek (Anaconda), Chrome Lake (Cyprus), Benbow (Anaconda), Nye Basin - east (Anaconda), Nye Basin - lip (Anaconda), Mouat nickel-copper (Anaconda), Initial Creek (Anaconda), Bluebird or Cathedral Creek (Anaconda), Crescent Creek (Anaconda), Crescent Peak (Anaconda), Iron Mountain - Iron Creek (AMAX), Iron Mountain - Camp deposit (AMAX), Forge Creek (Lindgren-Freeport-Cyprus), Contact Mountain - Hi claims (AMAX), Boulder River (includes Bobcat Creek and Gish areas and Nicon claim group - Anaconda).

Tract Delimiting Permissive Environment

The permissive tract for the Stillwater nickel-copper deposit type is drawn to include the near-surface extent of the Basal series and the Peridotite zone of the Ultramafic series (plate 14-B). The tract boundary was extended to include metasedimentary rocks where the lower contact of the complex is exposed because mineralization in the Stillwater Complex commonly extends into underlying metasedimentary rocks. Deposits tend to be localized toward the southern margin of the tract, near the lower, intrusive contact of the Stillwater Complex. If the tract outline was modified to show the areal extent of permissive rocks that are within a kilometer of the surface, the northern boundary of the tract would shift less than a kilometer to the north.

Geologic Factors That Localize Deposits

Deposits of this type are found near the lower intrusive contact of the Stillwater Complex, but processes that localize mineralization along the contact are not understood. Generally, significant sulfide mineral occurrences are present in the eastern part of the complex, where the overlying rocks of the Peridotite zone are the thickest, and in the Iron

Mountain area where the complex intrudes and contains xenoliths of iron formation.

Gravitational settling of droplets of immiscible sulfide liquid should localize mineralization in structural depressions in the lower contact. Geologists with several exploration companies have attempted either to locate primary troughs or footwall depressions that could contain undiscovered deposits or to relate known mineralization to them. So far, no one has demonstrated that higher proportions of sulfides in the rocks are related to irregularities in the lower contact of the complex. To the contrary, the distribution of sulfide minerals in the Mouat nickel-copper deposit in the Mountain View area is erratic and not obviously associated with topographic irregularities, troughs, or depressions along the basal contact (Zientek and others, 1989).

Assimilation of sulfur from sources outside an intrusion may cause a sulfide-liquid exsolution event; examples of magmatic sulfide mineralization that are located near an inferred source of sulfur include the deposits associated with the Moxie intrusion, Maine, (Thompson and Naldrett, 1984) and the Dunka Road deposit of the Duluth Complex, Minnesota (Ripley, 1986). This concept can be tested using the isotopic composition of sulfur. In rocks younger than about 2.0 b.y., biogenic fractionation of sulfur isotopes caused the isotopic composition of sulfur in sedimentary rocks to be significantly different than the isotopic composition of sulfur in mantle-derived magmas. As a result, variations in the isotopic composition of sulfur in magmatic sulfide minerals may indicate if crustally derived sulfur is present. Variations in sulfur isotopic composition are expressed in terms of $\delta^{34}\text{S}$, which is defined as:

$$\delta^{34}\text{S} = \left[\left(\frac{\frac{34}{32}\text{S}}{\frac{32}{34}\text{S}} \right)_{\text{unknown}} - \left(\frac{\frac{34}{32}\text{S}}{\frac{32}{34}\text{S}} \right)_{\text{standard}} \right] \times 1,000$$

where ^{34}S and ^{32}S are the concentrations of isotopes of sulfur with atomic masses of 34 and 32 respectively. Even though the sedimentary rocks adjacent to the complex show only slight fractionation of sulfide isotopes because of their age (older than 2.7 b.y.), $\delta^{34}\text{S}$ values for magmatic sulfide mineralization at the base of the complex is most like sulfide minerals in the iron formation near the complex and unlike sulfide minerals in other metasedimentary lithologies

and other mineralized rocks in the complex (Zientek and Ripley, 1990). Sulfur in the magmatic sulfide minerals near the base of the complex may in part be derived from iron formation. Magmatic sulfide mineralization of the Camp deposit, the Iron Creek area, and the Crescent Peak area is situated in the area where the Stillwater Complex is in contact with iron formation, suggesting that these deposits may be localized near the sulfur source. However, sulfide concentrations derived from magmas contaminated with crustally derived sulfur may be found some distance from possible sources of sulfur; an example is the Babbitt deposit, Duluth Complex, Minnesota (Ripley, 1986). This is also true for Stillwater; the majority of magmatic sulfide mineral occurrences near the base of the complex have $\delta^{34}\text{S}$ values similar to those in iron formation but are found in areas where iron formation is not present. If the sulfur was derived from iron formation, emplacement of the complex either chemically or mechanically removed all iron formation from these areas or magmas with crustally derived sulfur were transported laterally. In either case, the country rock adjacent to the complex cannot be used to predict the location of mineralization.

Barker (1975) proposed that bulk contamination of magma caused the exsolution of sulfide liquid that accumulated to form the mineralization near the base of the Stillwater Complex. Inclusions of metasedimentary rock are present in many of the areas where there is mineralization; however, spatial association between magmatic sulfide concentrations and the occurrence of metasedimentary xenoliths is difficult to demonstrate. In the Mouat nickel-copper deposit, xenoliths are quite common but cannot be related to the distribution of sulfide accumulations. The distribution and textures of the sulfide minerals in parts of this deposit indicate that sulfide liquids were transported to the site of emplacement (Page and others, 1985a).

Geologic and Exploration Activity Within Tract

Exploration programs have been conducted by several companies to characterize the nickel and copper resources near the base of the Stillwater Complex (Page and others, 1985b). Some of the resulting data are illustrated in plates 14-C and 14-D and summarized in table F1. Almost all the rocks along the base of the complex have been examined by methods that include geologic mapping at scales ranging from 1:1,200 to 1:12,000, aeromagnetic surveys, geochemical surveys, and ground-based

geophysical surveys (most typically IP). Bulldozer trenching was done in the Iron Mountain and Benbow areas, drilling was done in most places, exploratory adits were driven in the Nye Basin and Mountain View areas, and metallurgical test work was conducted on ores from the Mouat nickel-copper and Camp deposits and mineralization from Nye Basin and Chrome Lake. However, only the Mouat nickel-copper and Camp deposits are drilled in sufficient detail to calculate reserves; resources listed in table F1 for other prospects must be considered minimum values because mineralization has not completely delimited. The limited number of drill holes west of the East Boulder River (west of the Camp deposit) reflect the low grades and thin intercepts found in this part of the complex.

Sulfide mineralization is evident from the presence of disseminated to massive sulfide minerals in outcrop or the presence of weathered limonite-stained, gossany outcrops or soils. Copper anomalies in soils typically are over 200 ppm and locally may exceed 1,000 ppm. The areal extent of soil anomalies in excess of 200 ppm indicates the wide distribution and presence of sulfide minerals in both the Basal series and Peridotite zone (plate 14-C).

Efforts by Anaconda and Cyprus Minerals principally focused on mineralization in the Basal series in the Chrome Lake, Benbow, Nye Basin, Mountain View, Initial Creek, Bluebird-Cathedral Creek, and Crescent Creek areas. AMAX discovered sulfide mineralization within the lower part of the Peridotite zone in the Iron Mountain area and extended their geochemical and geophysical surveys in the Iron Mountain and Contact Mountain areas to include all the Peridotite zone in the area of their land holdings. Anaconda became aware of Peridotite zone mineralization from their own work in the Mouat nickel-copper deposit and through joint-venture discussions with AMAX after most of their geochemical surveys were completed. Anaconda drill tested some geophysical anomalies and geologic targets in the Peridotite zone but did not conduct systematic geochemical surveys over the Peridotite zone in their holdings. Cyprus made no systematic effort to test the potential for Peridotite zone mineralization in their holdings although several drill holes did penetrate the lowermost Peridotite zone.

Exploration activity was not restricted to mineralization that was exposed near the surface. The Chrome Lake prospect in the Benbow area is completely concealed beneath glacial deposits. Mineralization associated with the prospect on the east slope of Iron Mountain does not crop out and

was indicated by geophysical anomalies. Anaconda unsuccessfully attempted to intersect mineralization beneath the upper plate of thrust faults near the base of the complex in the Fishtail Creek (Cooper, 1985), Bluebird Peak, and Initial Creek areas.

Factors Affecting Exploration Success

With few exceptions, the Basal series of the complex is poorly exposed. Poor color contrast between minerals, fine-grain size, and weathering hindered lithologic identification and interpretation. Thrust-cored folds near the base of the intrusion form complex fault and layering geometries. Geophysical surveys produced many anomalies not directly related to sulfide mineralization. Some IP anomalies were found to correspond to faults and serpentized, deformed olivine-rich ultramafic rock that contain closely spaced subparallel secondary magnetite veinlets. EM surveys were not routinely utilized because they were difficult to run and correct for terrain. Results of aeromagnetic surveys were dominated by the presence of iron formation in the footwall of the complex.

Geologic Factors Affecting Resource Development

Low copper and nickel grades.--The copper and nickel grade of the mineralization found near the base of the complex is low. For some prospects, resources estimates were made at different cut-off values in order to consider the potential for either a low grade-high tonnage deposit that would be amenable to open-pit mining or a higher grade but lower tonnage deposit that would be amenable to selective, underground mining techniques (table F1). In either case, grades determined for the deposits and prospects near the base of the complex are substantially lower than grades for principal nickel-producing districts and deposit types (table F4).

Low concentration of PGE.--The economics of deposits can be enhanced by the presence of elements that can be produced as a by-product of mining. The copper and nickel grades and geology of the Stillwater deposits and prospects are similar to the Platreef of the Bushveld Complex. The Platreef was mined from 1926 to 1930 (Buchanan, 1987) and a new mine is planned at the PPRust project near Potgietersrus because these ores have high concentrations of PGE (Coombes, 1992). Ores that comprise the Platreef contain about 5 ppm PGE. When the Stillwater

Table F4.--Cu and Ni grades for Ni-producing districts and deposit types

Deposit or mineral deposit model	Cu, wt. percent	Ni, wt. percent
Oktyabr'sk deposit, Noril'sk-Talnakh district, Russia	4.7 ²	3.65 ²
Sudbury district, Ontario, Canada	0.8 to 1.03 ¹	1.25 to 1.5 ¹
Talnakh deposits, Noril'sk-Talnakh district, Russia	3.0 ²	1.5 ²
Komatiite nickel-copper - Model 6a	0.094 ³	1.5 ³
Jinchuan, Peoples Republic of China	0.5 - 0.6 ²	1.1 ²
Selebwe-Pikwe district, Botswana	0.86 ¹	1.06 ¹
Dunitic nickel-copper - Model 6b	0.14 ³	1.0 ³
Synorogenic-synvolcanic Ni-Cu - Model 7a	0.47 ³	0.77 ³
Noril'sk deposit, Noril'sk-Talnakh district, Russia	0.8 ²	0.5 ²
Lateritic Ni - model 38a	--	1.4 ³

¹ Grade based on cumulative production (DeYoung and others, 1985).

² Grade of resources (DeYoung and others, 1985).

³ Median grade reported in Cox and Singer (1986).

deposits and prospects were evaluated, PGE concentrations were not systematically determined for mineralized samples. Some information was obtained by the analysis of flotation concentrates (table F5), composite samples, and select rock samples (Page and others, 1976). Subsequently, the U.S. Geological Survey analyzed drill core samples and composite splits from the Chrome Lake area, the Benbow area, the Mouat nickel-copper deposit, the Crescent Creek

area, and the Iron Mountain area (Zientek and others, 1986, and unpublished data summarized in table F6).

Two observations can be made on the available PGE data for mineralized rock near the base for the complex. First, PGE concentrations are low compared to ores from the Platreef and the other deposits described earlier. Median concentrations of platinum and palladium for samples of disseminated, matrix, or massive ore from the Chrome Lake,

Table F5.--Analyses of sulfide concentrates from Ni-Cu mineralization in the Nye Basin and Iron Mountain areas, Stillwater Complex

	Fe, wt %	Cu, wt %	Ni, wt %	Pt, ppb	Pd, ppb	Rh, ppb	Au, ppb	Ag, ppm
NB17A 724-802 flotation concentrate (Cooper, 1980)	47.7	2.74	1.49	480	205	--	--	--
Bulk concentrate prepared by Lakefield research for AMAX (A.G. Scobie, written commun., 1973)	--	6.55	8.54	3390	3630	170	680	8.67

Table F6.--Pt, Pd, and Rh contents of sulfide mineralization near the base of the Stillwater Complex. Summary statistics are for uncensored values only

Area and stratigraphic unit	Total samples analyzed (number below limit of determination Pt, Pd, Rh)		90% have at least (ppb)	50% have at least (ppb)	10% have at least (ppb)	Maximum value (ppb)
Samples with S between 0.1 and 3.5 wt. percent (disseminated ores)						
Chrome Lake Basal series	82 (0,1,40)	Pt Pd Rh	29.3 27 2.2	7 11 1.1	2.7 4.6 0.6	52 41 2.7
Benbow Basal series	105 (0,0,36)	Pt Pd Rh	17 20 1.34	7.5 10 0.8	2.8 3.8 0.5	600 51 3.3
Mouat Basal series	32 (6,1,26)	Pt Pd Rh	30.4 34.4 1.98	7.15 15 1	1.46 3.76 0.50	140 78 2
Mouat Mafic norite in footwall	13 (1,1,10)	Pt Pd Rh	23.3 18 -	7.55 7.5 0.6	2.7 2.29 -	24 18 7
Crescent Peak Basal series	64 (0,0,33)	Pt Pd Rh	29.8 71.7 2.74	7.2 16.5 1.4	2.45 3.77 0.6	65 180 8
Iron Mountain Basal series	51 (0,0,0)	Pt Pd Rh	170 632 35.4	34 80 6.5	15 24.8 1.72	550 1400 79
Iron Mountain Peridotite zone	14 (5,5,5)	Pt Pd Rh	80.8 490 18.4	17 64 2.4	8.4 23.8 1.02	88 570 20
Samples with S between 0.1 and 3.5 wt. percent (disseminated ores)						
Benbow Basal series	10 (0,0,0)	Pt Pd Rh	24 86 3.4	7.15 21 1.5	2.7 13.5 0.85	24 92 4.5
Mouat Basal series	20 (10,0,11)	Pt Pd Rh	41 44.5 16.4	3.3 13 8.1	1 2.85 1.94	62 83 18
Mouat Mafic norite in footwall	48 (5,0,25)	Pt Pd Rh	12 40.7 1.68	4.2 14.5 1	1.2 8.12 0.68	49 130 9

Table F6.--Pt, Pd, and Rh contents of sulfide mineralization near the base of the Stillwater Complex. Summary statistics are for uncensored values only (continued)

Area and stratigraphic unit	Total samples analyzed (number below limit of determination Pt, Pd, Rh)		90% have at least (ppb)	50% have at least (ppb)	10% have at least (ppb)	Maximum value (ppb)
Samples with S between 3.5 and 21 wt. percent (net-textured ores)						
Crescent Peak Basal series	26 (0,1,7)	Pt Pd Rh	23.7 92 4.6	3 22 1.5	1.61 7.8 0.64	130 120 13
Crescent Peak Mafic norite in footwall	7 (0,0,1)	Pt Pd Rh	54.4 59.4 7.36	7.4 29 2.2	1.56 13.8 0.64	64 65 7.8
Iron Mountain Basal series	13 (0,0,0)	Pt Pd Rh	81.2 980 42.2	25 190 28	3.38 63.6 5.58	230 1700 47
Iron Mountain Peridotite zone	5 (0,0,0)	Pt Pd Rh	420 1200 39	25 980 24	3.1 690 18	420 1200 39
Samples with S greater than 21 wt. percent (massive ores)						
Mouat Mafic norite and massive sulfide	17 (1,0,5)	Pt Pd Rh	8.98 78.6 4.1	3.05 22 1.3	1 9.16 0.87	150 410 9
Iron Mountain Basal series	6 (1,1,1)	Pt Pd Rh	110 1400 61	6.5 120 49	1.7 52 42	110 1400 61
Iron Mountain Peridotite zone	7 (2,2,2)	Pt Pd Rh	530 2900 100	78 1600 72	3.5 1500 58	530 2900 100

Notes for table. PGE analyses by U.S. Geological Survey. Values for Chrome Lake, Benbow, and Iron Mountain are based on analysis of pulps of composited drill core, whereas values from Mouat and Crescent Peak are based on hand-specimens of drill core. Drill holes sampled are: Chrome Lake - ST-11 and ST-12; Benbow - BB-7; Iron Mountain - 355-1, 355-16, 355-59, and 355-64; Mouat - M-14, M-17, M-19A, M-20, 368-313, 370-316, 373-322, 378-338, 383-334, 384-326, 384-333, 386-332, and 387-339; Crescent Peak - CC-1 and CC-2.

Benbow, Mountain View, and Crescent Peak areas range from a few ppb to tens of ppb. Second, PGE concentrations in mineralized rock from the Iron Mountain area are significantly higher than deposits and prospects in the eastern part of the complex. Even though median platinum and palladium abundances range from tens of ppb to over 1,000 ppb, concentrations of PGE in the sulfide mineralization from Iron Mountain area are still low relative to the examples of mineralization given earlier. PGE concentrations of the mineralization near the base of the complex will not significantly contribute to the value of, or interest in, these deposits in the foreseeable future.

Summary results as presented in table F6 can obscure trends or spatial patterns in the data. Closely spaced samples were analyzed from three drill holes in the eastern part of the complex to determine if local concentrations of PGE may be present. Plots of platinum plus palladium versus depth for drill holes ST-11 (Chrome Lake area, figure F2), BB-7 (Benbow area, figure F3), and 373-322 (Mouat nickel-copper deposit, figure F4) show that local enrichments of PGE are present, but absolute values are not high enough to be economically viable in the near future. Sampling strategies based upon macroscopic observations that would selectively test those parts of deposits and prospects likely to be enriched in PGE cannot be devised using the information in these boreholes; samples with maximum concentrations of platinum and palladium are not distinguished by either the sulfur [sulfide minerals] or chromium [chromite] contents of the rocks or their stratigraphic position. If known mineralization is to be evaluated for local concentrations of PGE, an extensive and systematically collected suite of samples from all deposits and prospects must be analyzed.

The drill hole data also show that the platinum and palladium contents in sulfide minerals are lowest for those rocks that have the highest proportion of ore minerals. In holes ST-11 and 373-322 (figs. F2 and F4), decreasing upwards trends in sulfur concentrations are accompanied by increasing upwards trends in whole-rock concentrations platinum and palladium. Despite the complex and erratic patterns seen in figure F3, a similar relationship is also true for drill hole BB-7. This indicates that rocks with the highest copper and nickel concentrations (highest proportion of sulfide minerals) have the lowest platinum and palladium concentrations.

Poor continuity.--The continuity of mineralization reflects both the primary distribution of sulfide accumulations as well as the effects of subsequent

deformation. Higher grade, discontinuous concentrations of massive sulfide minerals are found in the prospects and deposits in the eastern part of the complex and in the Iron Mountain area. The dimensions of the largest higher grade mineralized zone investigated by Anaconda in the 1930's in the Mountain View area (Red Bird zone) are 590 ft long by 890 ft deep by 250 ft wide (Hart, 1938). Studies by Zientek and others (1989) confirmed that the largest higher grade mineralized zones are of these approximate dimensions but also document massive sulfide mineralization that forms lenses or veins that extend only a few meters.

Ore reserves for the Mouat nickel-copper deposit were calculated in the early 1970's, prior to use of statistically based methods. In the early 1980's, the U.S. Geological Survey entered into a cooperative project with Anaconda; one objective was to calculate statistically the reserves of higher grade mineralization in the Mouat nickel-copper deposit. Attempts to use the kriging method for ore reserve estimation were unsuccessful; variograms indicated the area of influence around a drill hole was less than the drill spacing. This is entirely consistent with the discontinuous nature of the higher grade mineralization noted by Hart (1938), Roby (1949), and Zientek and others (1989). Only two small parts of the Mouat nickel-copper deposit had the lithologic integrity to allow an estimate of contained resources using more traditional methods (table F1; Attanasi and Bawiec, 1987).

Massive sulfide mineralization is also discontinuous in the other deposits and prospects; intercepts of massive sulfide mineralization are difficult to correlate in fan drilling and step off drilling in Benbow, Nye Basin, and the Iron Mountain areas. The continuity of massive sulfide mineralization in the Iron Creek prospect area near Iron Mountain was tested by downhole geophysical methods (mise-a-la-masse, in-hole, and radial IP measurements); laterally continuous conductive zones were not found (F.P. Fritz, written commun., 1978).

The discontinuous and irregular distribution of massive sulfide mineralization indicates resource estimates based upon the simple projection of high-grade intercepts in drill core over substantial distances are suspect. Disseminated mineralization within cumulates near the base of the complex are more continuous than massive sulfide mineralization. However, significant changes in thickness of disseminated mineralization can take place over short distances.

The local continuity of disseminated and massive mineralization is also affected by subparallel faults

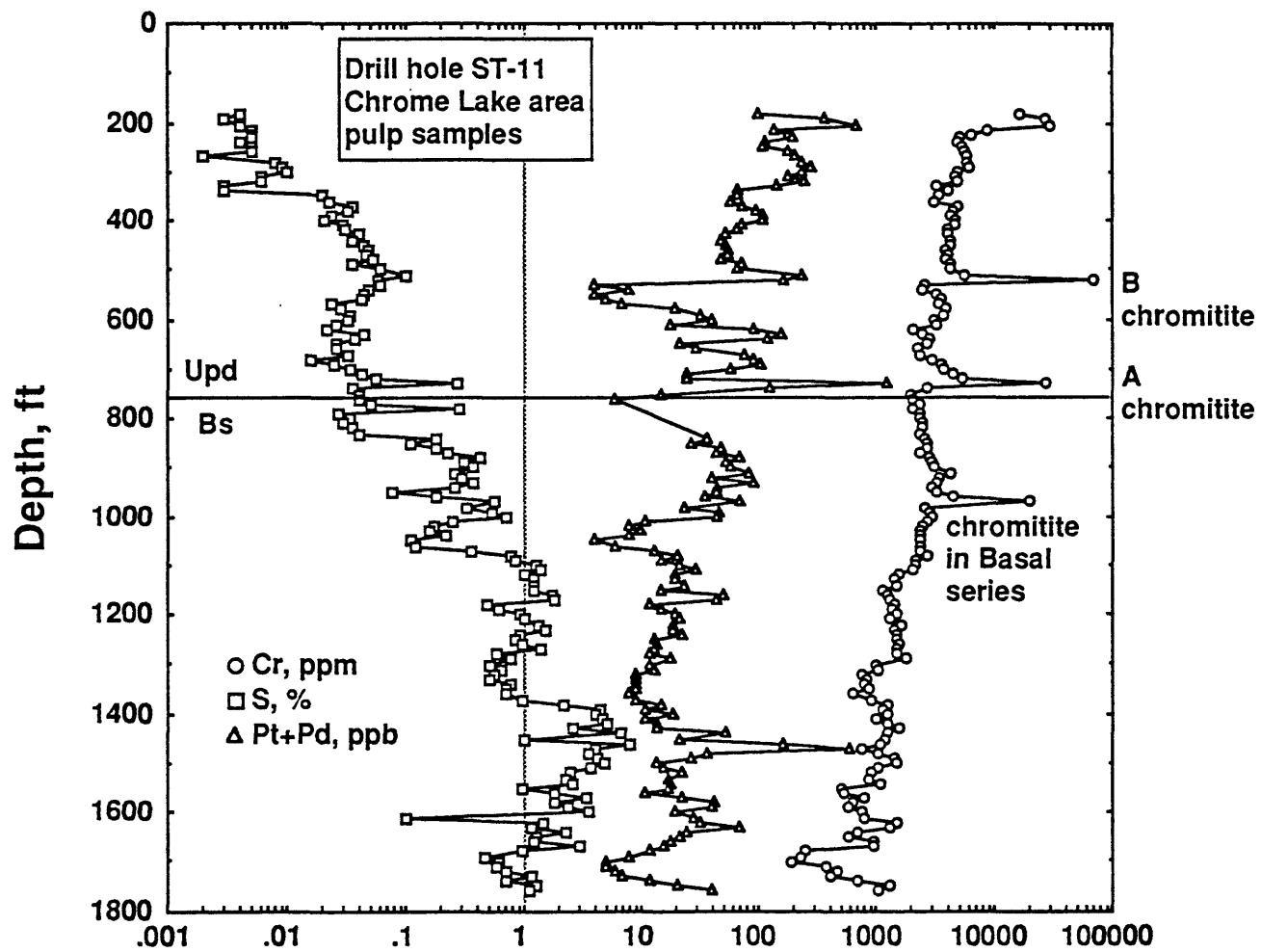


Figure F2.--Downhole variation in Cr, S, and Pt+Pd in drill hole ST-11, Chrome Lake area, Stillwater Complex. Analyses are on composite samples of split drill core through the lower part of the Peridotite zone (Upd) and the upper part of the Basal series (Bs).

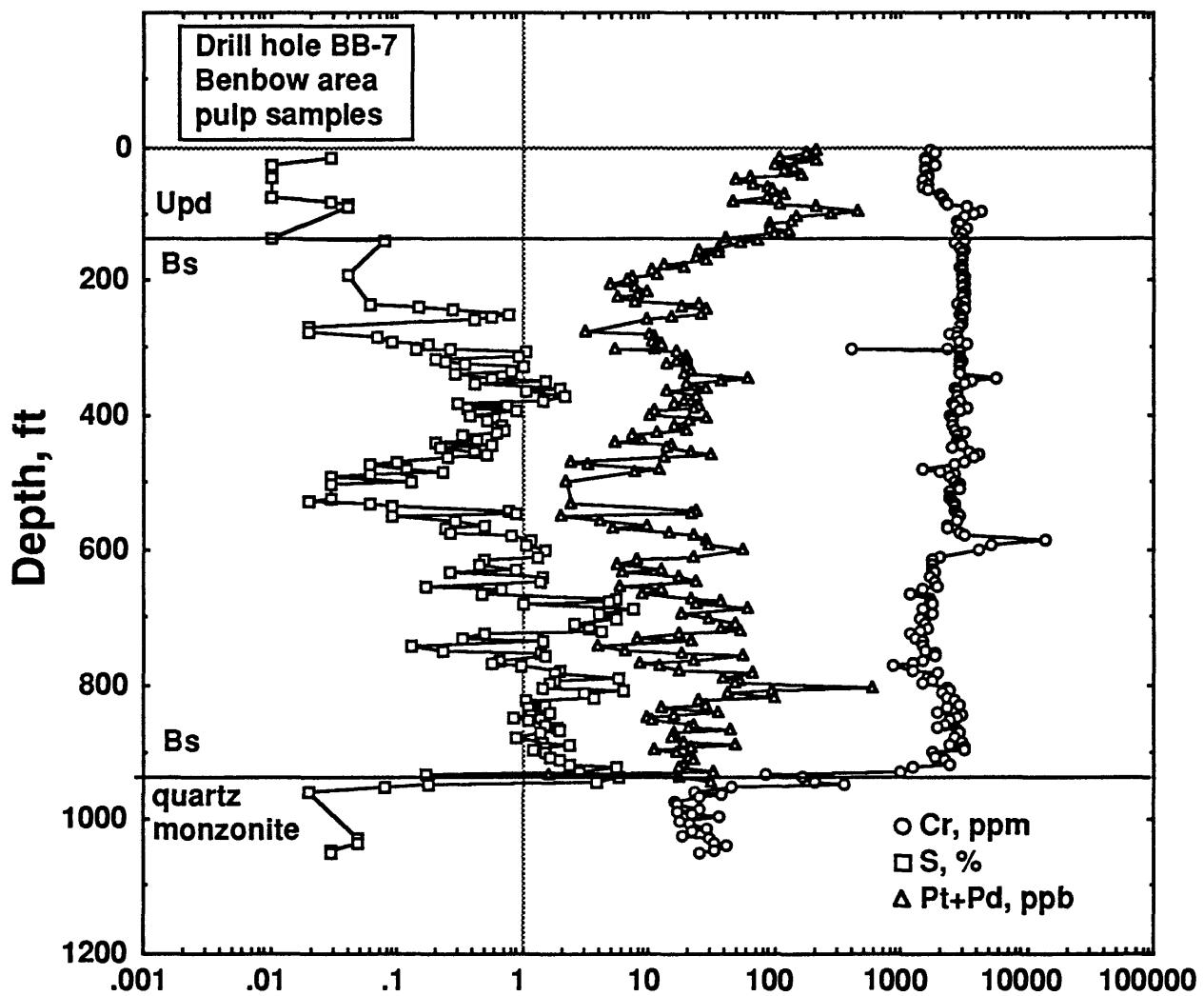


Figure F3.—Downhole variation in Cr, S, and Pt+Pd in drill hole BB-7, Benbow area, Stillwater Complex. Analyses are on composite samples of split drill core through the lower part of the Peridotite zone (Upd), the Basal series (Bs), and quartz monzonite intruding rocks near the base of the Stillwater Complex.

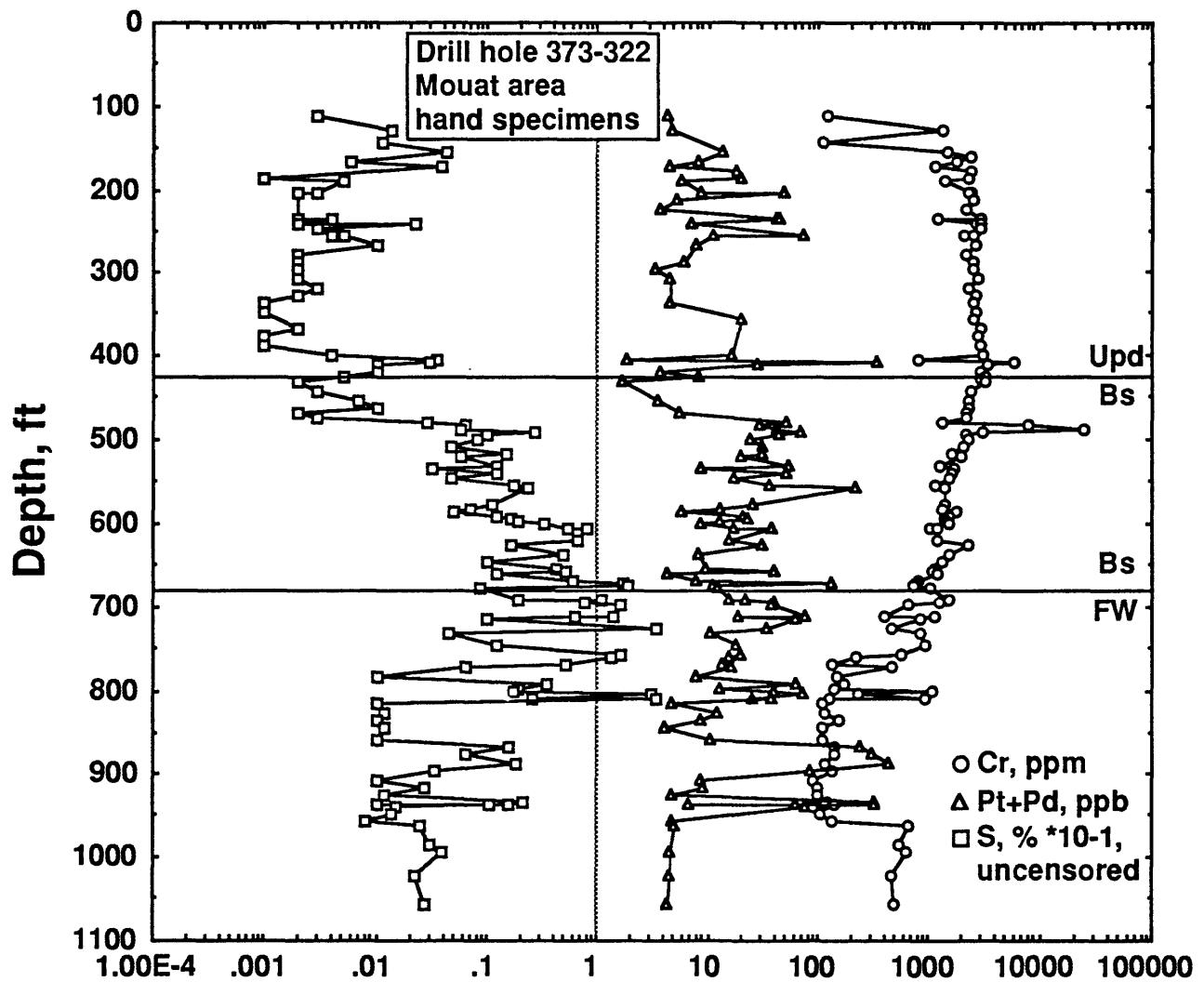


Figure F4.—Downhole variation in Cr, S, and Pt+Pd in drill hole 373-322, Mouat area, Stillwater Complex. Analyses are of hand samples of split drill core through the lower part of the Peridotite zone (Upd), the Basal series (Bs), and metasedimentary rocks intruded by Stillwater associated sills and dikes (FW).

that are normal to layering, vary in dip from about 50° to vertical, and for a given area, have the same sense of offset. These faults are evident at all scales. At the outcrop scale, subparallel fractures spaced several feet apart may show offsets ranging from inches to feet. Faults with more substantive offset (tens of feet) are spaced 50 to 650 ft apart and faults with offsets measured in hundreds of feet are spaced 2,000 to 5,000 ft apart. This style of faulting is clearly seen on outcrop maps of rocks near the base of the complex (Howland and others, 1949; Jackson and others, 1954; Peoples and others, 1954; Howland, 1955; Zientek and others, 1989). Exploration programs, resource estimation, and mine plans were and will be adversely affected by this type of faulting.

Unfavorable metallurgy.--Metallurgical investigations on the sulfide mineralization near the base of the complex were conducted or supported by the U.S. Bureau of Mines, Anaconda, Cyprus, and AMAX (table F7). The mineralogy of ores near the base of the complex is dominated by pyrrhotite which contains substantial amounts of nickel in solid solution (typically from 0.1 to 0.4 wt. percent; Humphreys, 1983). Pentlandite, a nickel-bearing mineral, and chalcopyrite, the principal copper-bearing mineral, are fine grained and intimately intergrown with pyrrhotite. One beneficiation scheme is to make copper-rich (chalcopyrite) and nickel-rich (pentlandite) separates by flotation. In order to liberate chalcopyrite and pentlandite from pyrrhotite, the rocks must be ground to a fineness of 200 to 400 microns. The fine grain size causes problems in the flotation process. Recoveries were low, particularly for nickel, because a substantial amount of this element is present in solid solution in pyrrhotite. Several studies focused on producing a bulk sulfide concentrate by conventional comminution-flotation procedures. The concentrates produced are high in iron and low in nickel and copper. Nickel recoveries are again generally lower than copper. Recoveries for nickel and copper were enhanced by pulling a larger weight fraction into the concentrate, regrinding and cleaning of the concentrate, and putting the concentrate through magnetic separation circuits. Despite these efforts, concentrates that would be appropriate for conventional smelting technology could not be produced. Metallurgy was also affected by the presence of nickel-bearing silicates, magnetite, and talc (which interferes with the flotation process). Technologies (hydrometallurgical or pyrometallurgical) used for treating pyrrhotite-rich mineralization are generally more expensive and were not investigated in detail. Anaconda conducted experiments using hydrometallurgical processes and

achieved over 95 percent recovery for both copper and nickel but the greater cost of the method was not warranted by value of the metal in the rock.

Partially Delimited or Undiscovered Deposits— Location and Potential Resources

The largest proportion of geologic resources that have not been defined by exploration are in extensions to known prospects or deposits (420 million metric tons of mineralized rock that may contain 0.28 wt. percent copper and 0.29 wt. percent nickel); a smaller amount may be in "undiscovered" deposits that are fault-offset extensions of known deposits or prospects (78 million metric tons; tables F8, F9, and F10). Mineralization in the Basal series and the Peridotite zone represent two different exploration targets and will be considered separately.

Basal series.--Almost all the areas where the Basal series may be exposed in the near surface have been explored. The exceptions are a few areas where the rocks are poorly exposed, covered by surficial deposits, or lie beneath high-angle reverse faults. One obvious area is between Crescent Creek and the West Fork of the Stillwater River. The Peridotite zone is exposed in cliffs north of the West Fork of the Stillwater River in this area suggesting the Basal series lies beneath talus and alluvial deposits near the bottom of the valley. The Basal series may be close to the surface but covered by rocks in the upper plate of high-angle reverse faults in the Fishtail Creek, Initial Creek, and Cathedral Creek areas. Efforts to drill through upper plate rocks to test the Basal series in these areas have been unsuccessful. With the lack of interest in known deposits and prospects, further efforts to test these targets are unlikely. No resource estimate was made for these areas.

Resources of the Chrome Lake and Benbow prospects have only been partially delimited by widely spaced, near-surface drilling (table F1 and plate 14). Surface mineralization can be projected down-dip because no faults have been mapped that would truncate the mineralization. Calculation of resources was made by multiplying areas measured from geologically constrained long-sections by assumed horizontal thickness of mineralized rock and appropriate tonnage factors. Potential resources listed in table F9 are large compared to the drill-indicated resources. Mineralization in the Crescent Creek area and the area along Forge Creek west of the East Boulder River may not be truncated at depth by high-angle reverse faults; however, no resource estimates were

Table F7.--Results of metallurgical studies of Ni-Cu ores near the base of the Stillwater Complex

	Bulk sample or head concentration, %		Concentrate analyses, %			Recovery, %		
Comminution and flotation to produce Cu-rich and Ni-rich concentrates								
Source of material	Ni	Cu	Cu	Ni	Fe	Cu	Ni	
North Mouat prospect - bulk samples from adits ¹	0.75	1.28	16.1	2.2	43	60.6	15.6	copper concentrate
	0.75	1.28	0.8	0.9	51	35.3	72.7	Ni-Fe concentrate
Chrome Lake - composite of samples from ST-4 ²	0.18	0.22	22	--	--	47	-	copper concentrate
	0.18	0.22	--	7.4	--	-	16	Ni-Fe concentrate
Comminution and flotation to produce a bulk Cu-Ni concentrate								
Source of material	Ni	Cu	Cu	Ni	Fe	Cu	Ni	
Iron Mountain area - composite sample from drill core ³	0.48	0.3	0.92	1.24	43.4	87.1	78.6	Test 6G7
	0.48	0.3	0.66	0.96	32.0	92.1	90.7	Test 45M6
	1.24	0.54	1.2	2.7	47.1	88.8	86.4	Test 6G8
Mouat deposit - composite from drill hole samples ⁴	--	--	--	--	--	>85%	<50 to 75%	
Comminution, flotation, roast with Na_2CO_3 , acid leach								
Source of material	Ni	Cu	Cu	Ni	Fe	Cu	Ni	
Nye Basin prospect- composite sample from drill hole NB17A ⁵	0.47	0.49	2.74	1.49	48	>95% recovery of both Cu and Ni		

¹ Roby (1949).

² E.A. Schmidt and G.R. Priest (written commun., 1975).

³ A.W. Gorman, A.E. Meyer, and G.J. Jansen (written commun., 1970).

⁴ Miller (1970).

⁵ Cooper (1980).

Table F8.--Estimate of geologic resources associated with Basal series Ni-Cu mineralization and with the G chromitite in the Nye Basin and Mountain View areas, Stillwater Complex. Horizontal width of mineralization assumed to be 50 ft for Ni-Cu mineralization and 5 ft for the G chromitite

Ni-Cu mineralization				
Area	Hanging wall - millions of tons of ore (millions of metric tons)	Comments	Footwall - millions of tons of ore (millions of metric tons)	Comments
Upper Nye Basin (from Big Seven fault to unnamed fault west of Nye adit)	71 (65)	Most ore above 5,000 ft. Mineralization cut off at progressively higher elevations to west.	50.5 (46)	Ore at shallowest elevations (5,000 - 6,000 ft) near Nye adit. Below 1,720 ft at Big Seven fault.
Nye Lip/Alice Lode (from unnamed fault west of Nye adit to fault at Nye lip)	58 (52)	Mineralization cut off between 4,000 and 5,000 ft.	9 (8)	Ore shallowest (3,000 ft) near the fault close to Nye adit. Below 1,720 ft at Nye Lip.
Mountain View	42.9 (39)	Extensions to drill indicated resources of 145 (132).	27 (24)	Ore between Stillwater River and unnamed fault east of Mouat mine site below 1,720 ft; truncated by Horseman fault. Top of ore between unnamed fault and continuing under Mouat mine site at elevations between 2,000 and 3,000 ft.
G chromite seam				
Upper Nye Basin (from Big Seven fault to unnamed fault west of Nye adit)	0.19 (0.17)	Ore above 7,500 ft near the Big Seven fault.	13 (11.7)	Ore at shallowest elevations (approx. 7,000 ft) near Nye adit. Below 4,000 ft at Big Seven fault.
Nye Lip/Alice Lode (from unnamed fault west of Nye adit Stillwater valley)	0.29 (0.26)	Mineralization present west of fault near Nye Lip.	6.4 (5.8)	Ore shallowest (4,000 ft) near the fault close to Nye adit. Below 3,000 ft at Nye Lip.
Mountain View	19.2 (17.4)		11.7 (10.6)	Ore between Stillwater River and unnamed fault east of Mouat mine site below 3,000 ft; truncated by Horseman fault. Top of ore between unnamed fault and continuing under Mouat mine site at elevations between 4,000 and 5,000 ft.

Table F9--Resources for Stillwater Ni-Cu, Bushveld Cr, and Merensky Reef PGE deposit types defined by exploration activity relative to total potential resource. Potential resources are projected to elevation of 1,720 ft. See also tables F1, 2, 3, and 8

Area	Resources constrained by surface sampling, drilling, or underground exploration - millions of short tons (millions of metric tons)	Grade	Potential resource - millions of short tons (millions of metric tons)	Comments
Stillwater Ni-Cu (Basal series Ni-Cu mineralization)				
Chrome Lake area	34 (30.9)	0.523 % Cu + Ni	128 (116) ¹	Assume horizontal width of mineralization equal to 50 ft. Resource determined by exploration not limited to this width.
Benbow area	10.2 (9.26)	0.26 % Cu 0.25 % Ni	208 (189) ¹	Assume horizontal width of mineralization equal to 50 ft. Resource determined by exploration not limited to this width.
Nye Basin area - upper plate of thrust fault	21.4 (19.4)	0.25 % Cu 0.22 % Ni	153 (138) ¹	Assume horizontal width of mineralization equal to 50 ft. Resource determined by exploration not limited to this width.
Nye Basin area - lower plate of thrust fault	none	—	59 (54) ¹	Assume horizontal width of mineralization equal to 50 ft.
Mountain View area - lower plate of thrust fault	none	—	26.7 (24.2) ¹	Assume horizontal width of mineralization equal to 50 ft.
Mountain View area - upper plate of thrust fault	145 (132)	0.29 % Cu 0.31 % Ni	42.95 (39) ^{1*}	* Mouat deposit has been extensively tested to 5,000 ft elevation; horizontal widths of mineralization range from 100 to 500 ft. Below elevation of 5,000 ft, resource is calculated assuming a horizontal width of mineralization equal to 50 ft.
Bushveld Cr (G-chromite seam)				
Benbow area - G chromitite	1.2 (1.1)	22.7 wt % Cr ₂ O ₃	19.8 (18.0) ²	
Nye Basin area - G chromitite in upper plate of thrust fault	0.04 (0.04)	21.2 wt % Cr ₂ O ₃	0.48 (0.43) ¹	Assume horizontal width of mineralization equal to 5 ft. Resource determined by exploration not limited to this width.
Nye Basin area - G chromitite in lower plate of thrust fault	none	—	19.4 (17.6) ¹	Assume horizontal width of mineralization equal to 5 ft.
Mountain View area - G and H chromitite in upper plate of thrust fault	19.2 (17.4)	23.0 wt % Cr ₂ O ₃	--	Deposit open at depth to northwest but limited potential for additional resources because of convergence of thrust faults.
Mountain View area - G chromitite in lower plate of thrust fault	none	--	11.7 (10.6) ¹	Assume horizontal width of mineralization equal to 5 ft.
Merensky Reef PGE (J-M Reef)				
Entire complex	less than 128 (116) ⁴	0.55 opt Pd + Pt	318 (289) ³	⁴ Estimate for surface to proposed adit levels based on data provided by Stillwater PGM Resources. For some areas, there is drill control from the surface to the adit level; in other areas, data is restricted to the near-surface and results have been extrapolated over considerable distances to the adit level.

¹ Resources determined to elevation of 1,720 ft (520 m). Long section constructed at 1:24,000. Area on section determined by computer graphics program. Horizontal width of mineralization used in calculation of volume indicated under comments. Tonnage factor of 9 cubic feet per ton was used.

² Based on extending resource estimates by Turner (1979) given in table F2 to elevation of 1,720 ft (520 m).

³ Based on geologic resource calculations by Stillwater PGM Resources (written commun., 1992). See text for additional information.

Table F10.--Summary by deposit type and commodity (reported in metric tons of metal) of resources associated with the Stillwater Complex. Resource estimated to elevation of 1,722 ft above sea level. Numbers rounded to two significant figures. Summarized from data in tables F1, 2, 3, 8, and 9

Resource constrained by surface sampling, drilling, or underground exploration - millions of short tons (millions of metric tons)	Potential resources in extensions of identified deposits - millions of short tons (millions of metric tons)	Resource potential for undiscovered deposits - millions of short tons (millions of metric tons)
Stillwater Ni-Cu (Chrome Lake, Benbow, Nye Basin, and Mountain View areas) - Custer National Forest		
210 (190) at 0.28 % Cu and 0.29 % Ni	470 (420)	86 (78)
Stillwater Ni-Cu (Camp deposit) - Gallatin National Forest		
6.4 (5.8) at 0.23 % Cu and 0.42 % Ni		
Bushveld Cr (Benbow, Nye Basin, and Mountain View areas) - Custer National Forest		
20 (19) at 23.0 Cr ₂ O ₃	19 (17)	31 (28)
Merensky Reef PGE (J-M Reef)		
Entire complex		
≤ 130 (120) at 0.55 opt Pt+Pd	190 (170)	--
Custer National Forest		
≤ 84 (76) at 0.52 opt Pt+Pd	87 (79)	--
Gallatin National Forest		
≤ 44 (40) at 0.57 opt Pt+Pd	97 (88)	--

	Custer National Forest			Gallatin National Forest			Total
	1	2	3	1	2	3	
Stillwater Ni-Cu							
Nickel	550,000	1,200,000	230,000	27,000	unable to estimate	unable to estimate	1,430,000
Copper	530,000	1,200,000	220,000	15,000	unable to estimate	unable to estimate	1,420,000
Bushveld Cr							
Chromium as Cr ₂ O ₃	4,300,000	4,000,000	6,500,000	--	--	--	10,500,000

Table F10 (continued).--Summary by deposit type and commodity (reported in metric tons of metal) of resources associated with the Stillwater Complex. Resource estimated to elevation of 1,722 ft above sea level. Numbers rounded to two significant figures. Summarized from data in tables F1, 2, 3, 8, and 9

	Custer National Forest			Gallatin National Forest			Total
	1	2	3	1	2	3	
Merensky Reef PGE (J-M Reef)							
Palladium	1000	1100	--	600	1300	--	2400
Platinum	310	320	--	180	390	--	710
Gold*	19	19	--	11	24	--	43
Rhodium*	11	11	--	6	13	--	24
Copper*	19,000	20,000	--	11,000	24,000	--	44,000
Nickel*	27,000	28,000	--	16,000	35,000	--	63,000

1 Resource constrained by surface sampling, drilling, and underground exploration. Numbers for the J-M Reef are geologic resources thought to be present between surface outcrops and proposed adit levels.

2 Resource potential for extensions of identified deposits.

3 Resource potential for undiscovered deposits.

* By-product metal resources estimated from metal ratios derived from data in R.W. Wallace (written commun., 1990) for concentrate and smelter products of the Stillwater mine, Thompson (1987), and Naldrett (1989).

made because of the low grades indicated by surface drilling.

Other prospects and deposits are in the upper plate of high-angle reverse faults that developed during Laramide fold-thrust foreland deformation and cut the lower part of the complex (plate 14-E). Rocks hosting mineralization are truncated by these high-angle reverse faults at depth. Resources can be estimated for extensions of partially delimited mineralization in the upper plate of these faults as well as for "undiscovered" deposits that could occur in the footwall of these structures. The amount of offset across the high-angle reverse faults is difficult to estimate because dips are variable due to folding, the high-angle reverse fault may be offset along transverse faults, there is little data on the dips of the faults and how dips change with depth, and there are multiple generations of high-angle reverse faults.

Although sulfide mineralization is present in almost all exposures of the Basal series, the proportion of sulfide minerals and grade is not uniform along strike. The largest concentrations of sulfide minerals are known from the eastern part of the Stillwater Complex, extending from the Chrome Lake area to the Mouat nickel-copper deposit. Likewise, the area extending from the East Boulder River to the western limit of the Stillwater Complex is characterized by sparse, low-grade mineralization. Because sulfide distribution patterns extend laterally for several miles on the surface, mineralization in the footwall of the high-angle reverse faults is assumed to be similar to mineralization in overlying upper plate rocks. On that basis, favorable areas for undiscovered deposits would be the footwall of the Nye Basin fault between the Stillwater river valley and the Big Seven fault, the footwall of the Lake fault in the Mountain View area, and the footwall of many poorly constrained faults in the Iron Mountain area. Mineralized rocks west of the Camp deposit near Iron Mountain also occur in the upper plate of high-angle reverse faults. No effort was made to constrain the size or location of undiscovered offset deposits because of the low grades typical of these prospects.

Faulting limits the size of known deposits and prospects and the magnitude of undiscovered resources that could be anticipated in the Nye Basin and Mountain View areas; resource estimates for extensions to deposits and prospects in the upper plate rocks and "undiscovered" deposits in the footwall rocks are summarized in table F8. Calculations were made by multiplying areas measured from geologically constrained long-sections by assumed horizontal thickness of mineralized rock and appropriate tonnage

factors. A number of assumptions were made in order to make the calculations. A horizontal width of mineralization of 50 ft was assumed. The orientation of faults was based on measurements taken from the surface and underground workings or calculated from drill hole intercepts (Jones and others, 1960; Page and others, 1985a) and assumed to remain constant. However, if dip of the fault changes with depth, resource estimates will be affected. For example, if the dip of the high-angle reverse fault is shallower than used in the calculations, the intersection of the top of the footwall mineralized zone with the fault will be farther south and at higher elevations (resulting in a higher volume of mineralized rock in the footwall). The Basal series in upper plate rocks in the Nye Basin area was assumed to dip 80°N and in the Mountain View area was assumed to dip 60°NW; shallower dips will cause mineralized rocks to intersect the fault at higher elevations and result in less tonnage; conversely, steeper dips will result in larger tonnages. The position of the lower contact of the complex beneath the upper plate was determined by measuring an appropriate distance from the contact between the Ultramafic and Lower Banded series that is exposed north of the leading edge of the high-angle reverse faults. The dips used were those measured for rocks near the contact between the Ultramafic series and the Lower Banded series. The thickness of the Ultramafic and Basal series varies significantly in the complex; nearest the Big Seven fault, the average thickness for the Ultramafic series in the Benbow area was used. For the rest of Nye Basin, a thinner estimate for the Bronzitite zone was used to be consistent with the map pattern. The average thickness of the Ultramafic series in the hanging wall of the Lake fault in the Mountain View area was used in estimates for that area. If the Ultramafic series is thicker than assumed, the intersection of the top of mineralized zone in the footwall will intersect the fault farther to the south and at lower elevations (resulting in a smaller volume of mineralized rock).

Although based on several assumptions, the calculations summarized in table F8 give some idea of the size of the possible resource that may be present and the accessibility of that resource for exploration or mineral development. First, the calculations indicate that most of the resource is likely to be found as extensions to the partially delimited deposits and prospects in the upper plate or hanging wall of the high-angle reverse faults. Second, little mineralized rock in the footwall in the Nye Basin or Mountain View areas will be above an elevation of 5,000 ft, the elevation of the floor of the Stillwater Valley.

Mineralized rock above 5,000 ft could be developed without having to lift the rock; ore below 5,000 ft would have to be raised up in shafts, increasing the mining costs. Efforts to locate the offset portions of the Nye Basin and Mouat nickel-copper deposits are considered unlikely in the foreseeable future considering the grade and mineralogical problems associated with this mineralization and the depths at which it may occur. Third, in the eastern part of Nye Basin, mineralization in the hanging wall of the reverse faults will be cut off by the Nye fault above the 5,000 ft elevation.

Peridotite zone.--Rocks of the Peridotite zone are not uniformly mineralized like those in the Basal series. The Camp deposit west of Iron Mountain and the prospect in the Iron Creek area east of Iron Mountain represent the most significant occurrences of disseminated to massive sulfide mineralization in the Peridotite zone. With the exception of work done by AMAX in the Iron Mountain and Chrome Mountain areas, there was no systematic effort to explore for sulfide mineralization within the Peridotite zone. AMAX staked the claims after defining a weakly anomalous zone of nickel and copper values along the contact by stream sampling (J.F. McKnight, written commun., 1969). Most mineralization was found by drilling IP anomalies; sulfides were penetrated at every location where strong IP anomalies were drilled (R.B. Hoy, written commun., 1976). Unfortunately, the processes that led to the accumulation of large quantities of sulfide minerals near Iron Mountain are not well understood and therefore provide little insight that can guide exploration.

There is no reason to think that mineralization in the Peridotite zone is limited to the area near Iron Mountain. Elevated copper concentrations for assay data collected during the evaluation of the Mouat nickel-copper deposit indicate that disseminated sulfide minerals are present in extended intervals of the Peridotite zone (Drew and others, 1985; Zientek and others, 1989). Resource estimates for the Mouat nickel-copper deposit in table F1 include 5.4 million short tons of ore in the Peridotite zone assaying 0.13 wt. percent copper and 0.21 wt. percent nickel (Miller, 1970). Disseminated sulfide minerals in the Peridotite zone have also been seen in drillcore in the Nye Basin, Mountain View, West Fork-Crescent Creek, and Chrome Mountain areas. Copper soil anomalies are widespread over areas underlain by the Peridotite zone in both the Iron Mountain and Chrome Mountain areas (plate 14-C).

Mapping may not be an effective way to locate disseminated sulfide mineralization in the Peridotite

zone. As part of the effort to study the chromite resources of the complex, much of the Peridotite zone was mapped at a scale of 1:1,200. Although this mapping included the area that overlies the Iron Creek prospect area (Howland, 1955), sulfide mineralization was not noted. Because maps are usually made with for a specific purpose, the existence of a detailed map that was concerned with chromite resource investigations for an area does not rule out the presence of disseminated sulfide mineralization.

Both geochemical and geophysical surveys (IP) succeeded in delineating mineralization in the Iron Mountain area. I am not aware of geochemical or IP surveys that systematically cover the Peridotite zone. Anaconda tested IP anomalies in the Peridotite zone in the Mountain View, Initial Creek, and Fishtail Creek areas that were found during the process of evaluating mineralization in the Basal series; all anomalies were caused by serpentized and sheared olivine-rich rock. Until more exploration data is collected, all the Peridotite zone remains permissive for the occurrence of undiscovered sulfide mineralization.

At present, the most favorable area to locate undiscovered resources is in the Iron Mountain area. This area is structurally complex; both the Camp deposit and the Iron Creek prospect are fault bounded. Obvious areas to prospect include: (1) the hanging wall of the high-angle reverse faults that offset the Camp deposit and Iron Creek prospect, (2) the area between the Iron Creek prospect and the Crescent Peak area and (3) the area between the Camp deposit and the Iron Creek prospect. The area has not been mapped in sufficient detail to make estimates of the resources in extensions of known deposits and prospects or "undiscovered" offset mineralization.

STRATIFORM CONCENTRATIONS OF DISSEMINATED SULFIDE MINERALS IN LAYERED INTRUSIONS (DEPOSIT TYPE—MERENSKY REEF PGE)

Stratiform, disseminated sulfide [reef-type] mineralization in layered, cumulate plutons can be enriched in PGE and are a major source of PGE in the world. Sulfide mineral abundance in these deposits is low, typically in the range of 1 to 5 volume percent. The mineralized interval is thin (inches to several feet) relative to the thickness of layered rocks in the host intrusion (miles). Mineralized intervals are laterally persistent and typically extend the length

of the layered intrusion (up to hundreds of miles). In most deposits and prospects, sulfide minerals are concentrated near an interval that marks a major lithologic and petrologic change in the cumulate stratigraphic section. Pegmatoidal textures are common in some deposits. Intense PGE exploration efforts worldwide in the late 1980's found several lower grade and currently subeconomic deposits; a cumulative frequency distribution for the grade of these deposits as well as the Merensky Reef, Republic of South Africa, and the J-M Reef is presented in figure F5.

The age of most intrusions known to host significant deposits of stratiform PGE-enriched sulfide disseminations range from late Archean to middle Proterozoic. In many of these intrusions, magmas with compositions similar to siliceous high-magnesium basalts are indicated by studies of border facies, satellite sills and dikes, and crystallization sequences in ultramafic rocks characterized by early and prolonged crystallization of orthopyroxene.

Deposits with Production

Merensky Reef, Bushveld Complex, Republic of South Africa.--The Merensky Reef consists of PGE-enriched magmatic sulfides associated with a pegmatoidal pyroxenite layer, typically 8 to 40 in. thick at the base of a cyclic unit in the Upper Critical zone of the Bushveld Complex (Naldrett and others, 1987). Economically exploitable resources are estimated at 1,151 million metric tons with recoverable grades ranging from 5.1 to 5.4 ppm total PGE (Sutphin and Page, 1986). Estimates for the total geologic resource (to depths of 1,200 m) range from 17 to 20 million kilograms contained PGE (Sutphin and Page, 1986; Naldrett and others, 1987). The average PGE grade in currently operating or developing mines varies from 4.8 ppm PGE over a 37 in. thickness to 10.1 ppm over 35 in. (Wyllie, 1987).

J-M Reef, Stillwater Complex, Montana.--The J-M Reef consists of a 3- to 9-ft-thick interval containing 1 to 2 volume percent PGE-enriched magmatic sulfide minerals that lies near the base of a cyclic unit in Olivine-bearing zone I in the Lower Banded series (Todd and others, 1982; Raedeke and Vian, 1986). When the Stillwater mine opened, reserves of 0.4 million metric tons of ore averaging 27.09 ppm palladium plus platinum and 1.45 million metric tons of possible ore averaging 31.89 ppm palladium plus platinum were announced (Engineering and Mining Journal, 1986). Geologic resource estimates range from 116 million metric tons of ore to

421 million metric tons of ore at 18.8 ppm palladium plus platinum (table F3). The minimum mining width is 3.9 ft.

Other Significant Deposits or Occurrences

Main sulfide zone, Great Dyke, Zimbabwe.--The Main Sulfide zone consists of 3 to 5 volume percent PGE-enriched magmatic sulfide minerals concentrated near the bronzitite-websterite transition in the P1 pyroxenite, cyclic unit 1 (Prendergast, 1988; Prendergast and Wilson, 1989; Wilson and Tredoux, 1990). Resources estimates range from 1,300 million metric tons averaging 4.3 ppm Pt+Pd+Rh to 4,401 million metric tons of ore over a width of 5.9 ft at an unspecified grade (Mining Journal, 1989; Prendergast and Wilson, 1989). The Main Sulfide zone is normally less than 5 ft thick at the margins of the intrusion but ranges to 65 ft thick along the axis. Grades vary with position from axis; platinum contents are 3 to 3.5 ppm near the margin and about 2 ppm near the axis.

Main sulfide layer, Munni Munni Complex, Western Australia.--The Main sulfide layer consists of 1 to 3 volume percent PGE-enriched magmatic sulfide minerals concentrated in a porphyritic websterite layer a few meters below the contact between the Ultramafic series and the Gabbroic series (Barnes and others, 1990). Resources are estimated at 20 to 30 million metric tons of ore averaging 2.9 ppm Pd+Pt+Au over an average thickness of 8 ft.

Ala-Penikka 1, Ala-Penikka 2, Sompujärvi, and Paasivaara Reefs, Penikat intrusion, Finland.--Four separate layers contain 1 to 5 volume percent PGE-enriched sulfide minerals in different subunits of megacyclic unit IV of the Penikat intrusion (Alapieti and others, 1990). Each appears to be continuous over the 14 mi of exposed strike length of the intrusion. Grades and thicknesses are as follow: Ala-Penikka 1 Reef--4.262 to 9.73 ppm PGE plus gold, normally 1 ft thick, but 65 ft thick in depression (Halhoaho and others, 1990b); Ala-Penikka 2 Reef--15.72 ppm PGE+gold (Halhoaho and others, 1990b); Sompujärvi Reef--6.106 ppm PGE plus gold, averages 3 ft thick (Halhoaho, and others, 1990a); and Paasivaara Reef--0.444 to 6.83 ppm PGE plus gold, mineralization ranges from tens of inches to several feet in thickness (Huhtelin and others, 1990).

Occurrence in the Stillwater Complex

The J-M Reef of the Stillwater Complex is the only deposit of its kind being mined other than the Merensky Reef. Howland and others (1936)

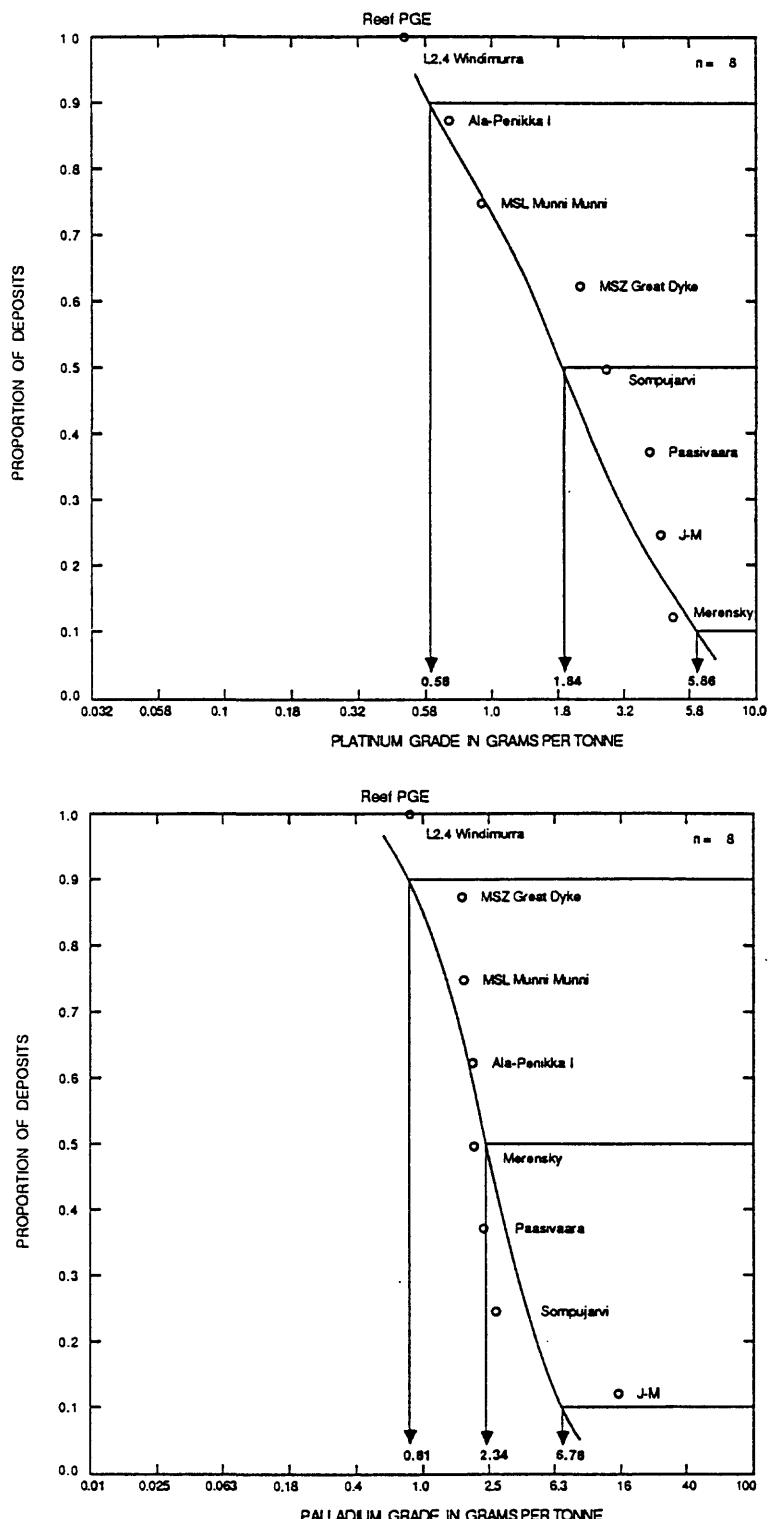


Figure F5.—Cumulative frequency distribution for PGE grades for stratiform reef-type PGE mineralization (Merensky Reef PGE). A) Platinum, B) Palladium, C) Rhodium, D), Gold, E) Nickel, and F) Copper. Values for 10th, 50th, and 90th percentiles are highlighted. Explanation for symbols: Merensky - Merensky Reef, Bushveld Complex, Republic of South Africa; MSZ Great Dyke - main sulfide zone, Great Dyke, Zimbabwe; MSL Munni Munni - main sulfide layer, Munni Munni intrusion, Western Australia; Ala-Penikka I, Sompujarvi, and Paasivaara - reef-type mineralization in the Penikat intrusion, Finland; J-M - J-M Reef, Stillwater Complex; L2.4 Windimurra - reef-type sulfide mineralization in Windimurra Complex, Western Australia.

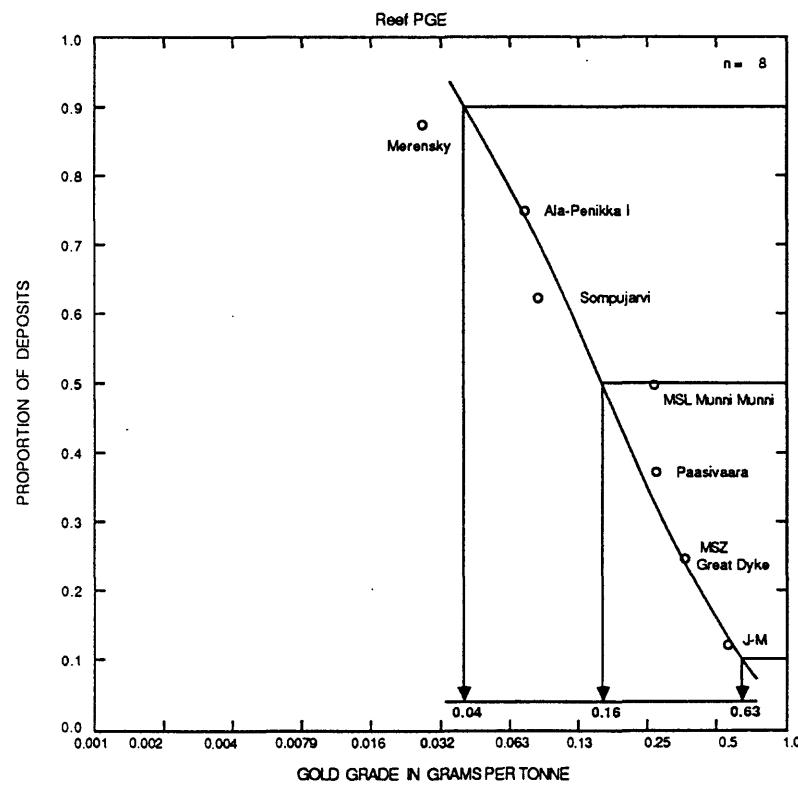
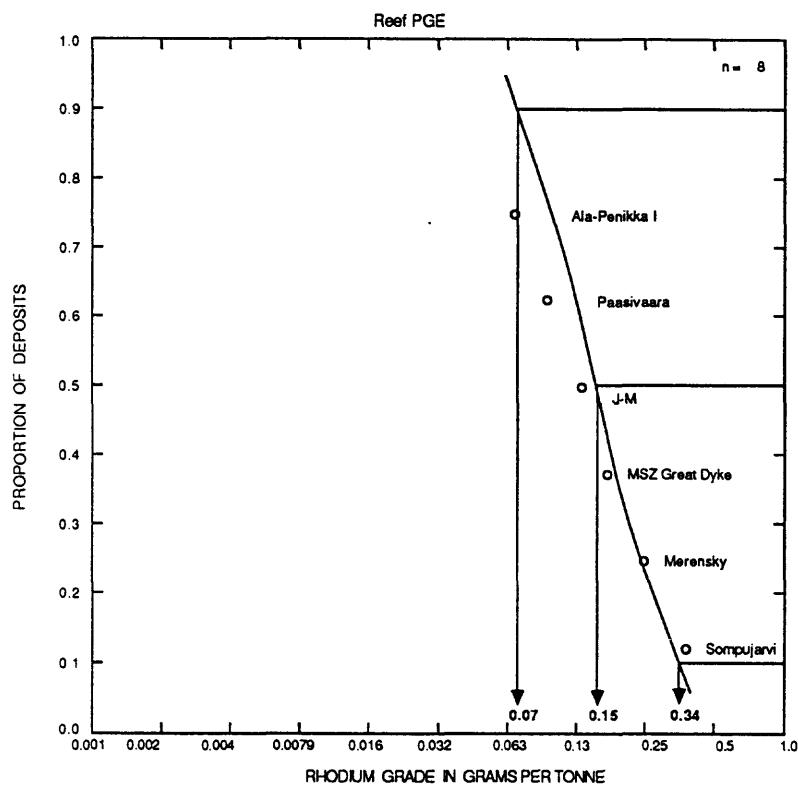


Figure 5.—Continued.

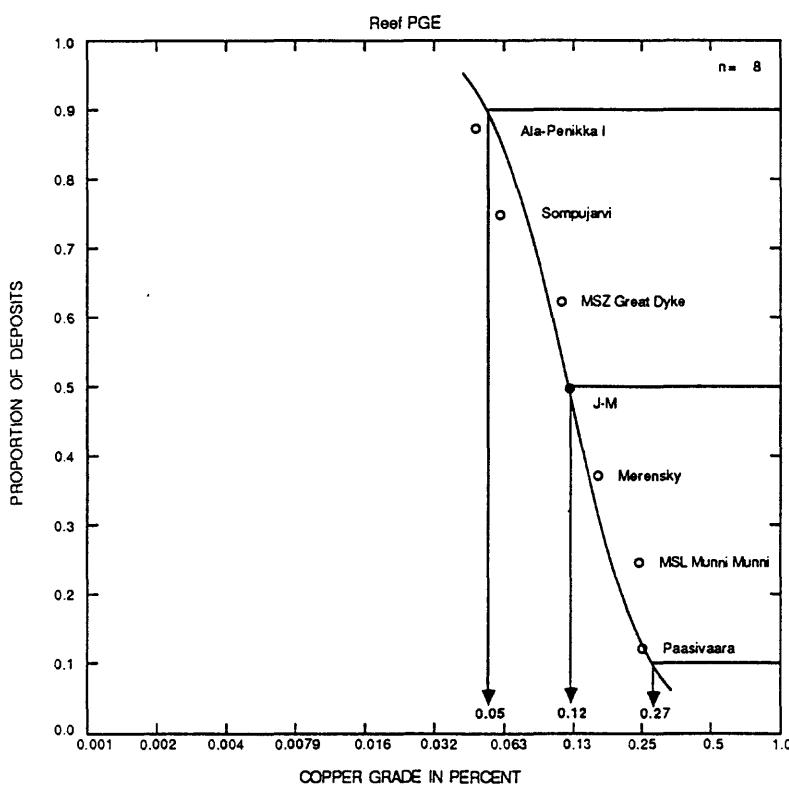
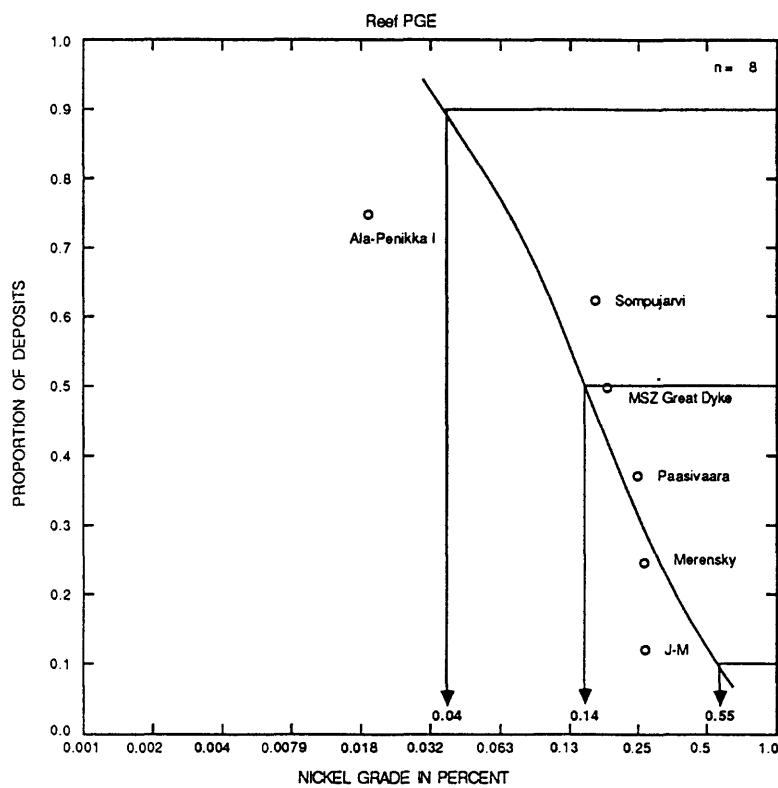


Figure 5.--Continued.

recognized the potential for finding reef-type PGE mineralization in the Stillwater Complex. Thirty-seven years later (1973), the J-M Reef was discovered by Johns-Manville exploration geologists (Conn, 1979; Todd and others, 1982; Barnes and Naldrett, 1985). The first mine on the J-M Reef, the Stillwater mine, went into production in 1986, producing platinum and palladium as well as gold, rhodium, copper, and nickel.

At least nine sulfide-enriched intervals are present in the Lower, Middle, and Upper Banded series of the Stillwater Complex (McCallum and others, 1980; Todd and others, 1982) including the J-M Reef and the Picket Pin zone (Boudreau and McCallum, 1986; see description below in section on deposits associated with impermeable layers). Other sulfide-enriched occurrences in addition to these have been observed (M.L. Zientek, unpub. data, 1988; W. Meuer, oral commun., 1992).

Tract Delimiting Permissive Environment

The geologic criteria to delineate permissive tracts are derived from deposit models; unfortunately, the descriptive model for reef-type PGE deposits is based on so few examples that features that are required and necessary to define these deposits are difficult to separate from those that are local or incidental. The permissive tract for reef-type mineralization in the Stillwater Complex will be defined by two characteristics shared by known deposits and prospects. (1) Reef type deposits are found in a restricted part of the stratigraphic section. Two of the known deposits, the Main sulfide zone of the Great Dyke and the Main sulfide layer of the Munni Munni complex, occur a few tens of feet below the contact separating ultramafic cumulates (below) and rocks containing abundant cumulus plagioclase (above). This position would correspond to the interval just below the contact between the Ultramafic series and the Lower Banded series in the Stillwater Complex. The Merensky Reef, the J-M Reef, and the Sompujärvi Reef occur in rocks with cumulus plagioclase that are less than 3,000 ft stratigraphically above sections that are dominated by ultramafic cumulates. (2) Mineralization is localized at or near major lithologic changes in parts of the stratigraphic section that are comprised of conspicuously layered cumulates. Generally, these lithologic boundaries show great lateral continuity.

Using these two simple criteria, three tracts showing the near-surface extent of rocks permissive

for the occurrence of reef-type mineralization can be delineated in the Stillwater Complex. If the tract outline was modified to show the areal extent of permissive rocks that are within a kilometer of the surface, the northern boundary of the tracts would shift less than a kilometer to the north. The stratigraphically lowest tract includes rocks that stratigraphically lie between the uppermost part of the Ultramafic series and the base of the Middle Banded series (A, plate 15-B); the second tract includes those rocks that stratigraphically lie between the two major anorthosites in the Middle Banded series (B, plate 15-B); and the third tract includes those rocks that make up the lower most part of the Upper Banded series (C, plate 15-B). The stratigraphic position of rocks that make up tract A are most like those that host reef-type deposits in other intrusions. On that basis alone, it is the most prospective of the three tracts. Although exploration activity was not at first limited to Tract A, this tract later became the focus of exploration that led to the discovery of the J-M Reef.

Excluded from the permissive tracts are ultramafic cumulates that form the Basal series, the Peridotite zone of the Ultramafic series, and most of the Bronzitite zone of the Ultramafic series; the foliated and laminated but weakly layered rocks forming most of the Upper Banded series; and the unfoliated and massive rocks forming the two major anorthosite zones in the Middle Banded series. The Peridotite zone has layering characteristics that would fit the second criteria listed above, but is not considered to be permissive because reef-type mineralization has not been found in stratigraphic sections dominated by ultramafic cumulates in other layered intrusions.

Factors That Localize Deposits

The formation of reef-type deposits is contingent upon: (1) an event felt throughout the magma chamber that caused immiscible sulfide liquid to exsolve, and (2) the equilibration of the sulfide liquid with a large volume of silicate magma (in order to achieve the high-degree of PGE enrichment). PGE-enriched sulfide-bearing intervals are typically associated with stratigraphic intervals that may correspond to a(n): base of a cyclic unit, abrupt change in crystallization order, abrupt discontinuity in fractionation pattern (re-appearance of cumulus minerals typical of earlier stage of differentiation; discontinuities or reversals in mineral fractionation patterns), abrupt change in isotopic composition of the

magma, abrupt decrease in platinum and palladium to sulfur ratios, and (or) unconformity in the layered sequence of rock. These features have been interpreted to be caused by chamber-wide influx and mixing of magmas of different composition. The mixing event causes exsolution of sulfide liquid and provides the physical conditions necessary to equilibrate the sulfide liquid with a large volume of silicate magma.

Factors Affecting Exploration Success

The rock record of a reef-forming event is subtle. Sulfide mineral abundances in mineralized rock are low. Ore-grade material may have less than 1 volume percent sulfide. The stratigraphic interval that is mineralized is thin relative to the stratigraphic thickness of the intrusion. Reef-type deposits form layers about three feet thick in layered rock sequences that may be thousands of feet thick. The stratigraphic section may have many lithologic discontinuities similar to one that is associated with mineralization. Petrologic changes in the stratigraphic interval associated with reef-type mineralization can only be documented with detailed, time-consuming, and laborious work. In addition, sulfide mineralization may be irregularly distributed in the plane of the mineralized interval.

A practical exploration approach is to look for anomalous concentrations of platinum and palladium in residual or transported media derived from a larger volume of rock and, if successful, to search for sulfide minerals in the rock that may be cause of the anomaly. For the J-M Reef, rocks with the highest modal proportion of sulfide minerals also have the highest PGE concentrations (Zientek and others, 1990). Grab sampling of rocks with visible sulfide minerals would locate PGE mineralization. However, several of the reef-type deposits are characterized by offset PGE patterns in which the highest PGE concentrations in a mineralized interval occur stratigraphically below the rocks with the highest sulfide mineral concentrations by a meter or more. Although offset patterns may be the exception, sufficient care must be taken in sampling to adequately test permissive stratigraphic intervals.

Geologic and Exploration Activity Within Tract

Exploration activities that led to the discovery of the J-M Reef were briefly described by Conn (1979).

Stillwater PGM Resources (written commun., 1991 and 1992) provided detailed information about their exploration work to assist in the assessment, some of which is summarized on plate 15. The location of geochemical surveys and results, bulk sample sites, and drill hole locations are shown for the areas west of the West Fork of the Stillwater River. East of the West Fork, only the areas covered by geochemical surveys are shown; the level of other exploration data is similar to what is illustrated to the west.

Tract A.--Systematic geochemical surveys by Johns-Manville were instrumental in locating the J-M Reef (plate 15c). Samples of soil, talus fines, seeps, and stream sediments were collected at 100-foot intervals on contour traverses or lines in grid patterns. The extent of sampling and the location of moderately and highly anomalous samples (for platinum and palladium) are shown on plate 15c. Almost all of tract A is covered by geochemical surveys. Grid sampling stratigraphically extends from below the contact between the Ultramafic series and the Lower Banded series to the Anorthosite I zone in the Middle Banded series. Where tract A is not completely covered by grid sampling, the stratigraphic section that comprises the tract was tested by sampling along contour traverses.

The J-M Reef is readily located by tight linear clustering of anomalies that extend 300 ft or more away from the reef. Clusters of anomalies below the reef correspond to lens-like or discordant PGE-enriched sulfide mineralization (see separate discussion on this style of mineralization). No anomalous samples were obtained from grid surveys that covered the contact between the Ultramafic series and the Lower Banded series (which is the position where reef-type mineralization is found in the Great Dyke and the Munni-Munni Complex). Scattered anomalies above the reef show no consistent spatial pattern (clustering). Results from the geochemical sampling do not indicate the presence of another laterally continuous, reef-type deposit in tract A.

Because the geochemical anomaly associated with the reef is spread over a large stratigraphic interval relative to the thickness of a typical reef-type deposit, additional, undiscovered reef-type deposits could possibly be found near the J-M Reef and not be resolved by soil geochemical anomalies. However, the results of mapping, surface sampling, drilling, and underground exploration did not locate continuous reef-type mineralization above the J-M Reef. The location of drill holes and bulk sample sites on the reef are shown on plates 15-D and E. The drill hole pattern reflects the dip of the reef; in order to

intersect the north-dipping reef at depth, drill holes were collared to the north and upsection of the reef. These holes provide information about the stratigraphic interval from slightly above the base of the Gabbronorite II zone (Lower gabbro zone) to the reef. Sulfide mineralization consistently occurs with thin anorthosite layers [2400 and 2500 plagioclase cumulate layers] near the base of the Lower gabbro zone. These layers are laterally persistent and are consistently mineralized. Although Todd and others (1982) report 7.13 ppm platinum and palladium from a sample that may come from this interval, no consistent pattern of soil geochemical anomalies are associated with these layers. Grab samples collected by the U.S. Geological Survey (M.L. Zientek, unpub. data) and Stillwater PGM Resources (oral and written commun., 1988) have platinum plus palladium concentrations that range up to a few hundred ppb. Numerous sites in tract A above the reef were sampled during the course of geologic mapping [outcrop maps at 1:1,200 were made along the trace of the reef] or geochemical sampling (plate 15-F). No other PGE-enriched or laterally persistent sulfide mineralization has been reported for the interval between the base of the Lower Gabbro and the reef.

With the development of the Stillwater mine, the stratigraphic section extending from the reef down to and through the contact with the Ultramafic series was exposed. Several holes were collared in the Bronzitite zone and drilled upsection to the reef. In addition, the reef is accessed from workings that are in the footwall to the reef. On the west side of the Stillwater River, the reef is not parallel to layering in the underlying rocks of the Lower Banded series. Proceeding west from the mine portals, the olivine-bearing rocks that are associated with the reef are in contact with rocks progressively lower in the stratigraphic section until the reef is about 300 ft from the contact between the Lower Banded series and the Ultramafic series. Therefore, development workings cut section starting in the Gabbronorite I zone and continue downsection through the Norite I zone into the Bronzitite zone. Stratified PGE-enriched sulfide mineralization (footwall mineralization of Raedeke and Vian, 1986) is found in a narrow interval of layered rocks in the Gabbronorite I zone. Mineralization is best developed near the contact with the olivine-bearing rocks that typically host the reef and pinches out away from this contact. This mineralization could represent sulfide minerals that infiltrated into layered rocks in the footwall of the reef. Alternatively, it may represent a laterally discon-

tinuous sulfide horizon within the Gabbronorite I zone that formed prior to the J-M Reef. Similar mineralization is not recognized elsewhere in Gabbronorite I zone. No sulfide mineralization was found near the contact between the Ultramafic and Lower Banded series.

Tracts B and C.--With the exception of contour traverses west of the Boulder River, no systematic geochemical surveys were made of tracts B or C. In the stratigraphic studies by McCallum and others (1980) and the 1:24,000 mapping by Segerstrom and Carlson (1982), many sulfide occurrences were described. Todd and others (1982) give analyses of samples from three sulfide-bearing intervals within Tract B. A sample from the lowest interval (within Olivine-bearing zone III) had 0.92 ppm platinum plus palladium. The other samples had platinum plus palladium concentrations below 200 ppb. There simply is not enough information to make an assessment of tract B. Tract C includes the lower part of the Upper Banded series (predominantly the Upper mixed zone or Olivine-bearing zone V). Exploration directed at the Picket Pin zone (near the top of the Middle Banded series in the Anorthosite II zone (Middle Anorthosite)) provides information pertinent to evaluate tract C. No systematic geochemical surveys were conducted, but the rocks were mapped in detail and drilled through to intersect the underlying Picket Pin zone. Stratiform disseminated sulfide intervals were noted in tract C by Boudreau and McCallum (1985) and Foose (1985). Palladium concentrations for some of these intervals are reported to be less than 5 ppb (Boudreau and McCallum, 1985). Although there is not information to make a definitive assessment of tract C, the exploration activity focused near this tract decreases the probability of finding undiscovered reef-type mineralization in the southern part of the tract.

Geologic Resources Associated with the J-M Reef

Resource estimates for the J-M Reef are summarized in tables F3 and F11. The estimate in table F11 is derived from information provided by Stillwater PGM Resources (written commun., 1992). Average grades and true widths based upon drill information, vertical longitudinal sections, and calculated geologic resources from the surface to proposed adit levels, the surface to 1,000 ft below proposed adit levels, and the surface to sea level were reported for 13 contiguous sectors along the reef.

Utilizing this information, the estimate in table F11 was made with the following assumptions and conditions:

- (1) With exceptions noted below, resources were calculated to an elevation of 1,722 ft (525 m) above sea level. This elevation is one kilometer below the lowest surface exposure of the J-M Reef in the complex.
- (2) East of the West Fork of the Stillwater River, the Horseman thrust will probably truncate the J-M Reef above the elevation of 1,722 ft. This fault flattens with depth; dips as shallow as 30° to 35° were estimated for the Horseman thrust at its lowest exposure in the Stillwater Valley (Jones and others, 1960). The fault may continue to flatten with depth; dips as shallow as 20° have been demonstrated for similar basement overhangs in other Laramide uplifts (Brown, 1988). Considering the sections in Jones and others (1960) and Turner and others (1985), resources were calculated to an elevation of 4,000 ft between the West Fork of the Stillwater and the Stillwater Rivers and 3,000 ft east of the Stillwater River.
- (3) Tonnage calculations were modified to reflect offset of the J-M Reef by a south-dipping thrust fault (Tick fault) on the east side of the Boulder River canyon. Calculations were modified only where the fault is mapped. The lateral extent of this fault is not known; tonnage estimates for the

reef may be too high if this fault extends for any distance and continues to offset the reef.

- (4) The grade and true width reported in the table were weighted by the total tonnage estimated for each sector.

This resource calculation also assumes that the entire interval that hosts the reef would be mined. In the area near the Stillwater mine, closely spaced drilling (intersections of the reef on 50 ft centers) has shown that sulfide mineralization is not uniformly distributed in the plane of the reef. Horizontal projections of ore on a vertical plane parallel to the reef show concentrations of sulfide minerals in patterns that resemble ore shoots in a vein. Only domains with higher proportions of sulfide minerals are mined; tonnages are less but grades are higher (approximately 27 ppm palladium plus platinum). By selectively mining roughly half the volume of the reef, 80 percent of the contained metal is recovered. The density of drill intercepts outside the area of the mine is insufficient to determine if the patterns of ore distribution in the Stillwater mine are typical for the rest of the reef. If these patterns are present in a geometry similar to the Stillwater mine area, the tonnages presented in table F11 may be too large by at least a factor of two and grades would be too low. In addition, complex ore geometries require more complex mining procedures that will make extraction more costly and perhaps limit the depths at which the reef could be mined.

Table F11.--Geologic resources associated with the J-M Reef, Stillwater Complex

	Millions of short tons (million of metric tons)	Pt+Pd grade, opt (grade, ppm)	True width, ft (m)	
Gallatin National Forest	141 (128)	0.57 (19.5)	5.0 (1.52)	See text for description of resource estimate
Custer National Forest	177 (161)	0.52 (17.8)	4.6 (1.40)	
Total for complex	318 (288)	0.55 (18.8)	4.9 (1.49)	
Previous estimate for Stillwater Complex (Sutphin and Page, 1986)	130 (118)	0.58 (20)	6.0 (1.83)	Resource estimate based on 26 mi length, 6 ft width, 1,970 ft depth, and rock density of 2.87 g/cm ³

Favorable Areas for Undiscovered Deposits

Does the discovery of the J-M Reef rule out the discovery of other reef-type deposits in Stillwater? The occurrence of multiple PGE-enriched intervals in the Penikat intrusion, Finland, suggests there is still potential for undiscovered deposits. The geochemical surveys, mapping, drilling, and underground development work would appear to preclude the presence of undiscovered, laterally extensive reef-type mineralization in tract A. The probability that a reef-type deposit remains undiscovered in the tract that contains the J-M Reef is low (less than 1 in 1,000?). However, laterally discontinuous stratiform mineralization may be found locally in tract A. Exploration activity in tracts B and C is limited and does not exclude or suggest the presence of undiscovered deposits. The geologic features of these tracts, the few analyses that are available, and the scarcity of reef-type mineralization worldwide suggest that the probability of undiscovered deposits is still low (less than 1 in 100?). Additional information is needed to adequately assess tract B and the northern part of tract C.

SULFIDE AND PGE CONCENTRATIONS OCCURRING AT OR BELOW IMPERMEABLE LAYERS

Concentrations of disseminated, interstitial sulfide minerals can be found beneath layers that appear to act as a barrier to the upward migration of interstitial liquids. The layer may have a lower permeability than adjacent ones due to differences in size or shapes of the cumulus minerals or may be reactive (out of equilibrium) with upward migrating fluids. The rocks hosting the sulfide minerals may be characterized by pegmatoidal textures, have a higher proportion of phases that crystallize late from a silicate magma, or be enriched in incompatible elements. Host rocks may also show evidence for infiltration metasomatism (offset mineral compositional discontinuities). Mineralization may be laterally continuous, similar to the overlying impermeable layer, but tends to form irregular lenses or pods.

Significant Deposits or Occurrences

Picket Pin zone, Stillwater Complex, Montana.-- Disseminated sulfide mineralization is concentrated against a grain-size contact near the top of the Anorthosite II zone in the Middle Banded series of

the Stillwater Complex (Boudreau and McCallum, 1986). The mineralization consists of 1 to 5 volume percent sulfide minerals that are associated with pyroxene-free, quartz- and apatite-bearing interstitial mineral assemblage. Crudely strata-bound mineralization is exposed for 13.5 mi along strike and tends to be concentrated over a 30 ft interval near the grain-size contact. However, scattered concentrations of sulfide minerals may be found as far as 500 ft below this contact. Sulfide concentrations are podiform (inches to feet), lenticular (5 ft thick by 60 to 100 ft long), or pipelike (3 to 6 ft diameter by 150 ft long). The highest values determined for this mineralization were obtained from a surface sample that contained 7.9 ppm palladium plus platinum (table F3).

Lower group platinum-bearing unit, Bird River Sill, Manitoba, Canada.--Sulfide mineralization is concentrated against the lower contact of a massive chromitite (Scoates and others, 1987). Textures suggest concentration of volatile components; olivine crystals are coarse grained and subskeletal. The sill has a strike length of 15.5 mi; mineralization has been traced laterally for 2,600 ft; the sulfide-mineralized unit ranges in thickness from inches to 10 ft. Mean concentrations of rhodium, platinum, palladium, and gold in mineralized samples are less than 0.6 ppm (table F12).

Occurrence in the Stillwater Complex

The PGE-enriched Picket Pin zone was one of the first PGE-enriched sulfide occurrences recognized in the complex (Howland and others, 1936). Detailed studies show this interval of sulfide-enrichment records a process of PGE-enrichment and entrapment that is unlike reef-type mineralization; this occurrence and analogues in other layered intrusions may be formed by obstruction of upward migrating postcumulus liquids by less permeable layers in unsolidified layered cumulates. Mineralization is stratabound but is more discontinuous locally than reef-type deposits. No economic deposits of this type, at Stillwater or elsewhere, have been discovered.

Tract Delimiting Permissive Environment

All the complex is permissive for this type of mineral concentration; the igneous layering that is characteristic of the Stillwater Complex presents many physical and chemical inhomogeneities that would affect intercumulus melt migration. Lithologic

Table F12.--Geometric means of Cu, Ni, Rh, Pt, Pd, and Au for samples from the PGE mineralized unit, Bird River sill, Manitoba (Scoates and others, 1987)

	Cu, wt %	Ni, wt %	Rh, ppm	Pt, ppm	Pd, ppm	Au, ppm
Disseminated sulfide-bearing peridotite	0.03	0.22	0.006	0.075	0.110	0.015
Disseminated sulfide-bearing coarse-grained peridotite	0.04	0.29	0.019	0.165	0.370	0.017

contrasts in the Peridotite zone and near the upper contacts of the large anorthosite units in the Middle Banded series that are more likely to impede melt migration are shown as favorable tracts on plate 15-G.

Geologic Factors That Localize Deposits

Chromite seams in the Peridotite zone appear to act as barriers to melt or fluid migration. Cumulus chromite is about an order of magnitude finer grained than coexisting cumulus silicate minerals; therefore, the grain size contrast (and porosity and permeability contrast) for layers rich in chromite in a layered sequence far exceeds what could be expected in a layered sequence of cumulate silicates alone. In addition, rheological properties of chromite seams appear to be different than adjacent silicate-rich layers; for example, chromite seams affected by soft-sediment deformation appear to behave more competently than the surrounding silicate rocks. Growth of interstitial silicate minerals is impeded by layers rich in chromite. Evidence that these finer grained, more competent layers affected melt migration is the

association of stratabound ultramafic pegmatoids with many chromite seams; commonly they are below the chromite seam but may also intrude and disrupt chromite-rich layers in the seam. In other cases, recrystallization associated with the development of pegmatoidal textures obscured the primary cumulus textures of the chromite seam.

The major anorthosites in the Middle Banded series are coarser grained than other cumulates in the complex and have anisotropic fabrics (McCallum and others, 1980; Boudreau and McCallum, 1986); presumably intercumulus melts or fluids migrating through the anorthosites would encounter few obstacles until they reached the finer grained, layered rocks overlying both anorthosite zones.

Geologic and Exploration Activity Within Tract

Exploration activity focused on the Picket Pin zone (plate 15-H) where PGE-enriched sulfide mineralization (tables F3 and F13) consistently occurs near the top of the Anorthosite II zone along its 13.6 mi strike-length. Exploration activity summarized in plate

Table F13.--Analyses of 730 kg bulk samples of Picket Pin mineralization, Stillwater Complex (Williams, 1981)

	S, wt pct	Cu, wt pct	Ni, wt pct	Pt, ppm	Pd, ppm	Au, ppm
West side of Contact Mountain	1.6	0.46	0.34	1.37	0.89	0.17
West side of Picket Pin peak	1.1	0.28	0.28	1.34	0.82	0.14

15-H was done by Anaconda in the late 1970's and early 1980's. The location of 14 holes drilled by International Platinum and 3 holes drilled by the claim holders along the eastern part of the zone in the late 1980's are not shown.

Work on the Picket Pin mineralization included sampling mineralized outcrops, bulk sampling, and drilling. Systematic geochemical surveys were not conducted; ground magnetic surveys were used to locate the olivine-bearing rocks overlying the Anorthosite II zone in areas where these rocks are not exposed.

Detailed mapping and sampling in the study areas shown on plate 15-H were critical to understanding the deposit; conclusions derived from this work along with analyses of sulfide-bearing samples are presented in Boudreau (1986) and Boudreau and McCallum (1986). PGE-bearing sulfide minerals are concentrated at or up to 500 ft below a grain size, modal, and textural transition approximately 30 ft below the top of the Anorthosite II zone. Sulfide mineralization above this transition and continuing up into Olivine-bearing zone V is stratiform and not enriched in PGE. Sulfide mineralization at or below the transition is PGE-enriched and associated with pyroxene-poor, quartz- and apatite-bearing assemblages; sulfide accumulations are podiform and lenticular near the transition. Discordant sulfide-bearing pipes are found up to 500 ft below the transition and may represent zones of channelized melt migration.

Exploration has not been intentionally directed toward this style of mineralization elsewhere in the complex. There was a lot of exploration activity that focused on the chromite seams in the Peridotite zone; however, concentrations of sulfide minerals were not observed in the stratiform ultramafic pegmatoids associated with these seams. Mapping, drilling, and geochemical surveys conducted near the base of the complex and about the J-M Reef did not find this type of mineralization. Scattered lenticular or podiform concentrations of sulfide minerals are present throughout the Anorthosite I and II zones; no effort has been made to characterize these occurrences.

Factors Affecting Exploration Success

Like reef-type mineralization, the proportion of sulfide minerals in the rock is low. In addition, sulfide mineral accumulations are more discontinuous and not as stratigraphically confined as reef-type mineralization.

Geologic Factors Affecting Resource Development

Mineralization in the Picket Pin zone is low grade relative to other PGE-enriched deposits. Known mineralized lenses are too small to be developed individually and too widely separated to be grouped together and maintain grade.

Favorable Areas for Undiscovered Deposits

The Picket Pin zone does not represent a stratiform reef that could be exploited continuously along strike. Exploration activity along the Picket Pin zone will likely focus on locating areally restricted, small deposits in which the sulfide accumulations are large enough or sufficiently closely spaced to exploit.

PEGMATOIDAL LENSES, PIPES, AND OTHER DISCORDANT MINERALIZATION

PGE mineralization can be associated with concentrations of magmatic sulfide minerals or PGE alloys in lens-like to pipe-like mafic pegmatoids. Deposits typically are small but can be high grade. Few deposits of this type are currently in production.

Deposits with Production

Vlakfontein nickel pipes, Bushveld Complex, Republic of South Africa.--Approximately 240 nickel- and copper-bearing sulfide ore bodies are associated with mineralized bronzitite pipes or veins in the Vlakfontein area in the western Bushveld Complex (Vermaak, 1976; von Gruenewaldt, 1979; Vermaak and von Gruenewaldt, 1981). The pipe-like ore bodies consist of a massive sulfide core surrounded by an outer fringe of disseminated and matrix sulfides (Vermaak and von Gruenewaldt, 1981). Six of the pipes were mined, producing 62,611 tons of ore averaging 1.66 wt. percent nickel, leaving proven reserves of 25,800 tons averaging 2.8 wt. percent nickel. The average cross-sectional area of the six pipes that were mined is 234 ft. Drilling of another 14 ore bodies proved an indicated resource of 100,000 tons of ore to 200 ft depth and an inferred reserve of 25,000 tons to 394 ft, with a grade varying between 0.5 and more than 2 wt. percent nickel. No PGE values were published, although Vermaak (1976) presented information on how the proportions of the different PGE change from the centers to the edges of pipes.

Wagner (1929) reported an average of 11.0 ppm gold and 6.0 ppm silver in the ores.

Hortonolite and dunite pipes, Bushveld Complex, Republic of South Africa.--Numerous small bodies of dunitic and pyroxenitic pegmatoids are found in the Critical zone in the Eastern and Western Bushveld. They are either lenticular, flat bodies parallel to layering or pipe-like bodies discordant to layering. Three of the pipe-like bodies, Onverwacht, Mooihoek, and Driekop, contained sufficiently high PGE to be mined (Wagner, 1929; Cameron and Desborough, 1964; Willemse, 1969; Schiffries, 1982; Stumpf and Rucklidge, 1982). These lithologically and compositionally zoned pipes are oriented roughly normal to cumulus layering and extend over a vertical distance of at least 820 ft. Diameters of the pipes range from 50 to 650 ft. Pegmatoidal textures and iron-rich olivine along with the presence of hornblende, ilmenite, or phlogopite characterized the mineralized portions of the pipes. PGE alloys were the predominant ore-bearing mineral. The average grade in the Onverwacht pipe was 15 to 30 ppm PGE and the grade reported for Mooihoek was 4.46 ppm PGE. Averaged analyses of a bulk sample from Mooihoek have 0.01 wt. percent copper, 0.08 wt. percent nickel, and 5.3 ppm PGE plus gold (Vermaak and von Gruenewaldt, 1981). The Onverwacht pipe contained a disrupted chromitite layer that had remarkably high platinum values (locally more than 2,000 ppm). Average grade of the Driekop pipe is reported to be 5.83 ppm PGE.

Occurrences in the Stillwater Complex

Pegmatoidal lenses and discordant mafic and ultramafic bodies are found throughout most of the complex but are not well characterized. Only a few of these bodies are known to contain sulfide mineralization. Prior to discovery of the J-M Reef, geologists with Johns-Manville found PGE-enriched sulfide mineralization in several pegmatoidal lenses in the upper part of the Bronzitite zone and the lower part of the Lower Banded series (described below). Exploration drilling and mine development in the area between the West Fork of the Stillwater River and the Stillwater River have located bodies of ultramafic rock in the Lower Banded series that contain disseminated sulfide mineralization. PGE are not enriched in these rocks.

Discordant bodies of dunite referred to as discordant dunites, intrusive olivine cumulate, or secondary dunite cut Peridotite zone cyclic units (Page

and Nokleberg, 1974; Raedeke and McCallum, 1984). Chromite stringers in a discordant dunite in the Gish area contain 4.8 ppm palladium plus platinum (Nicholson and Lipin, 1985).

Tract Delimiting Permissive Environment

The entire complex is permissive.

Geologic Factors That Would Contribute to Localization of Deposits

The features that localize mafic and ultramafic pegmatoids are not well documented. The areal distribution of the Vlakfontein deposits suggests they are clustered over structures that are in the country rocks that host the Bushveld Complex. Syndepositional faults may channelize magma or fluids.

Geologic and Exploration Activity Within Tract

The geochemical surveys directed at locating reef-type mineralization in the Lower Banded series located several anomalies in the Ultramafic series and Lower Banded series below the Reef that turned out to be PGE-enriched pegmatoidal lenses or discordant bodies. These areas were mapped, trenched, and drilled (plate 15-H). The Janet 50 occurrence in the upper part of the Bronzitite zone extends over an area of 100 by 165 ft and consists of a pegmatoidal bronzitite with disseminated sulfide minerals and local concentrations of graphite (Volborth and Housely, 1984). The average of 5 analyses of samples from surface exposures of the Janet 50 pegmatoid gave the following results: 0.38 wt. percent sulfur, 0.09 wt. percent copper, 0.27 wt. percent nickel, less than 2 ppb iridium, 5 ppb ruthenium, 16 ppb rhodium, 692 ppb platinum, 1,278 ppb palladium, and 130 ppb gold. Trenching, drilling, and mapping in Coors 602 area have located several bronzite-rich pegmatoids in the Lower Banded series below the J-M Reef and a dike-like body of bronzitite that cuts the Lower Banded series. An interval 25 ft wide from one of the mineralized pegmatoids contained 4.4 ppm platinum and 11 ppm palladium (Conn, 1979). Although many of the pegmatoids in the Coors 602 area contain sulfide minerals, not all are enriched in PGE. The Janet 55W zone consists of disseminated sulfide mineralization associated with bronzite-rich pegmatoids immediately below the J-M Reef. An

interval 4.6 ft wide contained 7.2 ppm palladium plus platinum.

Factors Affecting Exploration Success

The principal problems are the small size and irregular geometry of the bodies, the numerous pegmatoid occurrences in the complex that could be examined, and variable grade between closely spaced pegmatoids.

Geologic Factors Affecting Resource Development

From what is known about the prospects, the volume of mineralized rock is likely to be quite small and unlikely to be of interest for development.

Favorable Areas for Undiscovered Deposits

Anomalies and occurrences appear to be clustered in the central part of the complex in the upper part of the Ultramafic series and the lower part of the Lower Banded series. Additional occurrences may be found in this area.

OXIDE-ASSOCIATED MINERALIZATION IN MAFIC AND ULTRAMAFIC ROCKS

Chromite deposits in stratiform layered complexes form tabular sheets of rock enriched in the mineral chromite. Chromite crystallizes directly from mafic silicate magma and can be concentrated into layers inches to several feet thick by cumulus processes. Elevated concentrations of PGE are associated with chromite-rich rocks; sulfide mineral abundances in PGE-enriched chromitites are generally low, much less than 0.1 volume percent.

Texture and distribution.--Chromite is a cumulus mineral and forms subhedral to euhedral, equant grains that are typically tenths of millimeters in diameter. Chromite seams are comprised of a sequence of cumulate layers that are variably enriched in chromite. Platinum-group element minerals in chromite ores are found with trace quantities of base-metal sulfide minerals, along grain boundaries, in silicates, and in chromite.

Ore mineralogy.--Chromite has the general formula $(\text{Mg}, \text{Fe}^{2+})(\text{Cr}, \text{Al}, \text{Fe}^{3+})_2\text{O}_4$; compositions of natural chromites vary depending on the composition of the magma and the conditions under which it crystallized. Composition of chromite can be modified

by subsolidus reaction with silicate minerals, metamorphism, and alteration. The trace mineralogy of PGE- and sulfide-mineral-enriched chromitites is dominated by laurite, cooperite, braggite, vysotskite, platinum-iron alloy, gold, and electrum. Numerous PGE alloys, sulfide, arsenide, antimonide, telluride minerals are also present. Base-metal-sulfide mineralogy is dominated by pyrrhotite, pentlandite, and chalcopyrite.

Ore chemistry.-- Cr_2O_3 contents and chromium-iron ratios of ores reflect the composition of the mineral chromite. PGE proportions in chromite seams vary depending on mineralogy and proportions of the platinum-group element minerals. PGE-enriched chromitite layers have elevated values of platinum and palladium and high $\text{Pt}+\text{Pd}$ to $\text{Ir}+\text{Rh}+\text{Ru}$ ratios (>1). Chromitite layers not enriched in PGE have lower platinum and palladium contents and $\text{Pt}+\text{Pd}$ to $\text{Ir}+\text{Rh}+\text{Ru}$ ratios (<1).

Structural setting.--Chromite seams are commonly associated with ultramafic rocks found in sequences of cyclically layered cumulates in the lower part of mafic and ultramafic complexes.

Effect of weathering.--Chromite seams are highly resistant to oxidation and weathering; they form blocks or lumps in soils.

Geochemical signatures.--Chromium, PGE.

Geophysical signatures.--There are no geophysical techniques that will specifically locate chromite seams in mafic or ultramafic rocks. Gravity and magnetic surveys have been used to define the extent of rocks that may contain chromite seams.

Ore controls/exploration guides.--Chromite is a cumulus phase that crystallizes from a silicate magma. Base-metal sulfides and PGE minerals (predominantly laurite and Os-Ir-Ru alloys) may occur as inclusions in chromite. High-temperature reaction between chromite and sulfide minerals causes removal of FeS from the sulfide mineral association resulting in a lower percentage of sulfide minerals and nickel-rich sulfide mineral assemblages.

For sulfide-enriched chromitite layers, the formation of a chromite seam may cause the exsolution of a small amount of immiscible sulfide liquid into which PGE will partition under favorable conditions. Sulfide minerals can be interstitial to chromite and may contain platinum and palladium minerals.

Chromite seams are typically found by geologic mapping in layered igneous complexes. Barren and PGE-enriched chromite seams are macroscopically indistinguishable, and geochemical analysis is required to establish if chromite seams are enriched in PGE.

STRATIFORM CHROMITE-ENRICHED LAYERS (DEPOSIT TYPE—BUSHVELD CHROMIUM)

Stratified concentrations of cumulus chromite occur in several layered igneous complexes. Chromite abundance in individual layers range from those where chromite is only slightly enriched relative to adjacent layers to those that consist entirely of chromite. Variations in the proportion of cumulus chromite and cumulus silicate minerals form cumulus layering. Chromite seams range from less than 0.5 in. to several feet in thickness and are laterally persistent, commonly extending the length of the layered intrusion. Chromite seams commonly are found in sequences of cyclically layered cumulates in the lower parts of the cumulus stratigraphy.

Chromite ores can be classified by the composition of the ores as well as the anticipated end use (table F14). Changes in production technology have made classification by end-use less useful.

Deposits with Significant Production

Bushveld Complex, Republic of South Africa.--Multiple chromite seams are found in the Bushveld Complex; the most important include the LG6 (Steelport or Magazine) layer in the eastern and western lobes of the Bushveld Complex, the F layer south of the Steelport River in the eastern lobe, and the "middle," Up, and Lo layers of the Marico area (Vermaak, 1986). These seams are predominantly high-iron ores. The thickness of important seams is approximately 3 ft. Resource information is summarized in table F15.

Great Dyke, Zimbabwe.--Multiple chromite seams are found in the Great Dyke; the most important include layers 1, 2, and 3 (Vermaak, 1986). All 10 chromite seams range from 4 in. to 1.3 ft in average thickness. These seams are predominantly high-chromium ore. Additional resource information is summarized in table F15.

Kemi Complex, Finland.--Chromite-rich layers less than 1 in. to 300 ft thick occur near the base of this deformed stratiform complex. The minable part of the layer is 2.8 mi long. In-situ ore reserves that can be mined by open pit are 40 million metric tons at 26.6 wt. percent Cr_2O_3 , with a cut-off value of 20 wt. percent; the chromium to iron ratio is 1.53 (Alapieti, Kujanpää, and others, 1989). The open pit plans do not include additional ore reserves of 110 million metric tons. From 1966 to 1982, 8.6 million metric

tons of ore averaging 27 wt. percent Cr_2O_3 were produced from this area (DeYoung and others, 1984).

Cuttack district, Orissa State, India.--Economically exploitable resources are 69.3 million metric tons averaging 33 wt. percent Cr_2O_3 with an additional 24 million metric tons of marginally economic mineralization averaging 30 wt. percent Cr_2O_3 (DeYoung and others, 1984). From 1952 to 1982, 7.3 million metric tons of ore were produced from this area.

Campo Formoso district, Bahia province, Brazil.--Chromite seams up to 20 ft thick are mined in a disrupted stratiform complex. Economically exploitable resources are 3.4 million metric tons with 38 to 46 wt. percent Cr_2O_3 with an additional 3.8 million metric tons of marginally economic mineralization. Preliminary estimates of extensions of economically exploitable and marginal economic mineralization are 33 million metric tons with 17 to 21 wt. percent Cr_2O_3 (Stowe, 1987). Chromium to iron ratio is 1.5 to 2.2.

Other Significant Deposits

Stillwater Complex, Montana.--Historical mining focused on two chromite seams, the G (up to 12 ft thick) and the H (up to 2.5 ft thick), that occur in the middle of the Peridotite zone (Jackson, 1968). Ore averages 20 to 22 wt. percent Cr_2O_3 from which concentrates were produced that average approximately 38.5 to 41.5 wt. percent Cr_2O_3 . The chromium to iron ratio is low, typically 1.44 to 1.61. Resource information is summarized in table F2.

Bird River sill, Manitoba, Canada.--Marginally economically resources are 3.7 million metric tons averaging 21.2 wt. percent Cr_2O_3 (DeYoung and others, 1984).

Fiskenaeset area, West Greenland.--Chromite seams in this deformed stratiform anorthosite complex range in thickness from 1.6 to 10 ft thick. Marginally economic resources are 38 million metric tons averaging 32.7 wt. percent Cr_2O_3 . Average chromium to iron ratio is 0.93. Preliminary estimates of subeconomic resources are over 100 million metric tons (Stowe, 1987).

Occurrence in the Stillwater Complex

Chromite seams were discovered early in the exploration of the Stillwater Complex (Page and others, 1985b). Up to 13 chromite seams are present

**Table F14.--Classification of stratiform chromite ore by composition and principal use
(DeYoung and others, 1984¹; Vermaak, 1986²)**

Class of ore	Composition of ore (weight percent) and Cr/Fe Cr_2O_3	Cr:Fe	Principal use
High-chromium ¹ Metallurgical ²	46-55 % ≥ 46 %	> 2.1 ≥ 2.0	Metallurgical (production of ferrochrome alloy)
High-iron ¹ Chemical ²	40-46 % 40-46 %	1.5 - 2.1 1.5 - 2.0	Metallurgical, chemical (production of chromium-based chemicals), and as foundry sands

Table F15.--Chromite ore resources (million metric tons) associated with the Bushveld Complex and the Great Dyke (Vermaak, 1986)

Ore type	Area	Reserves	Indicated resources	Inferred resources	Cr_2O_3 in wt. percent	Cr/Fe
High-chromium	Bushveld - LG4 Bushveld - Potgietersrus Great Dyke	7.93 1.67 150	26.3 5.57 296	132 27.9 1428	51.25 54.41 53.25	2.12 2.38 2.31
High iron	Bushveld - western and eastern lobes Bushveld - Marico	190 44.6	455 148	2445 279	47.53 44.69	1.67 2.04
Conditional (by-product of PGE mining)	Bushveld - UG2	89.2	208	1190	43.3	1.36
Subeconomic (Cr/Fe < 1.5)	Bushveld - MG and UG1	374	871	4979	42.44	1.36

within the Peridotite zone, but chromite seams other than the A, B, G, H, and K are rarely more than a few inches thick (Jackson, 1968). Some development and mining were done along Little Rocky Creek (Benbow) and the Boulder River (Gish) preceding and during World War I. Mine development at Gish, Mouat-Sampson, and Benbow took place during the second World War. Between 1952 and 1962, approximately 2.1 million short tons of ore yielding 920,000 short tons of concentrate averaging 38.5 wt. percent Cr_2O_3 were produced from the Mouat-Sampson mine. Mining was done under contract to the U.S. government as part of a program to create stockpiles of materials critical for U.S. defense needs. The stockpile was sold in 1973. The Stillwater chromite deposits comprise most of the identified chromium resources in the United States.

Tract Delimiting Permissive Environment

The tract delineated for the Bushveld chromium deposit type includes near-surface exposures of the Peridotite zone of the Ultramafic series. The northern boundary of the tract would shift less than a kilometer to the north if the tract outline was modified to show the areal extent of permissive rocks that are within a kilometer of the surface. Higher grade chromite seams thick enough to be considered favorable for development in the near future include the G chromite seam in the Benbow, Nye Basin, and Mountain View areas and the H chromite seam in the Mountain View area. The G chromite seam in the Gish area is thinner and lower grade than in the eastern part of the complex.

Rocks and layers enriched in chromite are found locally in the Basal series, the upper part of the Bronzitite zone, in association with Olivine-bearing zone I in the Lower Banded series, and a prominent anorthosite in the Norite I zone in the Lower Banded series. However, these occurrences are too thin or discontinuous to be considered a resource for chromium.

Geologic Factors That Localize Deposits

Chromite seams are typically associated with the lower parts of cyclic units in the Peridotite zone. The thickness of chromite seams in the middle part of the Peridotite zone appears to vary directly with the overall thickness of the Peridotite zone.

Geologic and Exploration Activity Within Tract

In exposed parts of the Peridotite zone, the thicker chromite seams are easily found by detailed mapping. Between 1939 and 1945, the U.S. Geological Survey and the U.S. Bureau of Mines undertook a cooperative project in which the geology and resources of chromite in the complex were studied. All exposures of the Peridotite zone with significant concentrations of chromite were mapped and sampled (Peoples and Howland, 1940; U.S. Bureau of Mines, 1945a-j; Wimmler, 1948; Howland and others, 1949; Jackson and others, 1954; Peoples and others, 1954; Howland, 1955; Jones and others, 1960). Outcrops were mapped at a scale of 1:1,200 for the most important prospect areas. Published locations of channel sample and trench sites and collar location of drill holes are shown on plate 14-F. Sample locations in areas of significant mineralization are so closely spaced that they appear as lines on this figure. This map under-represents the amount of prospecting work that was done because almost all significant exposures of chromite-enriched rock in the complex were sampled, pitted, or trenched.

Underground development work at the Gish mine, the Benbow mine, and the Mouat-Sampson mine during World War II allowed the chromite seams to be examined over a vertical extent of 500 to 1,000 ft (Wimmler, 1948). Both the American Chrome Company (14 drill holes in 1956 and 1957) and Chrome Corporation of America (14 drill holes in 1989) conducted drilling programs to extend the resources of the G and H chromite seams in the Mouat-Sampson mine; intercepts of the G and H chromite seams were intersected at least 300 ft below the number 5 level of the mine.

A poorly exposed chromite seam less than 8 in. thick crops out in the upper part of the Basal series in the Benbow area (Jackson and others, 1954). Drilling to investigate nickel-copper deposits near the base of the complex encountered chromite-enriched rocks in the Basal series in the Chrome Lake (fig. F2), Benbow (fig. F3), and Mountain View areas. The chromite seams in the Mountain View area were the thickest, with drill intercepts up to 4.9 ft (Zientek and others, 1989). Cr_2O_3 contents of these chromite seams are not known. These seams are too thin or laterally discontinuous to be of economic interest.

Other occurrences of rocks enriched in chromite in the complex were found during the course of stratigraphic studies or exploration focused on the J-M Reef. The chromite-enriched layers near the top of the Bronzitite zone range in thickness from less than

1 in. to approximately 6 in. Chromite-enriched layers associated with the olivine-rich layers of Olivine-bearing zone I are laterally discontinuous and rarely more than 0.2 in. thick; podlike accumulations several inches to one foot thick were found in one location in the Stillwater mine (M. Koski, written commun., 1989). Thin stringers or xenoliths of chromitite are described from what is locally referred to as the All American anorthosite layer in the Norite I zone (Todd and others, 1982; S.G. Todd, oral commun., 1985). Although all these occurrences may be of petrologic significance, they are too thin or discontinuous to be of economic interest.

Factors Affecting Exploration Success

Chromite seams are generally easy to locate by mapping; the color contrast with adjacent silicate minerals and the vitreous luster of chromite make concentrations of chromite easy to identify. Chromite seams are highly resistant to weathering and may form blocks or lumps in soil. Geochemical or geophysical methods have not been used for chromite exploration.

Recovery of chromite seams in drilling programs can be lower than silicate-rich rocks. Chromite seams commonly are more friable and may disaggregate and be flushed away with drilling fluids.

In highly serpentinized rock, chromite seams may be harder to locate. Chromite seams have been confused with magnetite stringers that form during serpentinization and the chromite seams may be disrupted and be partly converted to ferrichromite. Exposures of rock surfaces which show primary textures may be rare; most surfaces may be joints, fractures, or small shears coated with secondary minerals.

Geologic Factors Affecting Resource Development

Thickness and grade.--Few of the Stillwater chromite seams are sufficiently thick to maintain reasonable grades over minimum mining widths likely to be considered. Only the A, B, G, and H chromite seams are thick enough to be routinely sampled.

The grades for the G and H chromite seams are low in Cr_2O_3 and have low chromium to iron ratios (table F2). Grades and chromium to iron ratio are higher at the Benbow area than at the Mountain View area. The grade of the chromite seam at the Gish mine is significantly lower than the seams at the

Benbow and Mountain View areas. Stillwater ores are only marginally suitable for chemical manufacturing, for direct conversion to ferrochrome alloy, or foundry sands. The ores are subeconomic compared to ores from stratiform complexes in southern Africa; these ores might become economic if a low cost method of ferrochrome production could be devised.

Continuity.--The local continuity of the chromite seams is affected by the same type of normal-to-layering faults that disrupt the rocks that host the basal nickel-copper mineralization. In the Benbow area, chromite seams are offset by tens of feet along subparallel faults spaced 50 to 650 ft apart. In contrast, the G and H chromite seams in the Mountain View area (between the Lake fault and Bluebird thrust) are minimally affected by this style of faulting.

Dilution.--The G and H chromite seams consist of a sequence of chromite-enriched layers; typically one or more layers of massive chromitite near the base of the package are overlain by layers with lesser and variable proportions of chromite. In the Mouat-Sampson mine in the Mountain View area, the G and H chromite seams both increase in thickness downdip and to the northeast. Not only does the package of layers increase in thickness but individual layers as well. Massive layers may be separated by thick layers poor in chromite so that for the same mining width the overall grade may be less.

The degree of serpentinization varies within the Peridotite zone; rocks at Benbow are more serpentinized than at Mountain View. Serpentinized rocks are more sheared and friable; increased dilution during drawdown of stopes may be expected. However, chromite ore in serpentinized rocks is easier to beneficiate because it is more friable.

Partially Delimited or Undiscovered Deposits—Location and Potential Resources

Potential resource development in the foreseeable future will be limited to the G chromite seam in areas east of the West Fork of the Stillwater River (and the H chromite seam in the Mountain View area). The largest proportion of geologic resources that have not been defined by exploration are in "undiscovered" deposits that are fault-offset extensions of known deposits or prospects (28 million metric tons). A smaller amount of mineralized rock may be in extensions to known prospects or deposits (17 million metric tons of mineralized rock that may contain 23 wt. percent Cr_2O_3 ; tables F8, F9, and F10).

It is unlikely that undiscovered chromite seams of any interesting thickness or lateral continuity remain to be found in near-surface exposures of the Peridotite zone.

Resources associated with the G chromite seam in the Benbow area have only been partially delimited by surface sampling, near-surface drilling, and underground exploration (table F2 and plate 14). Surface mineralization can be projected down-dip because no faults have been mapped that would truncate the mineralization. Previously, potential resources that are an extension to the identified resources have been estimated to elevations of 7,500 ft, 5,300 ft [elevation of the town of Dean, at the intersection of Montana Highway 419 and the Benbow road, U.S.F.S. Road 1414], and 5,000 ft [elevation of the Stillwater River valley near the Stillwater mine] (table F2). The calculation of resources was made by extending the previous resource estimates to an elevation of 1,722 ft. Potential resources listed in table F9 are large compared to the drill-indicated resources.

The exposures of the G chromite seam in the Nye Basin and Mountain View areas are in the upper plate of high-angle reverse faults (plate 14-E). Like the sulfide mineralization near the base of the complex, the chromite seams are truncated by these high-angle reverse faults at depth. Resources estimated for extensions of partially delimited mineralization in the upper plate of these faults are less than what may exist in "undiscovered" deposits that are the offset parts of the chromite seam that occur in the footwall of these structures (table F8). Calculations were made by multiplying areas measured from geologically constrained long-sections by assumed horizontal thickness of mineralized rock and appropriate tonnage factors. Assumptions used are similar to those made in the calculations of resources associated with sulfide mineralization near the base of the complex. A horizontal width of mineralization of 5 ft was assumed. In the Mountain View area, most of the resources lie in the upper plate of the fault. No extensions were made to the resources in the upper plate rocks (Mouat-Sampson mine). Resources below the fault are estimated to be below an elevation of 5,000 ft. In the Nye Basin area, only a trivial resource is associated with the G chromite seam in the rocks above the Nye Basin fault. Again, most of the resources estimated to be in the footwall of the fault are below an elevation of 5,000 ft. Efforts to locate the offset portions of the Nye Basin and Mouat-Sampson deposits are considered unlikely until low cost methods for processing Stillwater chromium ore are developed.

STRATIFORM PGE-ENRICHED CHROMITITE LAYERS

Stratiform chromite seams like those in the Bushveld chromium model can be enriched in PGE to the extent that they can be considered for development strictly on their PGE content alone. The UG2 chromite seam in the Bushveld Complex represents one of the major repositories of PGE in the world. Sulfide mineral abundance is very low (much less than 1 volume percent); sulfur content of the PGE-enriched chromite seams is typically less than 100 ppm.

Deposits with Production

UG2, Bushveld Complex, Republic of South Africa.--The UG2 chromite seam is within the Upper Critical zone of the Eastern and Western compartments of the Bushveld Complex. The thickness of the UG2 ranges from 6 to 100 in. (McLaren and DeVilliers, 1982). The UG2 is a significant world resource of PGE (Sutphin and Page, 1986) and is currently being mined at Western Plats, Impala, and in the Union section of Rustenburg Plats in the Western Bushveld Complex (Wyllie, 1987). Economic resource estimates range from 1,485 to 2,136 million metric tons of ore with recoverable grades ranging from 5.6 to 7.4 ppm PGE. Buchanan (1979) reported an average in place grade of 8.71 ppm PGE for the UG2 chromite seam.

Other Significant Deposits or Occurrences

A and B chromite seams, Stillwater Complex, Montana.--The A and B chromite seams consist of one or more massive chromitite layers in a 5 to 15 ft interval with disseminated chromite in olivine cumulate and thin chromitite layers in a cyclic unit near the base of the Peridotite zone. Resource investigations focused on these seams near the West Fork of the Stillwater River, where they can be traced for about 1 mi on strike. Using a nominal mining width of 4 ft, approximately 3.8 million metric tons of ore averaging 2.06 ppm palladium plus platinum were identified. Analyses of select samples can exceed 33 ppm PGE plus gold.

Upper, Middle, and Lower Group chromite seams, Bushveld Complex, Republic of South Africa.--PGE contents of higher grade samples of the Upper, Middle, and Lower Group chromite seams of the

Bushveld Complex range from 1.03 to 5.37 ppm for layers that are 2.6 to 4.3 ft thick (von Gruenewaldt and others, 1986). For the LG6 chromite seam with chromium to iron ratio greater than 1.5, Vermaak (1986) reported economic resources of 1,560 million tons of ore over widths of 2.9 to 5.1 ft. An analysis of the LG6 published by Lee and Parry (1988) showed 1.034 ppm PGE plus gold.

Great Dyke, Zimbabwe.--The main chromite seams on the Sebakwe and Darwendale subchambers contain about 1 ppm platinum and palladium with a mean palladium to platinum ratio of 0.70 (Prendergast and Wilson, 1989).

A-seam chromitite, Panton Sill, Western Australia.--An indicated and inferred resource of 2.0 million metric tons grading 6.02 ppm PGE plus gold and 0.28 wt. percent nickel has been estimated for part of the A-seam chromitite in the Panton sill (Perring and Vogt, 1991). The A-seam has an average thickness of 31.5 in. Average grades for the seam are: 3,175 ppb platinum, 3,720 ppb palladium, 70 ppb rhodium, and 530 ppb gold.

Occurrence in the Stillwater Complex

Chromite seams with elevated concentrations of PGE are present in the Peridotite zone. However, not all chromite seams are enriched in PGE. The highest PGE concentrations are consistently associated with the A and B chromite seams, the lowest in the Peridotite zone. Exploration activity focused on these chromite seams in the eastern part of the Stillwater Complex (plates 14-G and 14-H and table F3).

The B chromite seam in the West Fork area was most thoroughly tested. PGE concentrations over 20 ppm were reported, but overall grades for nominal mining widths of 4 ft are considerably lower (about 2 ppm) because of inclusion of unmineralized rock. These results can be compared to other PGE-enriched stratiform chromitites in the cumulative grade distributions in figure F6. Of all the chromite seams illustrated, only the UG-2 is being mined for its PGE content. The general applicability of the grade distribution to the Stillwater Complex for modeling can be questioned because most points on the

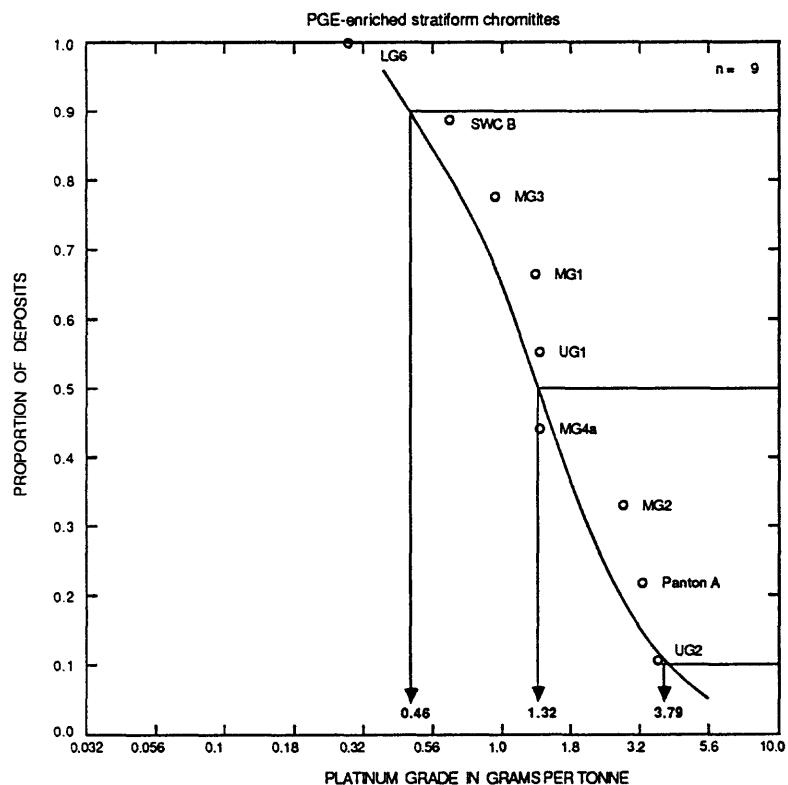


Figure F6.--Cumulative frequency distribution for PGE grades in PGE-enriched stratiform chromitites. A) Platinum, B) Palladium, C) Rhodium, D) Rhuthenium, and E) Iridium. Values for 10th, 50th, and 90th percentiles are highlighted. Explanation for symbols: LG6, MG3, UG1, MG4a, MG2, and UG2 - chromitite zones in the Bushveld Complex, Republic of South Africa; Panton A - A chromitite zone in the Panton sill, Western Australia; SWC B - B chromite seam, West Fork area, Stillwater Complex.

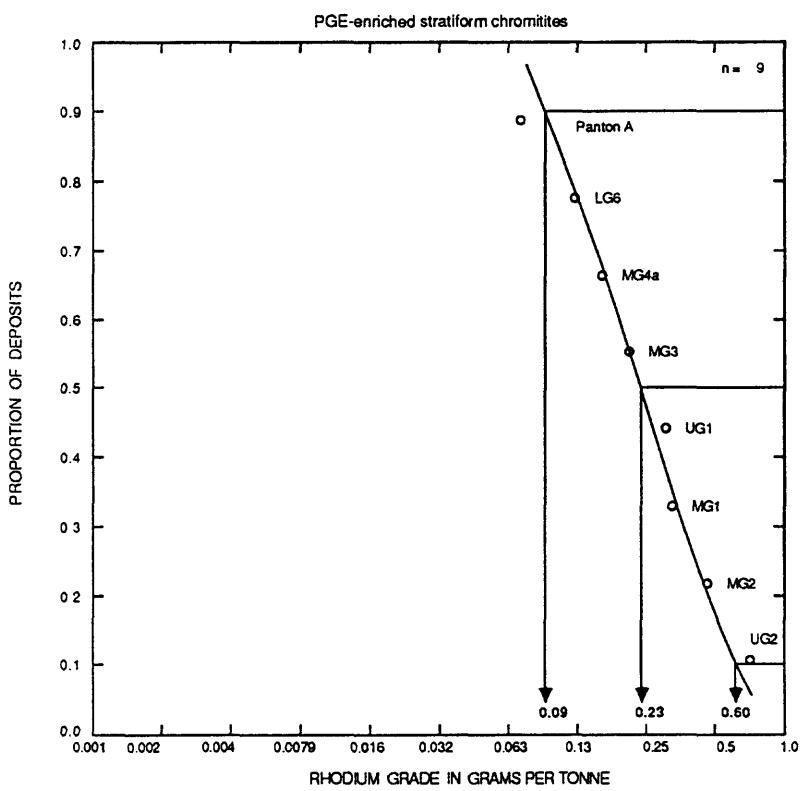
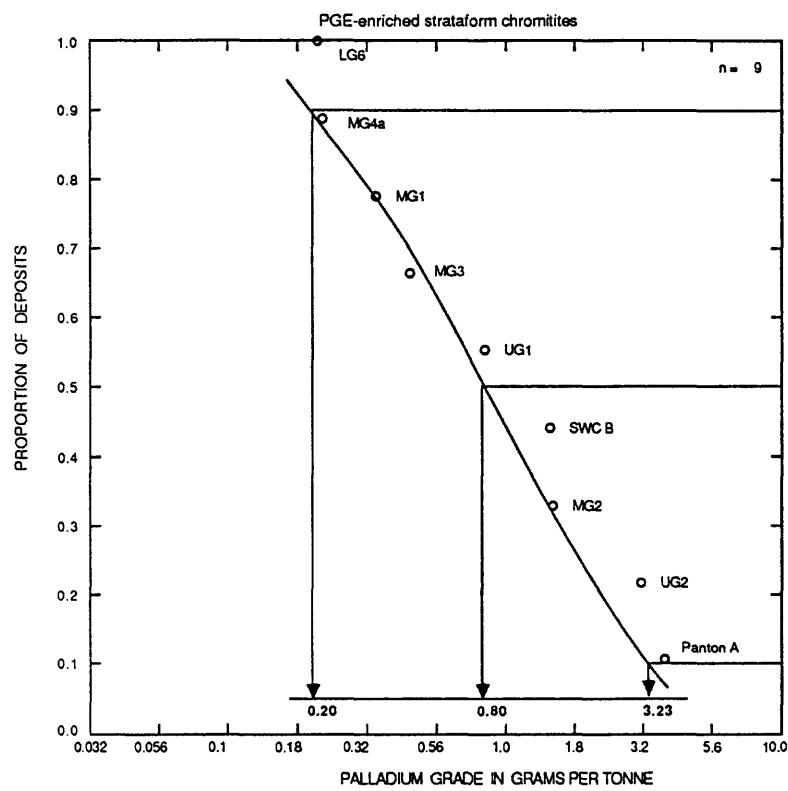


Figure F6.--Continued.

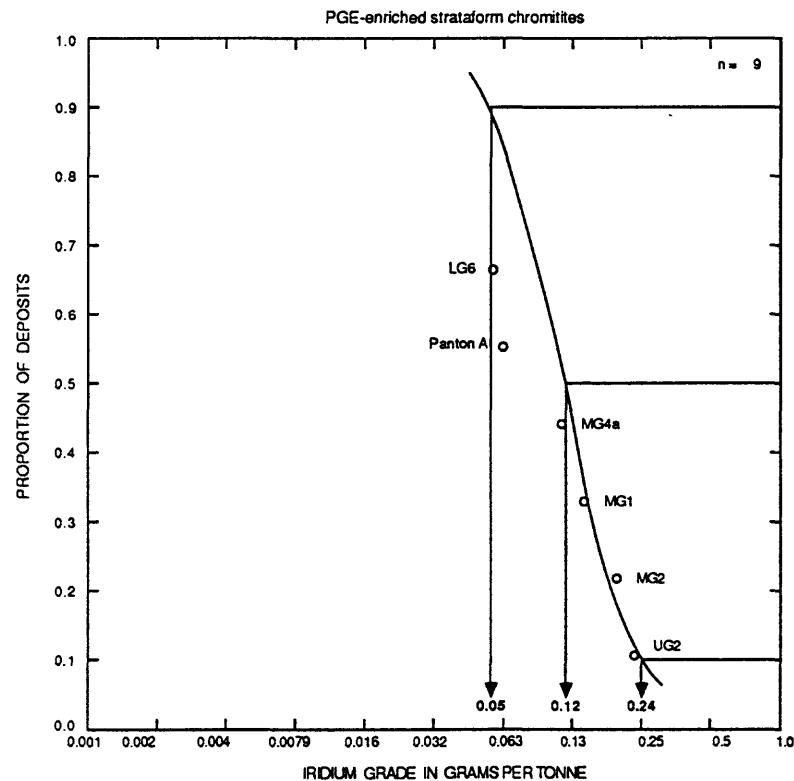
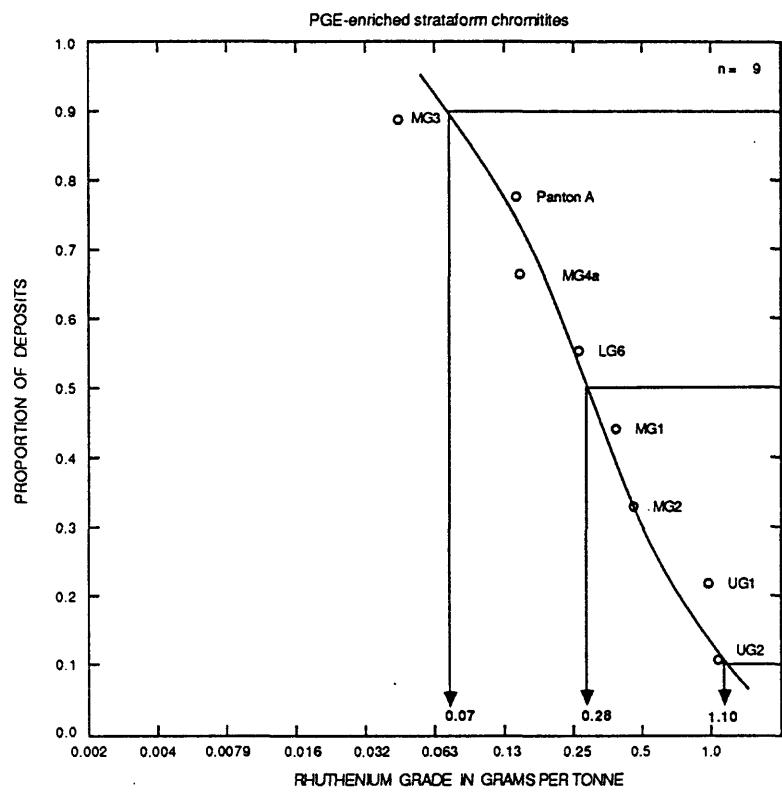


Figure F6.—Continued.

distribution are from the Bushveld Complex. In that intrusion, a large proportion of the chromite seams have elevated PGE concentrations. Based on incomplete sampling, median PGE concentrations of most Stillwater chromite seams fall well below the grade distribution in figure F6.

Tract Delimiting Permissive Environment

The tract delineated for PGE-enriched stratiform chromitites is the same as for the Bushveld chromium deposit type: near-surface exposures of the Peridotite zone of the Ultramafic series. Chromite seams occur outside the Peridotite zone but are too thin and discontinuous to be an important resource even if they were enriched in PGE.

Geologic Factors That Localize Deposits

As discussed earlier, chromite seams are typically associated with the lower parts of cyclic units in the Peridotite zone. Chromite seams that are PGE-enriched cannot be distinguished from those that are not except by analysis. The PGE-enriched chromitites could have slightly higher sulfide mineral contents, but the distinction is not easily determined by visual inspection of the rocks.

Geologic and Exploration Activity Within Tract

Interest in the PGE concentrations of chromite-rich rocks postdates the wartime effort to evaluate the chromium resources in the complex. Exploration efforts are less comprehensive than the work to evaluate the chromium resources of the complex or the potential for reef-type mineralization in the Lower Banded series (plates 14-G and 14-H). Reconnaissance sampling reported by Page and others (1969; 1972; 1976) focused on obtaining a suite of samples that would stratigraphically represent all chromite seams in the Peridotite zone (table F16); the A chromite seam in the West Fork area was clearly anomalous. [Subsequent investigations in the West Fork area subdivided the A into two chromite seams (Mann and others, 1985). The lower chromite seam, the A, is finer grained and laterally discontinuous; the upper group of chromite-enriched layers is coarser grained, shows greater lateral continuity, and is referred to as the B chromite seam.]

Based on the results summarized by Page and coworkers, several episodes of exploration activity focused on the PGE-enriched chromite seams in the West Fork-Crescent Creek area, first by Anaconda in 1969 (Adler, 1971) and 1979 (Loehr, 1979) and later by Boulder Gold in the late 1980's and continuing to present. Results of the work in 1979 identified 3.4 million metric tons of rock averaging 2.4 ppm platinum and palladium over a nominal width of 4 ft. The best assays reported by Boulder Gold for this area are surface samples of the B chromite seam with 10.97 ppm PGE over 3.6 ft and 21.6 ppm PGE over 5.9 in. (Boulder Gold, written commun., 1991). The extent of sampling and drilling for this area is illustrated in plates 14-G and 14-H.

Work outside the West Fork area includes the occasional analysis of rocks encountered during nickel-copper exploration drilling from 1969 to 1971 (table F17), a regional sampling program conducted by Anaconda in 1978 (Kell and Loehr, 1979), and sampling of the A and B chromite seams in the eastern part of the complex and of the G and H chromite seams in the Mountain View area by the U.S. Geological Survey (M.L. Zientek, unpub. data; B.R. Lipin, unpub. data; Talkington and Lipin, 1986). In the Mountain View area, Boulder Gold sampled the B chromite seam in outcrop and drilled three holes; in the Benbow area, they sampled the A chromite seam in new trenches and drilled one hole. The results of these investigations show how little is known about this type of mineralization and suggest that additional work will be necessary to fully evaluate the PGE resources that may be associated with Stillwater chromite seams.

Within a chromite seam, no lithologic feature can be observed that will indicate which samples will be enriched in PGE. Analysis of results from several studies shows that anomalous values of PGE are not restricted to layers that are most rich in chromite and that chromite-rich layers that make up a chromite seam are not uniformly enriched in PGE. Analytical data for grab samples of chromite cumulate, olivine-chromite cumulate, and olivine cumulate from the West Fork area are summarized in figure F7. Chromite cumulates have the highest maximum PGE contents and a larger proportion of samples with elevated PGE concentrations relative to the other groups. However, PGE concentrations of chromite cumulate vary over 3 orders of magnitude, indicating samples of chromite cumulate from the same seam are not uniformly enriched in PGE. Median values

Table F16.--PGE analyses of chromitites from the Peridotite zone, Stillwater Complex. From Page and others (1976). Results for the A is the range for 5 samples; others are single samples

Chromitite zone	Area	Pt, ppb	Pd, ppb	Rh, ppb
A	West Fork	1900 - 8000	5000 - 11000	430 - 1700
B	Benbow	82	51	57
C	Benbow	45	36	42
E	Benbow	10	5	11
G	Mountain View	36	4	60
H	Mountain View	46	52	48
I	Nye Basin	52	40	38
J	Benbow	330	270	190
K	Nye Basin	110	72	50

Table F17.--Pt and Pd analyses of drill core from Anaconda's Ni-Cu exploration project, Mouat and Nye Basin areas, Stillwater Complex. Samples are of chromite-enriched rocks from the lower part of the Peridotite zone unless noted otherwise

Area	Drill hole	Intercept (ft)	Pt, ppm	Pd, ppm
Mouat	380-321 ¹	210.5-212	3.42	0.41
		254.5-279	5.14	0.68
		279-303 *	0.68	0.34
		363-422 *	1.37	5.14
Nye Basin (east)	NB-9 ²	4 inch sample of chromitite from 789.5 ft	0.68	3.87

* No chromitite noted in drill core.

¹ Adler (1971).

² Page, N.J, undated, unpublished data.

for the 3 groups of samples with different proportions of chromite are similar and the maximum values for olivine-chromite cumulates and olivine cumulates have anomalous PGE concentrations. A similar relation is observed for grab samples collected in the B chromite seam in the Mountain View area (fig. F8). Analytical data for composite samples from 2 drill holes through the B chromite seam in the West Fork area are illustrated in figure F9. For these intercepts, the samples of massive to semi-massive chromitites have higher PGE contents and lower variance than the samples of olivine cumulates. However, some samples of olivine cumulate have elevated PGE concentrations; samples with the highest PGE concentrations do not consistently have either the highest concentration of sulfide minerals (fig. F10) or chromite (fig. F11).

In summary, elevated PGE values are not restricted to chromite-rich layers in chromite seams and all chromite-rich layers are not enriched in PGE. PGE mineralization associated with stratiform chromitites cannot be assessed by grab sampling of the more chromite-rich rocks at any locality. Lateral variation in PGE concentrations within an individual layer within a chromite seam have not been documented. Systematic channel sampling or analysis of contiguous composite samples of drill core required to adequately test the PGE potential of chromite seams has only been done systematically for the West Fork area.

Keeping the sampling problems in mind, the exploration data from the rest of the complex show significant lateral differences in the PGE concentrations in a chromite seam. Sampling results from the different localities in the eastern part of the complex show that the A and B chromite seams are not uniformly enriched in PGE (fig. F12). Samples with the highest PGE concentrations come from the area extending from the West Fork of the Stillwater to the Stillwater River. The A and B chromite seams from Nye Basin to the east have lower platinum and palladium concentrations. Some of this variation may reflect what is being sampled; there are differences of opinion about correlations of chromite seams. The G chromite seam shows similar on-strike variations (fig. F13). Sampling of the same seam by different investigators in the same geographic area gave similar results. Page and others (1976) reported 40 ppb for the G chromite seam in the Mountain View area, consistent with the results obtained on analysis of Mountain View drill core pulps collected in 1990 (fig. F14). Reconnaissance sampling of the G chromite seam in the Mountain View area by Anaconda in 1978 had slightly higher, but still relatively low con-

centrations (fig. F13). Data collected during the 1978 survey show the seam that was referred to as the G chromite seam in the Gish mine area has significantly higher platinum and palladium concentrations than the G chromite seam anywhere else in the complex. Maximum concentrations of platinum and palladium at the Gish mine area are in excess of 1 ppm. Although the median platinum and palladium concentrations for the G chromite seam collected away from the Gish mine area are low, some samples of the G chromite seam in the Benbow area are enriched in platinum and palladium. Data for the G, E, H, and K chromite seams in the eastern part of the complex are summarized in figure F15.

The remainder of the data from the 1978 survey is summarized only by geographic area because samples could not be referenced to specific chromite seams. Regardless, samples of chromite seams with platinum and palladium in excess of 1 ppm were found in the Iron Mountain, Lost Mountain, Chrome Mountain, West Serpentine, and Blakely cliffs area (fig. F16).

Factors Affecting Exploration Success

The comments on chromite seams in the section on the Bushveld chromium deposit model are equally appropriate here. In addition, several other topics are relevant to the PGE potential of chromite seams.

Exposure.--With exceptions, chromite seams are seldom completely exposed vertically or laterally. Trenching and drilling are normally necessary to get a complete profile.

Non-uniform distribution of the PGE.--To adequately test for PGE-enrichment, a large number of samples must be collected and analyzed systematically along and through the permissive zone. With the exception of a few areas, sampling has not been adequate for comprehensive evaluation of PGE contents of the chromite seams.

Correlation questions.--Exploration activities have focused on lateral extensions of chromite seams from which PGE-enriched samples were collected in a few localities. This strategy has two problems. As discussed previously, PGE concentrations of a chromite seam can vary along strike. Second, a PGE-enriched seam may be difficult to sample on strike because of uncertainties in correlation. In most cases, chromite seams cannot be physically traced across the complex.

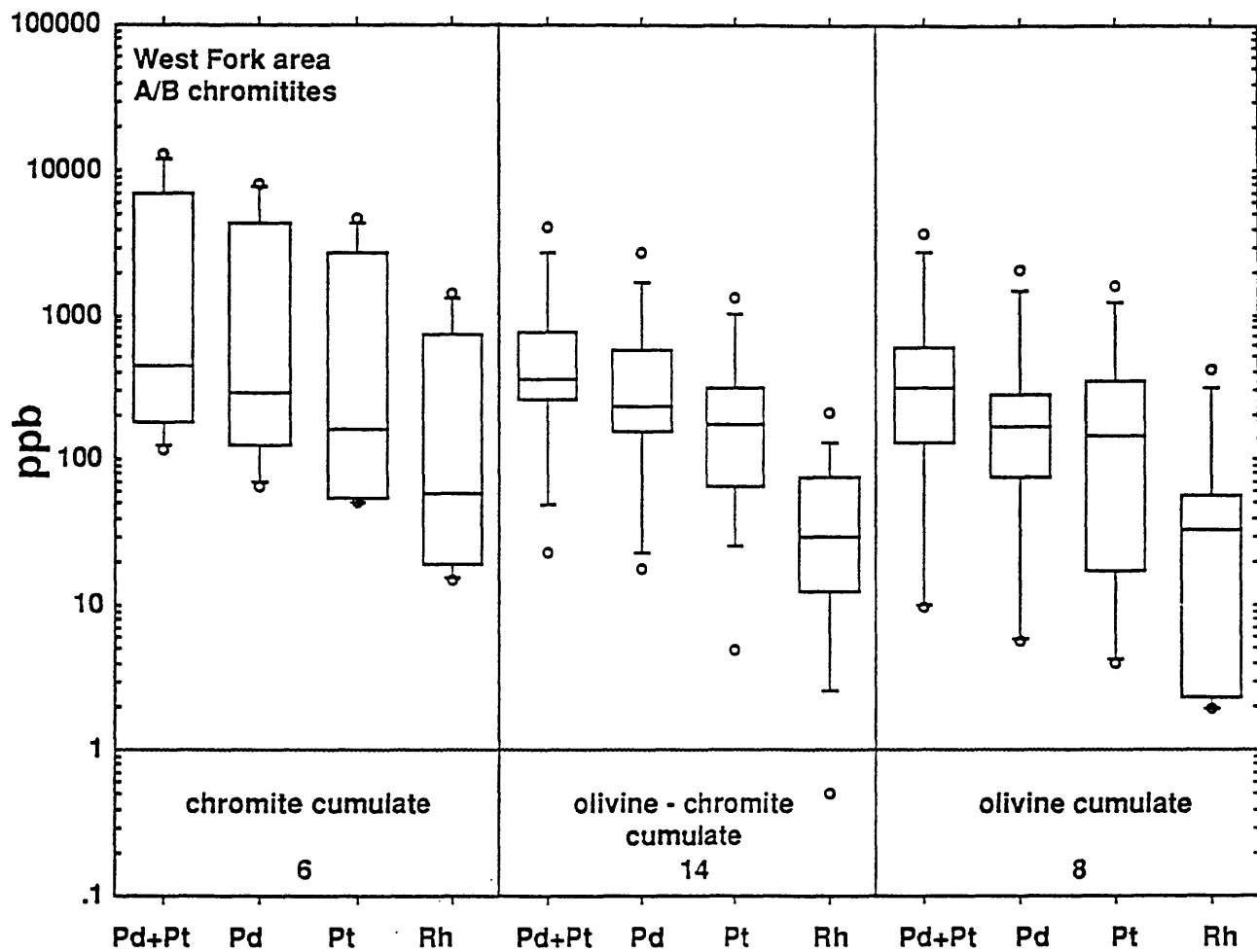


Figure F7.—Box-and-whisker plots illustrating the distribution of Pd+Pt, Pd, Pt, and Rh concentrations for rock types associated with the A/B chromite seams, West Fork area, Stillwater Complex. Samples are hand specimens. Key to symbol - horizontal line in box is median value of the data; open box extends to the 25th and 75th percentiles of the data; lines at the end of the box ("whiskers") extend to the 10th and 90th percentiles of the data; small circles show values falling outside the 10th to 90th percentiles of the data. Numbers below each symbol are the number of samples in each group. Data from Lipin (written commun., 1991).

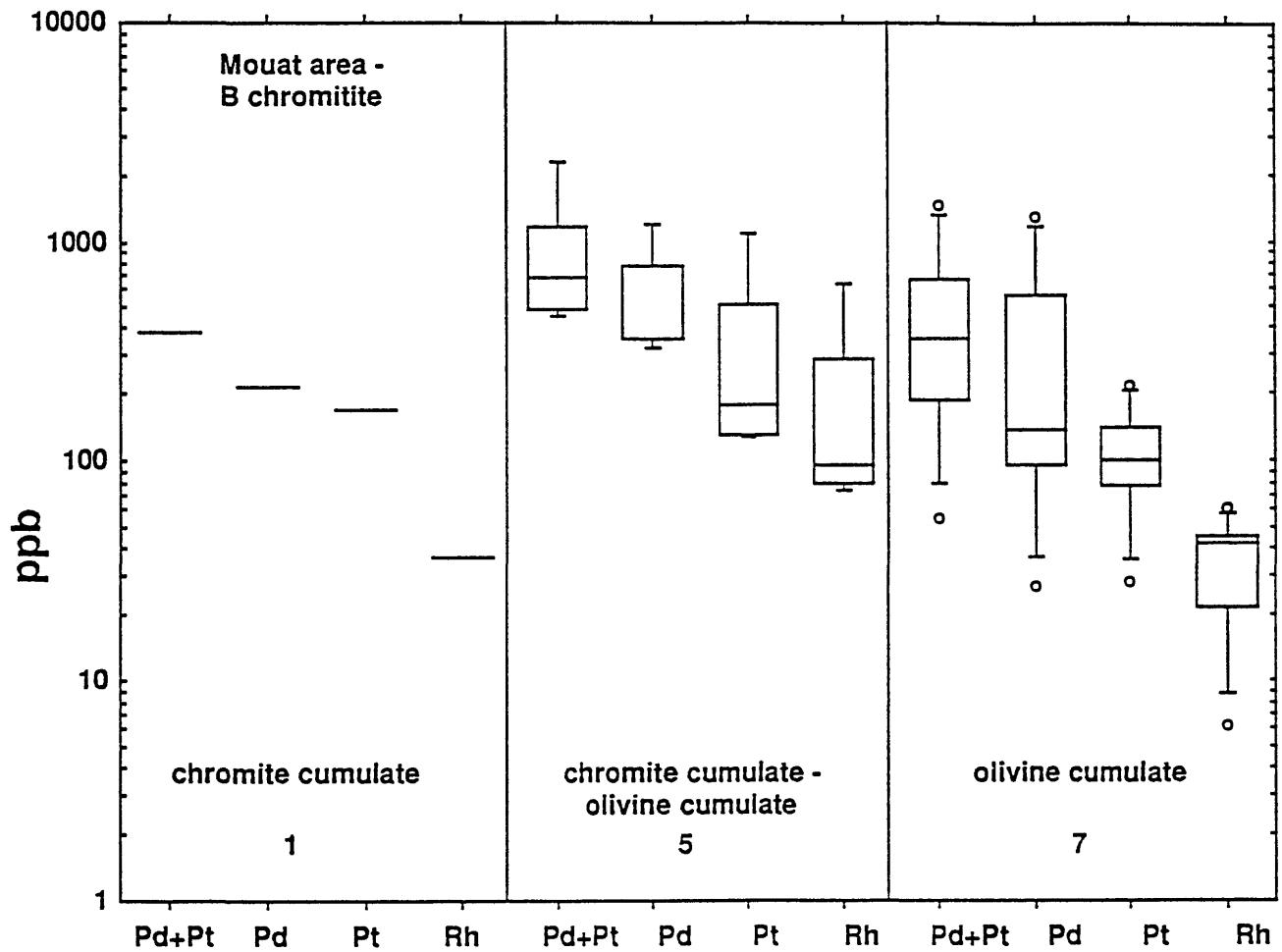


Figure F8.—Box-and-whisker plots illustrating the distribution of Pd+Pt, Pd, Pt, and Rh concentrations for rock types associated with the A/B chromite seams, Mouat area, Stillwater Complex. Samples are hand specimens. Key to symbol - same as figure F7. Data from Lipin (written commun., 1991).

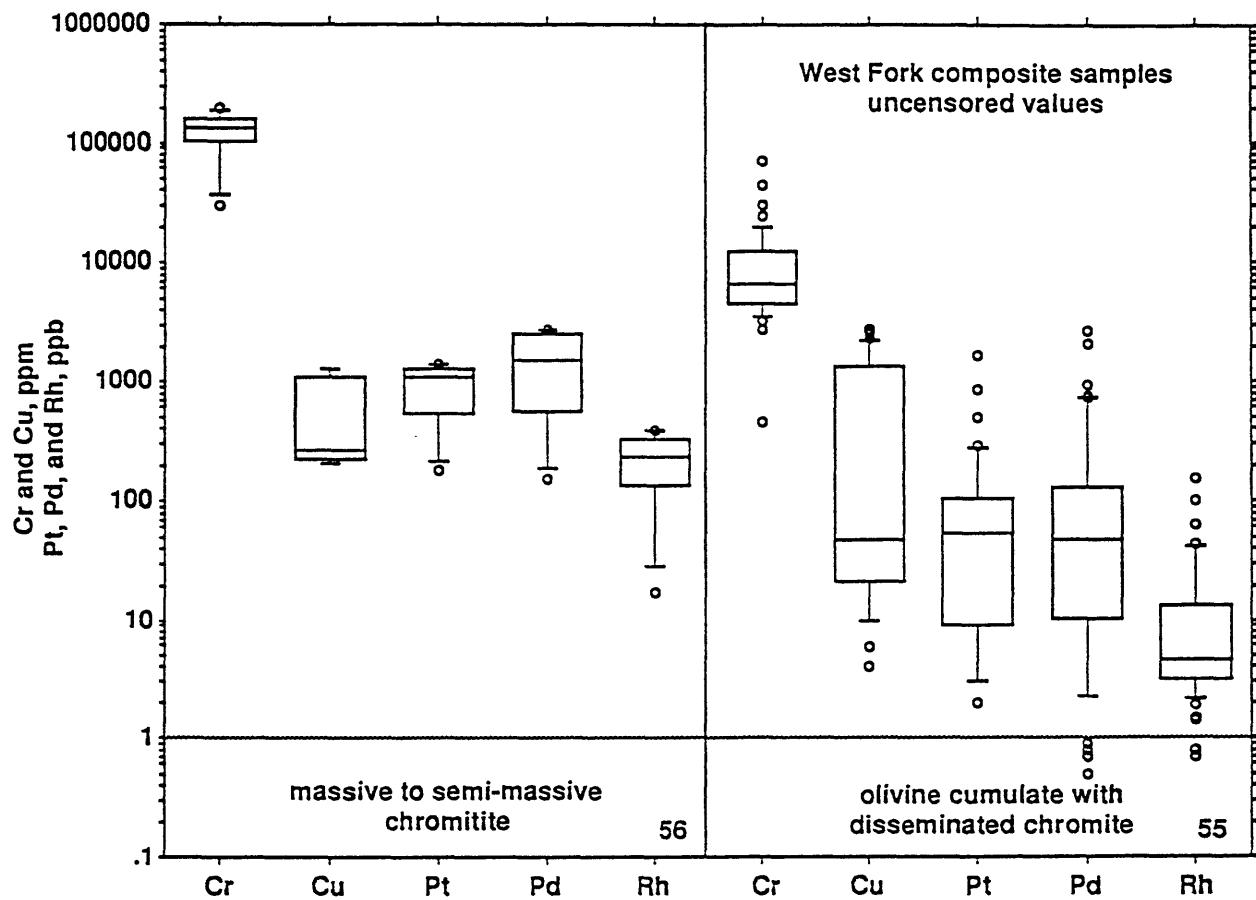


Figure F9.—Box-and-whisker plots illustrating the distribution of Cr, Cu, Pt, Pd, and Rh concentrations for rock types associated with the A/B chromite seam, West Fork area, Stillwater Complex. Samples are composites of drill core. Key to symbol - same as figure F7.

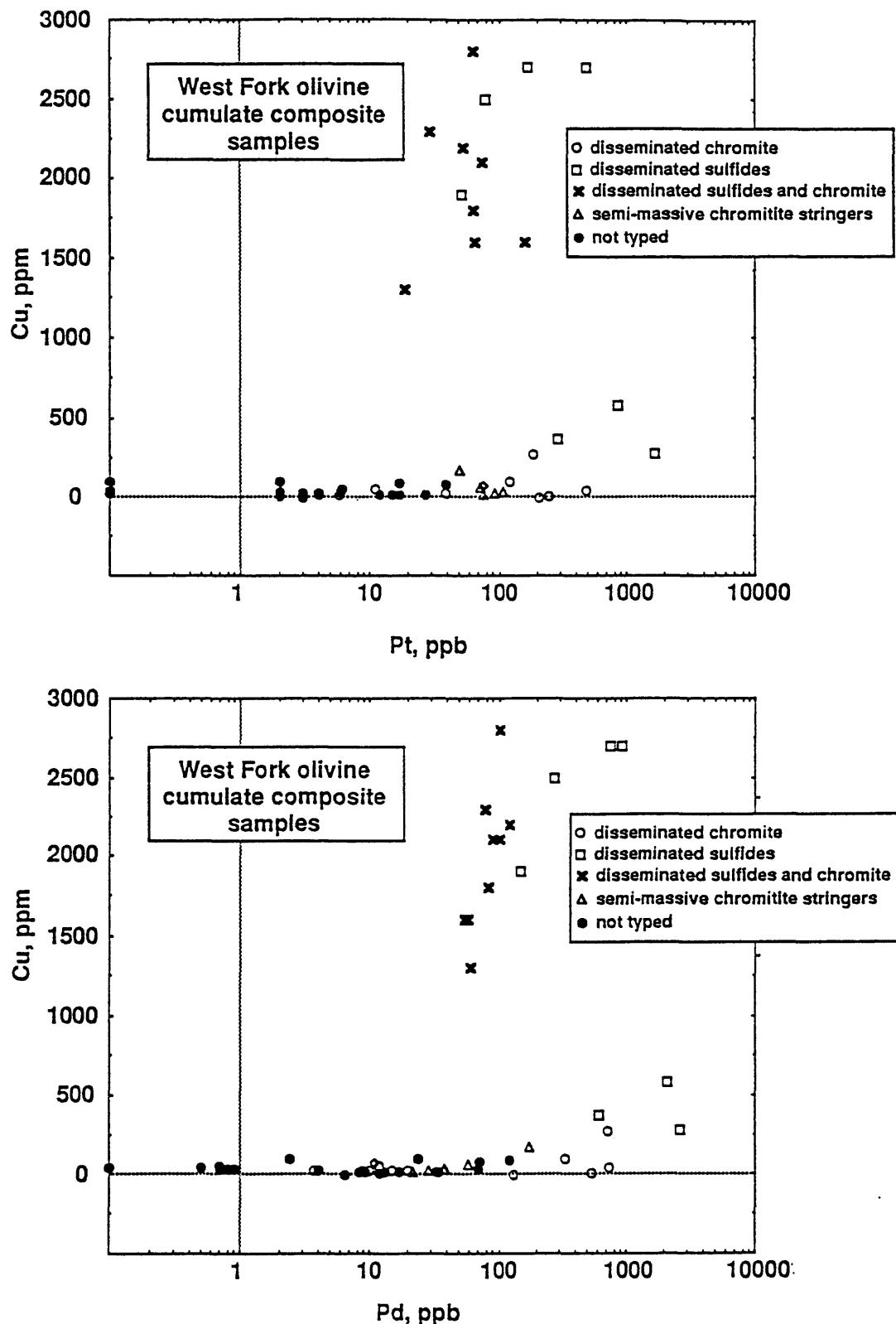


Figure F10.—Variation diagrams for Cu versus Pt and Pd for drill core composite samples consisting predominately of olivine cumulate in vicinity of the A/B chromite seam, West Fork area, Stillwater Complex.

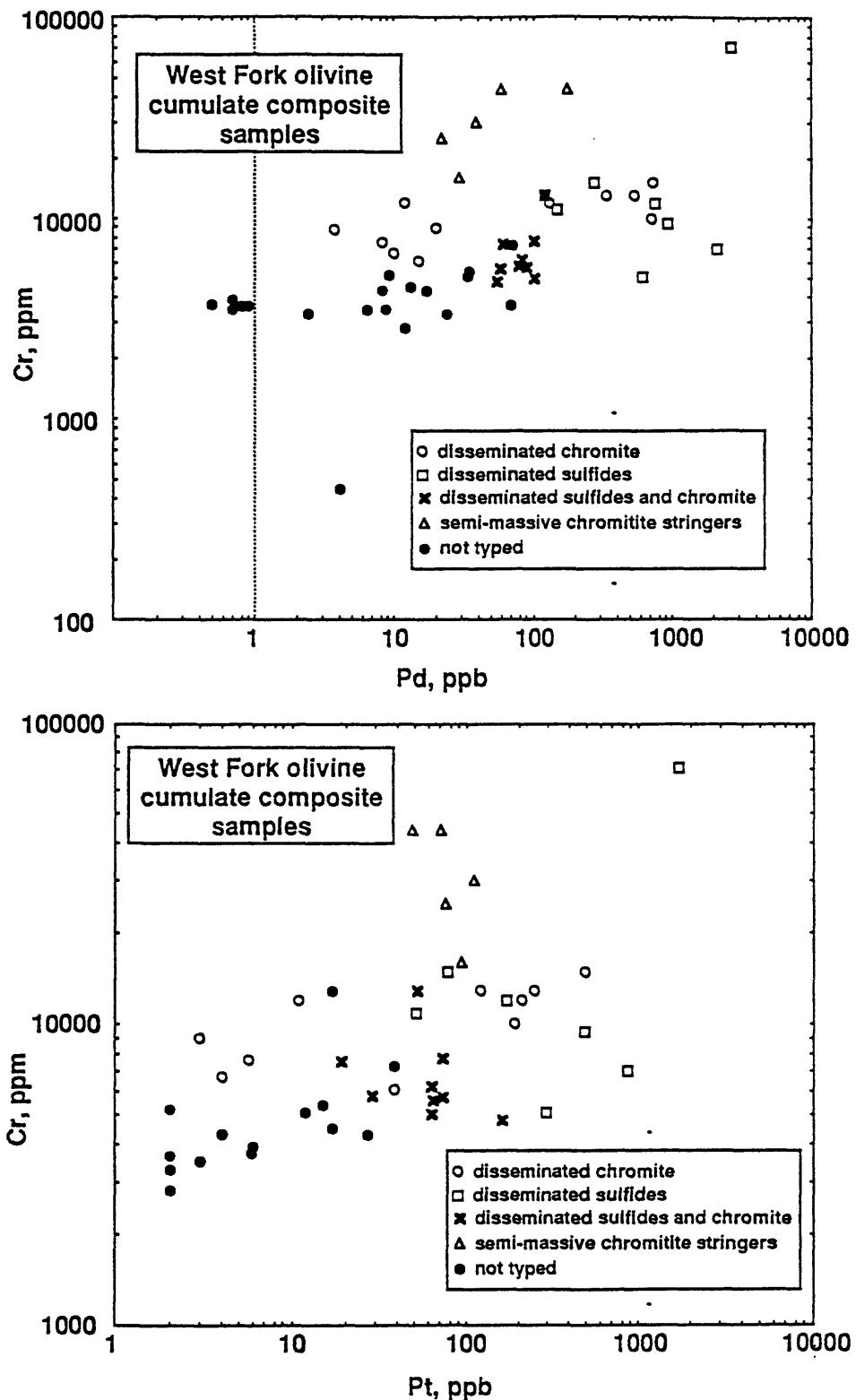


Figure F11.—Variation diagrams for Cr versus Pt and Pd for drill core composite samples consisting predominately of olivine cumulate in vicinity of the A/B chromite seam, West Fork area, Stillwater Complex.

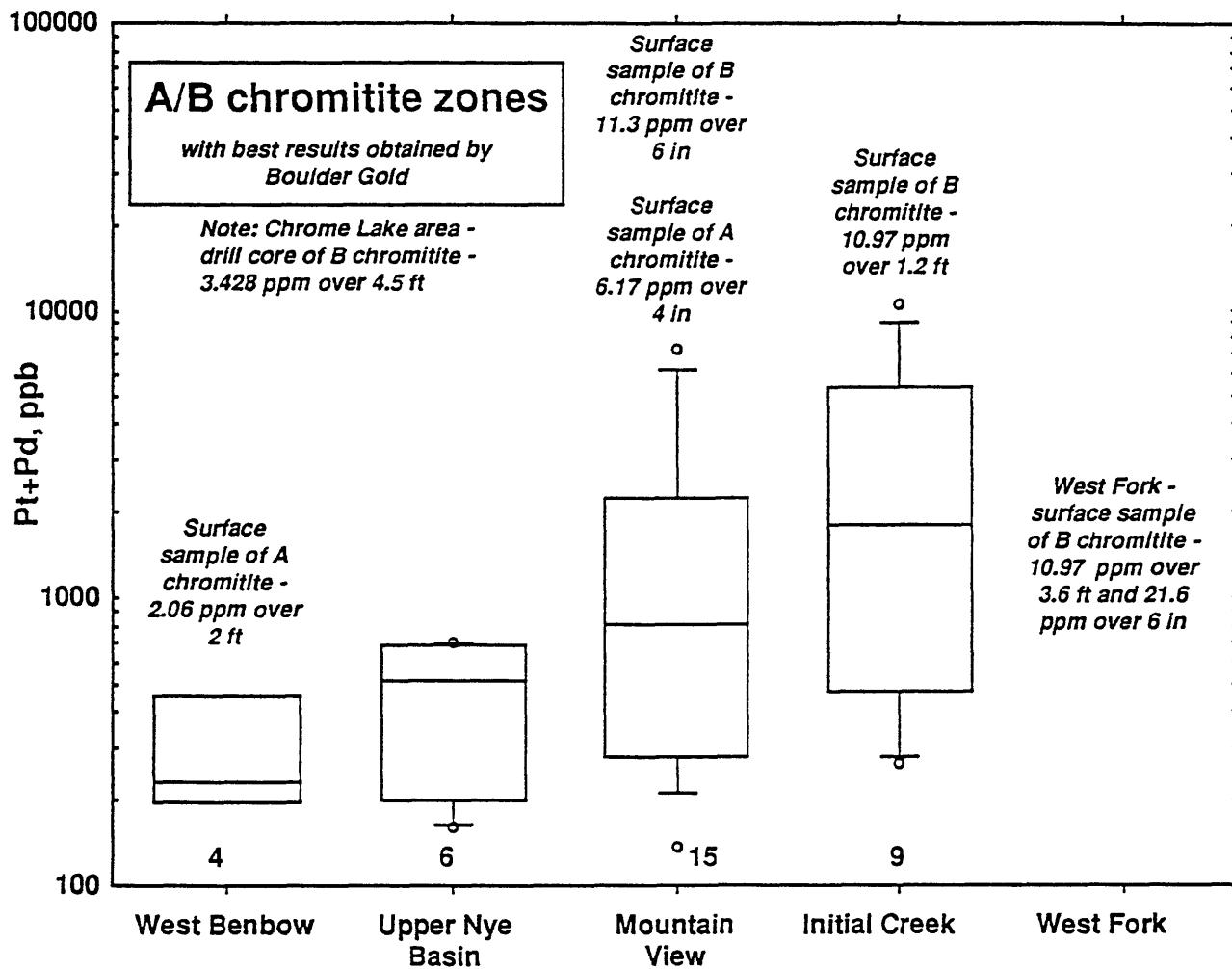


Figure F12.—Box-and-whisker plots illustrating the lateral variation in Pt+Pd in the A/B chromite seam, Stillwater Complex. Key to symbol - same as figure F7. Data from Kell and Loehr (1979). Best assays determined by Boulder Gold (written commun., 1991) are also given for each area.

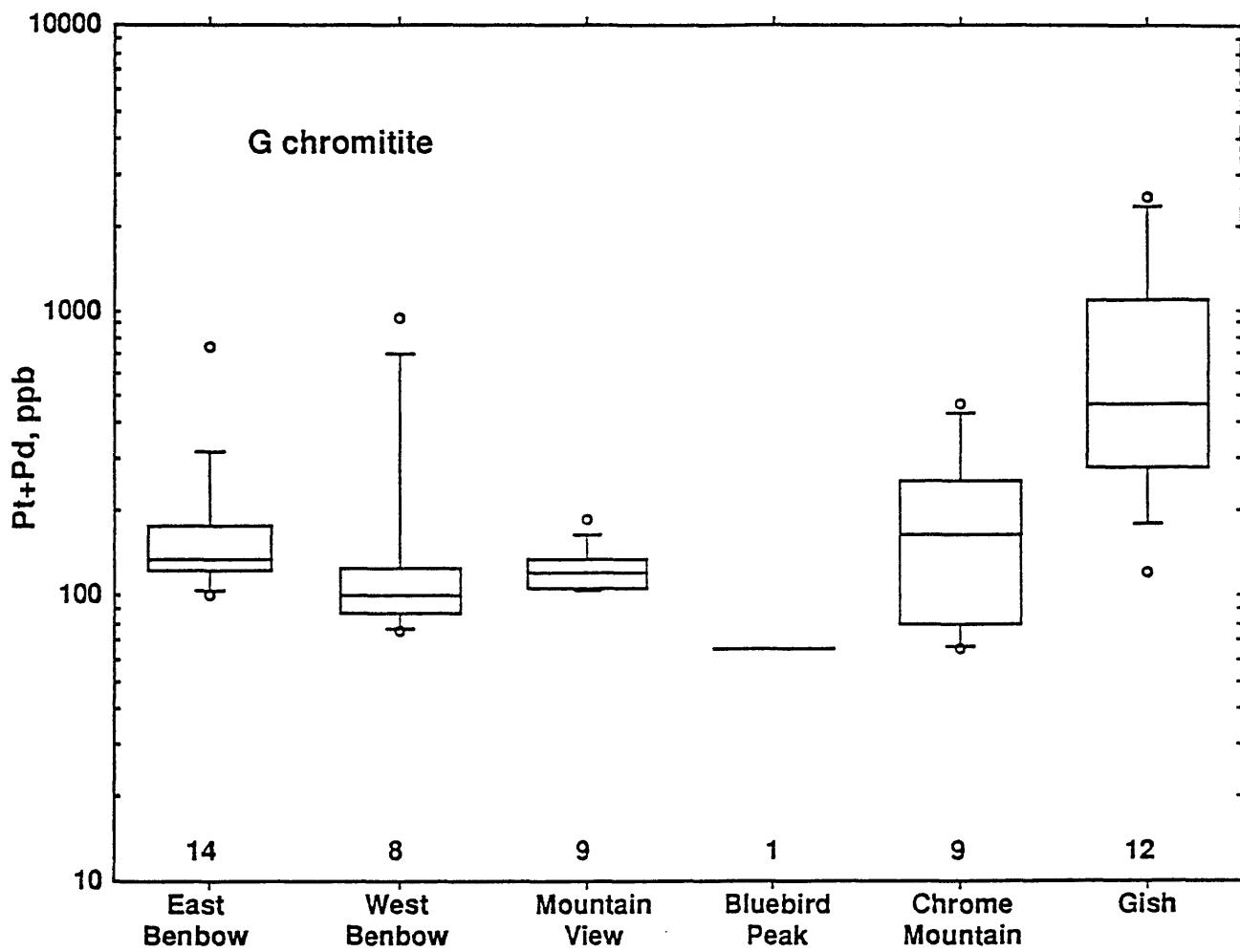


Figure F13.—Box-and-whisker plots illustrating the lateral variation in Pt+Pd in the G chromite seam, Stillwater Complex.
 Key to symbol - same as figure F7. Data from Kell and Loehr (1979).

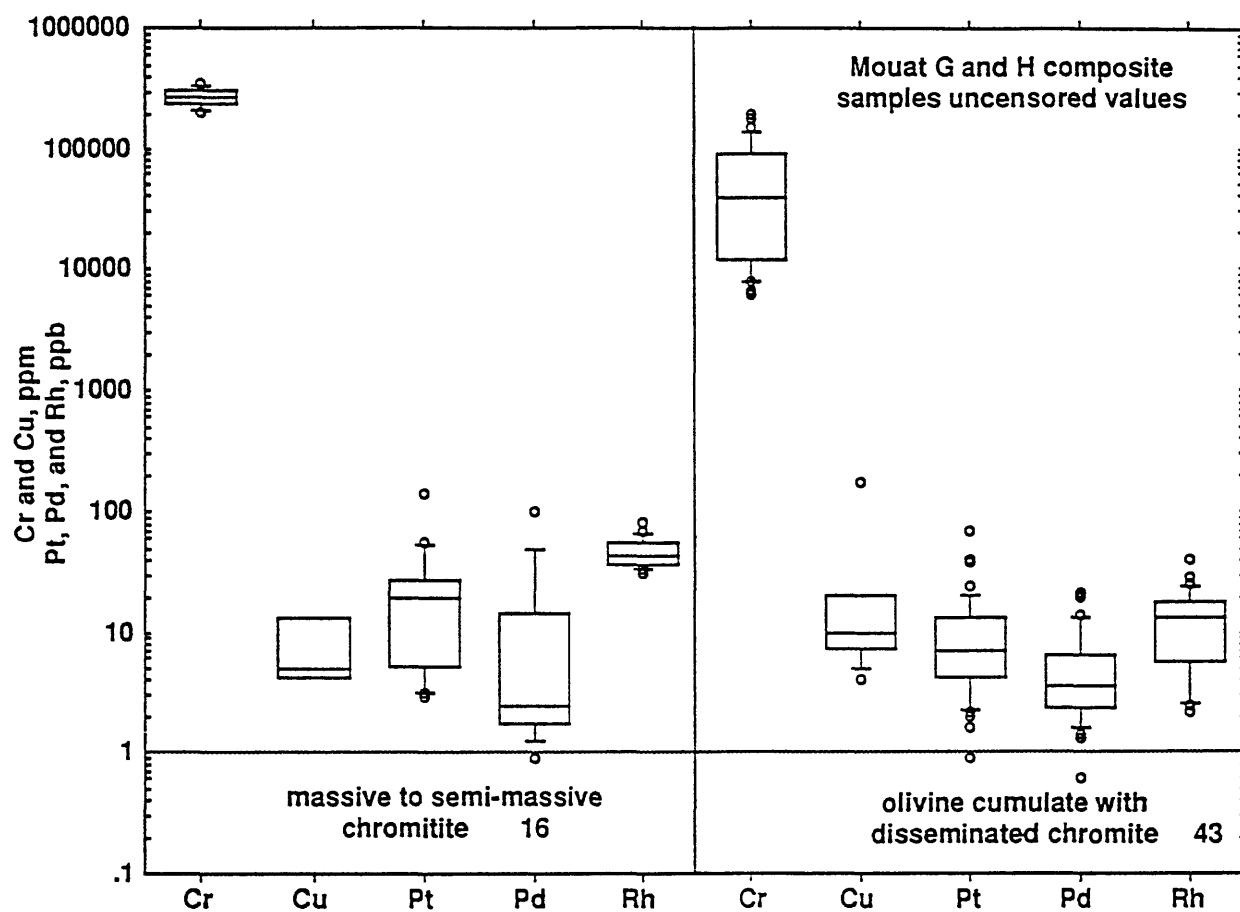


Figure F14.—Box-and-whisker plots illustrating the distribution of Cr, Cu, Pt, Pd, and Rh concentrations for rocks types associated with the G chromite seam, Mouat-Sampson mine area, Stillwater Complex. Samples are composites of drill core. Key to symbol - same as figure F7.

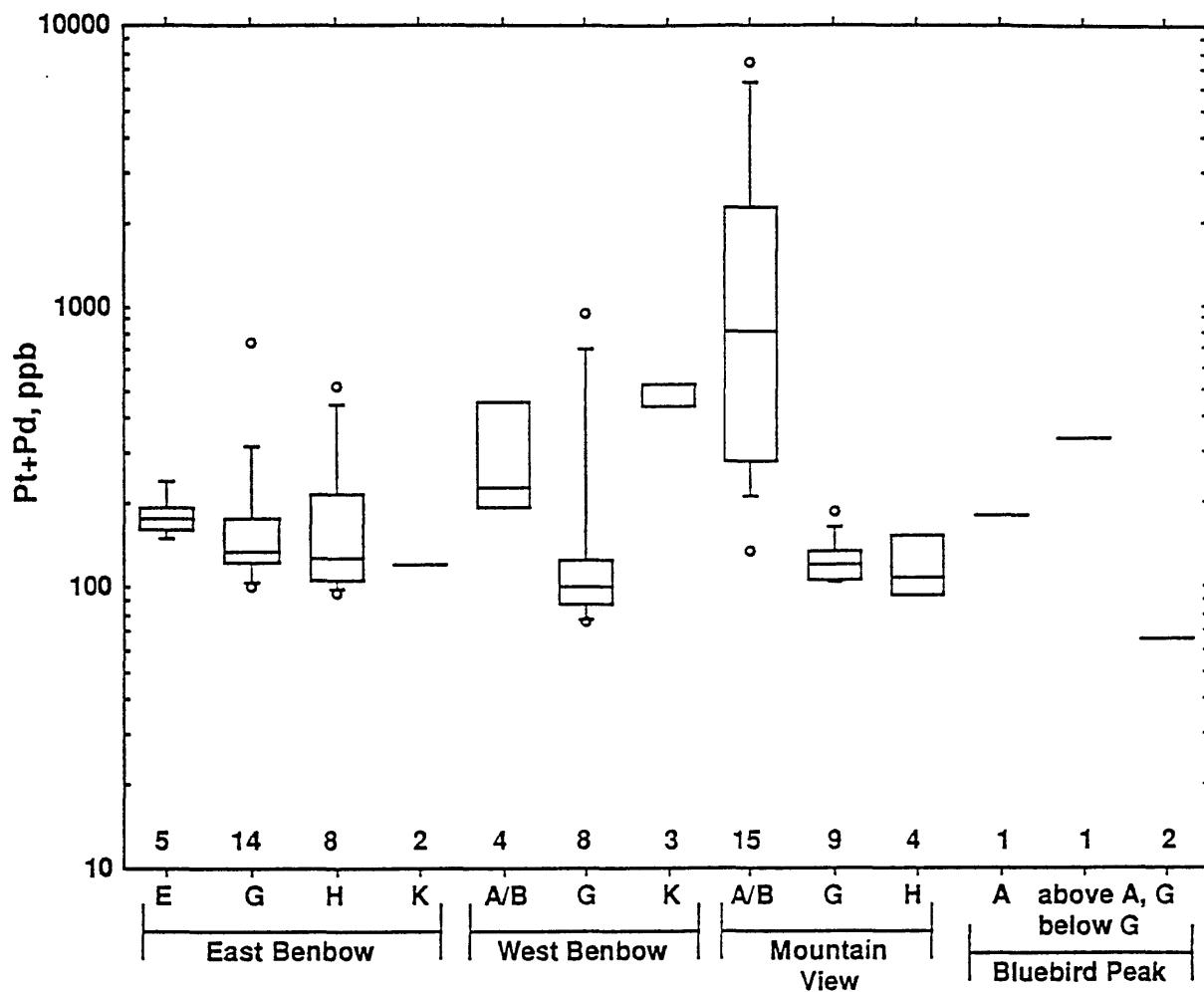


Figure F15.—Box-and-whisker plots illustrating the lateral variation in Pt+Pd in the A/B, E, G, H, and K chromite seams, Stillwater Complex. Key to symbol - same as figure F7. Data from Kell and Loehr (1979).

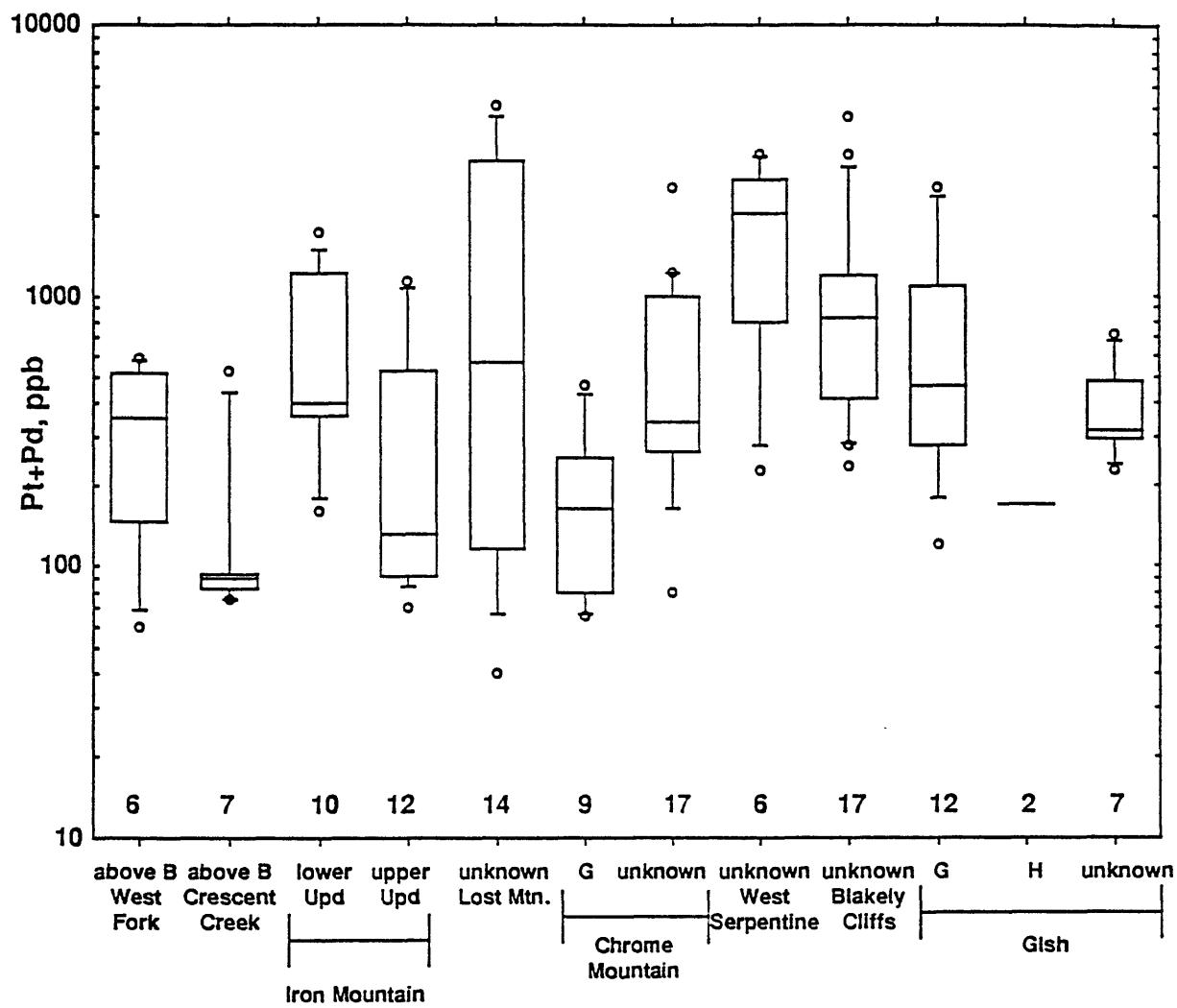


Figure F16.—Box-and-whisker plots illustrating the lateral variation in Pt+Pd in uncorrelated chromite seams, Stillwater Complex. Key to symbol - same as figure F7. Data from Kell and Loehr (1979).

One case previously mentioned is the correlation of the A and B chromite seams in the eastern part of the complex. The correlation of the G chromite seam from the Benbow area to the Gish mine is based upon the occurrence of a texturally and lithologically similar, thick chromite seam in the same relative position in the Peridotite zone section. The correlation may or may not be valid when differing number of cyclic units in various sections of the Peridotite zone, lateral changes in thickness and pinch-out of some seams, and evidence for unconformities in the Stillwater section are considered. With this uncertainty, all chromite seams should be analyzed regardless of any correlations that can be made.

Layers enriched in PGE within a seam may be difficult to trace or correlate because the internal stratigraphy of chromite seams can vary substantially along strike. Stratigraphic variability may result from low-angle layer truncation (similar to cross bedding, channels-like features, or unconformities), soft sediment deformation, and modification of layering features by processes related to the formation of ultramafic pegmatoids.

Variation in PGE concentration with thickness of chromite seams.--In the Union section of Rustenburg platinum mines, the total contained PGE and base-metal content of the Merensky Reef remains constant regardless of the thickness of the mineralized interval (Viljoen and others, 1986). As a result, whole rock PGE and base-metal concentrations are higher in thinner reef sections and lower in thicker sections. This observation has some interesting implications for the evaluation of the PGE potential of chromite seams in the Stillwater Complex. As discussed earlier, the thickest chromite seams are in the eastern part of the complex and are the most likely to be developed for their chromium contents. Studies of the PGE concentrations have also focused on the thickest seams. The data from the Merensky Reef suggest that the thinner chromite seams in the western part of the complex could be an attractive PGE exploration target if the relation from the Union section of the Merensky Reef holds for Stillwater chromite seams. In addition to the complex-wide changes, chromite seams can show local variation in thickness as well. In the Mouat-Sampson mine, the G chromite seam shows a five-fold change in thickness (from 4.6 ft at the No. 1 to 24.9 ft near the proposed No. 8 level) over a distance of 492 ft downdip (Boulder Gold, written commun., 1991). Studies to establish how changes in layer thickness affect PGE concentrations seem warranted.

Geologic Factors Affecting Resource Development

Although significantly elevated PGE concentrations are found in the A and B chromite seams, the enriched layers in the seam are thin. When reasonable mining widths are considered, the grade of the Stillwater occurrences is low compared to other PGE-enriched stratiform chromitites (fig. F6).

Potential for Undiscovered Deposits

Exploration west of the Crescent Creek area would likely identify chromite seams with PGE enrichments comparable to the A and B chromite seams in the eastern part of the complex. Undiscovered deposits may be found beneath the high-angle reverse faults that cut the lower part of the complex (plate 14-E).

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CHAPTER G

MINERAL RESOURCE ASSESSMENT FOR LOCATABLE MINERALS (EXCLUSIVE OF THE STILLWATER COMPLEX)

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INTRODUCTION

The U.S. Geological Survey has developed a three-part format for assessing mineral resources (Singer, 1992; Menzie and Singer, 1990; Singer and Cox, 1987; Ludington and others, 1992). This format, shown schematically in figure G1, uses various methods to generate probabilistic estimates of undiscovered resources provided that (1) sufficient data are available to identify the types of mineral deposits present in the area of interest, and (2) appropriate grade and tonnage models exist for the deposit types identified. The three-part format includes:

(1) delineation of areas (tracts) permissive for the occurrence of different mineral deposit types;

(2) comparison of geologic, grade, and tonnage characteristics of identified resources within the study area with those of well-characterized mineral deposits drawn from a worldwide population;

(3) estimation of the numbers of undiscovered mineral deposits of selected types that might occur within the tracts.

Parts 2 and 3 result in probability distributions of numbers of deposits, tonnages of deposits, and metal grades. Sampling of these distributions by computer simulation provides estimates of tons of metal in potential undiscovered mineral deposits. These estimates can be used by land-use planners to evaluate the mineral resource potential of an area of interest. Mineral deposit models are the basis for delineating permissive tracts, selecting grade and tonnage models, and estimating undiscovered deposits.

Definitions of the terms "identified" and "undiscovered" resources and their use in this report are given in Chapter A. Other terms pertinent to mineral resource assessment were defined by Cox, Barton, and Singer (1986) as follows:

mineral occurrence: a concentration of a mineral that is considered valuable by someone somewhere, or that is of scientific or technical interest.

mineral deposit: a mineral occurrence of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have economic potential.

ore deposit: a mineral deposit that has been tested and is known to be of sufficient size, grade, and accessibility to be producible to yield a profit.

MINERAL DEPOSIT MODELS

Mineral deposit models are systematically arranged lists of essential characteristics of a given class of mineral deposits. Models are constructed from data for well-studied ore deposits that have produced ore or have quantifiable known reserves. Descriptive models identify the geologic environment (rock types, textures, age range, depositional environment, tectonic setting) and the characteristics of individual deposits of a type (mineralogy, texture, alteration, ore controls, weathering, geochemical signature). Grade and tonnage models demonstrate the size and grade distributions for commodities produced from given deposit types; both economic and currently uneconomic deposits are included in grade-tonnage models. Recently, spatial distribution models have been developed for some deposit types to examine the number of deposits per unit area for well-explored areas (Bliss, Menzie, and others, 1987; Bliss and Menzie, in press). Models provide a framework for classifying geologic characteristics of mines, prospects, and occurrences in a given area and provide a basis for predicting the likelihood of occurrence of undiscovered deposits or deposit types. Cox and Singer (1986) compiled 87 descriptive models

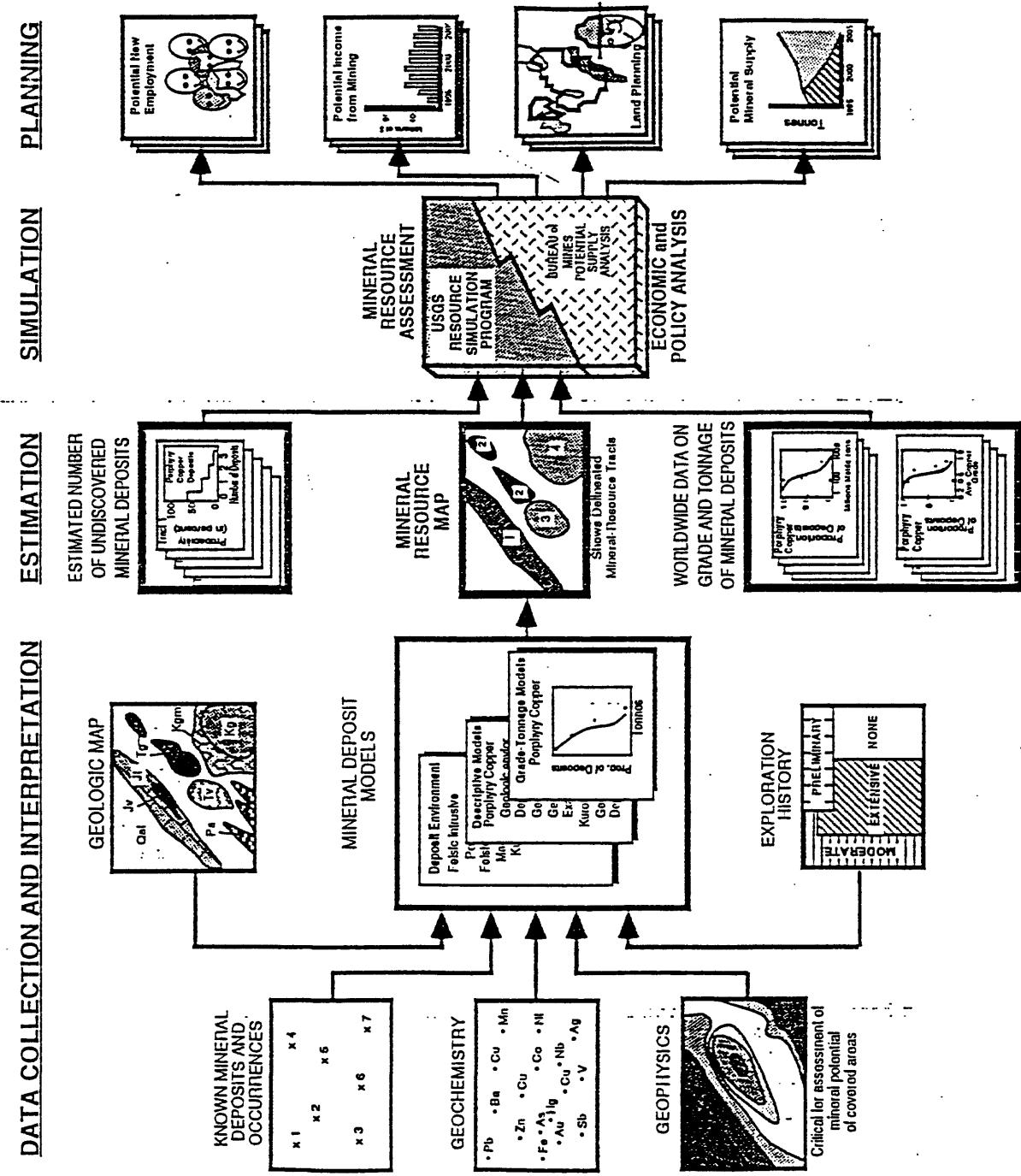


Figure G1.—Schematic diagram of the stepwise process of mineral resource assessment (as modified from Singer and Cox, 1987, by J. Briskey and D. Menzie).

and 60 grade-tonnage models for various types of mineral deposits; Bliss (1992a) compiled 10 additional models. Orris and Bliss (1991) compiled descriptive models for industrial mineral deposits. Many other descriptive mineral deposit models are available; some of these models are noted in discussions in this chapter. We tried to use descriptive models that have associated grade and tonnage models, wherever possible. More than 20 mineral deposit models (table A1) are considered relevant to the Absaroka-Beartooth study area (ABSA). Mineral deposit models used in this study are described in this chapter. A new model to describe magmatic sulfide segregations in alkaline gabbro and syenite is included as an appendix to this chapter.

The mineral resource assessment of the ABSA is organized by mineral deposit type. A brief description of the generalized geologic, tonnage, and grade characteristics of each deposit type is given along with references to more complete model descriptions. Examples of deposits within the ABSA, descriptions of permissive and favorable tracts, estimates of numbers of undiscovered deposits, and results of computer simulation to estimate resources contained in undiscovered deposits are discussed following model descriptions.

TRACT DELINEATION

A tract is delineated as permissive for the occurrence of one or more deposit types based on knowledge of the geologic environments throughout the world in which various types of mineral deposits are known to occur. Tracts are based largely on mapped surface geology and distribution of mines, prospects, and mineral occurrences. Geophysical data are used to extend rock units under cover, to identify potential buried intrusions and regional structures, and to identify anomalous areas that may indicate changes in rock type at shallow depth or areas of widespread alteration. Geochemical associations from chemical analysis of stream sediment and rock samples help establish the types of deposits considered and indicate the presence or absence of specific elements in an area. For example, geochemical anomalies are used to extend identified tracts into less well-mapped areas that are drained by streams sampled in stream-sediment surveys. Tracts are delineated to encompass areas where certain types of deposits could possibly occur. Subtracts (for example, Ia, Ib, Ic) delineate geographically separate areas that otherwise have similar geologic characteristics. Favorable areas (for

example, Va1, Va2, etc.) are delineated within some permissive tracts if sufficient data are available to indicate that deposits are more likely to be present in some parts of permissive areas than in others.

Mineral resource tracts associated with Precambrian rocks in the ABSA (tracts I through IV) are shown on plate 16. Tracts associated with Phanerozoic rocks (tracts V through IX) are shown on plates 17 and 18. Tract IVa (Stillwater Complex) is described in Chapter F. Tract locations (maps) and criteria for tract delineation (tables) are included in this chapter. Most tracts are permissive for more than one type of mineral deposit (table A2).

ESTIMATION OF NUMBERS OF UNDISCOVERED DEPOSITS

If sufficient data are available to indicate that additional deposits are likely to be present within the study area, estimates of numbers of undiscovered deposits are made by an assessment team. For this study, the authors of this chapter comprised the team. Estimates were made by reaching a consensus after extensive discussion and study of the available data. Estimates are made for deposits within 1 km (3,281 ft) of the surface. Factors that were considered in making estimates for the ABSA include the following: presence or absence of favorable areas (targets) within permissive tracts, spatial distribution of known deposits and mineral occurrences in the study area, size and spatial distribution of the identified deposit types elsewhere, nature and magnitude of geochemical and geophysical anomalies, mineralogy of occurrences, nature and extent of alteration, presence or absence of structures (faults and folds), degree of metamorphism, and assay metal grades and tonnage estimates for partially delineated identified resources.

Estimates are made in terms of the probabilities that at least a given number of deposits are present at a specific confidence level (usually at the 90th, 50th, and 10th percent, or lower confidence levels) to construct a probability density function. The assessment team estimated the minimum number of deposits expected at fixed probabilities (90 percent represents a high degree of certainty and 10 percent or less represents a low degree of certainty). For some tracts, estimates were made at the 5 and 1 percent confidence level to indicate a low, but non-negligible chance for undiscovered deposits.

Several factors affect the subjective estimation of the number of undiscovered deposits within a tract (Root and others, 1992; Menzie and Singer, 1990).

Probability estimates are based on the assumption that undiscovered deposits can be characterized by existing grade and tonnage models for a given deposit type. The data used in grade and tonnage models are dependent on definitions of mineral deposits used by the authors of the models (for example, all mines within 1.6 km (1 mi), all mines within a district, above specified cutoff grades or minimum tonnages, etc.). The estimator assumes that 80 percent of the undiscovered deposits will lie between the 90th and 10th percentile values on the grade and tonnage curves for the appropriate model. Other factors that affect the estimates are the amount and nature of the geologic data available for the study area and the level and nature of exploration. For example, some parts of the ABSA were intensively explored in the past for porphyry copper deposits and for chromite deposits but were not thoroughly evaluated for gold or platinum potential associated with these deposit types.

ESTIMATION OF ORE AND METAL CONTAINED IN UNDISCOVERED DEPOSITS

Estimated numbers of deposits are combined with a Monte Carlo computer simulator (MARK3 program) that utilizes grade and tonnage models to provide a probability distribution of the ore and metal tonnages (Root and others, 1992) in undiscovered deposits. For this study, the MARK3 program was run using the empirical option which uses a piecewise linear distribution with 10 line segments to approximate the distributions of the grades and tonnages. The simulator performs 4,999 iterations using a random number generator to sample the number of deposits, grades, and tonnages in a cycle and sorts the results to allow reporting of ore and metal tonnages at various percentiles. We report estimated numbers of deposits for four deposit types. For each tract that is permissive for one of these four deposit types, we report the expected mean number of deposits computed from the probability distribution, the probability of zero deposits for each tract, and the results for ore and metal tonnages in terms of three percentile values (90th, 50th, and 10th) as well as the mean value. For example, the 90th percentile tonnage reported represents a 90 percent chance that undiscovered deposits will contain at least that many metric tons of ore or metal. Estimates represent in-place, undiscovered resources that may be compared with past production and (or) reserve data (table A3) for a perspective on the undiscovered mineral endowment of the study area. These estimates must

be filtered through an economic analysis (for example, by the U.S. Bureau of Mines) to estimate the value of the minable (that is, removable as opposed to in-place) undiscovered resources. Estimates of total values for all commodities in all undiscovered deposits in the ABSA, and within each national forest, are reported in Chapter J along with a summary of results of the appraisal of the resources in the Stillwater Complex (Chapter F).

In some cases, the predicted 90th and 50th, or even 10th percentile values for ore grades or metal tonnages are 0, because non-zero tonnages were encountered in less than 10 percent of the 4,999 cycles of the simulation. However, some value is always obtained for the mean because at least a few deposits with associated tonnage or grade values are encountered in some cycles of the simulation. The mean is the total amount of ore or metal obtained in the simulation divided by the number (4,999) of cycles.

Frequency distributions of grades and tonnages are commonly asymmetric, with a tail towards larger values that represent the less common very large or very high grade deposits. The lowest values in a grade or tonnage frequency distribution (that is, a model) are truncated because mineral deposit models, by definition, are made up of deposits (as opposed to mineral occurrences) that have some possibility of being economic. Therefore, a grade or tonnage model reflects some specified minimum cutoff ore grade or deposit size. Because of these asymmetric frequency distributions, the mean (arithmetic average) and median (midpoint) for the grade and tonnage distributions are different numbers. The ore and metal tonnages from the 4,999 cycles of each simulation are sorted and ranked to provide percentile values. The median (50th percentile) values represent a midpoint in the simulation; that is, one might expect that in half of the cases the undiscovered deposits would have deposit tonnages and metal contents greater than the median value and in half of the cases they would contain less. Mean values are additive, so the amount of gold in the ABSA is equal to the sum of the mean gold values obtained for each gold-bearing mineral deposit type in each tract for which an estimate was made. Median (or any other percentile values) are not additive because they reflect a ranking within a particular simulation. Therefore, the median values reported for the entire ABSA in Chapter J are not equal to the sums of the median values reported for each tract in this chapter. Percentile values may be more familiar to the reader in other situations; for example, standardized test scores such as the SAT test are reported as percentiles. Although mean values

are considered more statistically robust, and are additive, means are influenced by random, large events in ways that median values are not. Mean values for simulations performed for this study always exceed median values. Median values may represent more reasonable estimates for undiscovered resources than mean values when considered in relation to demonstrated resources and past production. Users of these data must chose the most appropriate values (90th, 50th, 10th percentile or mean) commensurate with their needs.

MINERAL DEPOSITS IN ARCHEAN ROCKS

Mineral deposit types that may occur in Archean rocks in the ABSA include lode gold, Algoma or Superior type banded iron formation, Red Lodge chromite, serpentine-hosted asbestos, pegmatite, and uranium deposits as well as the various types of chromite, platinum group element, and copper-nickel deposits associated with the Stillwater Complex. Four permissive tracts (I, II, III, and IV) are delineated for various combinations of these deposit types. Figure G2 shows the location and extent of these tracts, along with geographically separate subtracts (for example, Ia, Ib, and Ic), and favorable areas (such as Ia1). Criteria used to delineate these tracts are summarized in tables G1 through G4.

ARCHEAN LODE GOLD DEPOSITS

Mineral Deposit Model

Descriptive model.--Lode gold deposits are mesothermal gold (\pm silver, tungsten, copper) quartz vein and metasomatic replacement deposits that form in a variety of rock types where regionally extensive shear zones or local faults or dilatant zones channel metamorphic (or magmatic) fluids. Lode gold deposits form in moderately deep environments (about 10 km or less) under greenschist to upper greenschist-lower amphibolite facies metamorphic conditions. Some deposits are spatially associated with magmatic complexes; others bear no apparent spatial relation to magmatism. Lode gold deposits include Precambrian to Tertiary low-sulfide gold-quartz (Mother Lode) veins and Archean lode gold (Homestake gold) veins. In Archean rocks, the most productive lode gold deposits are found in greenstone terranes. In Archean greenstone-sedimentary belts,

deposits in predominantly metavolcanic parts of greenstone terranes, such as the deposits of the Abitibi belt of Canada, are localized by regional shear zones that extend for distances on the order of 20 to 200 km (Boyle, 1991). Large deposits (>10 metric tons of gold) along favorable structural zones in greenstone belts are likely to be spaced on the order of a minimum of 12 km apart, and more likely tens of kilometers apart, based on observed distributions of deposits in western Australia and consideration of volumes of source rocks required (Groves and others, 1987). Deposits in parts of greenstone terranes dominated by metasedimentary rocks (graywacke/turbidite, banded iron formation, argillite, slate), such as the Proterozoic Homestake mine of South Dakota, tend to occur in more localized structures, especially in dilation zones in axial zones of folds, in saddle reefs, and in areas of local shearing and brecciation. Boyle (1991) listed the following criteria as requirements for the formation of lode gold orebodies in argillite-graywacke sequences in Archean greenstone-sedimentary belts: presence of pyrite-bearing argillites and slates and (or) iron formations; evidence of tight folding with development of dilatant zones on fold noses and (or) local shearing; and evidence of metamorphism and granitic magmatism.

Cox and Singer (1986) include two descriptive models for lode gold deposits: the Homestake (Archean lode gold) model (Berger, 1986a), and the low-sulfide gold-quartz vein (Mother Lode) model (Berger, 1986b). The Homestake model includes deposits from both volcanic and sedimentary parts of Archean greenstone terranes. Bliss (1992b) constructed new models for a subclass of low-sulfide gold quartz veins to describe vein deposits in the Chugach National Forest, Alaska. These three descriptive models for lode gold deposits have a number of overlapping characteristics, but compilations of grade and tonnage statistics show that they define three separate populations. Berger's (1986a) Homestake model is the most appropriate model for the ABSA for reasons discussed below. We prefer to use the synonym "Archean lode gold" rather than "Homestake" for the name of the model because most of the deposits in this model are Archean; the Homestake deposit is Proterozoic.

Mesothermal gold deposits of all ages share a number of characteristics (Kerrick, 1990), the most important of which may be a complex geologic setting characterized by contemporaneous magmatism, deformation, and metamorphism. Much has been written on gold deposits in greenstone terranes (see Robert and others (1990) for a recent perspective on

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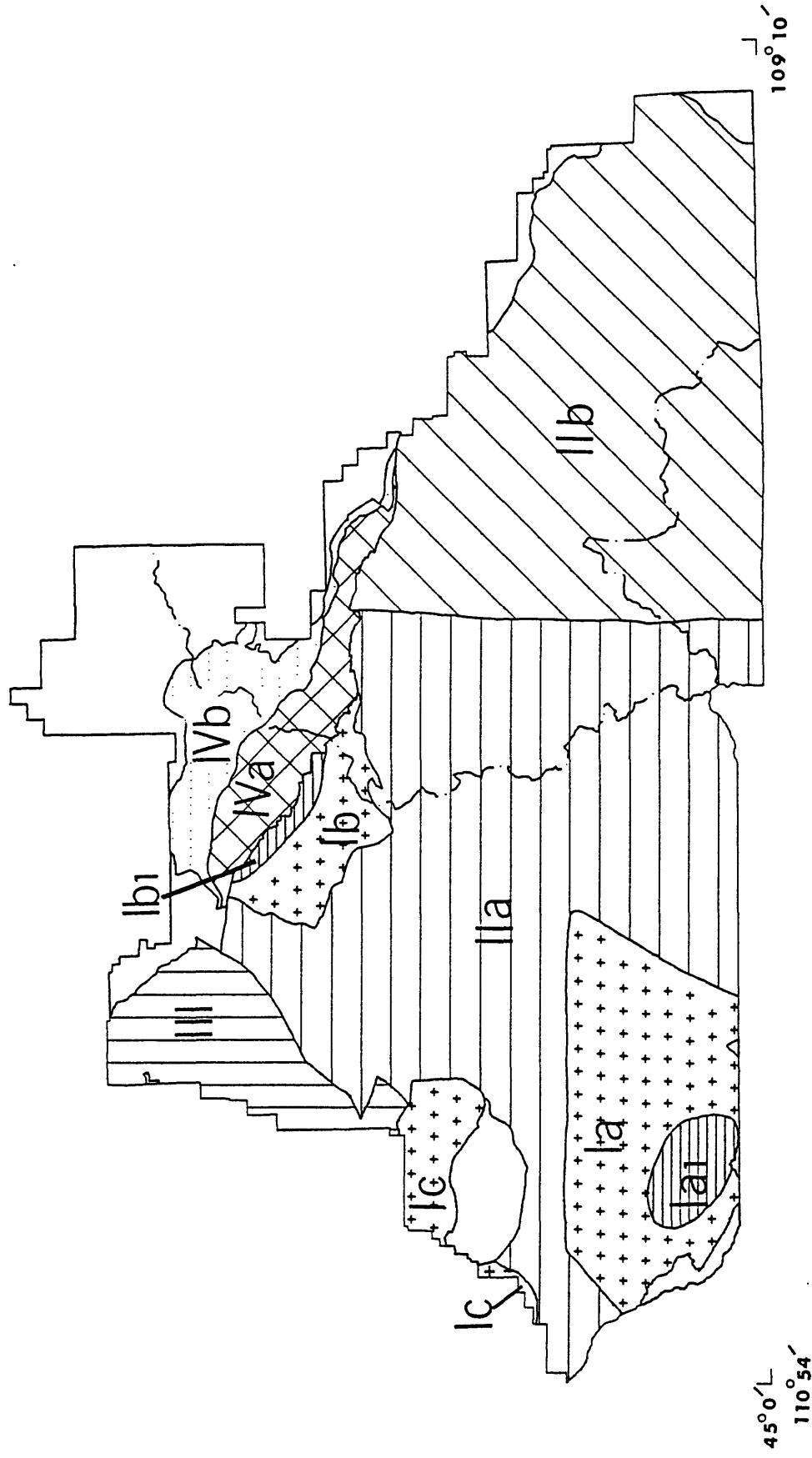


Figure G2.--Location map for mineral resource assessment tracts in Precambrian rocks.

Table G1.--Criteria for tract I

Description: Archean supracrustal rocks. Predominantly metasedimentary (metamorphosed sandstone, shale, iron formation), upper greenschist to lower amphibolite facies rocks. Hornblende- and pyroxene-hornfels facies rocks near the Stillwater Complex.

Permitted deposit types

Archean lode gold (Homestake type)
Banded iron formation (Algoma or Superior type)

Au, As, W, Pb, Zn, Cu, B, Sb
Fe

Expected geochemical signatures¹

Tract	Ia (Jardine subtract)	Ib (Stillwater-Boulder River subtract)	Ic (Mill Creek-Sixmile Creek subtract)
Area (km ²)	575	104	172
Geologic criteria ²	Archean metasedimentary rocks of the South Snowy block (Ash). N boundary based on change to higher grade gneissic rocks in Yankee Jim Canyon area near mouth of Cedar Creek; SW boundary, Gardiner fault; E boundary based on NE-trending fault that separates migmatites and granitic gneisses to the east from lower grade rocks to the west. Volcanics are < 1 km thick, so deposits may be present under cover; S-plunging syncline at Jardine may localize ores.	Archean metasedimentary rocks (Ash). SE boundary, Mill Creek fault. N boundary, Stillwater Complex. W and SW boundaries, intrusive contact between metasedimentary rocks and granitic gneiss. Metasedimentary rocks are locally contact metamorphosed to hornblende- and pyroxene-hornfels facies by the intrusion of the Stillwater Complex.	Archean metasedimentary rocks (As) exposed N and W of the Emigrant stock. Tract boundaries delineated on mapped extent of lithology dominated by biotite schist, minor quartzite, iron formation, and amphibolite. E boundary, granitic gneiss terrane (Agn) of tract IIa.
Geophysical signatures ³	Distinctive gravity and magnetic signatures. East-west trending pattern of gravity highs and lows occurs in SW part of tract (E1). Magnetic lows and reduced gradients are associated with exposed metasedimentary rocks (11). Low magnetic values are used to infer presence of metasedimentary rocks beneath thin volcanic cover.	Magnetic highs centered along the northern boundary of the tract are due to banded iron formation along the contact with the Stillwater Complex. The contact between the Stillwater Complex and the metasedimentary rocks of this tract is expressed as a gravity gradient.	E-W trending gravity highs and lows (E1) associated with metasedimentary rocks W of Emigrant stock, similar to pattern observed for Ia. E-W trending gravity high associated with metasedimentary rocks N of Emigrant stock (E2). Relatively low magnetic values (11a and b).
Geochemical signatures ⁴	Au, As, W, (Cu) Factor Spec-4 (Au, Ag, Mo, Pb, Cu)	Au, (As), (W), (Pb), (Zn), (Cu), (Sb) Factor Spec-4 (Au, Ag, Mo, Pb, Cu)	Au, (As), (W), (Pb), (Zn), (Cu), (Sb) Factor Spec-4 (Au, Ag, Mo, Pb, Cu)

Table G1.--Criteria for tract I (continued)

Tract	Ia (Jardine subtract)	Ib (Stillwater-Boulder River subtract)	Ic (Mill Creek-Sixmile Creek subtract)
Mines, Prospects, and occurrences	<p>Archean lode gold: Active mining at Mineral Hill and past production from the Jardine mine and small mining operations in the Crevice area. Numerous Au, As, and W occurrences and gold placers along streams that drain the tract.</p> <p>Banded iron formation: No deposits. Local occurrences of banded iron formation; magnetite-bearing banded iron formation is more abundant in the Crevice area than in the Jardine area.</p>	<p>Archean lode gold: Geologic information is limited; however, Au and Ag occurrences at the Red Fox mine, the Sky Baby claims, and the Skillman mine may indicate this deposit type.</p> <p>Banded iron formation: U.S. Steel Corp. explored the Big Group claims along the base of the Stillwater Complex in the 1950's. No development. U.S. Bureau of Mines sampled their exploration trenches to estimate iron resources.</p>	<p>Archean lode gold: No occurrences in Ic can be unambiguously assigned to this deposit type because gold and other metal occurrences in Archean metasedimentary rocks may represent polymetallic vein-type mineralization associated with the nearby Tertiary Emigrant stock.</p> <p>Banded iron formation: Magnetite in schist reported at two localities in the Sixmile Creek area may indicate local occurrences of banded iron formation in the metasedimentary rock sequence.</p>
Favorable subtracts	<p>Ia1 (Bear Creek-Palmer Mountain favorable area)</p> <p>Ia1 outlines the most favorable area for additional Archean lode gold deposits within tract Ia based on the distribution of mines, prospects, and occurrences and favorable geochemical signatures. Previous studies noted that veins are concentrated in two distinct belts - a NE-trending belt through Mineral Hill and a N-trending belt through the summit of Crevice Mountain - and identified a potential for additional Au-As-W deposits in the areas of upper and lower Pine Creek, Oregon Mountain, near Hellroaring ranger station, and under Paleozoic sedimentary and Tertiary volcanic cover rocks.</p>	<p>Ib1 (East Boulder River-Boulder River favorable area)</p> <p>Ib1 outlines a favorable area for banded iron formation deposits along the basal contact of the Stillwater Complex in the northern part of tract Ib.</p>	<p>None.</p>
Comments	<p>Ia is more favorable than Ib or Ic for Archean lode gold deposits because it hosts an active mine of this type, is extensively folded, has numerous mineral occurrences and appropriate geochemical anomalies, and appropriate rock types (graywacke protolith and banded iron formation).</p>	<p>Ib is less folded than Ia, and therefore may be less prospective for lode gold deposits. Banded iron formation in Ib appears to be more laterally continuous than in other parts of tract I.</p>	<p>Ic is less favorable than Ia and Ib for either of the permitted deposit types due to lack of known deposits or occurrences and differences in structure (lack of major faults, less folded). Precious metal occurrences and geochemical anomalies are difficult to interpret because of the superposition of hydrothermal alteration associated with the Emigrant stock.</p>

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively).

⁴ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Refer to Chapter D for explanation of Factor-Spec geochemical associations.

Table G2.--Criteria for tract II

Description: Archean granitic gneisses and migmatites (Archean batholith) with minor septa of metasedimentary, metavolcanic, and metamorphosed ultramafic rocks.

Permitted deposit types

Red Lodge chromite	Cr, Fe
Serpentine-hosted asbestos	None
Pegmatites	Mo, Be
Unconformity type uranium deposits	U, Th, Ni, Co, As, Se, Ag, Au, Mo
Other uranium deposits	U, Th, + others depending on deposit type

Expected geochemical signatures¹

Tract	Ia (Western Beartooth subtract)	IIb (Eastern Beartooth subtract)
Area (km ²)	1,937	1,939
Geologic criteria ²	Archean granitic gneisses and migmatites (Agn) with minor septa of Archean Archean schist (As) and amphibolite (Aag).	Archean gneisses and migmatites (Agn) with minor septa of Archean metasediments and metavolcanic rocks (Ash, As, Am, Aag). Local pods of metamorphosed ultramafic rocks (Au) host chromite deposits near Red Lodge. Other rock types are granitic intrusive rocks (Agr), hornblende quartz diorite (Ahd), and metanorite and metagabbro (An).
Geophysical signatures ³	Tracts IIa and IIb are separated on the basis of a N-S trending geophysical gradient apparent as a gradient in the gravity data and as a change in anomaly extent and intensity in the magnetic data. The metagneous rocks along Yankee Jim Canyon in the westernmost part of IIa are part of a high-density gneiss terrane that extends west of the study area. They are distinct from other Archean gneisses and have high gravity signatures. Volcanic cover in the Emigrant area overwhelms any geophysical signature of the gneisses.	Local high magnetic anomalies associated with chromite deposits in the easternmost part of IIb. Broad, high-gradient magnetic high anomalies are characteristic of the eastern half of tract IIb.
Geochemical signatures ⁴	Au, Mo, Pb, U, Zn, (Ag), (As), (Bi), (Cu), (Cr), (Ni), (Sb), (W) Factor Spec-4 (Au, Ag, Mo, Pb, Cu)	Au, Cr, Mo, Ni, Pb, U, W, Zn, (Ag), (As), (Bi), (Cu), (Sb) Factor Spec-1 (Mg, Ni, Cr, Co, Fe, Sc, V, Ca, Mn, Ti, Cu)

Th > U for rock samples of granitic gneiss; U > Th for stream sediments; bedrock source for stream-sediment anomalies uncertain but probably from stratiform zones or veins in gneiss (Agn)

Two geologically unsupported geochemically anomalous areas are recognized in the stream-sediment data for tract IIb:
East and West Rosebud Creek drainage: Au, Mo, Pb, Zn, Bi
Upper East Rosebud Creek and drainages to the east: W.

Table G2.--Criteria for tract II (continued)

Tract	IIa (Western Beartooth subtract)	IIb (Eastern Beartooth subtract)
Mines, prospects, and occurrences	<p>Red Lodge chromite: None.</p> <p>Serpentine-hosted asbestos: No deposits. One isolated asbestos occurrence reported; geologic association unknown.</p> <p>Pegmatites: No deposits. Claims located for Mo and U in quartz-feldspar pegmatite dike swarms in Archean gneiss in the Mount Cowen area. Local molybdenite pods in pegmatites.</p> <p>U occurrences: Two occurrences reported in the Independence district. Private industry staked 200 claims for U in a 60 mi² area that includes Hawley Mountain and Speculator Creek. Euxenite present in pegmatite near Mount Cowen.</p>	<p>Red Lodge chromite: Numerous small, mostly mined out deposits on Silver Run, Hellroaring, and Line Creek plateaus.</p> <p>Serpentine-hosted asbestos: No deposits. Two asbestos occurrences reported - probably in altered ultramafic rocks. Antigorite is a common mineral in the Red Lodge chromite ores.</p> <p>Pegmatites: The Rosebud Mo prospect was drilled in the 1960's; no production data or resource estimates.</p> <p>U occurrences: Identified submarginal resources associated with the unconformity at the base of the Cambrian Flathead Sandstone near Red Lodge. U appears to be associated with tear faults along the range front.</p>

Comments

In the North Absaroka study area, no mineral resources were found although U-bearing minerals were found in the Mount Cowen and Hawley Mountain areas and highly anomalous concentrations of U were recorded from stream-sediment samples in the Hawley Mountain-Speculator Creek area (Elliott and others, 1983).

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively).

⁴ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group.

Refer to Chapter D for explanation of Factor-Spec geochemical associations.

Table G3 .--Criteria for tract III

Description: Archean gneisses, amphibolite, and metasedimentary rocks of the North Snowy block.

<u>Permitted deposit types</u>	<u>Expected geochemical signatures¹</u>
Banded iron formation (Algoma or Superior type)	Fe
Pegmatites	Mo, Be
Tract	III (Suce Creek-Pine Creek tract)
Area (km ²)	281
Geologic criteria ²	Amphibolite, schist, quartzite, iron formation, marble, and gneiss; includes rocks of the nappe core complex (Anc) and other units (Aga, As, Agn, Aqa). W boundary, range front normal faults. NE boundary, inferred extent of rocks to a depth of 1 km based on 40° dip beneath Phanerozoic rocks. E boundary, West Boulder fault and tract II gneiss. S boundary, Elbow Creek and Mill Creek-Stillwater faults.
Geophysical signatures ³	Gravity high over the nappe core complex. Magnetic high over nappe core complex; both surrounded by short wavelength high and (or) low anomalies. E boundary expressed in magnetic and gravity gradients.
Geochemical signatures ⁴	Cu, Pb, (Au), (Bi), (W), (U), (Zn) Factor Spec-1 (Mg, Ni, Cr, Co, Fe, Sc, V, Ca, Mn, Ti, Cu)
Mines, prospects, and occurrences	Banded iron formation: No deposits or prospects. Minor, local occurrences of iron formation within the nappe core complex. Pegmatites: No deposits. Cu associated with pegmatite at the Northern Pacific claim; numerous pegmatite dikes in metamorphic rocks.
Comments	Cu, Ag, Au, Mo, Co, Cr, and Ni have been reported from miscellaneous properties in metamorphic rocks and associated pegmatites in the Suce Creek area. These occurrences may be structurally controlled; exposed rocks lack favorable criteria for occurrences of mineral deposits.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively).

⁴ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group.

Table G4.--Criteria for tract IV

Description: Layered mafic to ultramafic cumulates of the Stillwater Complex.

Permitted deposit types

Stillwater nickel-copper
Bushveld chromite
Merensky Reef platinum group elements (PGE)
PGE-enriched stratiform chromitites
Sulfide and PGE concentrations occurring at or below impermeable layers
Pegmatoidal lenses, pipes, and other discordant mineralization

Expected geochemical signatures¹

Cu, Ni, (Co, PGE)
Cr
Cu, Ni, PGE
Cr, Cu, PGE
Cu, Ni, PGE
Cu, Ni, PGE

Tract	IVa (Stillwater Complex subtract)	IVb (Dry Fork Creek-Meyer Mountain subtract)
Area (km ²)	188	191
Geologic criteria ²	Tract IVa outlines mapped extent of stratiform mafic to ultramafic rocks that comprise the Stillwater Complex. The complex is subdivided into seven units (Asw1 to Asw7).	Postulated subsurface extension of the Stillwater Complex that underlies younger rocks north of Stillwater exposures in tract IVa. Inclusions of Stillwater Complex occur in the Lodgepole, Enos Mountain, and Susie Peak intrusions (TK1). Extent of tract is based on stratigraphic considerations: The Stillwater Complex is unconformably overlain by Cambrian sedimentary rocks. The tract shows the mapped extent of the middle Paleozoic (Madison Group) which is approximately 1 km above the basal unconformity.
Geophysical signatures ³	Regional: The Stillwater Complex lies along a persistent high-gradient gravity and magnetic zone that is related to the front of the Beartooth Mountains and the Nye-Bowler structural zone. Local: Aeromagnetic data show lineated magnetic anomalies parallel to the lithologic layering and structure of the Stillwater Complex.	Tract IVb overlies part of a W-NW trending gravity ridge that has been interpreted to result from the subsurface extension of the Stillwater Complex.
Geochemical signatures ⁴	Regional surveys: Cr, Ni, Cu, Zn, (Au) High scores for Factor ICP-3 {Ni, Cr, P, Mg, Sc, Co, (-K), (As)} Local surveys: soil geochemical anomalies for Cu, Ni, Pt, Pd	(Cr), (Ni), (Zn), (Au) Factor ICP-3 (Ni, Cr, -P, Mg, Sc, Co, (-K), (As))
Mines, prospects, and occurrences	Large tonnage, low-grade Cu-Ni prospects and deposits in eastern half of the Complex. Chromitite zones with significant grades and thicknesses at Gish, Benbow, and Mountain View. PGE-enriched chromitites occur along the length of the Complex but have been prospected mainly in the eastern half. Active mine and proposed mine on the PGE-enriched J-M Reef. Pt-Pd prospect along the Picket Pin Zone. Numerous small, PGE-enriched sulfide occurrences in the lower part of the Norite and lower gabbro zones (Asw3) and at the top of the Peridotite zone (Asw1).	None.

Table G4.--Criteria for tract IV (continued)

Tract	IVa (Stillwater Complex subtract)	IVb (Dry Fork Creek-Meyer Mountain subtract)
Comments	See plates 14 and 15 for detailed assessment.	Controversy over geophysical modelling. Inclusions and stratigraphic arguments support extension of Stillwater Complex to the north.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively).

⁴ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in stream-sediment samples. Refer to Chapter D for an explanation of Factor-Spec geochemical associations.

the topic). In addition to the models mentioned above, descriptive models have been developed for lode gold veins based on the nature of the host rock (chemical-sediment, volcanic, and turbidite) using characteristics of Canadian deposits (Eckstrand, 1984). Wallrock differences influence the style, grade, alteration style, mineralogy, and geochemical signature of lode gold veins. However, Böhlke (1989) showed that the nature of the hydrothermal fluid (typically low salinity, CO_2 -rich aqueous fluids relatively reduced in sulfur, at temperatures around 250 to 450 °C and pressures of 0.5 to more than 3 kbars) probably accounts for the many of the shared characteristics of lode gold deposits throughout the world. These characteristics include high gold to silver ratios, low base metal contents, and the presence of quartz \pm carbonate \pm feldspar as gangue minerals. Many of the Mother Lode type veins, such as those studied by Böhlke (1989) in the Alleghany district, California, are structurally discordant, whereas most Archean lode gold (Homestake model) veins are stratabound to stratiform. Metamorphic fluid migration accompanying Cordilleran-type terrane convergence may be an important control on the localization of both Archean and younger low-sulfide lode gold districts (Goldfarb and others, 1990). The different models proposed for lode gold deposits may all reflect variations on a common theme.

Archean lode gold orebodies form as structurally controlled veins or thinly laminated beds, irregular pods and local disseminations in host rocks, and commonly thicken in hinge zones of folds. Gold is associated with sulfides or disseminated in quartz. Ore mineral assemblages include gold, pyrite, pyrrhotite, arsenopyrite, telluride minerals, magnetite, sphalerite, and chalcopyrite. Some deposits contain tungsten minerals (scheelite or wolframite), other sulfide minerals, molybdenite, and fluorite. Ore is present in thinly laminated beds, veins, lenses, or stockworks. A carbonate mineral (siderite or ankerite) is common in alteration assemblages in wallrocks, along with cummingtonite, mica, chlorite, quartz, magnetite, and tourmaline. Fuchsite is common in volcanic-associated deposits.

The characteristic geochemical signature of these deposits is gold, iron, arsenic, boron, and antimony, but can include bismuth, tungsten, mercury, copper, lead, zinc, silver, and molybdenum. Arsenic is commonly the best pathfinder element.

Grade and tonnage models--Mosier (1986) constructed tonnage and grade models for Homestake (Archean lode gold) deposits (fig. G3) using 116 deposits that fit the descriptive model for Homestake

gold deposits of Berger (1986a). Deposits within 1.6 km of each other were combined as a single entry and the data showed no statistically significant differences as a function of differences in host rocks. The median deposit size in the tonnage model is 0.94 million metric tons; the largest deposits are on the order of 100 million metric tons and the smallest deposits included in the data set are on the about 5,000 to 6,000 metric tons. Gold grades range from about 2 to 40 g/t, with a median value of 9.2 g/t. Silver grades range from <0.2 to 40 g/t. Comparison of grade and tonnage characteristics shows that deposits included in the Homestake model tend to be larger than deposits classified as low-sulfide gold-quartz veins (median tonnage of 0.93 million metric tons for Homestake versus 0.03 million metric tons for low-sulfide gold-quartz veins) and have slightly lower median gold grades (9.2 g/t for Homestake, 16 g/t for low-sulfide gold-quartz veins) and comparable silver grades. The Chugach veins (Bliss, 1992b) typically have lower grades and tonnages than deposits included in the low-sulfide gold-quartz vein model.

Examples in the Study Area

The Jardine-Crevasse Mountain district in the southwestern corner of the study area has produced gold since the 1860's and intermittently produced significant amounts of arsenic and tungsten, as well as silver, copper, and lead. Most of the production came from the Jardine mine. Similarities to the Homestake, South Dakota, gold mine were noted by Seager (1944). A number of mining companies conducted extensive exploration and drilling programs in the Jardine area in the 1970's, using the Homestake deposit as an exploration model. The successes of those exploration efforts led to the development of a new mine, the Mineral Hill mine, currently owned by TVX and Homestake Mining Company. At the present time (1992), the Mineral Hill mine, near the original Jardine mine, is operated as an underground mine to produce gold.

The Jardine deposits occur in 5 mile wide by 10 mile long package of metasedimentary rocks (tract Ia) that includes quartz-biotite schists, grunerite-bearing iron formation, chlorite schists, amphibolite, and massive quartz layers. The Jardine rocks are lower in metamorphic grade (greenschist to amphibolite facies versus granulite facies) and are structurally distinct from many of the other Archean rocks in the study area, but similar rocks are present northwest of Jardine, along the base of the Stillwater Complex, and

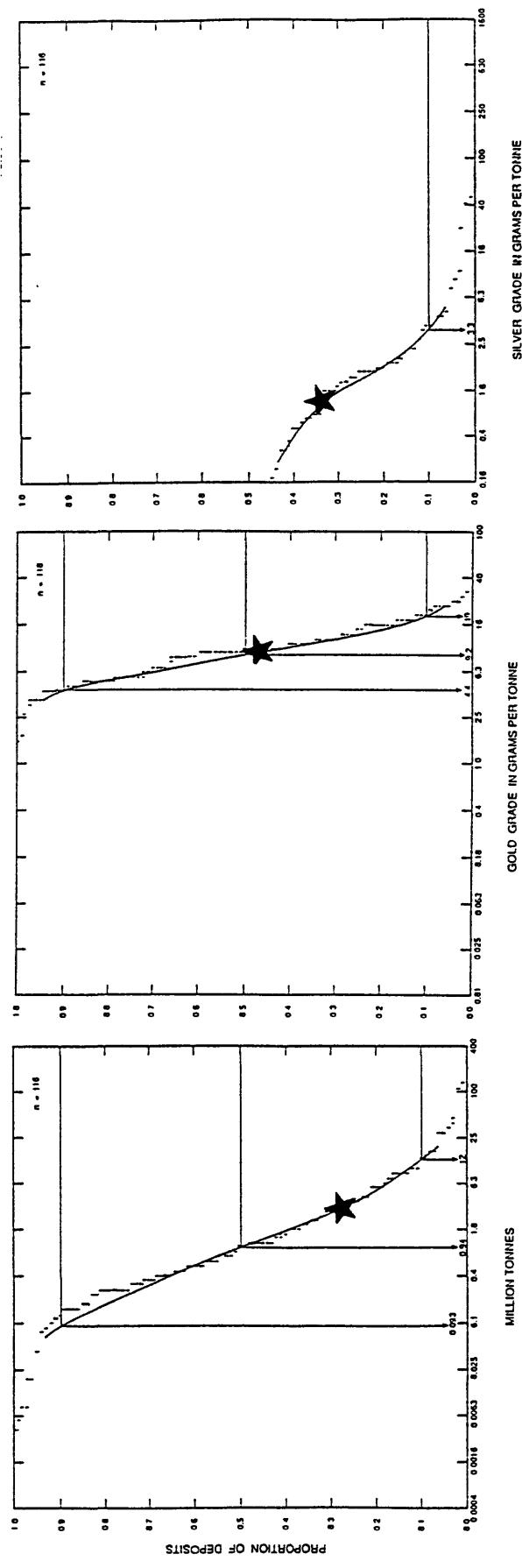


Figure G3.—Grade and tonnage models for Archean lode (Homestake) gold deposits (from Mosier, 1986). Star, combined production and reserve estimate data for the Mineral Hill and Jardine mines.

as inclusions in the gneissic Archean granitic batholiths that form much of the core of the Beartooth Mountains.

Gold mineralization is present in quartz biotite schist, in quartz bands, in sulfide-bearing iron formation, and in association with grunerite-bearing iron formation. The protoliths for the Jardine rocks have been interpreted as graywackes and mudstones with interbedded dacitic volcanics that were deposited by turbidity currents along an active continental margin. The geologic setting is typical of the metasedimentary parts of Archean greenstone belts. Similar rocks and styles of mineralization are observed elsewhere in the Wyoming Province, to the south of Jardine in the Wind River area and in the gold deposits in the Atlantic City-South Pass-Lewiston area of Wyoming (Spry and others, 1990) where isolated patches of Archean greenstone terrane host iron formation and lode gold deposits.

At Jardine, gold ore is associated with pyrrhotite, pyrite, and arsenopyrite in iron formation and in quartz veins and boudins adjacent to iron formation. Galena, chalcopyrite, loellingite ($FeAs_2$), and gersdorffite ($NiAsS$) are also present, as well as scheelite in quartz-rich ores. The orebodies are highly irregular in form, and appear to be structurally controlled by f_1 and f_3 fold zones. The entire orebody at Mineral Hill, including previous workings at the Jardine mine, is about 1,000 ft wide by 1,200 ft long by 800 ft deep.

Reserves for the Mineral Hill mine in 1990 were 1 million short tons (0.9 million metric tons) averaging 0.3 ounces gold per ton (10.3 g/t). Seager (1944) reported production from the Jardine mine from 1899 through 1943 as 0.66 million metric tons. Grades computed for this tonnage from reported amounts of gold and silver produced are 7.2 and 1.3 g/t, respectively. Arsenic, tungsten, copper, and lead were produced from the Jardine mine intermittently up until 1943.

Gold was also produced in the early part of the century from a number of mines in the Crevice (Crevasse in the older literature) Mountain area, which lies about 2 miles southeast of Mineral Hill. No reliable tonnages or grades are available for these mines, but the Conrad property produced over \$100,000 worth of gold bullion from 1891 to 1906. The Crevice Mountain area deposits are similar to the Mineral Hill deposits; gold was mined from quartz lenses in schist.

The Jardine deposits are similar to the relatively deep parts of Archean lode gold systems associated with banded iron formation elsewhere, such as the

Lupin deposit of the Superior Province, Ontario. Lupin is a 3.9 million metric ton deposit that averages 10.6 grams of gold per metric ton. At Lupin, ores were deposited in iron formation adjacent to late Archean quartz veins in a turbidite basin distal to a greenstone belt. Mineralization at Lupin is zoned outwards from the quartz veins; proximal zones include scheelite-bearing calc-silicate assemblages that share some characteristics with tungsten skarns (Lhotka and Nesbitt, 1990). Gold and sulfides (pyrrhotite, arsenopyrite, and loellingite) are concentrated in more distal zones which grade out into barren, grunerite-rich zones.

Sulfur, carbon, and oxygen isotopic characteristics of the Mineral Hill and Crevice Mountain deposits are similar to data for other Archean lode gold deposits (Liu and Spry, 1991; Spry and others, 1990). Fluid inclusion studies on quartz from the Jardine area deposits have shown that CO_2 - or CH_4 -bearing, relatively low salinity inclusion fluids are similar to inclusions in other Archean lode gold deposits described by Colvine (1989) and Colvine and others (1988). However, elevated $CaCl_2$ contents in primary and secondary fluid inclusions from the Jardine area, as well as from the Atlantic City area further south in the Wyoming Province, are uncommon in Archean lode gold deposits elsewhere (Spry and others, 1990).

A cumulative tonnage and grade for the Jardine-Mineral Hill mines based on past production and announced reserves is about 1.6 million metric tons of ore averaging approximately 7 to 10 g/t gold; overall gold to silver ratios average 6 to 1 (David Oliver, oral commun., 1990). These values plot near the median values for the tonnage and grade distributions on the Homestake grade and tonnage models (fig. G3), so these models appear to be appropriate for estimating additional resources in undiscovered deposits in the Absaroka-Beartooth area.

Permissive Tracts

Permissive tracts for Archean lode gold deposits include Archean supracrustal rocks in subtracts Ia, Ib, and Ic (fig. G2, table G1). Similar metasedimentary rocks are present as septa and inclusions in gneiss and migmatite in tract II (fig. G2, table G2) and interlayered with gneiss and amphibolite in tract III (fig. G2, table G3).

Tract I--Ia (Jardine subtract). Tract Ia includes Archean metasedimentary rocks (Ash on plate 1), all stratiform gold deposits that have a record of production, as well as all occurrences of gold, arsenic, and

tungsten that appear to be related to this deposit type. These three elements are present in anomalous concentrations in stream sediments that drain the area. Tract boundaries are drawn along contacts with higher grade rocks and structures; mapped surface structures are also apparent as gradients in the geophysical signature. Previous studies noted that workings are concentrated in two distinct belts, and identified a potential for additional deposits in lower and upper Pine Creek, at Oregon Mountain, in the vicinity of the Hellroaring Ranger Station, and buried under volcanic cover northeast of Jardine. Brox and Cavalero (1978) described results of exploration programs conducted by the Anaconda Company in the Jardine district during the 1970's. Exploration included drilling, aeromagnetic surveys, and geochemical sampling over the area between the Jardine mine and Crevice Mountain as well as west and northwest of the Jardine mine. This work showed that the area of the old Conrad workings represented the most significant, albeit erratic, mineralization in the Crevice Mountain area and that amphibolite in the Crevice Mountain area, where present, is thinner, more garnetiferous, and less pyrrhotite-rich than in the Jardine mine area. Geophysical exploration identified a series of linear, NW-SE magnetic anomalies across the district that appear to correlate with a magnetite-bearing amphibolite unit in the basal part of the gold-bearing amphibolite. Gold and arsenic were found to be the most consistent geochemical indicators of mineralization and anomalies showed a southeasterly trend from the Jardine mine to Crevice Mountain, parallel to the trends established by geophysics. Subtract Ia is characterized by a series of east-west trending gravity highs and lows and the mapped faults are evident as gravity gradients (plate 2). The eastern boundary of subtract Ia is delineated on the basis of a NE-SW-trending high angle fault that separates the Jardine package of greenschist facies metasedimentary rocks from higher grade granitic gneisses to the east. The NW-SE-trending Gardiner fault forms the SW boundary of subtract Ia. Identified lode gold resources are confined to relatively narrow, crudely N-S trending zones within the subtract. Favorable area Ia1 outlines this zone as an area between Bear Creek and Palmer Mountain within subtract Ia that includes the Mineral Hill-Crevise Mountain mines and prospects.

Ib (Stillwater-Boulder River subtract). Subtract Ib outlines an area of Precambrian schist (Ash on plate 1) in the area south of the Stillwater Complex, north of the Mill Creek fault, and west of the Boulder River. Gold was produced from two mines (Red Fox

and Skillman) in the Natural Bridge district within subtract Ib; however, data are inadequate to determine deposit type. At the Red Fox mine, arsenopyrite is present with auriferous pyrite and pyrrhotite in a quartz-filled shear zone in hornfels. Anomalous gold and arsenic are detected in stream sediments without tungsten. Subtract Ib lacks the complex folding and major structures that may have been important in localizing ores at Jardine (Ia).

Ic (Mill Creek-Sixmile Creek subtract). Subtract Ic includes areas of Precambrian biotite schist (Ash on plate 1) west and north of the Tertiary Emigrant intrusive center. No occurrences of combined gold-arsenic-tungsten are reported. None of the gold occurrences within the tract, nor the single arsenic occurrence (an arsenopyrite vein in a shear zone in mafic rocks at the Platinum Ridge claim in the Mill Creek district), appear to represent lode gold-type mineralization.

Estimate of numbers of undiscovered deposits.-- Based on these data, we estimate that in addition to the known lode gold deposit at the Mineral Hill/Jardine mine in subtract Ia, there is a 90 percent chance of 1 or more additional deposits, a 5 percent chance of 2 or more additional deposits, and a 1 percent chance of 3 or more deposits. For subtract Ib, we estimate at most a 5 percent chance of 1 or more deposits of this type and for subtract Ic, we estimate a 1 percent chance of 1 or more undiscovered deposits.

Results of a computer simulation based on these estimates of numbers of undiscovered deposits (table G5) indicate that the probability of 0 additional deposits for subtract Ia is 7 percent, whereas the probabilities of 0 deposits in subtracts Ib and Ic are high, 93 percent or more. Median estimates for undiscovered deposits in subtract Ia predict 860,000 metric tons of ore containing 8.1 metric tons of gold and negligible silver. Note that the estimated mean value for gold for subtract Ia is 79 metric tons, or about 10 ten times the median amount. Announced reserves and past production within subtract Ia total 1.6 million metric tons of ore containing 15 metric tons of gold and about 3 metric tons of silver. Median estimated values for undiscovered deposits suggest that the amount of ore in lode gold deposits that remains to be found within the ABSA is about half of the amount that has already been discovered.

For comparison, we computed the area and production from Archean lode gold deposits of the South Pass granite-greenstone belt in the southern Wind River Range of Wyoming. The South Pass deposits are hosted by the Miners Delight Formation,

Table G5.--Estimate of mineral resources contained in undiscovered Archean lode gold deposits within the Absaroka-Beartooth study area (tract I)

Simulator input

Estimate of the minimum number of deposits expected at each of the following probabilities:

Subtract	90%	50%	10%	5%	1%
Ia	1	1	1	2	3
Ib	0	0	0	1	1
Ic	0	0	0	0	1

Simulator output

Estimated numbers of undiscovered deposits

Subtract	Mean expected number of deposits	Probability of 0 deposits
Ia	1.05	7%
Ib	0.07	93%
Ic	0.03	97%

Estimated amounts of commodities contained in undiscovered deposits (in metric tons)¹

Commodity /Subtract	90th percentile	50th percentile Median	10th percentile	Mean
Gold	Ia	0.28	8.1	190
	Ib	0	0	0
	Ic	0	0	2.3
Silver	Ia	0	0	13
	Ib	0	0	0
	Ic	0	0	0.30
Ore	Ia	42,000	860,000	21,000,000
	Ib	0	0	0
	Ic	0	0	270,000

¹ Output from Mark3 program reported to 2 significant figures.

a 2.8 Ga (same age as Jardine rocks) unit composed of metagraywacke, schist, amphibolite, metachert, metavolcanic rocks, and marble, and by Archean greenstone formations. Banded iron formation of the Archean Goldman Meadows Formation hosts iron

deposits along the northwest edge of the greenstone belt; gold has not been mined in the past from the iron formation, but the gold potential has not been fully evaluated (Hausel, 1991). A 2.6 Ga granitic batholith intrudes the greenstone belt rocks. Production figures cited by Hausel (1991) for lode gold production from 30 mines in the 800 km² South Pass-Atlantic City-Lewiston district total about 7.6 metric tons of lode gold and an additional 3.2 metric tons of gold from placer deposits. Many of the mines are closely spaced, so the area contains fewer than 30 "deposits." In order to compare the number of deposits represented by these 30 mines with deposits that fit our model, a proximity rule of grouping all properties within 1.6 km of one another as a single deposit was applied, and only those deposits that produced 3,000 ounces or more of gold were included. The 3,000 ounce threshold was computed from the lowest 10th percentile gold grade and ore tonnage values reported for the Homestake grade-tonnage model (Mosier, 1986) to insure that the South Pass deposits considered fit the model. Using these rules, the South Pass-Atlantic City district contains 4 Archean lode gold deposits and the Lewiston district contains 1 deposit. Production figures for many properties in the district are unknown. The South Pass district is about the same size as the total area of tract I (851 mi², table G1) and the amount of gold produced, 7.6 metric tons, is comparable to the median value, 8.1 metric tons, estimated for the amount of gold in undiscovered deposits in tract I and is about half of the amount of gold known to be present at Jardine (15 metric tons based on past production plus announced reserves). This comparison shows that an area comparable in size to tract I can contain as many 5 deposits, so our estimated numbers of undiscovered deposits are not unrealistic.

ALGOMA AND SUPERIOR IRON DEPOSITS (BANDED IRON FORMATION)

Mineral Deposit Model

Descriptive model.--Precambrian banded iron formations occur in two major geologic associations: (1) in mafic to felsic submarine volcanics and deep-water clastic and volcaniclastic sediments in tectonically active, mostly Archean, submarine volcanic belts, and (2) in laterally extensive sedimentary layers interbedded with quartzite, shale, or dolomite deposited in stable, mostly Early Proterozoic, shallow-water marine environments. Cannon (1986a,b)

presented separate descriptive models for Algoma (volcanogenic) and Superior (sedimentary) banded iron formation deposit types. These two models represent end-members; Superior-type deposits may grade laterally into more volcanogenic types (W. Cannon, oral commun., 1992). Algoma-type deposits occur in greenstone belts of Precambrian shields with turbidites and thick volcanic sequences and may be associated with Archean lode gold or massive sulfide deposits. Superior-type deposits are commonly exposed in forelands of Proterozoic orogenic belts and may be spatially associated with sedimentary manganese deposits. A number of features are common to both types. These include mineralogy (magnetite, hematite, siderite, and fine-grained quartz), texture (banded on a centimeter scale), lack of syngenetic alteration, weathering of iron minerals to iron hydroxides to form high-grade supergene ores in extreme cases, and associated magnetic anomalies.

Facies changes from shallow-water oxide facies through carbonate facies to deep water sulfide facies in the central part of the basin are recognized in both Archean and Proterozoic settings (Goodwin, 1973). Archean banded iron formations are typically associated with volcanic centers, are generally smaller in lateral extent, and have thin and discontinuous carbonate and sulfide facies relative to Proterozoic iron formations.

Grade and tonnage models.--Grade and tonnage characteristics (fig. G4) for 66 Superior and Algoma iron deposits were described by Mosier and Singer (1986). They combined both deposit types because they found no statistically significant differences in the tonnage or grade distributions between the two types. Tonnages range from less than 10 to nearly 100,000 million metric tons; median tonnage is 170 million metric tons. Grades range from about 20 to 70 percent iron, with a median value of 53 percent iron. Maximum phosphorous grades are less than 1 percent and range down to 0.02 percent.

Examples of Banded Iron Formation in the Study Area

Banded iron formation is present in Archean rocks in several geographically separated areas within Archean rocks of the study area: at Jardine, along the southern margin of the Stillwater Complex, in the Pine Creek Lake area of the North Snowy block, in the Broadwater River area, and at Quad Creek. None of these areas have produced iron ores. The most prospective areas for banded iron formation deposits

are the areas that have had some exploration in the past—for iron along the Stillwater Complex contact and for gold in the Jardine district.

Near Jardine, Archean iron formation is present in discontinuous, 5 cm to 10 m + thick lenses in schist (Casella and others, 1982). Silicate facies iron formation is more common than oxide, sulfide, or carbonate facies, but all facies are recognized. The Jardine rocks were metamorphosed to greenschist to lower amphibolite grade about 2.8 Ga, were contact metamorphosed by intrusion of the Crevice Granite at 2.7 Ga and were affected by a lower grade metamorphic event at 1.8 Ga. Hallager (1980) noted that oxide facies iron formation, mapped by airborne magnetometer by the Anaconda Company during exploration for gold, consists of fine-grained quartz, magnetite, and minor amounts of grunerite and hornblende. This unit is present in drill holes at Mineral Hill and at Crevice Mountain, and may have extended over an area of more than 100 km² (Hallager, 1980) before it was tectonically disrupted.

Chemical analyses of Jardine iron formation range from 25 to 30 weight percent iron; phosphorous content ranges from 0.06 to 0.22 weight percent P₂O₅ (Hallager, 1980; Casella and others, 1982). Identification of possible volcanic protolith, age, irregular distribution, thickness, and lenticular form (result of structural modification to some extent), presence of a sulfide facies, and continental margin setting suggest that the Jardine iron formation is more typical of the Algoma model.

In the 1950's and early 1960's, the Columbia-Geneva Steel Division of the United States Steel Corporation conducted exploration for magnetite iron deposits in the Stillwater area between the Crescent Creek and Boulder River areas. Their work, which included airborne geophysics, magnetometer traverses, trenching and sampling, and drilling (10 holes) resulted in an estimate of inferred resources of about 200 million short tons of ore at grades ranging from 15 to 40 percent iron (Walker, 1960) for the area of the Big Group claims. Page and Nokleberg (1974) mapped the iron formation underlying the Stillwater Complex and described it as lenses and beds of interbanded layers rich in quartz, magnetite, pyroxene and other minerals including grunerite, albite, and garnet. These lenses occur within the cordierite-orthopyroxene-biotite hornfels aureole of the Stillwater Complex and are typically associated with adjacent layers of blue metaquartzite. Outcrops of iron formation are typically small and discontinuous; however, the most intense and most continuous magnetic anomaly associated with the Stillwater

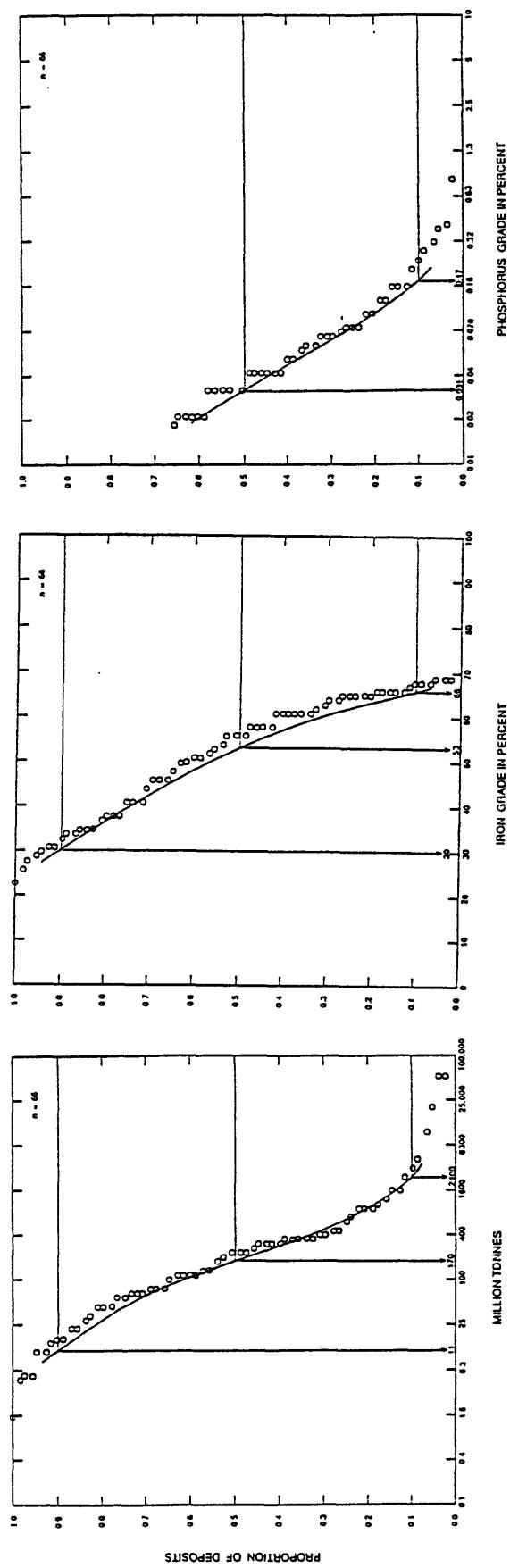


Figure G4.--Grade and tonnage models for Algoma and Superior iron deposits (Mosier and Singer, 1986).

Complex coincides with outcrops of iron formation (Blakely and Zientek, 1985). Page (1977) constructed stratigraphic columns for 14 localities to estimate the thickness of iron formation along the approximately 15-mile-long extent of the unit. This study showed that the maximum thickness of iron formation is in the East Boulder River area (approximately 1,000 ft thick) and suggested that continuous iron formation might be present in an area roughly 3 mi long by 400 ft wide, from Blakely Creek on the east to an area west of the Boulder River.

The Stillwater iron formation has been modified by metamorphism and does not readily fit into either the Algoma or Superior models. The Archean age suggests an Algoma affinity; however, a number of other features are consistent with a Superior model. These include lack of any obvious volcanic component, presence of associated pelitic rocks and blue metaquartzite (possibly a metamorphosed quartz-pebble conglomerate; Page and Zientek, 1985).

Iron formation is present in boudins with quartzite in xenoliths in Archean granitic gneisses and migmatites in the Broadwater River area, northeast of Cooke City. Timm (1982) estimated that the xenoliths (pelitic schist > quartzite > metamorphosed banded iron formation) comprise less than 1 percent of the Precambrian rocks in the area. Magnetite makes up only about 5 percent of the iron formation.

In the Quad Creek area, Henry and others (1982) described a single unit of iron formation associated with metagraywacke, quartzite, and amphibolite. These metasedimentary rocks comprise one of the numerous supracrustal inclusions in the granites, granitic gneisses, and migmatites of the eastern Beartooth Mountains. Mueller and others (1982) analyzed two ironstones from the Hellroaring Plateau area, just west of Quad Creek, in the same geologic setting (24 and 31 weight percent iron; 0.08 and 0.14 percent phosphorous as P_2O_5).

The Archean metasedimentary rocks of the Beartooth Mountains formed in a continental margin similar to the continental margin or intracratonic basin environments of deposition for most exposed Proterozoic sedimentary rocks; most exposed Archean sedimentary rocks (including banded iron formation) elsewhere in the world formed in a volcanic-dominated marine environment (Gibbs and others, 1986). Therefore, the trace element (rare earth element) chemistry and characteristics of the banded iron formation in the ABSA is somewhat atypical of banded iron formation elsewhere (Stanley, 1988) and neither end-member descriptive model is particularly appropriate.

The chemical analyses of samples of banded iron formation cited above give some indication of iron and phosphorous grades that might be expected for deposits in the ABSA; however, these data do not provide a reliable estimate of the expected average grade of undiscovered deposits. Apparent iron grades for banded iron formation are low (≤ 40 percent iron) compared to the median iron grade (53 percent iron) reported by Mosier and Singer (1986) for the Superior and Algoma model; measured phosphorous concentrations are within the range of the Algoma iron and Superior iron phosphorous grade model.

The resource estimate for the Big Group claims plots near the median in the tonnage model (fig. G4). These grade and tonnage models are probably appropriate for estimating undiscovered iron deposits in the ABSA.

Permissive Tracts

Tracts I (table G1), II (table G2), and III (table G3) are permissive for Algoma or Superior iron deposits.

Tract I--Ia (Jardine subtract). There are no iron prospects in the Jardine area, and although the iron formation has been used as an ore guide for gold exploration, no attempt has been made to evaluate the iron ore potential of the banded iron formation. Silicate facies iron formation is present in the North Fork area, north of Jardine and to the Yellowstone Park boundary to the south, but appears to be most extensive, albeit discontinuous, in the Mineral Hill and Crevice Mountain areas.

Ib (Stillwater-Boulder River subtract). Subtract Ib is delineated on the presence of Archean metasedimentary rocks that include the only significant prospect in banded iron formation (Big Group claims) in the study area, as well as small, discontinuous occurrences of iron formation along the basal contact of the Stillwater. These are associated with an aeromagnetic anomaly. The banded iron formation associated with the Stillwater Complex is not a discovered deposit because it has not been mined or thoroughly delineated. Its extent away from the explored area is unknown.

Ib1 (East Boulder River-Boulder River favorable area). Favorable area Ib1 outlines the most prospective area for the occurrence of iron deposits in tract I, based on mapped outcrops of iron formation, magnetic anomalies, and results of exploration.

Ic (Mill Creek-Sixmile Creek subtract). Magnetite occurrences in Archean schist are reported at two localities in the Sixmile Creek area of the

Emigrant district. Although no occurrences of banded iron formation have been documented, the rock types in subtract Ic are similar to those in subtracts Ia and Ib, and therefore are permissive for the occurrence of banded iron formation. The presence of banded iron formation is not indicated in the aeromagnetic data available for this study; more detailed geophysical studies are needed to rule it out.

Tract II.--Very minor occurrences of iron formation are present in poly lithologic xenoliths in granitic gneisses in the Quad Creek and Hellroaring Plateau areas of subtract IIb; however, we consider these occurrences too small to host undiscovered deposits.

Tract III (Suce Creek-Pine Creek tract).--Elliott and others (1983) noted minor occurrences of iron formation in the Mission Creek drainage area (20-ft bed associated with marble, schist, and amphibolite) as part of the nappe core complex in the northwestern part of the study area (North Snowy block).

Estimate of numbers of undiscovered deposits.--Favorable area Ib1 is the most prospective area for Algoma or Superior iron deposits in the ABSA. Although additional occurrences of banded iron formation may be present in the study area, it is highly unlikely that large numbers of undiscovered deposits remain to be found or that even the most prospective areas will be developed for iron because of the small size, discontinuous nature, and low iron grade of known occurrences. We estimate a 90 percent probability of 1 or more undiscovered deposits and at most a 5 percent chance of 2 or more deposits (table G6) for all of tract I. The high certainty level (90 percent) for 1 deposit reflects the fact that (1) the iron formation along the base of the Stillwater Complex is relatively continuous on the basis of its magnetic signature, and (2) exploration partially delineated a resource that appears to be compatible in tonnage and grade with known deposits elsewhere.

Simulator output for this distribution of undiscovered deposits predicts that tract I contains 1 deposit with (median values) 62 million metric tons of iron, 30,000 metric tons of phosphorous, and 130 million metric tons of total ore. In the Atlantic City-South Pass-Lewiston district of Wyoming, which is comparable in size to tract I (discussed under Archean lode gold deposits), more than 90 million short tons of ore averaging 33.5 percent iron (equivalent to about 27 million metric tons of iron) were recovered between 1962 and 1983 from the Atlantic City open pit mine in banded iron formation (Hausel, 1991; Bayley and others, 1973). Hausel

Table G6.--Estimate of mineral resources contained in undiscovered Algoma or Superior type banded iron formation deposits within the Absaroka-Beartooth study area (tract I)

Simulator input

Estimate of the minimum number of deposits expected at each of the following probabilities:

Tract	90%	50%	10%	5%	1%
I	1	1	1	2	2

Simulator output

Estimated numbers of undiscovered deposits

Tract	Mean expected number of deposits	Probability of 0 deposits
I	1.01	7%

Estimated amounts of commodities contained in undiscovered deposits (in metric tons)¹

Commodity /Tract	90th percentile	50th percentile Median	10th percentile	Mean
Iron I	1,600,000	62,000,000	1,300,000,000	650,000,000
Phosphorous I	0	30,000	640,000	280,000
Ore I	4,500,000	130,000,000	2,600,000,000	1,900,000,000

¹ Output from Mark3 program reported to 2 significant figures.

(1991) reported the occurrence of four other small iron deposits associated with the South Pass greenstone belt. The average grade for the Atlantic City mine and the assay iron grade values for occurrences of banded iron formation in the ABSA are more similar to the lower grade deposits (90 percent of the deposits in the model have average ore grades greater than 30 percent iron) than to the median iron grade (53 percent iron) in the Algoma and Superior iron model of Mosier and Singer (1986) that was used in the simulation. The model may overestimate the amount of iron in undiscovered deposits in the ABSA. The reported 90th percentile values (table G6), that is the lowest and most likely amount of ore expected, may provide a more realistic estimate of potential ore than the median or mean in this case.

CHROMITE DEPOSITS

Mineral Deposit Model

Descriptive model.--Chromite deposits of the world can generally be classified in one of two deposit types: (1) podiform (or Alpine-type) deposits or (2) stratiform (or Bushveld-type). Podiform chromite deposits have been described as podlike masses of chromitite in ultramafic parts of ophiolite complexes of Phanerozoic age (Jackson and Thayer, 1972). Stratiform chromite deposits represent layered chromite-rich seams in lower to intermediate zones of large, cyclic layered mafic-ultramafic intrusions such as the Bushveld Complex of South Africa and the Stillwater Complex of Montana (Chapter F of this report; Page, 1986a).

Grade and tonnage models.--Grade and tonnage models are unavailable for stratiform chromite deposits (Bushveld chromite model of Page, 1986a). Cox and Singer (1986) include two grade-tonnage models for podiform chromite deposits: (1) a minor podiform chromite deposit model based on grade-tonnage compilations for 435 deposits from California and Oregon (Singer and Page, 1986) and (2) a major podiform chromite model for 174 deposits throughout the world (Singer, Page, and Lipin, 1986). These two models represent two different grade-tonnage populations of deposits that share descriptive model characteristics. Median ore tonnages and chromium grades for the two models are 130 metric tons and 44 percent Cr_2O_3 (minor) and 20,000 metric tons and 46 percent Cr_2O_3 (major).

Red Lodge Chromite Deposits

The chromite deposits near Red Lodge, Montana, occur as polymetamorphosed, tectonically disrupted, isolated remnants of mafic to ultramafic rock in Archean metavolcanic and metasedimentary rocks within Archean granitic gneiss. Both podiform and stratiform origins have been postulated for these deposits. Primary features of these deposits, mineral assemblages, and mineral compositions have been modified by high-grade (amphibolite to granulite facies) metamorphism (Lofterski, 1986). James (1946) mapped the known deposits and recognized that the Red Lodge deposits are quite different from the stratiform chromite deposits in the Stillwater Complex to the north. The Red Lodge deposits form pods and lenses in masses of serpentinite. Deposits range in size from a few pounds to 35,000 short tons of ore

and average about 20 percent Cr_2O_3 . Magnetometer surveys (James, 1946) showed that the ores and serpentinite are highly magnetic relative to surrounding country rocks. The Red Lodge chromite deposits do not fit existing descriptive deposit models because (1) although irregular in present form, the deposits occur in Archean rocks and are not associated with ophiolites such as one finds in the Phanerozoic podiform chromite deposits, and (2) ore grades are low, reflecting the metamorphic compositions (iron-enriched, magnesium- and aluminum-depleted) of the chromites. Therefore, we have chosen to use the name "Red Lodge chromite" to describe these deposits.

Many of the Red Lodge chromite deposits are completely mined out and have remained inactive since the 1940's. The district produced about 62,000 metric tons of ore averaging 24 to 40 percent Cr_2O_3 from deposits on Hellroaring and Line Creek Plateaus in the 1940's (Simons and others, 1979). It is important to note that the only reason the Red Lodge chromite deposits were ever developed was because of wartime subsidies to stockpile minerals of strategic importance to the country. Although some of the Red Lodge deposits have ore tonnages comparable to those in the podiform chromite models, the ore grades tend to be low (table E1).

Permissive tracts.--Volumetrically minor septa of the metamorphosed mafic and ultramafic rocks that host Red Lodge chromite deposits are present within the predominantly gneissic and migmatitic terrane of tract II on the Silver Run, Line Creek, and Hellroaring Plateaus. Known deposits and stream sediment geochemical anomalies in chromium and nickel are confined to the Eastern Beartooth subtract (IIb). A north-south-trending gradient in both gravity and magnetic data separates the Western Beartooth subtract (IIa) from the Eastern Beartooth subtract (IIb) of the gneiss terrane (tract II). Stream sediment geochemical anomalies for chromium and nickel and high scores for factor Spec-1 (mafic rocks) are present in subtract IIb to the west of the identified deposits.

Undiscovered deposits.--Previous mineral resource assessments estimated reserves of 77,000 short tons (70,000 metric tons) of ore averaging 12.8 percent Cr_2O_3 remaining in known deposits (Simons and others, 1979) and about 100,000 short tons (91,000 metric tons) of ore in undiscovered deposits (James, 1946). Undiscovered deposits are likely to be similar in size and grade to discovered deposits (table E1) and are unlikely to be an important exploration or development target in the foreseeable future. Chromite deposits associated with the Stillwater

Complex are of much higher grade, are more laterally continuous, and have important by-product metal associations compared with the Red Lodge deposits and are therefore more attractive exploration targets.

SERPENTINE-HOSTED ASBESTOS

Mineral Deposit Model

Descriptive model.--Serpentine-hosted, or Quebec-type asbestos deposits, are stockwork deposits of chrysotile asbestos in serpentinized ultramafic rocks that usually occur in multiply deformed and metamorphosed ophiolite sequences (Page, 1986b).

Grade and tonnage models.--Orris (1992) constructed tonnage and grade models for 64 serpentine-hosted asbestos deposits, mainly from Canada. Deposits range in size from approximately 300,000 to more than 400 million metric tons of ore; ore grades, reported as percent of asbestos fibers, range from 1 to 40 percent.

Asbestos Occurrences in the Study Area

Three "asbestos" occurrences are reported in the study area (plate 19). The geologic setting and mineralogy of these occurrences are unknown. Loferski (1980) identified serpentine minerals in all of the ultramafic bodies associated with the Red Lodge chromite deposits. Antigorite is the most common serpentine mineral present, but lizardite and chrysotile (the fibrous form of serpentine known as chrysotile asbestos) occur as well. Isolated "asbestos" occurrences reported in the ABSA probably represent local occurrences of chrysotile in septa of serpentinized ultramafic rocks within the gneiss terrane (tract II). These occurrences are too small and isolated, and the volumes of potential serpentinized rocks within the study area are considered too small to form chrysotile asbestos deposits, such as those described by the models.

PEGMATITES

Mineral Deposit Model

Descriptive model.--Pegmatites are very coarse grained igneous rocks of granitic composition that represent the last and most hydrous parts of a magma to crystallize (Bates and Jackson, 1987). Pegmatites

form irregular dikes, veins, and pods. Simple pegmatites consist of quartz and feldspar, with or without mica. Complex pegmatites may be zoned, and may include minerals enriched in lithophile elements such as lithium, boron, halogens, rare earth elements, niobium, and tantalum. Pegmatites are ubiquitous in many granitic and gneissic granitoid terranes throughout the world, but they rarely form ore deposits. Exceptions are pegmatites that contain concentrations of unusual minerals such as the spodumene-bearing pegmatites of the Black Hills, South Dakota, that were mined for lithium or pegmatites that are mined for feldspar, mica, or gemstones, and pegmatites associated with tin deposits.

Strong (1988) included pegmatites in a general model for granophile mineral deposits which he characterized as high temperature, deep seated, early magmatic, lithophile-element enriched deposits hosted by quartz-rich leucocratic granitoids. In contrast, low-temperature, shallow, late hydrothermal, chalcophile-element enriched porphyry-type deposits represent the other end of a spectrum of characteristics of mineral deposits associated with granitoid rocks. Pegmatites may be concentrated near the margins or tops of batholiths or plutons. Tin-mineralized granites typically exhibit a pattern of geochemical zoning from proximal tin-tungsten-arsenic associated with pegmatites and disseminations in the pluton outward and upward through zones of copper, bismuth, uranium-nickel-cobalt, lead-zinc-silver, and iron-antimony sulfides associated with veins and stockworks. Pegmatite-stage ore minerals typically include arsenopyrite, wolframite, cassiterite, and molybdenite in a gangue of quartz, feldspar, mica, and tourmaline (Strong, 1988).

Grade and tonnage models.--Orris and Bliss (1992) compiled industrial mineral grade and tonnage models for lithium, feldspar, and quartz in pegmatites. Descriptive models were not included, so the relevance of these models for this study cannot be established.

Pegmatite Occurrences in the Study Area

Pegmatites are present in Archean granitoids at a number of localities within the Absaroka-Beartooth study area; in the Lake Plateau area, Richmond (1987) noted that pegmatites and aplites comprise nearly 20 percent of the exposed volume of granitic rock. Published descriptions of pegmatites in the ABSA imply that most are barren, but molybdenite is

present in some pegmatites. The quartz and feldspar content of pegmatites in the ABSA has not been evaluated. None of the pegmatites in the Absaroka-Beartooth study area have been exploited for any commodity in the past.

Molybdenite is present in pegmatites in the Mount Cowen area of the Western Beartooth subtract (IIa) and at the Rosebud molybdenum prospect in the Eastern Beartooth subtract (IIb). Reed (1950) described gneiss, schist, and quartzite cut by quartz-feldspar pegmatite, aplite, and basic dikes at the Mount Cowen molybdenum prospect where molybdenite crystals are present in pegmatite and in gneiss. In the 1960's, Anaconda drilled 2 shallow (92 ft and 101 ft long) holes on the Rosebud prospect based on surface exposures of disseminated sulfide minerals (molybdenite, pyrite, chalcopyrite, and traces of molybdate) in a quartz lens associated with pegmatite along a contact between schist and granite. The drill holes encountered schist, granite, and pegmatite similar to that at the surface. Pyritized schist and granite were found in the first ten feet of one of the two drill holes; the remainder of that core and the other hole were essentially barren. A 100-ft-wide mineralized zone averaged 0.33 percent MoS_2 ; average grades for the two holes were 0.005 and 0.007 percent MoS_2 . These data led to the conclusion that the prospect was not commercially important (Brox, 1962).

Permissive tracts.--Archean granitic gneiss terranes within the ABSA (tract II) are permissive for the occurrence of mineralized pegmatites. Geochemically anomalous areas within subtract IIb upstream (south) from the Rosebud molybdenum prospect may contain weakly mineralized pegmatites. Aspects of the geochemical signature of tract IIb (W, Mo, Bi, Pb, and Zn) are suggestive of mineral deposits associated with granites (tungsten-bearing veins and tin-bearing veins or greisens). However, no tin anomalies are observed and the mineralogic source of the tungsten anomaly is unknown. Geochemical data for Archean granitoids show that chemically distinct groups of dominantly granitic rocks are present throughout the eastern and central Beartooth Mountains (Wooden and others, 1988); the porphyritic texture of granitoids in the East Rosebud Creek area is distinctive, but chemically, these granitoids are similar to other Archean granitoids in the eastern and central Beartooth Mountains. Although trace element data are variable, none of the reported analyses show the extreme incompatible trace elements enrichments (for example, rubidium, uranium, thorium) characteristic of tin granites.

The observed stream sediment geochemical anomalies may reflect metallization associated with an unrecognized variant of Archean granite. Alternatively, the geochemical anomalies may reflect a signature associated with Tertiary or Cretaceous latite porphyry dikes near the headwaters of East Rosebud Creek (Granite Peak subtract Vd) or with the Late Cretaceous alkalic complex at Goose Lake (tract VI and subtract Ve). In any case, pegmatites have not been mined for molybdenum content alone in the past in the ABSA or elsewhere, and are unlikely to be economically important in the future.

URANIUM

Mineral Deposit Models

Uranium is a lithophile element that exists in nature in multiple oxidation states. Under oxidizing conditions, uranium forms ions that are soluble in water, and therefore uranium can be a highly mobile element in some geologic environments and can be recycled in the earth's crust. This geochemical behavior leads to variety of different mineral deposit types. The major Archean to Early Proterozoic uranium deposits of the world are quartz-pebble conglomerate gold-uranium deposits (paleoplacers) that formed thick sedimentary deposits in epicontinental basins in a relatively reducing earth atmosphere that preserved detrital pyrite and uraninite, UO_2 (Cox, 1986b; Marmont, 1988). The major uranium deposits of Early to Middle Proterozoic age have been described as unconformity-type, vein-type, and carbonaceous pelite-hosted deposits that represent remobilization of uranium during metamorphism, weathering, and supergene enrichment (Grauch and Mosier, 1986; Tilsley, 1988).

Uranium Occurrences in the Study Area

Two types of uranium occurrences are present within the ABSA (plate 19). The nature of these occurrences and their relation to mineral deposit types are insufficiently understood. There has been some exploration for uranium in the ABSA, but no development or mining.

In the Archean rocks of tracts II and III, uranium occurrences and uranium and thorium geochemical anomalies are associated with Archean gneisses; however, the bedrock source of the stream sediment anomalies is uncertain. Elliott and others

(1983) noted that radioactive, partly to completely metamict minerals such as allanite, sphene, and ilmenorutile are present in Precambrian granitic gneisses (especially Falls Creek Gneiss) and in pegmatites. Anomalous concentrations of uranium and thorium in bedrock are associated with biotite-rich zones in gneiss, and may be present as disseminations or in fractures fillings. In the North Absaroka Wilderness Study, a northwest-southeast-trending area of uranium potential was delineated extending from Hawley Mountain to the West Boulder River. The Johns Manville Corporation explored this area for uranium and located about 200 claims. Stream sediment and surface water geochemical surveys conducted for the North Absaroka study showed that some of uranium is present in resistate minerals such as xenotime and much of the uranium correlates with organic carbon and is present in leachable form (Suits and Wenrich-Verbeek, 1980a,b); highly anomalous stream sediment uranium values (>100 ppm) were encountered along Speculator Creek and other creeks that drain Archean gneisses of tract IIa.

The other type of uranium occurrence in the ABSA may be related to the unconformity, or vein type deposit model. Armstrong (1957) noted that radioactivity anomalies along the eastern front of the Beartooth uplift near Red Lodge occur in quartzite of the Middle Cambrian Flathead Sandstone where it unconformably overlies Archean rocks. A relationship between radioactivity and fault zones near the contact between basal Cambrian Flathead Sandstone and Precambrian crystalline rocks had been noted in a 1953 reconnaissance scintillometer and Geiger counter survey over an area of about 5,000 mi² in south-central Montana and northern Wyoming (Stow, 1953); the anomalous rock is the Cambrian sandstone. Private industry conducted helicopter radiation reconnaissance surveys in the vicinity of the Elk claims in the Grove Creek district (Adler, 1969). Anomalies of about 0.04 milliroentgens per hour are associated with Flathead Sandstone in section 34 of T8S, R20E. Background radiation levels were measured by helicopter (0.015 milliroentgens per hour) and on the ground (0.007 milliroentgens per hour). Higher levels, up to 0.12 milliroentgens per hour, were detected near copper-bearing veins over a distance of about 1,000 ft away from the granite-sandstone contact. Jarrard (1957) described the Red Lodge area uranium occurrences as contact-type and noted that the occurrences are spatially related to tear faults and thrusts. He did not describe the granite at the contact; the granite could be either Cretaceous or Tertiary if this is really an

intrusive contact, or could be Archean granite or granitic gneiss at a tectonic contact. In the Pryor Mountains to the east of ABSA, uranium deposits formed in brecciated Mississippian Madison Limestone. The uranium mineral at Red Lodge and in the Pryor Mountains is tyuyamunite; a yellow, hydrated, calcium-uranium vanadate that occurs as coatings, in fractures, and as disseminations.

Amethystine (possibly due to radiation damage) quartz is exposed in prospect pits along the contact between Precambrian rocks and Cambrian Flathead Sandstone on Baboon Mountain in the Independence district. Stow (1953) described a number of slight to moderate radioactive anomalies in the Independence district (7777 claim, gold mines) and at the Hart claim on the west side of Goose Lake.

MINERAL DEPOSITS IN PHANEROZOIC ROCKS

Mineral deposit types that may occur in Phanerozoic rocks in the ABSA are (1) deposits related to Cretaceous and Tertiary intrusive centers, including porphyry copper-gold-molybdenum deposits and epithermal veins (tract V), alkaline gabbro-syenite hosted magmatic segregation deposits (tract VI), skarns (tract VII), and polymetallic vein deposits (tract VIII); and (2) deposits related to Quaternary processes including placer gold deposits (tract IX) and bog iron-manganese deposits. Permissive tracts for Phanerozoic deposits are shown on plates 17 and 18; the location and extent of individual tracts, subtracts, and favorable areas and criteria for delineation are described in the following discussions of mineral deposit types.

MINERAL DEPOSITS ASSOCIATED WITH TERTIARY AND CRETACEOUS INTRUSIVE ROCKS

Many of the mining districts in the ABSA are associated with Cretaceous or Tertiary intrusive centers. Some of these centers (such as Emigrant, Independence, Cooke City) probably represent deeply eroded stratovolcanoes. A variety of mineral deposit types may form in these geologic environments, including porphyry deposits, skarns, polymetallic vein and replacement deposits, and epithermal veins. Deposits may or may not form in a given intrusive center depending on the availability of metals

(many intrusive centers are barren), the extent of development of a hydrothermal system, and the nature (structure and composition) of the intruded country rocks. The preservation of deposits in a given center depends on the depth of erosion as well as the tectonic history. Figure G5 illustrates the types of deposits that might possibly form in different parts of an idealized stratovolcano.

Major belts of porphyry copper deposits throughout the world are spatially associated with linear, predominantly calc-alkaline arcs related to subduction zones along convergent plate boundaries (Sillitoe, 1972). The tectonic setting of the Absaroka-Gallatin volcanic province is problematic, in part because it is situated well inboard of the Cretaceous to Tertiary continental margin. Furthermore, the linear alignment and patterns of age progressions typical of subduction-related volcanic provinces have not been recognized and some unusual aspects of Absaroka magma chemistry (locally alkalic, especially to the north of the ABSA) are not resolved by subduction models (Dudas, 1991). Models involving mantle upwelling have been proposed for the generation of the Absaroka magmas (Meen and Eggler, 1987; Dudas, 1991). The tectonic setting and geochemical character of the crust/mantle tapped during formation of the Cretaceous and Tertiary magmas in the ABSA may represent a distinctive metallogenic terrane formed during transition from a regional compressional (subduction?) to an extensional tectonic setting.

PORPHYRY COPPER-GOLD-MOLYBDENUM DEPOSITS

Mineral Deposit Model

Descriptive model.--Porphyry copper deposits are defined as chalcopyrite-bearing disseminated and stockwork zones in hydrothermally altered porphyry and adjacent country rock. Cox and Singer (1986) include several models for porphyry-type copper mineralization, including a generalized model and subsets that may be used for porphyry copper-gold, porphyry copper-molybdenum, or porphyry copper skarn-related deposits. Stocks that host porphyry copper deposits are typically 1 to 4 km wide. An idealized sequence of alteration zones (fig. G6) that may be present includes a central potassic zone \pm late phyllitic overprint (chalcopyrite + pyrite + molybdenite) flanked by similar scale propylitic alteration zones (pyrite) which can include copper and gold-bearing

skarn, polymetallic vein, and polymetallic replacement deposits.

Mineralogy and gold:molybdenum ratios distinguish gold- and molybdenum-rich subtypes, but a continuum exists among such deposits. Cox and Singer (1992) showed that metal ratios, magnetite content, deposit morphology, depth of emplacement, and deposit tonnages vary among copper-, gold-, and molybdenum-rich porphyry copper deposits. Associated igneous rock type (quartz diorite, tonalite, syenite, monzonite, granodiorite, monzogranite) does not appear to be a reliable discriminant of deposit subtype. Important characteristics of various subtypes are summarized in table G7.

Breccias.--Porphyry systems typically include breccias (fig. G6) that may contain higher concentrations of ore than associated stockworks. No separate descriptive or grade-tonnage models exist for breccias associated with porphyry systems. However, breccia pipes in porphyry systems may constitute separate orebodies and exploration targets from the mining industry's viewpoint. In a review paper on ore-related breccias in volcanoplutonic arcs, Sillitoe (1985) noted that breccias are present in more than half of the known porphyry deposits. Breccias vary in form (lenses, dikes, pipes), horizontal dimensions (a few meters to as much as 2 x 0.7 km), vertical extent (commonly 500 to 1,000 m), number (single pipe to as many as 35 pipes), location within the porphyry system (central, peripheral), and age relative to the porphyry deposit. Potassic, as well as sericitic, alteration is common in breccias and metals may be zoned both laterally and vertically within breccia pipes.

Grade and tonnage models.--Singer, Mosier, and Cox (1986) constructed grade-tonnage models for porphyry copper deposits based on data for 208 deposits throughout the world, including gold- and molybdenum-rich subtypes and parts of the deposits which could be considered skarn and breccia. These models include the huge and (or) high-grade porphyry copper deposits of South America, such as the Chuquicamata deposit of northern Chile. For the purposes of this study, new grade and tonnage models were constructed based on the worldwide data set used by Singer, Mosier, and Cox (1986). These new models (fig. G7) include only deposits from North America (U.S., Mexico, and Canada) and therefore provide a more comparable geologic context for the assessment of undiscovered porphyry copper deposits in the Absaroka-Beartooth study area. The North American subset of the worldwide porphyry copper includes both gold- and molybdenum-rich subtypes.

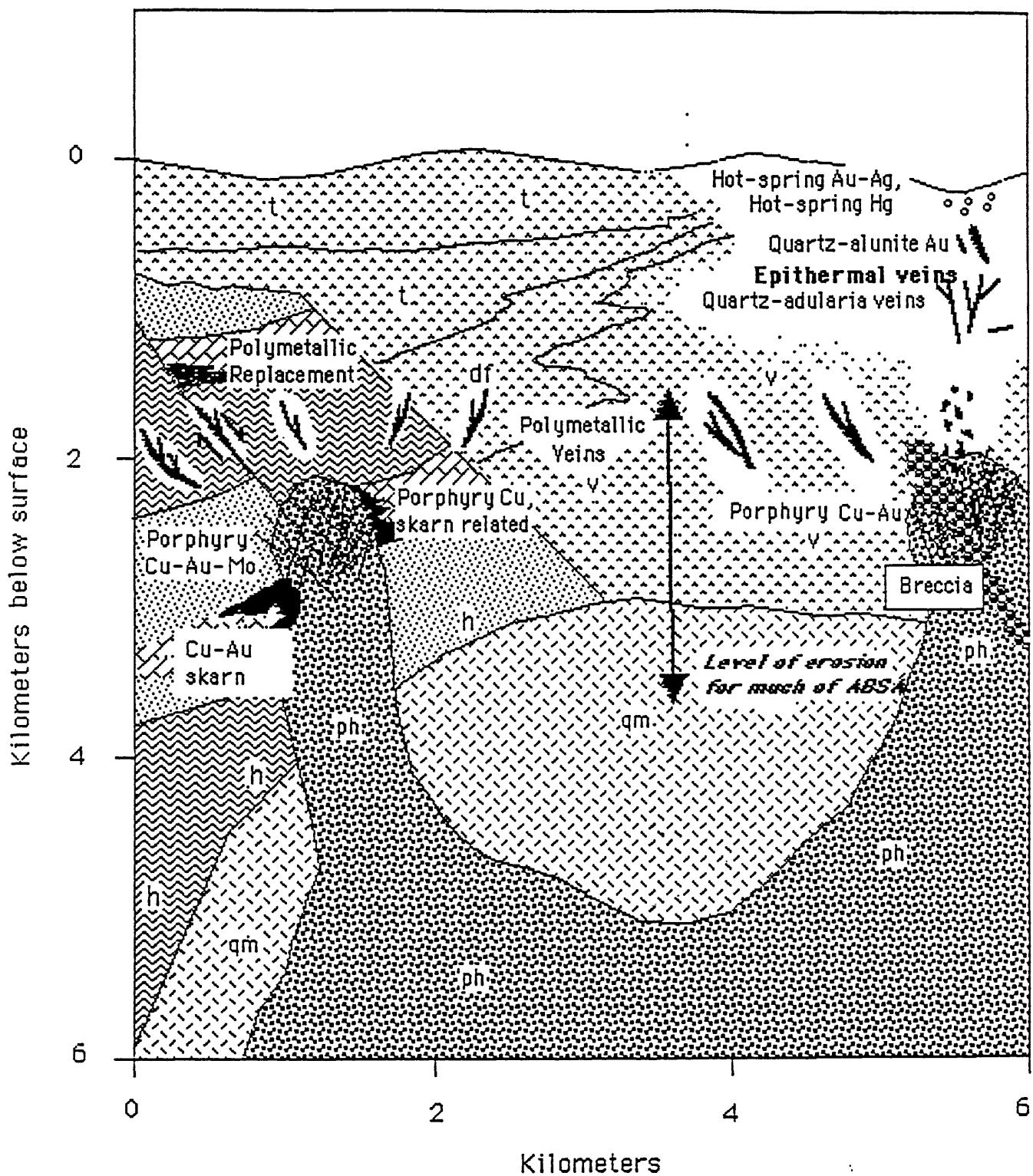


Figure G5.--Generalized geologic model for mineral deposit types associated with stratovolcanos. Modified from Drew and Menzie, 1993. (qm - quartz monzonite, ph - porphyry, v - volcanic flows, df - debris flows, s - volcanoclastic sediments, t - tuffs, h - hornfels, - carbonate, - sandstone, - shale).

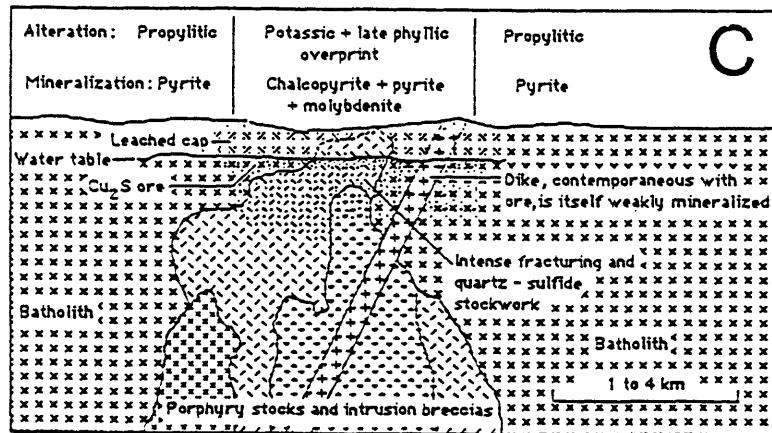
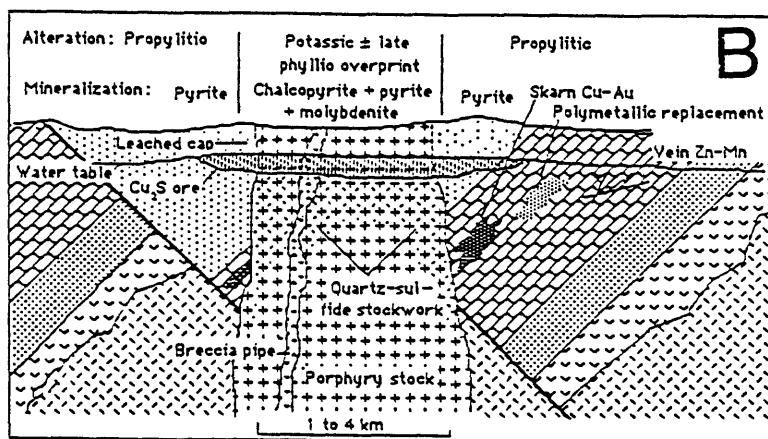
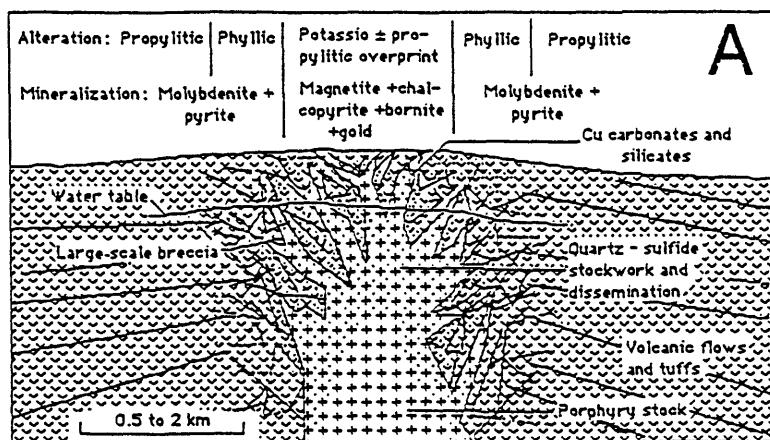


Figure G6.—Generalized geologic models showing the types of alteration and mineralization, typical dimensions, and geologic environments in which types of porphyry copper deposits form (from Cox and Singer, 1986). **A**, porphyry copper-gold model; **B**, porphyry copper model; **C**, porphyry copper-molybdenum model.

Table G7.--Characteristics of porphyry copper (-gold, -molybdenum) deposits

[Based on Cox and Singer, 1992]

Subtype	Copper-gold	Copper-gold-molybdenum	Copper-molybdenum
Au / Mo (ppm) (%)	Au/Mo \geq 30	3 > Au/Mo < 30	Au/Mo \geq 3
Morphology	Irregular or dikelike intrusions; coeval volcanics present	<-->	Integral zones of mid-size plutons; coeval volcanics commonly absent
Main ore minerals	Chalcopyrite, bornite, magnetite	<-->	Chalcopyrite, molybdenite
Magnetite content	2.6%	1.0%	0.05%
Depth of emplacement	1.0 km	0.9 km	3.6 km
Tonnage (metric tons)	160 x 10 ⁶	390 x 10 ⁶	500 x 10 ⁶
Ore grades			
Copper (%)	0.55	0.48	0.41
Molybdenum (%)	0.003	0.015	0.016
Gold (g/t)	0.38	0.15	0.012
Silver (g/t)	1.69	1.63	1.22
Examples	Copper Mountain, British Columbia	Bingham, Utah	Morenci, Arizona

Examples in the Study Area

Several shallow-level plutonic complexes in the ABSA have alteration and styles of mineralization that are typically associated with porphyry copper deposits. Locations can be specified (favorable areas), but the level of exploration is such that the grades, quantity, and quality of ores have not been thoroughly evaluated. Porphyry copper (-molybdenum) deposits have been an exploration target within the ABSA in the past (table A3); however, no porphyry copper deposits have been mined or developed and exploration to date has failed to delineate an economically viable porphyry deposit. Small, precious- and (or)

base-metal vein deposits that have been mined in the past may be related to larger mineralized systems centered about volcanoplutonic centers that include potential porphyry copper-gold-molybdenum deposits. Gold and silver in veins, such as at the Independence mine (table E1) and as disseminations in intrusive rock (plate 19) are probably related to porphyry-style mineralization.

Intensive exploration in the Emigrant district by a number of mining companies (table A3) delineated a potential large (but unspecified) tonnage porphyry copper-molybdenum system. Reserves, based on drilling, are available for the Basic Metals breccia pipe in the Emigrant district (Ahrens, 1968). Stotelmeyer

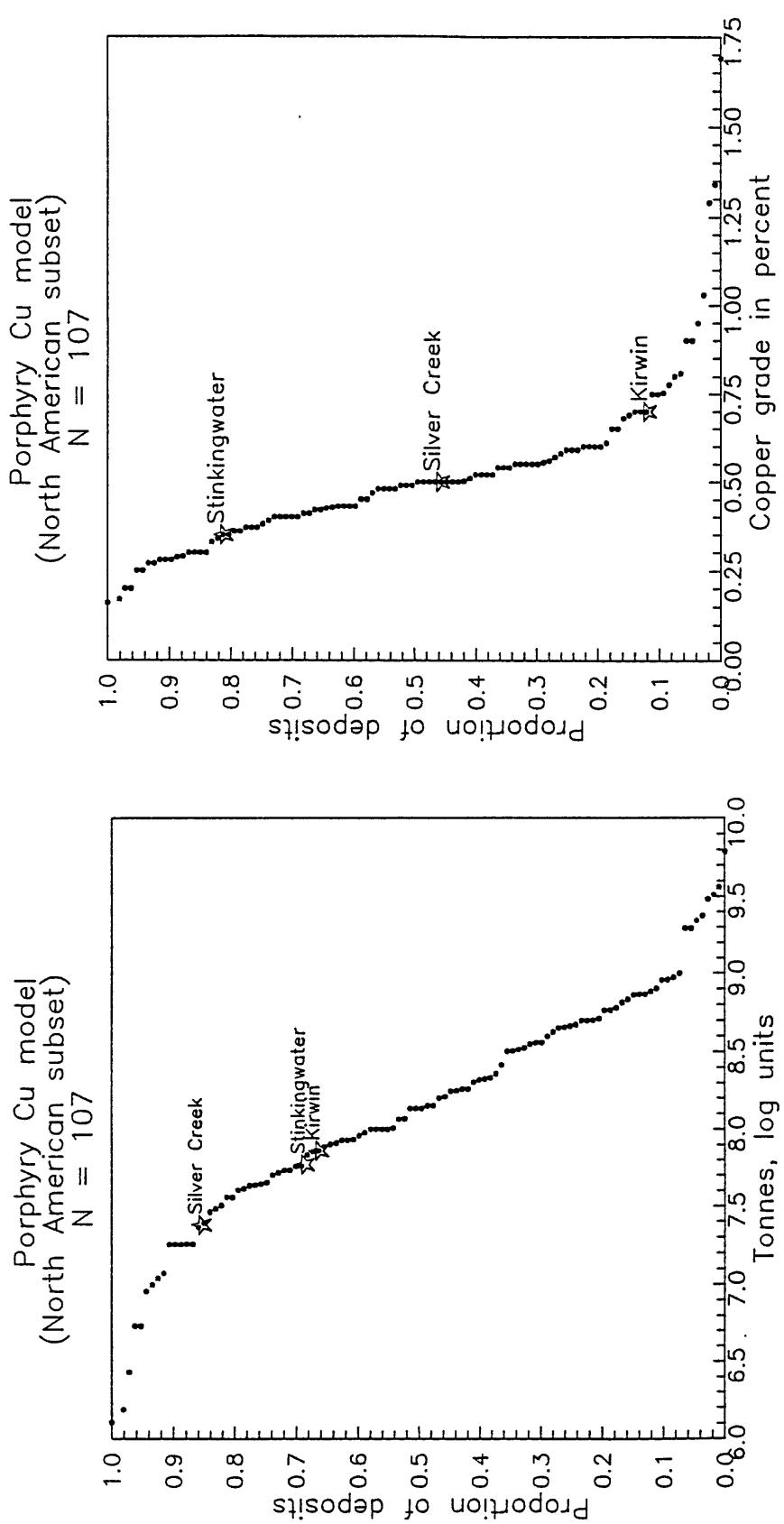


Figure G7.—Grade and tonnage models for North American porphyry copper deposits. Subset of Singer and others' (1986) grade and tonnage model of porphyry copper. Stars, data for porphyry copper deposits in the Absaroka-Gallatin volcanic province of Wyoming.

and others (1983) estimated resources for some of the other breccia pipes in the Emigrant district based on surface samples (table E1).

In the New World district, several mining companies conducted exploration for large tonnage porphyry copper-molybdenum deposits in the 1960's and 1970's (Elliott and others, 1992), which led to identification of gold-copper-silver skarn and replacement deposits in the Como area. The Como and other skarn, replacement, vein, and breccia deposits of the district are associated with altered and weakly mineralized porphyritic intrusions. Current development is focused on exploitation of the gold-rich parts of the mineralized system rather than the potential low-grade porphyry copper ores.

The Independence district includes an intrusive center that lies along the Cooke City structural zone. The crudely defined, district-wide zoning from gold-silver-copper bearing mines, prospects, and occurrences (skarns, veins) to more distal lead-zinc occurrences (polymetallic veins) noted for the Emigrant, Independence, and New World districts (note distribution of deposit types on plate 19) is typical of porphyry copper systems.

No reliable grade or tonnage data (that is, no deposits that can be compared with grade-tonnage models) are available for the identified porphyry copper deposits in the ABSA. Areas that have already been identified as having a high potential for such deposits will therefore be favorable for undiscovered deposits and this favorability is reflected in the confidence levels assigned to estimates of numbers of undiscovered deposits.

The style of mineralization (disseminated, stockwork, and vein) and hydrothermal alteration associated with mineralized volcanic centers of the Absaroka province is similar to porphyry copper models developed for the Basin-and-Range deposits of the southwest U.S. Hausel (1982) described the porphyry copper deposits of the Absaroka volcanics in Wyoming, and included the Cooke City-New World intrusive-volcanic complex, noting that it is more deeply eroded than any of the other known centers of mineralization in the Absaroka volcanics. He summarized the characteristics of these deposits as follows: (1) the centers generally have a central intrusive complex with adjacent vent facies breccias, flows, and tuffs that are fractured, altered, and may grade out into volcaniclastics; (2) mineralization occurs as disseminations and stockworks in altered stocks and locally in vent-facies wallrocks, fracture-fill veins and veinlets that extend outwards from centers,

veins and replacements in Paleozoic carbonates, supergene-enriched deposits, and placer gold deposits spatially associated with porphyry districts; (3) mineralization and alteration are zoned from (typically) copper-molybdenum and trace gold core to distal lead-zinc-silver; all districts have widespread deuterian propylitic alteration, where veins and veinlets of calcite, epidote, chlorite, and pyrite reflect a hydrothermal overprint on deuterian alteration of the intrusive; phyllitic (quartz-sericite-pyrite) alteration is recognized at most of the deposits near disseminated copper mineralization; argillic and potassic alteration zones are present at a few deposits.

Grade and tonnage data are available for a few of the Absaroka porphyry deposits in Wyoming. The Kirwin deposit, 64 million metric tons of mineralized rock averaging 0.75 percent copper (Rosenkranz and others, 1979) is included in the grade and tonnage models in figure G7. In addition, Hausel (1982) reported a minimum estimate of 27 million short tons (24 million metric tons) of mineralized rock averaging 0.5 percent copper for the Silver Creek stock (Fisher and others, 1977) and drill-indicated reserves for the incompletely delineated Stinkingwater deposit (Fisher, 1972) of 65 million short tons (59 million metric tons) containing 0.35 percent copper. Molybdenite is reported as a major sulfide mineral at Kirwin, Silver Creek, and Stinkingwater but no grades are available. A small amount (100 short tons) of gold, silver, and copper ore was mined from vein deposits in the Sunlight district, another Absaroka intrusive center (Nelson and others, 1980) around 1900.

These data show that known porphyry copper deposits in the region have copper grades comparable to those in the grade model for North American porphyry copper deposits (median copper grade 0.50 percent). Available tonnages for Absaroka deposits are minimums; tonnages are low compared to the median value of 136 million metric tons for the North American deposits. Insufficient data are available for Absaroka porphyry copper deposits to use copper, molybdenum, and gold grade ratios to classify deposits by subtype (table G7). There is no *a priori* evidence to suggest that all undiscovered deposits are likely to be porphyry copper-molybdenum deposits rather than porphyry copper-gold, or porphyry copper deposits. Therefore, we use the generalized descriptive porphyry copper model of Cox and Singer (1986) and we use grade and tonnage models for North American porphyry copper deposits that include copper-gold, copper-molybdenum, and skarn-related subtypes.

Permissive Tracts

Tertiary and Cretaceous volcanoplutonic centers and possible buried centers within one kilometer of the surface that are permissive for the occurrence of porphyry copper-gold-molybdenum deposits are delineated by tract V (fig. G8, table G8). Tract V includes five geographically separate subtracts. Within subtract Va (South Snowy block subtract), five favorable areas are delineated around known igneous centers associated with mines, prospects, and occurrences, geophysical anomalies and (or) geochemical signatures that indicate that these area may be more favorable for the occurrence of porphyry copper deposits than other areas within tract V (table G9).

Tract V--Va (South Snowy block subtract). Subtract Va outlines Tertiary intrusive and volcanic rocks of the Absaroka-Gallatin volcanic province in the South Snowy block based on surface geology (plate 1) and inferred intrusive centers within 1 kin of the surface indicated by geophysical data (Chapter C).

Va1 (Emigrant favorable area). The Emigrant stock was extensively explored (drilling, IP surveys, geochemical surveys) for porphyry copper-molybdenum targets in the 1960's and 1970's by a number of mining companies. The Anaconda Company identified at least two centers of mineralization in a regional geochemical survey conducted in the 1960's (Ahrens, 1968). These two centers, one east of Emigrant Gulch centered about a small stock of granodiorite porphyry, and one to the west on Emigrant Peak (Savelson, 1979), probably represent surface expressions of a single, large mineralized system. Potassic alteration is present in each center (Pfau, 1981) and other types of alteration associated with porphyry copper deposits, including phyllitic, argillic, propylitic, and silicic, are recognized in various parts of the Emigrant stock. A gravity low and a composite magnetic high (plate 3, anomaly 1a,1b) are associated with the Emigrant stock. The western part of the magnetic high is centered over the Emigrant Creek breccia pipe, whereas the eastern magnetic high lies east of the surface exposure of the stock, which may indicate a larger intrusion at shallow depth.

The eastern center is currently being evaluated for its gold potential by Pegasus. Pfau (1981) mapped parts of Emigrant Gulch and described the porphyry-type mineralization as well as six mineralized breccia pipes which range from about 100 ft (Allison pipe) to as much as 3,500 ft (St. Julian pipe) in diameter. Many of the old workings of the district exploited these breccia pipes. Pfau's study of the surface

geochemistry of the district showed (1) copper anomalies (100 ppm to 1,000 ppm) associated with all of the breccia pipes in the district as well as centered over the porphyritic granodiorite, (2) erratic molybdenum values, mainly associated with the Allison and Peter Pear breccia pipes, and (3) highest gold and silver concentrations associated with breccia pipes and shear zones.

Previous exploration in the western center, the Emigrant Peak porphyry copper-molybdenum target and Emigrant Peak breccia pipe, identified a roughly triangular (4,800 ft on a side) red-yellow-brown surface color anomaly. Such color anomalies result from oxidation of sulfide minerals and are typical features in porphyry copper deposits.

Samples collected for this study from breccia pipes, altered porphyries, and altered volcanic rocks all contain detectable gold (0.004 to 0.84 ppm), silver (0.2 to 3.3 ppm), and copper (4 to 2,000 ppm). Breccia pipes are anomalous in lead, zinc, and locally in molybdenum relative to the igneous rocks (Hammarstrom, unpublished data).

The presence of at least one porphyry copper system at Emigrant is highly probable. Favorable factors cited in past reports include geochemical anomalies for copper and molybdenum, presence of mineralized breccia pipes, alteration, quartz veining, quartz-eye porphyry dikes, high salinity fluid inclusions, ore minerals (chalcopyrite, pyrite, molybdenite, minor bornite), and the occurrence of ore minerals as veinlets and disseminations. Negative factors cited in exploration reports (Ahrens, 1968), which may in part explain the lack of development in the area, include the absence of extensive supergene enrichment, the presence of steep slopes which could necessitate costly underground mining, and low average copper grades (<0.5 percent) based on assay data.

Va2 (Independence favorable area). Favorable area Va2 is centered on the Independence stock. Previous studies of the Independence district by Moyle and others (1989) recognized the potential for porphyry copper deposits, although no resource has been delineated. Proximal, precious-metal vein deposits (pyritic gold-quartz ores) in the stock have been mined in the past (for example, the Independence and Daisy mines). Gravity and magnetic highs are associated with the Independence intrusive center. Chalcopyrite occurs in veinlets and disseminations in propylitic zones. The texture of the granodiorite porphyry (phenocrysts set in a quench-textured, fine-grained groundmass) near the Independence mine is typical of intrusive rocks associated with porphyry

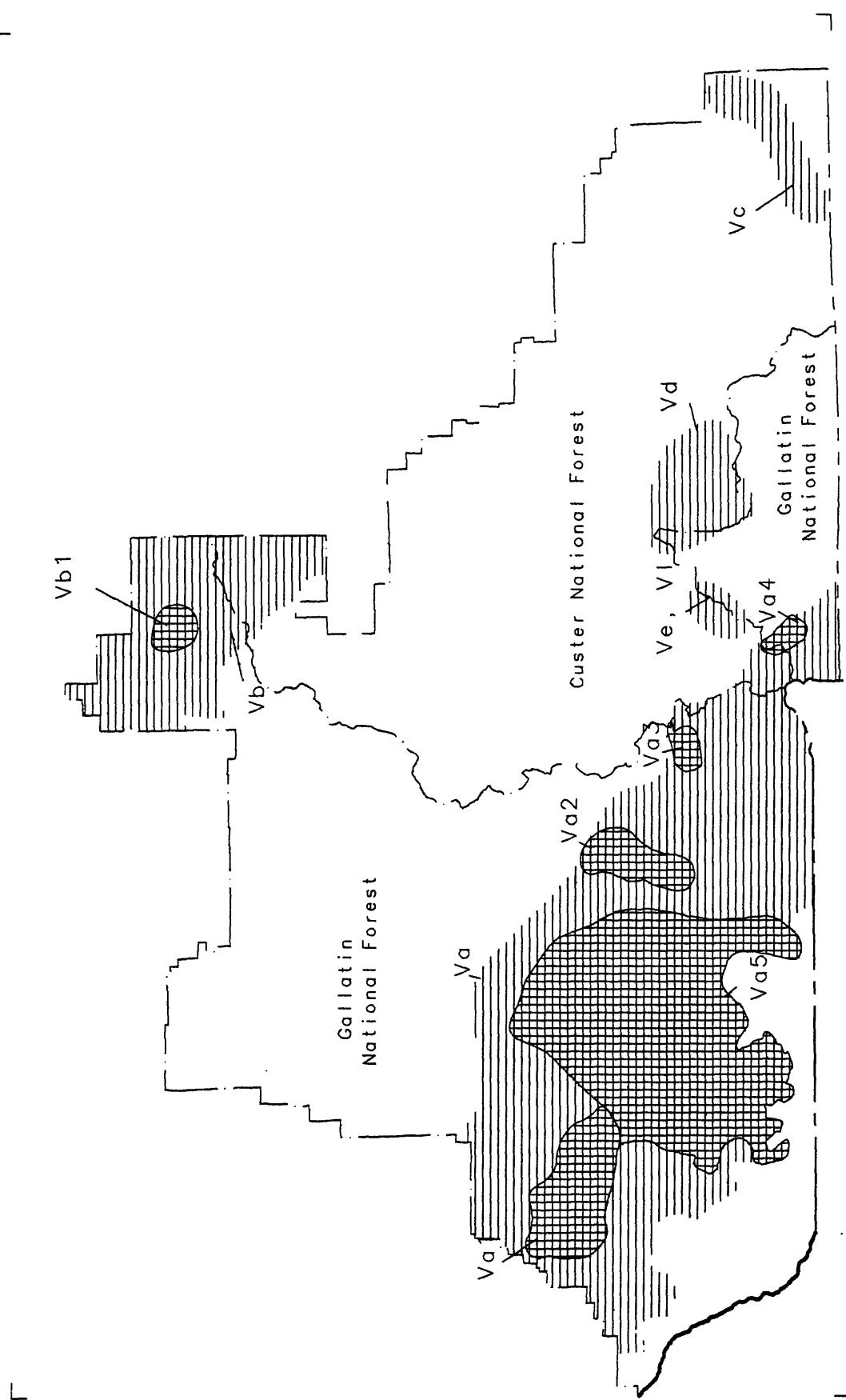


Figure G8.—Location map for mineral resource tracts V and VI delineated around Tertiary, Cretaceous, and Tertiary or Cretaceous intrusive centers.

Table G8.--Criteria for tract V

Description: Tertiary, Cretaceous, and Tertiary or Cretaceous intrusive and volcanic rocks.
Stocks, plugs, laccoliths, sills, and dikes of intermediate to felsic composition.

Permitted deposit types

Expected geochemical signatures

Porphyry copper (-gold, -molybdenum)

Cu, Mo, Au, Ag, W, B, Sr centers
Pb, Zn, Au, As, Sb, Se, Te, Mn, Co, Ba, Rb, outer.
Locally Bi and Sn may form distal anomalies.
High S throughout; weak U anomalies possible.

Epithermal veins (in volcanic rocks)

Au, As, Sb, Hg, Ag, Pb, Zn, Cu, Te, (W, Bi possible)

Tract	Va (South Snowy block subtract)	Vb (Sliderock Mountain subtract)	Vc (Line Creek Plateau subtract)	Vd (Granite Peak subtract)	Ve (Goose Lake subtract)
Area (km ²)	1,450	284	69	98	24
Geologic criteria ²	Tertiary intrusive centers (Ti), associated volcanic (Tv), and volcaniclastic rocks of the Absaroka volcanic province in the SW part of the ABSA. Tract boundaries are partly based on mapped extent of volcanic rocks. Favorable areas (Va1 through Va5) are delineated around known and inferred intrusive centers that appear to represent variably eroded root zones of stratovolcanoes.	Late Cretaceous intrusive centers and associated volcanic and volcaniclastic rocks of the Sliderock area. Includes lahars (K1), andesite flows and flow breccias(Kad), and the diorite intrusive complex of Sliderock Mountain. Intrusive centers (TKi) that lack alteration (Lodgepole laccolith, Enos Mountain and Susie Peak intrusions) are excluded.	Small, Cretaceous or Tertiary intermediate to felsic stocks and dikes (TKi) intrusive into Archean gneiss and into Paleozoic sedimentary rocks along the range front in the southeastern corner of the study area.	Tract is delineated on the basis of the areal extent of mapped Tertiary or Cretaceous latite porphyry dikes (TKi) intrusive into Archean granitic gneisses of tract IIb in an area near Granite Peak.	Tract is delineated on the basis of the mapped extent of a locally altered and mineralized Late Cretaceous syenite stock (Kg) at Goose Lake. Tract Ve is coextensive with tract VI.

Table G8.--Criteria for tract V (continued)

Tract	Va (South Snowy block subtract)	Vb (Sliderock Mountain subtract)	Vc (Line Creek Plateau subtract)	Vd (Granite Peak subtract)	Ve (Goose Lake subtract)
Geophysical criteria³	Geophysical anomalies are used to define the subsurface extent of known, and possible buried, intrusive centers to a depth of 1 km.	Regional: No gravity signature. A magnetic anomaly (high) is more extensive than the area of exposed intrusive. Local: Exploration by private industry in the 1960's identified a 2,600 ft x 4,000 ft E-NE trending IP anomaly related to pyritized dikes at Gold Hill.	Moderately high magnetic values may indicate buried intrusions.	Moderately high gravity and magnetic values on northern flank of higher anomalies.	Magnetic high (1Sd) extends beyond mapped outcrop indicating that the intrusive body is more extensive in the shallow subsurface.
Geochemical criteria⁴	Ag, As, Au, Bi, Cu, Cr, Mo, Pb, W, Zn, (Ni), (Sb), (U) Factor Spec-4 {Au, Ag, Mo, Pb, Cu} Factor ICP-2 {Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As}	As, Au, Bi, Pb, Sb, W, (Ag), (Cu), (Mo) Factor ICP-2 (see Va) For Vb1: Ag, As, Au, Pb, Sb, (Bi), (Cu), (Mo) Factor ICP-2	(Au)	Mo, Pb, W Factor Spec-4 (see Va) Factor Spec-1 {Mg, Ni, Cr, Co, Fe, Sc, V, Ca, Mn, Ti, Cu}	Cu, Mo, (Bi) Factor Spec-4 (see Va)
Mines, prospects, and occurrences	Porphyry copper: No deposits of this type have been mined. Exploration for porphyry copper-molybdenum deposits in the 1960's included drilling; no announced reserves. See favorable subtracts for description of five intrusive centers that show various aspects of this deposit type. Epithermal veins: No deposits. Scattered precious metal occurrences in volcanic rocks.	Porphyry copper: No deposits of this type have been mined. Sericitized and pyritized porphyry exposed in Gold Hill mine area. Recent exploration for gold indicates potential for a subsurface deposit of this type.	None	None	Vein and disseminated chalcocite occurrences. Explored for low-grade copper porphyry potential in 1960's; drilling by Bear Creek mining company showed mostly low grades; highest grade drill core interval assayed 0.3% Cu over 126 ft core length. High-grade copper occurrences are related to magmatic segregation deposit (tract VI) rather than porphyry copper deposit type.
Favorable areas	See table G9	Vb1: Outlines Gold Hill stock, includes all known mineral occurrences	None	None	None

Table G8.--Criteria for tract V (continued)

Tract	Va (South Snowy block subtract)	Vb (Sliderock Mountain subtract)	Vc (Line Creek Plateau subtract)	Vd (Granite Peak subtract)	Ve (Goose Lake subtract)
Comments	Magmatic, hydrothermal breccia pipes are common in the upper parts of porphyry copper deposits and may indicate buried intrusions. In tract Va, breccia pipes have been mined and are discrete exploration targets for gold and other metals. The intrusive centers may be too old and (or) too deeply eroded to preserve epithermal veins.	Exploration for porphyry copper-molybdenum deposits in the 1960's and 1970's identified NE-trending, gold-bearing quartz veins in the intrusive complex and an associated copper-lead-zinc geochemical anomaly. Active exploration 1990.	Tract is delineated on the basis of exposed and possible buried intrusive centers. Lack of volcanics suggests that this area may be too deeply eroded to preserve shallow deposit types. Local hydrothermal alteration.	Local concentrations of dikes indicates post-Archean magmatism and possible buried intrusions. Absence of volcanics suggests relatively deep levels of erosion.	In addition to the magmatic segregation deposit in syenite at the Copper King mine, the intrusive complex at Goose Lake is permissive for porphyry copper deposits.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively). ⁴ Moderately to highly anomalous elements in stream-sediment samples. Elements are listed in alphabetical order within each group. See Chapter D for explanation of factors.

Table G9.--Criteria for favorable areas for porphyry copper and epithermal vein deposits within the South Snowy block subtract Va

Description: Tertiary intrusive and volcanic rocks of the Absaroka-Gallatin volcanic province

Permitted deposit types

Porphyry copper (-gold, -molybdenum)

Cu, Mo, Au, Ag, W, B, Sr centers
 Pb, Zn, Au, As, Sb, Se, Te, Mn, Co, Ba, Rb, outer.
 Locally Bi and Sn may form distal anomalies.
 High S throughout; weak U anomalies possible.

Expected geochemical signatures¹

Epithermal veins (in volcanic rocks)

Au, As, Sb, Hg, Ag, Pb, Zn, Cu, (W, Bi possible)

Tract	Va1 (Emigrant favorable area)	Va2 (Independence favorable area)	Va3 (Horseshoe Mountain favorable area)	Va4 (New World favorable area)	Va5 (Ash Mountain-Mill Creek favorable area)
Area (km ²)	94	42	11	10	482
Geologic criteria ²	Stocks of dacite (Tdp) and grandiorite porphyry (Tgr). Andesitic and dacitic volcanic rocks (Tv) intruded by composite dacite porphyry-grandiorite porphyry stock and associated dikes (Ti).	Independence stock (Tmz).	Altered dacite porphyry (Ti).	Favorable area includes Fisher Mountain and Homestake intrusive complexes, rhyodacite porphyry stock of Henderson Mountain, and Homestake and Alice E. breccias. Excludes diorite stock of Scotch Bonnet Mountain and rhyodacite porphyry of Lulu Pass.	Favorable area includes the Ash Mountain eruptive center (Ti), a diorite porphyry plug at the head of Mill Creek (Tdi), and intervening Tertiary volcanic cover (Tv).
Geophysical criteria	Gravity low and magnetic high associated with tract.	Gravity and magnetic highs associated with tract.	Magnetic high	Occurs on gravity and magnetic gradients. Nose of a magnetic high suggests eastward extension of intrusive rocks in the subsurface. No gravity data within tract boundaries.	Area is mainly delineated on the basis of a magnetic signature permissive for the occurrence of intrusions at shallow depth (local high anomalies bounded by steep gradients).

Table G9--Criteria for favorable areas for porphyry copper and epithermal vein deposits within the South Snowy block subtract Va (continued)

Tract	Va1 (Emigrant favorable area)	Va2 (Independence favorable area)	Va3 (Horseshoe Mountain favorable area)	Va4 (New World favorable area)	Va5 (Ash Mountain-Mill Creek favorable area)
Geochemical criteria ³	Ag, Au, Bi, Cu, Mo, Pb, U, Zn Factor Spec-4 {Au, Ag, Mo, Pb, Cu}	(Au), (Cr), (Ni), (Zn) Factor Spec-4 (see Va1)	Ag, Au, Bi, Cu, Mo Factor Spec-4 (see Va1)	Au, Cu, Mo, (Ag) Factor Spec-4 (see Va1)	Au, W, (Ag), (As) throughout tract; Au is the only anomalous element at Ash Mountain; Mo noted at Ash Mountain by other studies (see text) Factor Spec-4 (see Va1)
Mines, prospects, and occurrences	Porphyry copper: Emigrant Peak area was drilled as a porphyry copper-molybdenum target. Active (1992) exploration for vein, stockwork, and disseminated gold deposits in the areas of the St. Julian, Allison, and Iron King mine workings. Breccia pipes were mined in the past, recently explored for base metals and molybdenum, and currently are being evaluated for gold. Epithermal veins: No deposits of this type have been identified. Numerous precious-metal veins and disseminations occur in intrusive and volcanic rocks. Barite veins are present at the High Point prospect.	Porphyry copper: No production or demonstrated resources for this deposit type. Minor precious metal production from vein deposits such as the Hidden Treasure mine. Recent exploration for porphyry type deposit. Epithermal veins: Some precious metal veins reported in andesite; no definitive occurrences of this deposit type.	No occurrences can be unequivocally related to porphyry copper or epithermal vein deposit types.	Porphyry copper: Porphyry style alteration and weak mineralization recognized at depth below discovered copper-gold breccia, skarn, and replacement deposits. Fisher Mountain Complex was drilled as a porphyry copper-molybdenum target; visible molybdenite. Henderson Mountain stock has surface indications of porphyry copper mineralization.	Largely devoid of occurrences of any type.

Table G9--Criteria for favorable areas for porphyry copper and epithermal vein deposits within the South Snowy block subtract Va (continued)

Tract	Va1 (Emigrant favorable area)	Va2 (Independence favorable area)	Va3 (Horseshoe Mountain favorable area)	Va4 (New World favorable area)	Va5 (Ash Mountain-Mill Creek favorable area)
Comments	Numerous gold and (or) silver occurrences as veins and disseminations in igneous rock; distal, structurally controlled polymetallic vein occurrences. Gold mineralization associated with Emigrant stock is the likely source of the placer gold in Emigrant Creek. District-wide zoning from gold-silver-copper to distal lead-zinc-silver: Widespread alteration zones, multiple mineralized breccia pipes, and surface color anomaly indicate potential for porphyry copper (-molybdenum-gold) deposits. Potential for volcanic-hosted epithermal veins.	Gold-bearing sulfide and quartz veins in fine-grained, porphyritic rocks of felsic composition that intrude coarser grained intermediate composition rocks of the Independence stock. Alteration style (magnetite veins, propylitic alteration) may indicate porphyry copper (-gold) potential. Locally abundant disseminated and vein pyrite and chalcopyrite in intrusive rocks. Distal polymetallic veins. USBM site-specific study (Moyle and others, 1989) noted resource potential for porphyry copper-gold deposits.	History of prospecting for gold, location midway between Cooke City and Independence intrusive centers, presence of altered intrusives and quartz stringers along with precious- and base-metal geochemical anomalies suggest potential for undiscovered, possibly buried porphyry copper deposit.	District-wide zoning from copper-gold-silver skarn and replacement near intrusives to distal lead-zinc-silver polymetallic vein deposits. Absence of volcanics (too deeply eroded) precludes epithermal vein potential.	Ash Mountain may represent an eruptive center, possibly a caldera, that was the source of the Slough Creek Tuff. If so, favorable area Va5 may be more prospective for epithermal deposits than other parts of subtract Va.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group. See Chapter D for explanation of factors.

copper deposits. Magnetite veinlets are locally abundant.

The Independence intrusive center lies northwest of the New World district, along the Cooke City structural zone which appears to control the alignment of vents within this part of the Absaroka volcanic field. Placer gold is present in most of the surrounding streams. The district appears to be zoned from gold-rich deposits on Independence Peak to lead-zinc-silver deposits to the north and south. Previous studies suggested that more copper-rich ores may lie at depth. Occurrences in the northwestern part of the district appear to be related to sills. These sills, such as the sill associated with skarn mineralization on War Eagle Mountain, may be older than the late, porphyry-related intrusions at Independence.

Va3 (Horseshoe Mountain favorable area). Favorable area Va3 outlines the altered dacite at Horseshoe Mountain, which is situated midway between the Cooke City (Va4) and Independence (Va2) intrusive centers along the Cooke City zone. A number of prospects for base- and precious-metals as well as gold placers were worked in the early 1900's. The tract is coincident with a small magnetic high. Geochemical anomalies for molybdenum, tungsten, precious- and base-metals are detected in sediments from streams draining the area.

Va4 (New World favorable area). Favorable area Va4 includes the Fisher Mountain complex, the Homestake stock, the rhyodacite porphyry of Henderson Mountain, and the Homestake and Alice E breccias in the New World (Cooke City) mining district. Past and present mining and exploration in the district have exploited copper-gold skarn and lead-zinc vein and replacement deposits. The Fisher Mountain complex contains visible molybdenite and was drilled as a porphyry copper-molybdenum target. Results of recent exploration drilling indicate weak, porphyry copper mineralization and classic, porphyry copper deposit alteration zones at depth. Both the Alice E and the Homestake breccia pipes are mineralized.

Va5 (Ash Mountain-Mill Creek favorable area). Favorable area Va5 is delineated largely on the basis of a magnetic high in an area covered by Absaroka volcanics between Ash Mountain and Mill Creek. The area includes the Ash Mountain eruptive center and a small porphyry stock at the head of Mill Creek. No mines, prospects, or occurrences are associated with the tract. Regional stream sediment geochemical reconnaissance studies by the Anaconda Company

identified a molybdenum anomaly associated with Ash Mountain (Anaconda Mining Company, 1986).

Our studies indicate geochemical anomalies for gold associated with Ash Mountain and scattered anomalies for gold, arsenic, and tungsten throughout other parts of the large (482 km²) area of Va5.

Vb (Sliderock Mountain subtract). Subtract Vb outlines the diorite stock of the Sliderock Mountain area as well as the lahars, andesite flows, and flow breccias that surround it. The tract includes areas centered over magnetic highs associated with the stock and the anomaly (plate 3, anomaly 12) of similar magnitude to the southeast. The Lodgepole and Enos Mountain intrusions near the Sliderock area are excluded from subtract Vb because no alteration, mineral occurrences, or geochemical anomalies are observed with either of these intrusives.

Vb1 (Gold Hill favorable area). Sericitized and pyritized porphyry is exposed locally at Gold Hill in a number of old workings. Exploration in the 1960's and 1970's by Kennecott Mining Company identified a potential shallow, buried copper-molybdenum porphyry deposit centered near Gold Hill (Jones and Swift, 1974) based on a number of geologic and geochemical characteristics such as the presence of a composite (diorite to quartz latite) zoned intrusion, quartz-eye porphyry dikes and intrusion breccias, zoned hydrothermal alteration, quartz stockworks, and anomalous copper (several hundred to 1,000 ppm) and molybdenum (10 to 50 ppm range) in whole rock samples. Subsequent shallow drilling and additional exploration by Cominco and by ECM, Inc. confirmed the earlier exploration work and led to the conclusion that the concentrically zoned hydrothermal alteration and geochemical anomaly patterns indicate the presence of a subsurface porphyry copper-gold deposit. Delineation of the potential deposit and its economic viability are contingent on further exploration by deep drilling (Cavanaugh, 1990).

Six rock samples from the Gold Hill mine area were collected and analyzed for this study (Hammarstrom, unpublished data). Analytical results are as follows: gold was detected in all six samples (0.002 to 0.26 ppm); silver ranged from 0.07 to 5.3 ppm; copper, 4 to 390 ppm; lead, 8 to 430 ppm; zinc, 9 to 47 ppm (6,600 ppm for one sample); and molybdenum, 0.4 to 4.6 ppm. Mapping conducted for this study shows that surface alteration is localized in the Gold Hill area.

Vc (Line Creek Plateau subtract). Cretaceous or Tertiary stocks and dikes (TKi on plate 1) intrude Archean gneisses of subtract IIb and Paleozoic

sedimentary rocks along the eastern margin of the Beartooth uplift near Red Lodge. Aeromagnetic highs (plate 3) throughout this area are not readily related to sources in the Archean basement and may represent intrusions that lie at shallow depths below the Archean gneiss cover. The intrusive rocks are unaltered porphyries of intermediate composition. No mineral occurrences are associated with the stock or dikes.

Vd (Granite Peak subtract). Subtract Vd outlines the extent of mapped Cretaceous or Tertiary latite porphyry dikes (TKi on plate 1) near Granite Peak. Dikes are unaltered and intrude Archean gneisses of tract II. Dikes may represent offshoots of a shallow buried intrusion. The geologic setting of the intrusive rocks in this part of tract V differs from subtracts Va and Vb because no volcanic or Paleozoic sedimentary rocks are present.

Ve (Goose Lake subtract). Subtract Ve outlines mapped exposures of the Late Cretaceous syenite stock of Goose Lake (Kgl on plate 1). The stock partly overlies a magnetic high (plate 3, anomaly 14). The tract encloses the Copper King mine, as well as a number of copper and (or) gold and silver prospects and occurrences. Polymetallic vein occurrences (plate 19) cluster in the southwestern part of the subtract. There is a continuous zone of mineral occurrences from Goose Lake to the New World district (favorable area Va4) to the southwest. Stream sediments from upper Goose Creek are highly anomalous in molybdenum and slightly anomalous in copper. High scores are obtained for spec factor -4 (gold, silver, molybdenum, lead, copper). Molybdenum and lead anomalies extend northeastward from the syenite stock. Lead-bearing polymetallic vein occurrences (SW) and lead anomalies to the NE may indicate metal zoning associated with the syenite stock.

Undiscovered Deposits

The boundary between the Gallatin and Custer National Forests subdivides a number of mineral resource tracts. In order to provide quantitative information on both Forests separately and yet preserve the geologic integrity of the assessment tracts, estimates of numbers of undiscovered porphyry copper deposits were made by considering parts of tract V within each Forest (table G10). Most of tract Va lies within the Gallatin National Forest. The southeastern corner of subtract Va includes part of the Custer National Forest as well as the Gallatin National Forest. For the part of subtract Va that lies

entirely within the Gallatin National Forest west of latitude 110°, an area of 1,388 km², we estimate a 90 percent chance of 1 or more deposits and a 10 percent chance of 2 or more deposits. For the part of subtract Va that lies to the east of latitude 110°, an area of 62 km², we estimate a 90 percent chance of one or more deposits and a 10 percent chance of 2 or more deposits. Both parts of subtract Va include favorable areas. Separate estimates for very small tracts based on U.S. Forest Service boundaries are unrealistic because (1) deposits may be large compared to the size of a small tract and (2) the subsurface extent of favorable areas at the surface is unknown. Therefore, we did not attempt estimates for individual favorable areas within each Forest. For land-use planning, mean ore and metal tonnage estimates may be allocated to each Forest by considering the relative areal proportion of each Forest within southeastern parts of subtract Va. Approximately 70 percent of southeastern part of tract Va lies within the Gallatin National Forest and 30 percent lies within the Custer National Forest.

Tract Vb also overlaps the boundary between the two Forests. However, favorable area Vb1 lies entirely within the Gallatin National Forest. We estimate at most a 5 percent chance for one or more deposits within tract Vb.

Subtracts Vc, Vd, and Ve are permissive for the occurrence of undiscovered porphyry copper deposits based on the geology; however, the lack of any known favorable characteristics led us to conclude that there was less than a 1 percent chance for undiscovered porphyry copper deposits and no estimate was made.

These estimates indicate a potential for about 2 undiscovered porphyry copper-gold-molybdenum deposits within the ABSA. Median ore tonnages of 180 million metric tons for tract V (Gallatin) and 190 million metric tons for tract V (Gallatin and Custer) are more than twice the total of 147 million (minimum) metric tons of identified ore reported for the three Wyoming Absaroka porphyry copper deposits. Differences in simulator results between the two parts of subtract Va, which had identical estimated numbers of undiscovered deposits as simulator input, are not statistically significant. Variations of about ± 10 percent of the mean metal and ore tonnages are expected; that is, these are very approximate estimates and one could interchange the results reported for Va (Gallatin National Forest) in table G10 with the results reported for Va (Custer and Gallatin National Forests). Expected median values for byproduct gold and silver are 0. This reflects the fact that gold and silver are reported in

Table G10.--Estimate of mineral resources contained in undiscovered porphyry copper deposits within the Absaroka-Beartooth study area (tract V)

[G, Gallatin National Forest; C-G, Custer and Gallatin National Forests]

Simulator input

Estimate of the minimum number of deposits expected at each of the following probabilities:

Subtract	90%	50%	10%	5%	1%
Va (G)	1	1	2	2	2
Va (C-G)	1	1	2	2	2
Vb (G)	0	0	0	1	1

Simulator output

Estimated numbers of undiscovered deposits

Subtract	Mean expected number of deposits	Probability of 0 deposits
Va (G)	1.23	7%
Va (C-G)	1.23	7%
Vb (G)	0.08	93%

Estimated amounts of commodities contained in undiscovered deposits (in metric tons)¹

Commodity/ Subtract	90th percentile	50th percentile Median	10th percentile	Mean
Copper				
Va (G)	30,000	840,000	7,400,000	3,000,000
Va (C-G)	28,000	850,000	8,000,000	3,200,000
Vb (G)	0	0	0	180,000
Molybdenum				
Va (G)	0	6,500	140,000	60,000
Va (C-G)	0	6,600	140,000	64,000
Vb (G)	0	0	0	3,800
Gold				
Va (G)	0	0	67	27
Va (C-G)	0	0	64	27
Vb (G)	0	0	0	2
Silver				
Va (G)	0	0	2,200	770
Va (C-G)	0	18	2,300	820
Vb (G)	0	0	0	54
Ore				
Va (G)	8,100,000	180,000,000	1,500,000,000	540,000,000
Va (C-G)	7,300,000	190,000,000	1,500,000,000	560,000,000
Vb (G)	0	0	0	32,000,000

¹ Output from Mark3 program reported to 2 significant figures.

less than half of the 107 deposits in the model used in the computer simulation and does not necessarily imply that undiscovered porphyry copper deposits in the ABSA are expected to lack byproduct precious metals. In fact, it is likely that any further exploration and development in favorable areas will focus on delineation and exploitation of gold-rich parts of porphyry copper systems.

ALKALINE GABBRO-SYENITE ASSOCIATION

Mineral Deposit Model

The unusual occurrence of copper-gold-platinum group element (PGE) mineralization in a Cretaceous syenite stock at the Copper King mine at Goose Lake in the New Word district does not fit existing mineral deposit models. Lovering (1929) described the deposit as a magmatic segregation. Mutschler and others (1985) included the Copper King deposit as a porphyry copper deposit in alkaline rocks. We consider the Copper King deposit as an example of a class of magmatic segregation deposits associated with alkaline gabbros and syenites. A new model was constructed by M.L. Zientek (see appendix) to describe the Copper King deposit and several other mineral deposits that appear to be similar. Intrusive complexes that host early, magmatic segregation deposits may also have associated mineral deposits such as porphyry deposits and (or) polymetallic vein deposits typical of later hydrothermal stages in epizonal volcanoplutonic complexes.

Descriptive model.--These deposits are essentially small segregations of copper-rich magmatic sulfide minerals in syenitic rocks that occur as parts of epizonal, alkaline intrusive complexes. Chalcopyrite and bornite are the typical sulfide minerals; platinum and palladium (10 to 100 ppm concentration range), silver, and gold are commonly present. A complete model description is provided in the appendix to this chapter.

Grade and tonnage models.--Production data from alkaline gabbro-syenite hosted magmatic segregation deposits is limited; existing data (appendix) suggest that production is generally on the order of a few hundred tons of ore or less. Copper and silver are the principal commodities produced.

Examples in the Study Area

Copper-rich sulfide mineralization in magmatic segregations in coarse-grained syenite (syenite of

Goose Lake; Elliott, 1979) in the Goose Lake district (contiguous with the northern part of the New World district) was initially explored in 1904-1907 (Reed, 1950), described by Lovering in 1929, and was explored for low-grade copper potential by Auto Copper and Zinc Company in 1957 and by Bear Creek Mining Company in 1959 and 1960 (Miller and Thompson, 1965). Exploration and limited development concentrated on the area of the Copper King mine (plate 13, Chapter E appendix), where a small amount of ore was mined and stockpiled but never shipped. Reed (1950) described chalcopyrite associated with feldspar gangue in syenite at the Copper Index property and chalcopyrite, galena, and limonite in a narrow sheeted zone in syenite and granodiorite at the adjacent Hecela-Flora property. Preliminary geophysical and surface geochemical sampling by mining companies in the 1950's identified a restricted zone of sulfide mineralization in syenite and in a brecciated contact. Subsequent drilling (7 vertical holes) by Bear Creek Mining Company intercepted low-grade copper mineralization with the exception of a 126 ft drill interval in the brecciated contact zone which assayed 0.39 percent copper.

High-grade ore exposed in a trench near the shaft house contains approximately 20 percent copper, 98 ppm silver, and up to 3 ppm platinum. Breccias and segregation veins have also been described (Simons and others, 1979). Analyses of samples of mineralized syenite from this area were reported by Simons and others (1979) and Mutschler and others (1985). These analyses and two new analyses are listed in the appendix.

Permissive Tracts

Tract VI (Goose Lake tract) is coextensive with tract Ve (fig. G8). Tract VI is delineated on the basis of the mapped extent of a locally altered and mineralized Late Cretaceous syenite stock (Kgl on plate 1) at Goose Lake that includes the Copper King mine and associated prospects and mineral occurrences of magmatic sulfide segregations in syenite (table G11).

EPITHERMAL VEINS

Mineral Deposit Model

Descriptive model.--Epithermal veins (fig. G5) represent volcanic-hosted, low temperature (<300 °C) precious- and base-metal deposits formed in

Table G11--Criteria for tract VI

Description: Cretaceous alkalic intrusive rocks.

<u>Permitted deposit types</u>	<u>Expected geochemical signatures</u> ¹
Alkaline gabbro-syenite hosted copper-gold-PGE	Cu, Au, Ag, PGE

Tract	VI (Goose Lake tract)
Area (km ²)	24
Geologic criteria ²	Tract is mainly delineated on the basis of the mapped extent of a locally altered and mineralized Late Cretaceous syenite stock (Kg) at Goose Lake. Tract VI is coextensive with subtract Ve (see comments).
Geophysical criteria ³	Magnetic high (15d) extends beyond mapped outcrop indicating that the intrusive body is more extensive in the shallow subsurface.
Geochemical criteria ⁴	Cu, Mo, (Bi) Factor Spec-4 {Au, Ag, Mo, Pb, Cu} PGE in rock samples
Mines, prospects, and occurrences	Copper King mine and associated prospects and mineral occurrences. Explored by Kerr-McGee Corp. and drilled by Bear Creek Mining Co. (1960). Locally high copper grades (0.5 percent copper), trace to 0.20 ounces gold, as much as 0.5 ounces silver in drill core. Recent exploration interest for PGE. Magmatic segregation deposit localized in syenite at Copper King mine.
Comments	Spatial distribution of geochemical anomalies suggests that mineralization may extend upstream from the Copper King mine area in Goose Creek basin, and possibly to the northeast across the drainage divide. Both geophysical and geochemical data are used to extend the permissive tract beyond the mapped surface extent of the syenite. In addition to the early, magmatic segregation deposit (copper, gold, silver, PGE), evidence of alteration in the syenite indicative of later, hydrothermal activity is permissive for the occurrence of porphyry copper and related mineral deposit types (tract Ve).

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively).

⁴ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group. Refer to Chapter D for explanation of factor-spec geochemical associations.

geothermal systems. Epithermal deposits are typically associated with Tertiary calderas or silicic domes and form during waning stages of volcanic activity. The magmatic heat source underlying epithermal vein systems is not necessarily associated with porphyry copper mineralization at depth. Pre-Tertiary epithermal deposits are uncommon; most have been eroded or obscured by metamorphism. Two major types of epithermal veins are distinguished largely on the basis of mineral assemblages: (1) adularia-sericite type veins, such as those at Creede, Colorado, (2) acid-sulfate type veins, such as at Goldfield, Nevada. Characteristics of the two subtypes are summarized in table G12, based on a compilation by Heald and others (1987). Gold- and silver-rich subsets of each type are recognized. Epithermal vein districts typically range from 2 to over 100 km² in lateral extent and from several hundred to 1,000 meters in vertical extent (Heald and others, 1987).

Gold-silver-tellurium veins associated with alkalic rocks represent an additional type of epithermal vein deposit. Bliss and others (1992) elaborated on the descriptive model of Cox and Bagby (1986), defined as gold telluride minerals and fluorite in veins and breccia bodies related to hypabyssal or extrusive alkalic rocks, by including breccia, replacement, and disseminated mineralization as well as veins. Recognition criteria for this deposit type are equivocal because some deposits included in the model have gold as the primary commodity or lack telluride minerals and the genetic relation of the deposits to igneous rocks is not always apparent.

Grade and tonnage models.--Cox and Singer (1986) include descriptive and grade-tonnage models for a variety of epithermal vein deposits, including Creede-, Comstock-, Sado-, and quartz-alunite-gold epithermal vein types. All of these may be viewed in light of the twofold distinction drawn above.

Table G12.--Characteristics of epithermal vein deposits in volcanic rocks

[Based on Heald and others, 1987]

Type	Acid-sulfate	Adularia-sericite
Host rock	Rhyodacite	Silicic to intermediate
Mineralogy	Enargite + pyrite ± Covellite Hypogene alunite Selenides absent Chlorite rare Mn minerals rare ± Bismuthinite Higher in sulfur minerals	Enargite absent Adularia No hypogene alunite Selenides common Chlorite common Mn minerals common Bismuthinite absent Lower in sulfur minerals
Alteration	Advanced argillic	Sericite-dominant
Size	Small productive area	Variable; some large
Commodities	Copper important	Variable base metals
Age	Host and ore similar	Host >1 m.y. older than ore
Examples	Goldfield, NV	Creede, CO

Inspection of the various grade-tonnage models shows that epithermal vein systems range in size from about 60,000 to 23 million metric tons. Gold grades are on the order of 0.2 to 27 g/t and silver grades range from about 2 to 1,300 g/t. Copper grades rarely exceed 2 percent, and lead and zinc grades range from 0 to 10 percent.

Bliss and others (1992) modeled 24 gold-silver-tellurium vein deposits associated with alkalic rocks and showed that tonnages for aggregated mining properties within 1 mile of one another range from about 25,000 to 100 million metric tons of ore. Ore grades are about 1 to 37 grams gold per metric ton and 0.4 to 100 grams silver per metric ton. Target areas for gold-silver-tellurium vein deposits based on the spatial distribution of deposits included in the model are on the order of 0.3 to 23 km².

Permissive Tracts

No epithermal vein deposits are identified within the ABSA. Volcanic rocks within volcanoplutonic tracts delineated as permissive geologic environments for porphyry copper deposits in tract V (fig. G8, table G8) are permissive for the occurrence of epithermal veins. The Absaroka volcanics are older and more mafic than most Tertiary volcanics that host epithermal veins, and volcanic centers may be too deeply eroded to preserve such deposits. Precious metal vein occurrences associated with volcanic centers such as Emigrant (favorable area Va1) or Ash Mountain (favorable area Va5) may represent this style of mineralization; however, neither the characteristic mineral assemblages nor appropriate geochemical signatures (such as gold + arsenic + antimony + mercury) have been recognized. Systematic mineralogic and fluid inclusion studies and additional geochemical sampling are needed to resolve the environment of deposition for many of the precious-metal occurrences within the ABSA. Some of the precious- and base-metal geochemical stream sediment anomalies associated with subtract Ia may reflect a signature stemming from epithermal vein type mineralization in volcanic rocks that overlie the Archean rocks in the northern part of subtract Ia.

Tellurium was not analyzed as part of the stream sediment geochemical surveys. Tellurium is reported in native gold samples from some samples in the New World, Horseshoe Mountain, and Independence districts (Wedow and others, 1975), but the potential for tellurium associated with alkalic rocks in the Goose Lake area has not been evaluated. The

Cretaceous alkalic complex at Goose Lake may be too deeply eroded to preserve shallow epithermal vein deposits if they ever formed. However, many of the precious metal occurrences associated with volcanoplutonic centers in the ABSA may represent epithermal or precious metal-rich polymetallic vein type mineralization, or some intermediate deposit type that has yet to be described.

SKARNS

Mineral Deposit Model

Skarns may form during the contact metasomatism that accompanies emplacement of plutonic and hypabyssal intrusives into carbonate-bearing sedimentary rocks (fig. G5). Skarns may be barren, or may carry significant, exploitable quantities of metals such as copper, iron, tungsten, lead, zinc, tin, and molybdenum. In recent years, skarns have become important exploration targets for gold. Copper, iron, lead-zinc, and gold-bearing skarns may occur in the same geologic setting, although lead-zinc skarns are usually more distal to intrusive centers than other skarn types; tungsten skarns typically form at deeper levels and in association with more evolved granitoids than most copper, iron, and gold-bearing skarns (table G13). Unless skarn deposits of a particular type are known to be present, it is difficult to predict the type of metallization that may occur in a geologically permissive terrane. Iron skarns and copper-gold skarns may be coeval and genetically related (Webster and Ray, 1990), or may form during separate pulses of magmatism or in different carbonate host rocks within a single mining district.

Skarn evolution through space and time can be described as a series of stages - (1) initial isochemical metamorphism, (2) multiple stages of metasomatism, and (3) retrograde alteration (Meinert, 1983). These stages may develop or be preserved to different degrees in different deposits, and may overprint one another resulting in complex zoning within a deposit. Garnet and pyroxene are the characteristic minerals that form during early, prograde calcic skarn development. Subsequently, hydrous minerals such as epidote, amphibole, and chlorite replace the anhydrous minerals. Ore minerals (sulfides) are generally deposited late in the paragenetic sequence.

Where carbonate rocks are intruded by volcanoplutonic complexes permissive for porphyry copper deposits, it is not uncommon to find skarn deposits that contain exploitable concentrations of

Table G13.--Characteristics of major classes of skarn deposits

[Based on Einaudi and others, 1981; Meinert, 1983]

Type	Copper	Zinc-lead	Tungsten	Iron
Environment	Shallow, oxidized, commonly associated with porphyritic intrusions.	Transitional, associated with stocks of intermediate size and composition; or distal to intrusions along structures.	Deep, reduced settings associated with coarse-grained intrusives.	Calcareous skarns are associated with mafic rocks in island arc settings; Cordilleran magnesian iron skarns occur with shallow, intermediate to felsic stocks that intrude dolomitic rocks in continental margin settings.
Typical size (million tons)	1 to 100	0.2 to 3	0.1 to 2	5 to 200
Typical grade	1 to 2% Cu	9% Zn, 6% Pb, 170 g/t Ag	0.7% WO ₃	40% Fe
Ore minerals	Chalcopyrite, pyrite, hematite, magnetite	Sphalerite, galena, pyrrhotite, pyrite	Scheelite, molybdenite, chalcopyrite	Magnetite
Gangue minerals	Andradite, diopside, wollastonite, actinolite minerals	Mn-rich hedenbergite and garnet; other Mn minerals	Hedenbergitic pyroxene, grandite, idocrase, wollastonite	Ferrosilite, grandite, epidote, amphibole

copper, gold, and silver. Local magnetite-rich zones often develop as well. Cox and Theodore (1986) compiled a mineral deposit model for copper skarn deposits, many of which produce byproduct gold and silver. Cox (1986c) described iron skarn (magnetite) deposits mined for their iron content alone. Theodore and others (1991) constructed descriptive and grade-tonnage models for gold-bearing skarns; most of the deposits they considered are copper-rich skarns and some of the deposits were included in the earlier copper and iron skarn models. Based on the characteristics of the known deposits in the ABSA, described below, we believe that the gold-bearing skarn model is the most appropriate general model for this study.

Gold-bearing Skarn Deposits

Descriptive model.--Gold-bearing (1 g/t or more) skarn deposits include mineral assemblages (calcsilicates) that are indicative of a skarn environment.

Theodore and others (1991) presented descriptive and grade-tonnage models for gold-bearing skarns based on data for 90 deposits throughout the world. Using the criteria that a deposit must contain a skarn gangue mineral assemblage and a minimum gold grade of 1 gram per metric ton, they found that some skarn deposits are mined for their gold content alone whereas others produce gold as a byproduct of copper, iron, lead, or zinc mining. Due to recent trends in mining and exploration, many skarn deposits that would have been mined in the past for their base-metal content are currently evaluated for their precious-metal content. Deposits are not grouped by any spatial proximity rules in this model; therefore, a single district or a single pluton or batholith may have several gold-bearing skarn deposits associated with it.

Gold is deposited very late in the paragenetic sequence during or subsequent to sulfide deposition. Advanced retrograde alteration may obliterate the characteristic calcsilicate minerals. Retrograde alteration is best developed in permeable areas within a skarn system, such as along faults or contacts. Some orebodies (for example, the McCoy deposit in Nevada) develop proximal to a stock or porphyry copper system; others lie several hundred meters away from an igneous center or have no apparent connection with any intrusion.

Pyrrhotite is the predominant sulfide mineral in some deposits; others are characterized by pyrite and

chalcopyrite. Local magnetic highs reflect pyrrhotite or magnetite abundances in some deposits.

Bismuth, arsenic, and (or) tellurium are useful geochemical pathfinders for many gold-bearing skarn deposits.

Grade and tonnage model.--Gold-bearing skarn deposits range from 5 metric tons to 40 million metric tons; median deposit size is 279,000 metric tons. Median gold grade is 5.7 g/t. Byproduct gold skarns tend to be slightly larger, and have lower median gold grades and higher median silver grades than skarns mined for their gold content alone.

Skarns in the Study Area

In the New World district, many of the copper-gold-silver deposits are gold-bearing skarns that formed in carbonate rocks (mainly Middle Cambrian Meagher Limestone), in breccia, and along faults adjacent to the Tertiary Fisher Mountain and Homestake intrusive complexes. Four main stages of alteration are recognized: (1) calcsilicate hornfels, (2) epidote-dominant prograde skarn, (3) retrograde skarn, and (4) late quartz-sericite-magnetite-pyrite (Johnson, 1991; Elliott and others, 1992). Gold is associated with retrograde or late quartz-pyrite-potassic alteration. Classification of such deposits is subjective. Johnson (1991) noted that aspects of the alteration and mineralization in the McLaren deposit are similar to aspects of porphyry copper, porphyry molybdenum, gold skarn, and copper skarn deposits and considered the McLaren deposit a gold-rich copper skarn. Comparison of announced reserves (table E1) for the deposits that have been delineated in the New World district with grade and tonnage models for various skarn and other deposit types indicates that the gold-bearing skarn model best describes the discovered deposits (fig. G9). The average copper grade for the New World deposits, 0.75 percent copper, is well below the median copper grade of 1.7 percent for copper skarn deposits (Jones and Menzie, 1986). Similarly, the average gold grade for the New World deposits, 7.5 g/t, is high compared to gold grades commonly encountered in copper skarn deposits.

In the Independence district, iron-copper skarns are present on War Eagle Mountain (Lori Kay prospects). Stotelmeyer and others (1983) described the prospects and estimated an inferred resource of about 10 million metric tons of ore; combined samples of iron-rich rock averaged 45.0 percent iron, 0.87

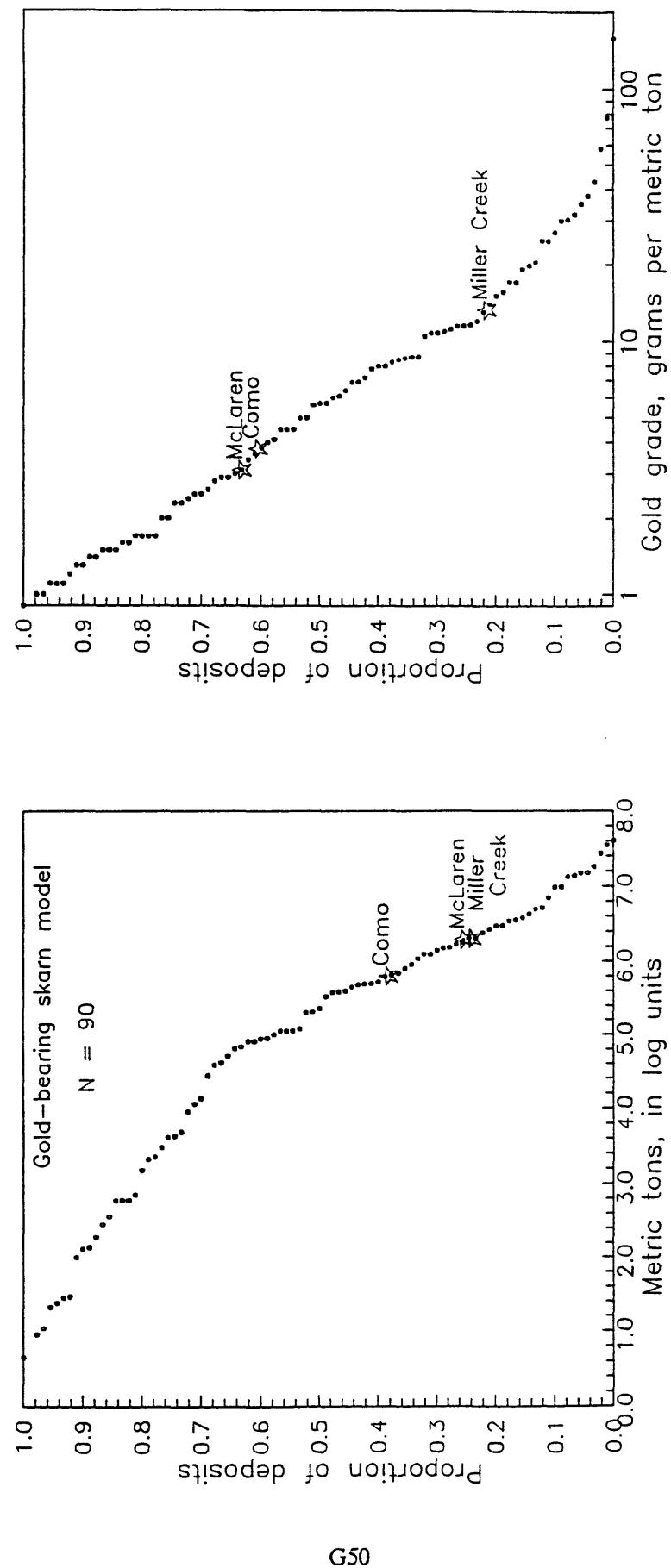


Figure G9.—Grade and tonnage models for gold-bearing skarn deposits (from Theodore and others, 1991). Stars, announced reserve data for copper-gold skarn deposits in the New World district.

percent copper, 0.05 percent molybdenum, 0.034 g/t gold, and 9.9 g/t silver. Silicate-, magnetite-, and sulfide-rich rocks are present. Samples collected for this study (Hammarstrom, unpublished data) indicate that trace amounts (0.002 ppm) of gold are present in garnet-rich skarn as well as in two samples of sulfide-rich skarn (0.53 and 0.75 ppm gold), one of which also contained 9.2 parts per billion palladium. The prospect has not been adequately evaluated to determine the nature of the mineralization. Relatively high copper and gold assays and possible platinum group element concentrations in sulfide-rich parts of the prospects suggest that the area may be more prospective for commodities other than iron. The skarn appears to be spatially associated with a Cretaceous (S. Harlan, oral commun., 1992) granodiorite sill.

In the Sliderock area, small magnetite skarn bodies formed in roof pendants of Mississippian Madison Limestone on Fire Ridge in the Late Cretaceous Sliderock laccolith. No production is reported from these occurrences. Geochemical analyses for 5 samples of magnetite skarn, garnet skarn, and calsilicate hornfels are as follows: gold, <0.002 ppm to 0.066 ppm; silver, <4 ppm in all samples; copper, 51 to 830 ppm; 56 and 60 weight percent in magnetite-rich samples; lead, 10 ppm or less; and zinc, 51 to 310 ppm (Hammarstrom, unpublished data).

Permissive Tracts

Tract VII is delineated for Paleozoic carbonate sedimentary rocks proximal to Tertiary, Cretaceous, and Tertiary or Cretaceous intrusive rocks (fig. G10, table G14) that are considered permissive host rocks for skarn deposits. The tract was drawn to include exposed carbonate rocks and subsurface projections of inferred carbonate rocks to a depth of 1 kin. Tract VII encircles tract V (permissive for porphyry copper deposits).

Tract VII--VIIa (South Snowy block subtract). Subtract VIIa outlines Paleozoic carbonate rocks proximal to Tertiary intrusive rocks of the Absaroka-Gallatin volcanic province and includes the skarn deposits in the New World district that contain demonstrated copper, gold, and silver resources and the skarn occurrences in the Independence district.

VIIB (Sliderock Mountain subtract). Subtract VIIB includes all rocks within a 5 kin radius of known and possible buried intrusive centers in the Sliderock area. These include Paleozoic carbonate rocks proximal to exposed Cretaceous intrusive rocks and

skarn occurrences in roof pendants of the Sliderock Mountain stock, as well as intrusive rocks that may host endoskarn, carbonate rocks in roof pendants, or conceal buried skarn beneath sill-like extensions of a laccolith.

VIIc (Mount Maurice-Line Creek Plateau subtract). Paleozoic carbonate rocks in the leading edge of the upper plate and in the lower plate of the Beartooth thrust fault that are proximal to Cretaceous or Tertiary intrusive rocks of subtract Vc are permissive host rocks for skarn deposits.

Estimate of Numbers of Undiscovered Deposits

The gold-bearing skarn model is appropriate for copper, iron, and lead-zinc skarns provided that their average gold content is 1 gram per metric ton or more. Separate estimates are reported for the western and southeastern parts of subtract VIIa and for the parts of subtract VIIb that lie within each of two National Forests (table G15). These estimates indicate a relatively high probability for undiscovered skarn deposits in subtract VIIa and a relatively low probability for deposits in subtract VIIb. Subtract VIIa includes the New World district, where intensive exploration by drilling over a period of several years resulted in substantial increases in known reserves and delineation of new deposits. Similar levels of intensive exploration in other parts of the New World district and throughout subtract VIIa, especially where favorable carbonate host rocks such as the Cambrian Meagher and Pilgrim Limestone units are cut by faults, in the interior and middle parts of districts zoned from proximal copper and gold occurrences to distal lead-zinc occurrences, and at depth where favorable host rocks may be present at intrusive contacts or along faults are likely to result in additional discoveries. The Meagher Limestone is the first thick carbonate unit overlying the basal Paleozoic unit, the Cambrian Flathead Sandstone, and is usually overlain by a shale; the Meagher is more reactive to hydrothermal fluids than the stratigraphic units above and below and may trap fluids. Cambrian carbonate units, including the Meagher Limestone, are favorable host rocks for gold deposits throughout southwestern Montana. Subtract VIIb is less prospective for near surface gold-bearing skarns; however, Jones and Swift (1974) noted several magnetite-bearing copper skarn occurrences in Mississippian Madison Limestone on the margins of the potential large, buried porphyry copper system in the Sliderock Mountain subtract that has recently been explored for gold. Gold-bearing

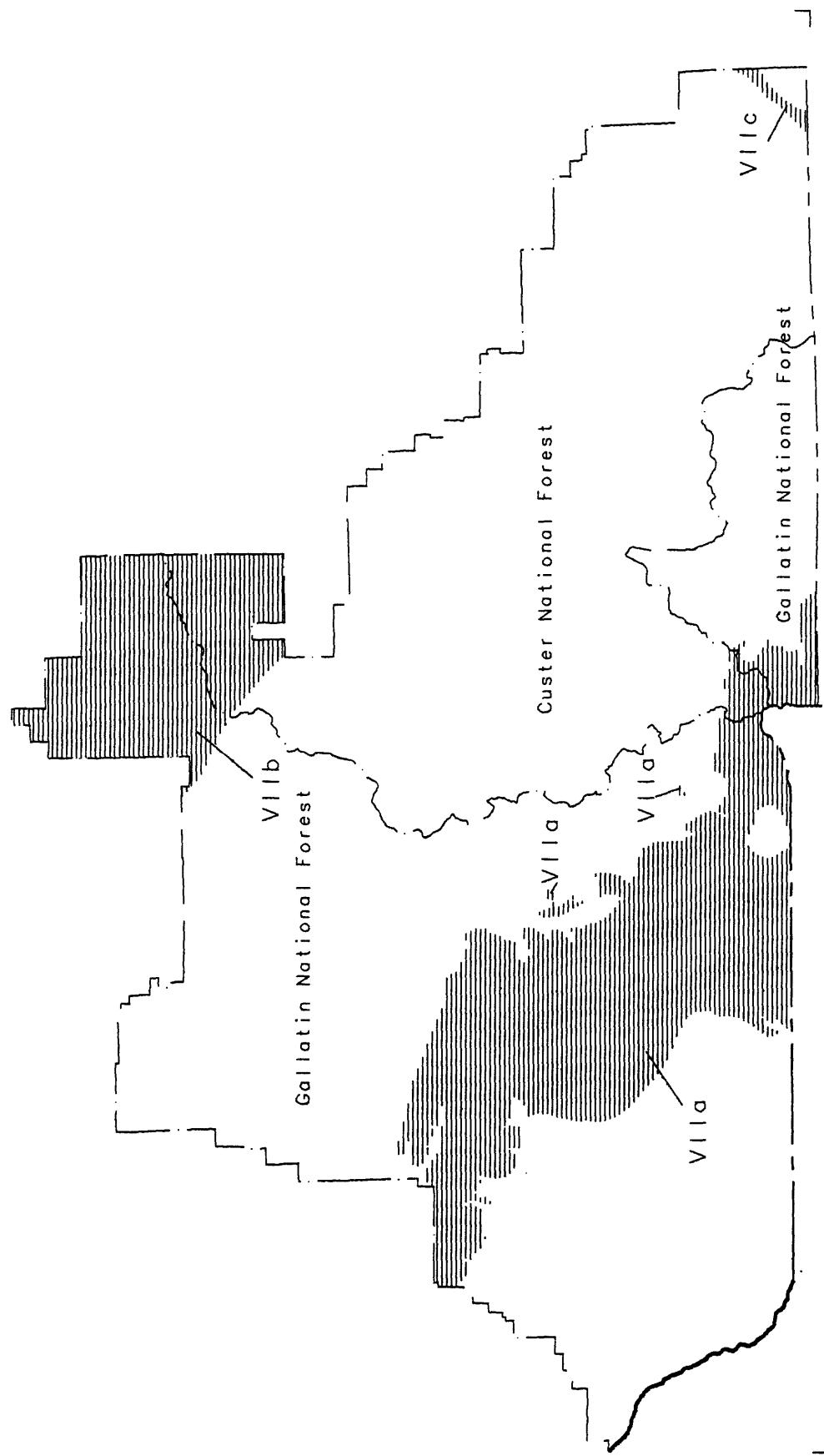


Figure G10.--Location map for mineral resource tract VII (permissive for skarns).

Table G14.-Criteria for tract VII

Description: Paleozoic carbonate sedimentary rocks proximal to Tertiary, Cretaceous, and Tertiary or Cretaceous intrusive rocks.

<u>Permitted deposit types</u>	<u>Expected geochemical signatures¹</u>
Copper skarn	Cu-Au-Ag inner zones grade outward to Au-Ag and Pb-Zn-Ag zones. Co, As, Sb, Bi in some deposits.
Gold-bearing skarn (Many are also copper or iron skarns)	Au, Ag, Cu, Fe, Zn, Pb, Bi, As, or Te in some deposits.
Iron skarn	Fe, Cu, Co, Au, possibly Sn.
Zinc-lead skarn	Zn, Pb, Mn, Cu, Co, Au, Ag, As, W, Sn, F, possibly Be.
Polymetallic replacement	District zoning from Cu core outwards to wide Pb-Ag zones and Zn-Mn fringe area. Local Au, As, Sb, Bi, Ba and Ag in related jasperoid.

Tract	VIIa (South Snowy block subtract)	VIIb (Sliderock Mountain subtract)	VIIc (Mount Maurice-Line Creek subtract)
Area (km ²)	829	367	8
Geologic criteria ²	Paleozoic carbonate rocks proximal to Tertiary intrusive rocks of the Absaroka-Gallatin volcanic province (subtract Va). Tract is extended under volcanic cover in areas where carbonate rocks are likely to be present at shallow depths (within 1 km of surface).	Paleozoic carbonate rocks proximal to Cretaceous intrusive rocks. Includes exposed Paleozoic carbonates as well as other rocks within a 5 km radius of the boundary of tract Vb, include laccolithic stocks that may conceal buried carbonate rocks, stocks that host carbonate rock pendants, and areas of potential endoskarn.	Paleozoic carbonate rocks in the leading edge of the upper plate and in the lower plate of the Beartooth thrust fault that are proximal to Cretaceous or Tertiary intrusive rocks (TKI).
Geophysical criteria ³	None.	Same as tract Vb.	None.

Table G14.--Criteria for tract VII (continued)

Tract	VIIa (South Snowy block subtract)	VIIb (Sliderock Mountain subtract)	VIIc (Mount Maurice-Line Creek subtract)
Geochemical criteria ⁴	Ag, Au, Cu, Mo, Pb, W, Zn, (As), (Bi), (Sb), Factor Spec-4 {Au, Ag, Mo, Pb, Cu} Factor ICP-2 {Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As}	As, Bi, Sb, W, (Ag), (Au), (Cu), (Mo), (Pb) Factor ICP-2 (see VIIa) Geochemical data for rock samples of magnetite-rich skarn in roof pendants on Fire Ridge (in ppm): Au, <0.002 to 0.006; As <50; Cu, 51 to 830; Co, 9 to 110; Zn, 51 to 310	No data.
Mines, prospects, and occurrences	Gold and copper production in past from the McLaren skarn and other copper-gold-silver skarn and replacement deposits in the New World district; current exploration and development for copper-gold-silver skarn and replacement deposits. Locally magnetite-rich skarn at the Lori Kay prospects on War Eagle Mountain in the Independence district.	Locally magnetite-rich copper-iron skarn occurrences in roof pendants of Sliderock Mountain diorite stock (Kd).	None.
Comments	Subtract VIIa is the most prospective subtract for undiscovered gold-copper skarn deposits because it contains identified resources of this deposit type.	Permissive subtracts for skarn and polymetallic vein are coextensive. VIIb is less prospective than VIIa because of lack of known deposits.	VIIc is the least prospective subtract for skarns because of lack of deposits and occurrences, lack of carbonate at intrusive contacts at the surface, and possibly too deep a level of erosion. VIIc also lacks deposits and occurrences of other deposit types that typically are present in skarn environments, such as porphyry copper deposits.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Gravity anomalies (letters) and magnetic anomalies (numbers) are keyed to gravity and magnetic maps (plates 2 and 3, respectively).

⁴ Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group. Refer to Chapter D for explanation of Factors-spec geochemical associations.

Table G15.--Estimate of mineral resources contained in undiscovered gold-bearing skarn deposits within the Absaroka-Beartooth study area (tract VII)

[G, Gallatin National Forest; C, Custer National Forest; C-G, Custer and Gallatin National Forests]

Simulator input

Estimate of the minimum number of deposits expected at each of the following probabilities:

Subtract	90%	50%	10%	5%	1%
VIIa (G)	0	2	3	3	4
VIIa (C-G)	2	3	4	5	5
VIIb (G)	0	0	1	1	2
VIIb (C)	0	0	0	1	1

Simulator output

Estimated numbers of undiscovered deposits

Subtract	Mean expected number of deposits	Probability of 0 deposits
VIIa (G)	1.73	20%
VIIa (C-G)	2.96	4%
VIIb (G)	0.31	70%
VIIb (C)	0.07	93%

Estimated amounts of commodities contained in undiscovered deposits (in metric tons)¹

Commodity/ Subtract	90th percentile	50th percentile Median	10th percentile	Mean
Copper				
VIIa (G)	0	260	94,000	48,000
VIIa (C-G)	4	15,000	200,000	75,000
VIIb (G)	0	0	2,800	6,500
VIIb (C)	0	0	0	2,000
Gold				
VIIa (G)	0	3	36	13
VIIa (C-G)	0	11	56	22
VIIb (G)	0	0	4	3
VIIb (C)	0	0	0	1
Silver				
VIIa (G)	0	4	140	67
VIIa (C-G)	0	24	260	120
VIIb (G)	0	0	7	12
VIIb (C)	0	0	0	3
Ore				
VIIa (G)	0	800,000	18,000,000	5,100,000
VIIa (C-G)	45,000	3,500,000	24,000,000	8,600,000
VIIb (G)	0	0	1,100,000	930,000
VIIb (C)	0	0	0	240,000

¹ Output from Mark3 program reported to 2 significant figures.

skarn deposits may be present at depth in this system in either Mississippian rocks or in Lower Paleozoic carbonate rocks at depth.

The mean values for estimated ore tonnages for subtricts VIIa and VIIb total to about 15 million metric tons. This amount of ore is roughly comparable to the 12 million short tons (11 million metric tons) of total preliminary reserves grading 7.5 g/t gold, 30 g/t silver, and 0.75 percent copper reported for the discovered deposits in the New World district (The Northern Miner, 1992).

POLYMETALLIC VEINS

Mineral Deposit Model

Descriptive model.--Polymetallic veins are quartz-carbonate veins with gold and silver associated with base metal sulfides related to hypabyssal intrusions in sedimentary and metamorphic terranes (fig. G5). Cox (1986a) presented a model for polymetallic veins, such as the silver-lead-zinc veins associated with felsic intrusions in the Marysville district, Montana, and the Slocan District, British Columbia. Where such veins intersect carbonate rocks, local replacement ore bodies may form. These local replacements are distinct in size and grade from the much larger, massive polymetallic replacement or manto deposits that form exclusively in sedimentary rocks, mainly in limestones, such as Morris (1986) described for deposits in the Tintic district of Utah, at Eureka, Nevada, and elsewhere.

Polymetallic veins are deposited in shallow fractures and breccias, along contacts, fault intersections, or other permeable zones within thermal aureoles of small intrusions, or peripheral to porphyry systems. A wide variety of ore minerals may be deposited, including native gold, electrum, pyrite, sphalerite, chalcopyrite, galena, arsenopyrite, tetrahedrite, and other sulfosalt minerals. Vein gangue minerals are typically quartz, chlorite, and calcite with other carbonates, barite, fluorite, or adularia. Geochemical anomalies may be zoned from central copper-gold outwards to lead-zinc-silver to peripheral manganese.

Grade-tonnage model.--Bliss and Cox (1986) constructed grade and tonnage models for polymetallic vein deposits. They found that two subtypes of deposits exist--one enriched in base metals and the other in precious metals. In districts that contain both subtypes, the base-metal subtype is much more abundant. No reliable data are available for the gold-

silver polymetallic vein deposits. The existing grade-tonnage model for polymetallic veins represents data from 75 base-metal type deposits, where a "deposit" is defined as all veins within a 1 km spacing with a minimum of 100 metric tons of ore and some data points represent entire districts. Median grades are 820 g/t silver, 9 percent lead, and 7.6 percent zinc. Gold ranges from 0.02 to about 40 g/t; copper ranges from about 0.05 to 2 percent or higher. Ore tonnages range from 100 metric tons to over 1.6 million metric tons; median deposit size is 7,600 metric tons.

Examples of Polymetallic Veins in the Study Area

Both base-metal and precious-metal enriched polymetallic veins are present in the ABSA. Mines, prospects, and occurrences (plate 19, Chapter E appendix) for which silver or lead or zinc and (or) gold, copper, and other metals are reported in veins or shear zones in any rock type are classified as polymetallic veins. Gold and (or) silver occurrences without other metals are classified as (1) precious-metal veins or disseminations in igneous rocks or (2) unknown deposit type.

In the New World district, the Irma-Republic mines and other mines in the southern part of the district produced silver, lead, and zinc from polymetallic vein and replacement deposits from before 1900 to about 1956. Butler (1965) described the geology and complex mineralogy of the most productive ores, the Irma-Republic vein system, as argentian galena and sphalerite in fissure-replacement type deposits in limestone of the Gallatin Formation (Upper Cambrian Snowy Range Formation of Elliott, 1979). Polymetallic veins form a "C"-shaped zone around the gold-bearing copper skarn deposits of the New World district (plate 19); the Irma-Republic mines are the southernmost and most distal of these deposits. More proximal deposits, such as the Black Warrior mine, appear to be enriched in gold relative to the Irma-Republic ores (table E1).

Polymetallic vein deposits in the Independence district include the Ski Line mine, which produced less than 140 metric tons of ore containing silver, lead, and gold prior to 1950, and the 7777 claim along Sheep Creek.

Polymetallic veins are present around the periphery of the Emigrant stock (plate 19). Production data for the Barbara Ann mine (table E1) and estimated resources for other occurrences along the same structure suggest that the Emigrant veins are enriched in gold (27 g/t) and depleted in base metals

(<1 percent lead, zinc) relative to the polynmetallic veins of the New World district.

Production data for the polynmetallic veins at the Irma-Republic mines fit existing grade-tonnage models for base-metal-rich polynmetallic veins. However, the deposits that are more proximal to the intrusive center are smaller and more gold-rich and are not well described by the model. Furthermore, the known polynmetallic vein deposits associated with the Independence and Emigrant intrusive centers have not been fully delineated and may not fit existing models. For example, at the Copper Queen and Lost Cabin claims in the Mill Creek area of the Emigrant district, shear zones in diorite carry anomalous concentrations of copper, nickel, silver, arsenic, and platinum-group elements (Stotelmeyer and others, 1983; Hammarstrom, unpublished data).

Copper and other metal geochemical anomalies are associated with sulfide-bearing veins at the Elk claims, in the Grove Creek subdistrict within the Custer National Forest near Mount Maurice, south of Red Lodge (Adler, 1969). The veins (0.01 to 1.1 percent copper, up to 0.06 percent nickel, trace lead, zinc, silver) are in Flathead Sandstone, near the Precambrian contact.

Permissive Tracts

Tract VIII is delineated as the permissive tract for polynmetallic vein deposits by outlining Precambrian, Paleozoic, Cretaceous, and Tertiary metamorphic, sedimentary, and igneous rocks within tract V (Tertiary, Cretaceous, and Tertiary or Cretaceous intrusive and volcanic rocks) or surrounding tract V for a distance of 5 km out from the tract V boundaries (plate 18). Tract VIII include five geographically separate subtracts (fig. G11, table G16) that coincide with the subtracts delineated for tract V and four favorable areas within the South Snowy block subtract VIIIa (table G17). Most of the identified polynmetallic vein deposits and occurrences lie within these favorable areas along faults and shears.

Tract VIII--VIIIa (South Snowy block subtract). Precambrian metamorphic and igneous, Paleozoic sedimentary rocks, and Tertiary intrusive and volcanic rocks of the Absaroka-Gallatin volcanic province within 5 km of the boundary of subtract Va are delineated as subtract VIIIa. The geochemical association of gold, silver, molybdenum, lead, and copper indicated by factor spec-4 for stream sediment geochemical data (table G17) is present in all of the favorable areas within subtract VIIIa.

VIIIa1 (Emigrant favorable area). In the Emigrant district, polynmetallic veins are concentrated in shear zones that trend northeast-southwest or in crosscutting faults and shears that trend northwest (plate 19). Contacts between Precambrian rocks and Cambrian Flathead Sandstone also localized ores. No occurrences in carbonate rocks have been identified. Base and precious metal geochemical anomalies and geochemical associations (table G17) from stream sediments that drain area VIIIa1 are compatible with polynmetallic vein mineralization.

VIIIa2 (Independence favorable area). Area VIIIa2 includes all precious and polynmetallic vein occurrences near the Independence intrusive center. Stream sediment geochemical anomalies are similar to other favorable areas in VIIIa, but the magnitude of the anomalies is less.

VIIIa3 (Horseshoe Mountain favorable area). No polynmetallic vein occurrences or appropriate geochemical signatures, other than gold and minor copper, are associated with the Horseshoe Mountain area.

VIIIa4 (New World favorable area). Area VIIIa4 includes the Irma-Republic mines and other polynmetallic veins of the New World district. Additional deposits may be present along structures at shallow depth, especially in peripheral parts of the district.

VIIIb (Sliderock Mountain subtract). The permissive tract for polynmetallic veins adjoining Cretaceous intrusive centers in the Sliderock area is coextensive with the previously described skarn tract (VIIb). No polynmetallic vein deposits are known to occur within the tract. The most favorable areas for such deposits are exposed or buried carbonate units, especially along structures radiating out from the known intrusive centers, and in the zones of anomalous lead-zinc around the periphery of the Sliderock Mountain stock.

VIIIc (Line Creek Plateau subtract). Subtract VIIIc outlines Precambrian metamorphic and igneous rocks including, and within 5 km of Cretaceous or Tertiary intrusive rocks of subtract Vc on Line Creek Plateau. No mineral occurrences are associated with the intrusive rocks of subtract Vc. Isolated geochemical anomalies for gold, silver, lead, and zinc as well as the factor spec-4 geochemical association are compatible with (but not necessarily indicative of) polynmetallic vein mineralization. Anomalous chromium, nickel, and uranium are probably related to other deposit types (Red Lodge chromite, uranium occurrences near Red Lodge). The Elk claims represent the only known mineral occurrence that may

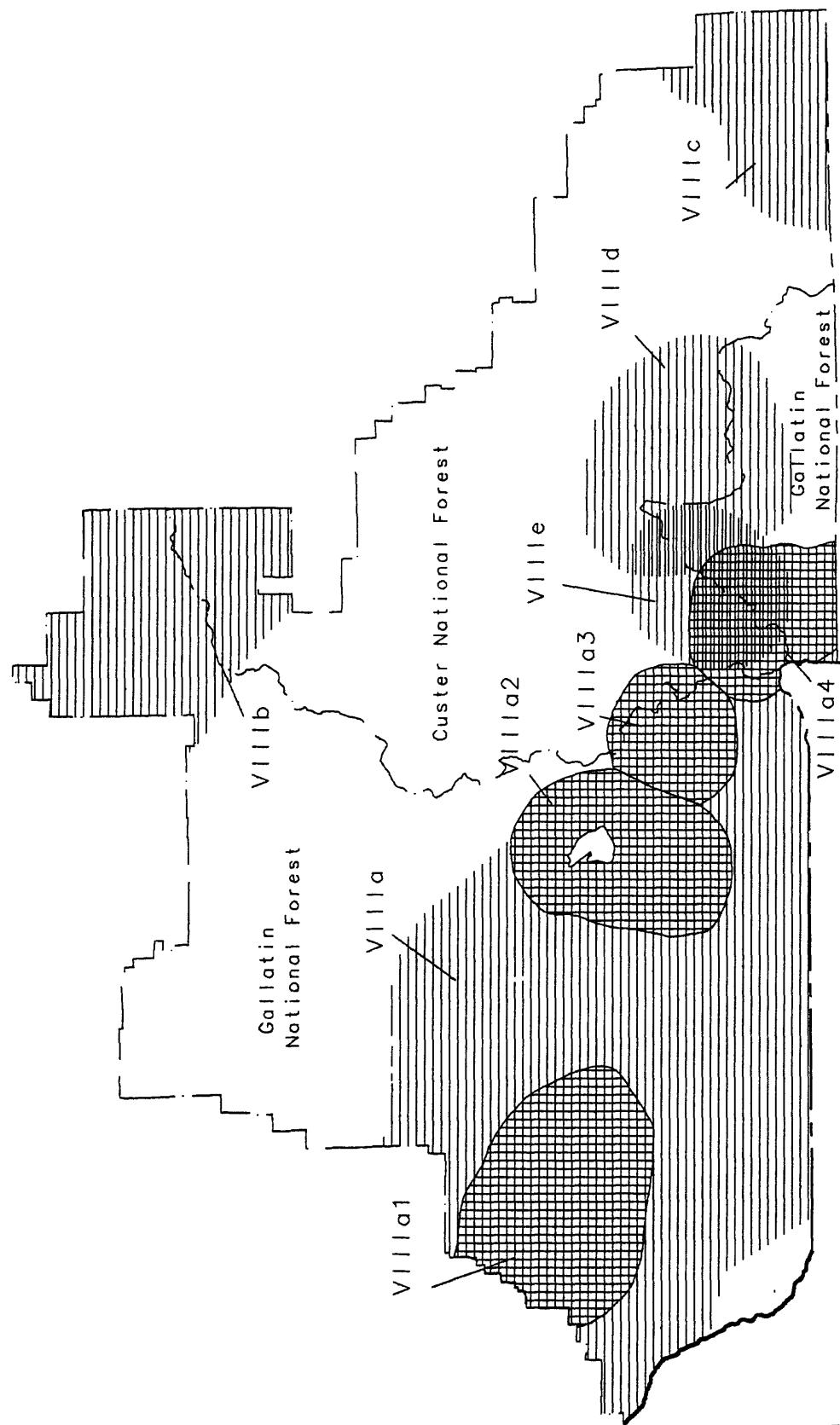


Figure G11.—Location map for mineral resource tract VIII (permissive for polymetallic veins).

Table G16--Criteria for tract VIII

Description: Precambrian, Paleozoic, Mesozoic, and Tertiary metamorphic, sedimentary, and igneous rocks within or surrounding tract V.

Permitted deposit types

Expected geochemical signatures¹

Zn, Cu, Pb, As, Au, Ag, Mn, Ba

Tract	VIIIa (South Snowy block subtract)	VIIIb (Slidderock Mountain subtract)	VIIIc (Line Creek Plateau subtract)	VIIId (Granite Peak subtract)	VIIIf (Goose Lake subtract)
Area (km ²)	344	367	211	344	185
Geologic criteria	Precambrian metamorphic and igneous rocks, Paleozoic sedimentary rocks, and Cretaceous intrusive and volcanic rocks. Tract is drawn to include all rocks within 5 km of the boundary for tract Vb. Tertiary intrusive and volcanic rocks of the Absaroka-Gallatin volcanic province. Tract is drawn to include all rocks within a 5 km distance out from intrusive centers and intervening volcanic rocks of tract Va. In areas where structure suggests that volcanic cover is less than 1 km thick, volcanic cover is included in the tract.	Paleozoic and Mesozoic sedimentary rocks and Cretaceous intrusive and volcanic rocks. Tract is drawn to include all rocks within 5 km of the boundary for tract Vb.	Tract is drawn to include all rocks within 5 km of the boundary for tract Vc. Include Precambrian gneisses as well as Paleozoic and Mesozoic rocks along the range front in the SE corner of the study area.	Precambrian metamorphic and igneous rocks and Cretaceous or Tertiary intrusive rocks within 5 km of subtract Vd.	Precambrian metamorphic and igneous rocks and Cretaceous intrusive rocks within 5 km of subtract Ve.
Geophysical criteria	None	None	None	None	None

Table G16.--Criteria for tract VIII (continued)

Tract	VIIIa (South Snowy block subtract)	VIIIb (Sliderock Mountain subtract)	VIIIc (Line Creek Plateau subtract)	VIIId (Granite Peak subtract)	VIIIf (Goose Lake subtract)
Geochemical criteria²	Ag, As, Au, Bi, Cu, Mo, Pb, W, Zn, (Cr), (Ni), (Sb), (U) Factor Spec-4 {Au, Ag, Mo, Pb, Cu} Factor ICP-2 {Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As}	Ag, Bi, Sb, W, (Ag), (Au), (Cu), (Pb) Factor ICP-2 (see VIIa)	(Ag), (Au), (Cr), (Pb), (Ni), (W), (Zn) Factor Spec-4 (see VIIa)	Mo, Pb, W, (Cr), (Ni), (Zn) Factor Spec-4 (see VIIa)	Ag, Au, Bi, Cu, Mo, Pb, (Ni), (Zn) Factor Spec-4 (see VIIa)
Mines, prospects, and occurrences	See table G17			Copper reported at the Elk claims may be an occurrence related to deposit type.	None
Comments	Mines, prospects, and occurrences around known intrusive centers indicate a general zoning pattern of polymetallic vein type from proximal Au-Ag-Cu to more distal Ag-Pb-Zn veins.				May include Au-Ag-Te veins developed around alkalic intrusive rocks.

¹ Elements are listed in approximate order from most to least common and(or) significant.² Moderately to highly anomalous elements in stream sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group. See Chapter D for explanation of factors.

Table G17.--Criteria for favorable areas within subtract VIIIa (South Snowy block)

Description: Precambrian metamorphic and igneous rocks, Paleozoic sedimentary rocks, and Tertiary intrusive and volcanic rocks of the Absaroka-Gallatin volcanic province.

Permitted deposit types

Expected geochemical signatures¹

Polymetallic veins

Zn, Cu, Pb, As, Au, Ag, Mn, Ba

Tract	VIIIa1 (Emigrant favorable area)	VIIIa2 (Independence favorable area)	VIIIa3 (Horseshoe Mountain favorable area)	VIIIa4 (New World favorable area)
Area (km ²)	312	236	120	162
Geologic criteria	All rocks within 5 km of the Emigrant intrusive center (subtract Va1). Includes Archean gneisses and meta-sedimentary rocks as well as Tertiary intrusive and volcanic rocks.	All rocks within 5 km of the Independence intrusive center (subtract Va2).	All rocks within 5 km of the outcrop area of altered dacite porphyry at Horseshoe Mountain (subtract Va3).	All rocks within 5 km of the Cooke City intrusive center. Includes Archean granitic gneisses, Paleozoic sedimentary rocks, and Tertiary intrusive and volcanic rocks.
Geochemical criteria ²	Ag, As, Au, Bi, Cu, Mo, Pb, Sb, Zn, (W) Factor Spec-4 {Au, Ag, Mo, Pb, Cu} Factor ICP-2 {Bi, Ag, Sb, Cu, Pb, Mo, Cd, Au, Zn, As}	Au, (Cr), (Mo), (Ni), (W), (Zn) Factor Spec-4 (see VIIIa1) Factor ICP-2 *	Ag, Au, Bi, Cu, Mo, Pb, Sb, (Cr), (Ni), (W), (Zn) Factor Spec-4 (see VIIIa1) Factor ICP-2 *	Au, Cu, Mo, W, (Ag), (Cr), (Ni), (Zn) Factor Spec-4 (see VIIIa1)
Mines, prospects, and occurrences	Numerous polymetallic vein occurrences are concentrated along an 11 km long by 0.8 km wide, NE-SW trending mineralized belt in the NW part of the Emigrant district. Local shear zones along contacts between Archean rocks and Cambrian Flathead Sandstone also control distribution of occurrences. Both precious-metal-enriched and base-metal-enriched veins are present.	Minor production from the Skid Line mine prior to 1950. Numerous vein occurrences contain precious and (or) base metals.	Base and precious metal occurrences in quartz veins and fractures in porphyry, Precambrian gneiss, and Cambrian sandstone at the Horseshoe Mountain claim; a few other gold occurrences (placer and unknown type) in the area.	Irma-Republic and numerous lead-zinc mines (past producers) and occurrences along structures in carbonate units distal (mostly S) to the intrusive center. Proximal deposits are enriched in gold relative to more distal deposits.

Table G17.--Criteria for favorable areas within subtract **VIIIa** (South Snowy block) (continued)

Tract	VIIIa1 (Emigrant favorable area)	VIIIa2 (Independence favorable area)	VIIIa3 (Horseshoe Mountain favorable area)	VIIIa4 (New World favorable area)
Comments	Stotelmeyer and others (1983) calculated indicated and inferred submarginal and paramarginal resource estimates for several occurrences in this tract (see table E1 of this report).	Apparent zonation from proximal precious metal- to distal base metal-enriched prospects and occurrences.	Mineral occurrences may be related to either polymetallic or epithermal vein mineral deposit types.	District-wide zoning from Cu-Au-Ag skarn and replacement near intrusives to distal Pb-Zn-Ag polymetallic vein deposits. Where structurally controlled vein deposits intersect carbonate units, deposit morphology changes from vein-like to replacement pods and lenses.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Moderately to highly anomalous elements in stream-sediment samples. Slightly anomalous elements in parentheses. Elements are listed in alphabetical order within each group. See Chapter D for explanation of factors.

be of this type in the subtract. Precambrian rocks, as well as the Paleozoic sedimentary rocks along the range front, are permissive for polymetallic vein occurrences.

VIIId (Granite Peak subtract). Precambrian metamorphic and igneous rocks and Cretaceous or Tertiary dikes and possible buried stocks near Granite Peak may host polymetallic base and precious-metal veins. No mines or prospects, are present. Scattered gold occurrences, gold and other geochemical anomalies (molybdenum, tungsten, lead) in stream sediments draining subtract VIIId cannot be unambiguously linked to this deposit type. The only tungsten occurrence in this part of the study area is a report of scheelite with cataclastic quartz in a shear zone south of Goose Lake (Simons and others, 1979); the tungsten may be related to pegmatites in tract II.

VIIIe (Goose Lake subtract). Precambrian metamorphic and igneous rocks and Cretaceous intrusive rocks associated with the syenite stock at Goose Lake are delineated as subtract VIIIe. The eastern half of subtract VIIIe intersects the Granite Peak subtract (VIIId) and the southern half intersects the New World favorable area (VIIIa4). The northern part of the New World district and the southern part of the Goose lake area include numerous polymetallic vein and precious metal occurrences (plate 19). These occurrences may be related to the Tertiary intrusive center in the New World district, to the Cretaceous alkalic center at Goose Lake, or both. Gold and silver occurrences in this subtract may reflect the gold-silver-tellurium vein style of mineralization associated with some shallow alkalic intrusive rocks that was described in the mineral deposit model for epithermal veins.

Undiscovered deposits.--In the past, the only area within the ABSA in which polymetallic veins have been important is in the southern part of the New World district, where fluids emanating from the Cooke City intrusive center traveled along structures to form vein and replacement deposits in Paleozoic carbonates. In each of the identified, mineralized intrusive centers (Cooke City, Independence, Emigrant, Sliderock Mountain) lead-zinc mines, occurrences, and geochemical anomalies form a poorly defined distal halo to copper-gold-silver occurrences. This metal zoning is largely independent of deposit type, and reflects metal deposition from hydrothermal fluids as they intersect successive saturation surfaces that migrate through space and time as a function of changing temperatures or chemical variables (Hemley and Hunt, 1992).

Undiscovered polymetallic vein deposits may be present within the ABSA, especially peripheral to intrusive centers. Based on available data however, we cannot predict the base- or precious-metal-rich nature of such deposits, nor can we establish that the available tonnage model is appropriate for quantitative assessment. Therefore, we did not estimate numbers of undiscovered deposits.

MINERAL DEPOSITS RELATED TO QUATERNARY PROCESSES

PLACER GOLD DEPOSITS

Mineral Deposit Model

Descriptive model.--Placer gold deposits consist of elemental gold (and platinum-group alloys) in grains and rarely in nuggets in gravel, sand, silt, and clay, and their consolidated equivalents, in alluvial, beach, eolian, and, rarely, glacial deposits. Descriptive models and production data for gold placer deposits are given by Yeend (1986) and Yeend and Shawe (1989). Placers form by processes of weathering and mechanical concentration, by the action of running water in streams and rivers. Placer deposits are subject to destruction and recycling by the same processes that led to their formation. Most placers are Cenozoic, but fossil placers may be preserved by burial under volcanic cover, alluvium, lake sediments, or glacial deposits, or may form perched beach or stream terrace deposits due to changes in shoreline or stream elevation (fig. G12). Ore controls include proximity to bedrock and availability of hydrologic traps, such as joints, fractures, or rough rock surfaces in the stream bed. Anomalous gold, silver, arsenic, mercury, antimony, copper, iron, and (or) sulfur found in geochemical stream sediment surveys and stream sediment heavy mineral suites that include arsenopyrite, native bismuth, scheelite, stibnite, sulfosalts, and platinoids indicate placer potential. The most prospective areas for placer deposits are in, or proximal to, known gold districts. Occurrences of placer gold have led to discoveries of many lode gold deposits by tracing the anomalies to bedrock sources upstream.

Grade-tonnage models.--Grades and tonnages for placer deposits are difficult to quantify because cutoff mining grades are a function of the mining method employed (Bliss, Orris, and Menzie, 1987). Small-volume methods include panning, sluicing, and drift

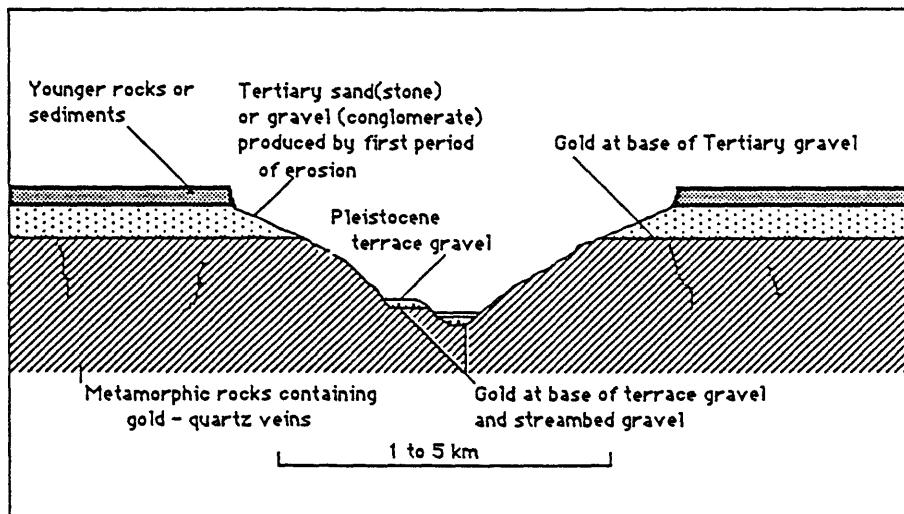


Figure G12.—Generalized geologic model (cartoon) for placer gold deposits (Yeend, 1986).

mining. Large-volume mining methods are dredging, draglining, and hydraulic. Median gold grade for deposits mined by drifts is higher (10 g/t) than median gold grade for other small volume (1.4 g/t) or large volume (0.28 g/t) mining methods. Orris and Bliss (1986) compiled grade and tonnage data for 65 placer gold deposits. They assumed a minimum ore tonnage of 100 cubic meters, excluded deposits mined by drifts but included both large and small volume mining methods, and grouped workings within 1.6 km of one another. Placer ore production is commonly reported in terms of cubic meters and grades are reported as grams per cubic meter, or more commonly, as dollars or cents per cubic yard. For the purposes of constructing a model, deposit volumes were converted to metric tons by assuming 2.0 metric tons per cubic meter, based on the average density of wet sand and gravel. Placer deposits included in the model produced between 3,000 and 100 million metric tons; median deposit size is 1.1 million metric tons. Ore grades range from 0.06 to 1.0 grams gold per metric ton; silver grades (rarely reported) do not exceed 0.2 grams per metric ton. Placer deposits chain together along rivers or streams; lengths of placer workings along streams typically range from 0.2 miles to 9 or more miles.

Placers in the Study Area

Known placer locations in the ABSA are plotted on plate 18. These locations are taken from the compilation of mines, prospects and occurrences described in chapter E and from a report on Montana placers by Lyden (1948). Streams within the ABSA that contain glacial outwash gravels and boulders (such as the Boulder River) may be locally auriferous, but are generally less favorable than other streams because glaciation generally destroys preexisting placers and scatters the gold. Few glacial deposits contain economically important concentrations of gold.

The most important placer deposits in the ABSA are along Emigrant Creek. These deposits have been worked intermittently since the 1800's, and Sandhurst/Montana Mining and Reclamation is currently exploring placer potential in the upper parts of Emigrant Creek. Mining methods varied over the years and included sluice, hydraulic, drift, and dredge methods. Production records are incomplete; however, cumulative production appears to be in excess of 4 million metric tons of auriferous gravels. Apparent ore grades declined over the years from a high of 1.49 g/t gold to 0.06 g/t gold. Stotelmeyer and others (1983) estimated that over 765,000 m³ (equivalent to 1.5 million metric tons) of auriferous

gravels remain in shallow (<20 ft) placer deposits in Emigrant Creek.

Placer gold discoveries in Bear Creek, near Gardiner, led to the discovery of the stratiform gold deposits in the Jardine and Crevice (Crevasse) Mountain areas. Reed (1950) reported total gold production from Jardine district placers of 407 ounces for the years 1903 to 1947 and 1 ounce gold from the Crevasse Mountain district in 1908; ore tonnages are unknown. Seager (1944) described isolated patches of potentially auriferous gravel and silt along the east side of Bear Gulch which were deposited as stream and lake sediments prior to the eruption and subsequent modification of the landscape by Quaternary basalts.

Minor gold placer production is recorded for Independence (26 ounces gold for 1930 to 1941), Basin Creek (1 ounce in 1947), and the New World district (201 ounces gold, mainly in 1933).

A number of placer claims noted in the older literature were sampled in the mineral assessment studies related to Wilderness during the 1960's to 1980's and no resources were found. These include the Slough Creek and Long Tom placers near Lake Abundance and the Pigs Eye placer along Wolverine Creek. Placer workings are evident along Placer Creek in the Sliderock Mountain area, but no production is reported.

Placer workings are visible throughout the ABSA and most represent small-scale operations that may have sustained minor production. Concentrations of flood gold, that is, very small particles of gold that travel long distances during floods and are deposited as superficial concentrations on bars as waters recede, may have misled many miners to explore apparent placer deposits in the past. Flood gold (also known as flour, float, skim gold) can be transported hundreds of miles from its source and is so fine grained that it does not readily sink in sand and gravel and form placers. Flood gold may contribute a false geochemical anomaly to stream sediment samples. The extremely high fineness (gold to silver ratio) of flood gold may be useful in detecting false anomalies.

Permissive Tracts

Streams that have produced gold from placer deposits are the most prospective targets for additional deposits in the study area. Tract IX, the permissive tract for placer gold deposits, is delineated as a series of segments along streams (plate 18, fig. G13, table G18). Stream segments permissive for the

occurrence of placer gold deposits are indicated by three different symbols to show (1) reported placer locations, (2) segments of streams where anomalous gold is encountered in stream-sediment samples, and (3) areas of known Quaternary sediments in gold-bearing drainages.

Anomaly thresholds for gold in stream sediments (table D1) are 0.02 or 0.05 ppm, depending on analytical technique. The lowest average ore grades reported for productive placer deposits are on the order of 0.05 ppm gold, so gold anomalies above threshold values in stream sediments may indicate a placer potential. However, these data give no indication of potential ore tonnages and may reflect the flood gold effects described above.

Undiscovered Deposits

Permissive tracts (IX) for placer gold deposits are distributed throughout the study area. Nearly all of the historic production is from placers within the Gallatin National Forest. Less gold has been produced from placers in the Custer National Forest. Additional placer deposits may be present in the ABSA. Actual numbers of undiscovered placer deposits are difficult to quantify, the validity of available grade and tonnage models for modeling size and grade of undiscovered deposits in the ABSA is difficult to evaluate based on available production data for the study area; therefore, estimates of numbers of undiscovered placer deposits were not made. The discovered Emigrant Creek placer deposit probably represents the largest deposit to be found in the study area. The most prospective areas for additional deposits are extensions of known placer deposits, especially streams draining known lode gold districts, and streams with little glacial debris.

BOG DEPOSITS

Mineral Deposit Model

Remobilization and separation of iron and manganese through ground water interaction with soils or marshes can result in local sedimentary accumulations of very high grade iron or manganese oxide minerals in bog deposits. These deposits are common in swamps, lakes, and slow streams of recently glaciated areas where reducing conditions associated with decaying organic matter promote iron and manganese dissolution and transport. Humate

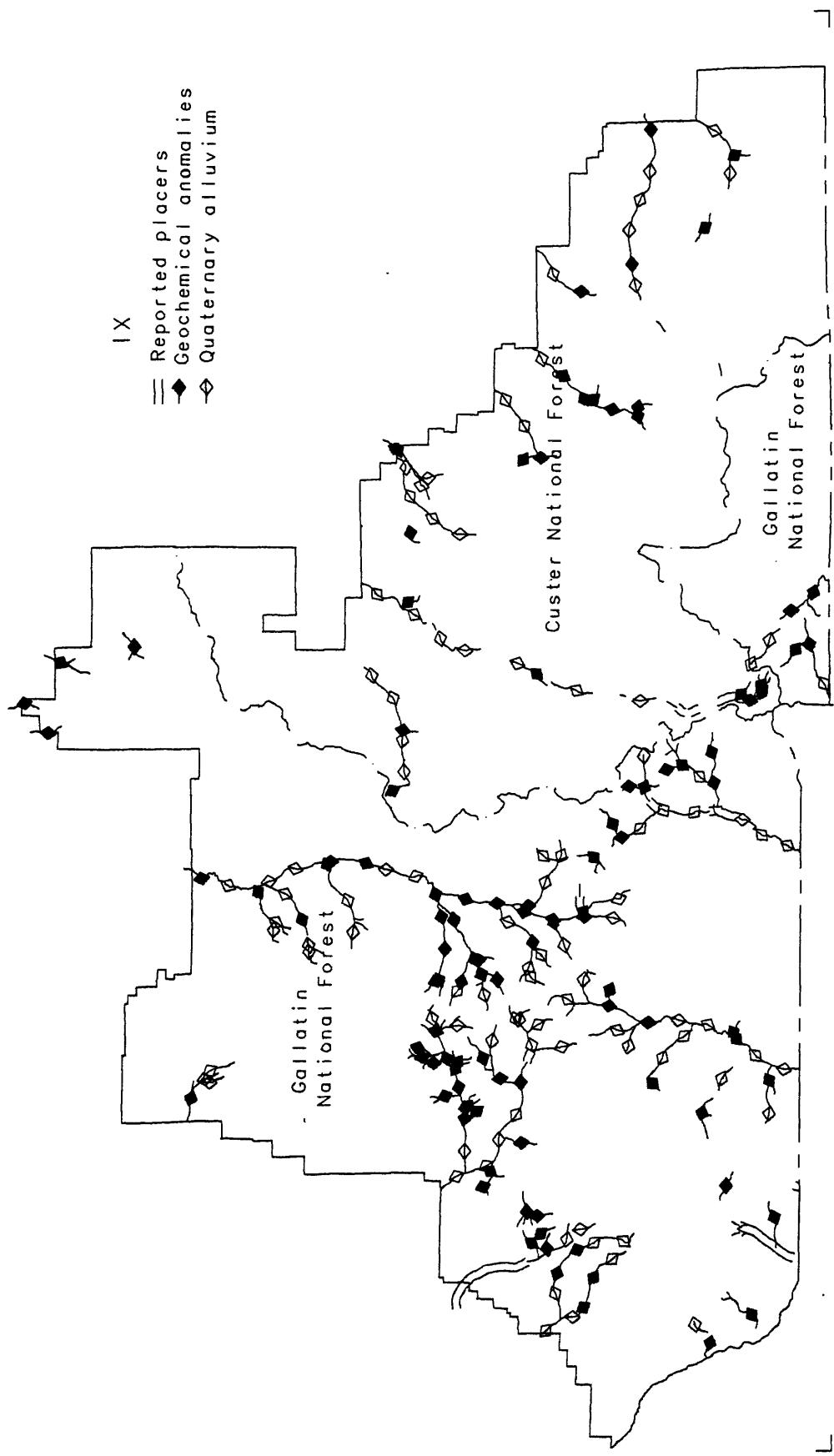


Figure G13.—Permissive tracts for placer gold deposits in the Absaroka-Bearooth study area. Double line, known placers. Filled diamonds, anomalous gold in stream sediments. Open diamonds, Quaternary alluvium in gold-bearing drainages.

Table G18.-Criteria for tract IX

Description: Stream valleys with evidence of gold-bearing alluvium.

Permitted deposit types

Expected geochemical signatures¹

Placer gold

Au, Ag

Tract	IX (Reported placers subtract)	IX (Geochemical anomalies subtract)	IX (Quaternary alluvium subtract)
Geologic criteria²	Segments of stream valleys with reported placer gold mines or prospects in Quaternary alluvium (Qs)	Segments of stream valleys within a 1 mile radius of stream-sediment sample localities that have anomalous concentrations of gold.	Segments of stream valleys that contain Quaternary alluvium (Qs) and are extensions of stream segments with reported placers or are extensions of stream segments that are proximal (radius of greater than one mile) to stream-sediment sample localities that have anomalous concentrations of gold.
Geophysical criteria	None.	None.	None.
Geochemical criteria³	Au, Ag	Au, Ag	Au
Mines, prospects, and occurrences	Largest production came from Emigrant Creek; recent exploration for additional placers along Emigrant Creek. Production from placers along Bear Creek in the Jardine area. Numerous reported occurrences, many of which appear to be unsubstantiated.	None.	None.
Comments	Many of the lode and other gold deposits in the ABSA were discovered by tracing sources of placer gold. Glacial alluvium and flood gold are problems in some streams of the ABSA (e.g., Boulder River), although some of these occurrences have historically sustained small-scale mining.	These areas are permissive for the occurrence of undiscovered placer deposits and may be favorable although the anomalous gold detected in stream-sediment samples may represent flood gold. These areas may also indicate extensions of known placer deposits.	These areas are permissive for the occurrence of undiscovered placers.

¹ Elements are listed in approximate order from most to least common and (or) significant.

² Map units given in parentheses refer to geologic map (plate 1).

³ Moderately to highly anomalous elements in stream-sediment samples.

and bicarbonate complexes precipitate iron (limonite, commonly pisolithic, that cements detrital and plant material) or manganese (crusts and nodules of psilomelane, pyrolusite) oxide minerals when more oxidizing conditions are encountered. Bog iron deposits have been mined in Europe and Scandinavia. Historically, such deposits have not been economically important in the United States.

Examples in the Study Area

Local occurrences of actively forming bog iron and manganese have been prospected in the Emigrant area. The low-grade, zinc-bearing manganese-wad and bog iron Midnight deposit in Arrastra Creek has been described as lenses and conglomeratic masses of sand, gravel, and cobbles cemented by iron and manganese oxide minerals (Reed, 1950). Inferred resources are 209,000 metric tons of ore averaging 10.7 percent iron and 3.5 percent manganese, although sample assays indicated that grades may be quite variable (Stotelmeyer and others, 1983) and include high-grade (68 to 75 percent MnO) spongy masses.

In the New World district, ferricrete deposits are exposed along Miller and Fisher Creeks and near springs in the vicinity of the old McLaren mine pit. These deposits consist of clasts of porphyry, limestone, and shale cemented by a fine-grained matrix of goethite (Johnson, 1991). None of these occurrences have produced ore.

NONMETALLIC DEPOSITS

TRAVERTINE

Hot spring travertine deposits (plate 19) related to the Yellowstone geothermal system are exposed in the southwestern part of the Absaroka-Beartooth study area at Gardiner, near the mouth of Bear Creek, and in the Emigrant district. The bedded travertine bench deposits at Gardiner are mined for building and decorative stone. Travertine has been continuously deposited at nearby Mammoth Hot Springs in Yellowstone National Park for the last 9,000 years. A minor amount of deposition is taking place at springs near the outlet of Bear Creek. Travertine was deposited at Gardiner about 47,000 years ago and again between 22,000 and 15,000 years ago (Sturchio and others, 1992). Hot springs and

travertine occurrences are localized along the Gardiner fault for a distance of 12 km, probably fed by Mission Canyon Limestone in the subsurface. Travertine deposition at Gardiner alternates with deposition at Mammoth through time, partly due to differences in the presence of glacial ice in the two areas in the recent past (Sorey, 1991), and the travertines from the two areas are isotopically distinct (Sturchio and others, 1992). The presence of plant casts in the bedded Gardiner travertine dated at 22,300 years indicates that glacial ice was absent at that time (Sturchio and others, 1992).

INDUSTRIAL STONE

In addition to the travertine mined as building stone, massive Archean granites and granitic gneisses in tract II and green quartzite in tract III are potential sources of decorative stone. In areas of extensive Paleozoic carbonate rocks (tract VII), Mississippian limestone and dolomite are prominently exposed in thick (650 to 1,300 ft) beds. These carbonate rocks are potential source rocks for cement and lime. Elliott and others (1983) noted the potential of rock units in the North Absaroka Wilderness Study Area for use as construction materials and pointed out that equally acceptable or superior sources of these same rock units are available in more accessible areas outside of the study area and closer to transportation centers.

CALCITE

Optical grade calcite occurs in veins in the sedimentary, volcanic, and volcanioclastic rocks of the Upper Cretaceous Livingston Group (Stoll and Armstrong, 1958). A roughly east-west-trending belt of calcite deposits borders the study area on the north, where very thick sequences of Livingston Group rocks are exposed. These deposits were mined for gunights in the 1940's and were locally mined for chicken grits. None of the deposits lie within National Forest boundaries, although calcite veins are present in prospect pits adjacent to the boundary in the Sliderock area and the rocks of the Livingston Group (map units K11, K1c, and K1d on plate 1) are present in the northern part of the study area. Although the calcite occurrences are not economically important, they may of interest to mineral collectors.

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APPENDIX

ALKALINE GABBRO-SYENITE ASSOCIATION

MINERAL DEPOSIT MODEL

By Michael L. Zientek

Environment: Linear belts of intrusive alkaline rock complexes that are temporally and spatially associated with calc-alkaline magmatic arcs at convergent plate margins. Lithologies are dominantly syenitic but range from ultramafic to mafic to felsic and have compositions that are spread along the boundary separating silica-oversaturated from silica-under-saturated rocks.

Principal commodities anticipated: Copper, gold, silver, platinum group elements (PGE)

Examples of typical occurrences:

Intermontane belt of alkaline plutons in British Columbia; Allard stock, Durango, CO; Trans-Pecos alkaline province, West Texas.

General references:

Barr and others (1976); Mortimer (1987); Barker (1987)

REGIONAL GEOLOGIC ATTRIBUTES

Tectonostratigraphic setting:

Alkaline magmatism that is a minor component in generally calc-alkaline interoceanic arcs or compositionally asymmetric arcs that occur in continental plate margin settings.

Regional setting:

In interoceanic settings, alkaline magmatism may occur near lateral edges of arc terminations, in rifted arcs, or where a fracture zone approximately perpendicular to the trench is being subducted. Examples include: Fiji, the Sunda arc of Indonesia, and the northern Mariana arc. In continental plate margin settings, alkaline plutonic and volcanic rocks typically occur in a belt parallel to the plate margin and the calc-alkaline magmatic arc but displaced

toward the interior of the continental plate. Plutons may occur in linear belts that may be several hundred kilometers in length. Examples include the volcanic rocks of the Aeolian arc, intrusive complexes in the Intermontane Belt of British Columbia (Barr and others, 1976) and the Trans-Pecos magmatic province of West Texas (Barker, 1989).

Age range:

Archean to Recent. Shoshonitic alkaline rocks have been described from the Archean Abitibi greenstone belt in Ontario (Windlay, 1977). Cenozoic alkaline magmatism has been described from a number of interoceanic and continental plate margin volcanic arcs in the circum-Pacific region and the Mediterranean. Duration of magmatism for a given magmatic province is on the order of tens of million years.

LOCAL GEOLOGICAL ATTRIBUTES

Host rocks:

Size and morphology of intrusion

Epizonal intrusive complexes that appear to represent the plutonic roots of alkaline volcanic centers and generally occur as small plutons, plugs, stocks, or ring complexes rarely more than a few kilometers to tens of kilometers in diameter. Laccoliths and sills are common in high level complexes. Clustering of plutons may suggest presence of subjacent plutons.

Igneous relations

Compositionally and lithologically zoned plutons are common. Typical lithologies include ultramafic rocks (such as clinopyroxenites), gabbros, diorites, syenodiorites, syenites, monzonites, and nepheline-syenites. Many intrusive centers are composite plutons; six to eight intrusive events are not uncommon. Plutons in which both silica-under-saturated and silica-oversaturated rocks are present

have been described. In other plutonic complexes, lithologies may be dominantly silica-saturated or undersaturated. Textures are typical for shallow level intrusions (fine grain size, porphyritic textures; chilled contacts; vesicular or miarolitic textures).

Composition of the parent magma:

Magmas may be peralkaline, metaluminous, or peraluminous. Alkaline compositions are variable in $\text{Na}_2\text{O}/\text{K}_2\text{O}$. Magmas that form these complexes generally belong to one of the following series: alkali olivine basalt - trachybasalt (hawaiite - mugearite - benmoreite) to trachyandesite - trachyte to phonolite. Source material for alkaline rocks may be different than the source for coeval calc-alkaline rocks. However, spatially and temporally associated calc-alkaline and alkaline rocks in the same arc complex generally share some geochemical characteristics, manifested by a compositional continuum between the suites (gradational compositional trends in major and trace elements spatially related to distance from the active subduction zone). Together with the calc-alkaline rocks, the alkaline rocks may have trace element geochemistry indicative of subduction related settings (low concentrations of titanium, zirconium, yttrium, and niobium and moderate to high concentrations of potassium, rubidium, barium, and strontium).

Associated rocks:

Coeval alkaline volcanic rocks (may be grouped into the shoshonitic association); spatially and temporally associated arc-related calc-alkaline rocks.

Mineralization:

Permissive geologic setting for PGE deposits:

Cu-Ag-PGE-enriched magmatic sulfide segregations in syenite

Small segregations of copper-rich magmatic sulfide in syenitic rocks or their differentiates. Production has rarely exceeded a few 100 tons. Sulfide minerals, typically chalcopyrite and bornite, occur interstitial to earlier crystallized silicate minerals or are concentrated into blebs or pods. Concentration information is presented below, typically platinum + palladium in the range of a few ppm to tens of ppm, with platinum greater than palladium. Silver typically in the range of 10's to 100 ppm with gold generally less than 1 ppm.

Copper Hill mine, La Plata mining district, Colorado

Sulfide minerals, principally chalcopyrite, occur

interstitially to cumulus minerals in a layered mafic syenite in the Copper Hill mine (Werle and others, 1984). Layering is described as phase layering caused by the appearance/disappearance of cumulus plagioclase in aegerine-augite-magnetite-apatite-zircon-sphene cumulates. The Copper Hill mine produced 2,336 tons of ore averaging 4.8 percent copper, 67.5 ppm silver, and 0.18 ppm gold (Eckel, 1949). Lower grade ore adjacent to the glory hole contained 1.87 percent copper, 17 ppm silver, and 0.17 ppm platinum group elements. Results from the analyses of two handpicked samples of ore reported by Eckel (1949) and of ore and sulfide concentrate reported by Mutschler and others (1985) are shown below:

Sample	Copper wt. percent	Platinum ppm	Palladium ppm	Gold ppm	Silver ppm
Hand picked samples	17.66 13.1	8.2 4.8	10.3 4.1	1.24 0.34	41.5
Syenite with high-grade chalcopyrite ore	18	2.88	1.92	1.23	130
Sulfide concentrate	27	3.935	2.32	1.74	160

Platinum-palladium-tellurium minerals (moncheite?) along with hessite, bismuthinite, enargite, sphalerite, gypsum, rare earth element minerals, and an unidentified silver-tellurium-sulfide phase have been identified during the course of SEM investigations of ore samples from the Copper Hill mine (R. Oscarson, written commun., 1990).

Comstock mine, Danville district, Washington

Chalcopyrite and bornite occurring as local concentrations in a syenite porphyry dike at the Comstock mine are reported to be enriched in platinum and palladium. No production has been reported. Textural descriptions of the ores are consistent with an origin by magmatic segregation (Parker and Calkins, 1964). Analyses of samples of ores and sulfide concentrates are reported by Mutschler and others (1985); their results and unpublished analyses by Zientek are listed below:

Sample	Copper wt. percent	Platinum ppm	Palladium ppm	Gold ppm	Silver ppm
Syenitic pegmatoids with chalcopyrite and bornite	1.3 4.9	<0.025 0.14	<0.003 0.01	7.9 53	0.22 0.176
Sulfide concentrates	36 35	3.45 3.94	0.19 0.225	78 87	0.099 0.2
90WAZ1 90WAZ2 syenites with disseminated chalcopyrite and bornite	7.6 7.1	0.019 0.089	0.023 0.0061	60 20	0.5 0.5
90WAZ3 90WAZ4 oxidized sulfides in syenite	0.19 0.19	2.3 0.73	0.17 0.94	<20 <20	0.4 0.35

Maple Leaf prospect, Franklin Camp, British Columbia, Canada

The Maple Leaf property is one of several prospects developed on chalcopyrite-pyrite-bornite ore in a shonkinite-pyroxenite that is a basic marginal differentiate to an augite syenite intrusion (Drysdale, 1915). Chalcopyrite and bornite are often surrounded by orthoclase feldspar or in small masses closely associated with it. Pyrite is disseminated throughout the ferromagnesian constituents of the rocks. Drysdale (1915) considered these deposits to be magmatic segregations. These deposits are enriched in the platinum group elements. Tonnage and grade of ore shipments reported in Hulbert and others (1988) and analyses of samples in Mutschler and others (1985) are reproduced below:

Sample	Ore metric tons	Copper wt. percent	Platinum ppm	Palladium ppm	Gold ppm	Silver ppm
1915 ore shipment	23	9.6	8.9	-	0.68	230
1917 ore shipment	17	5.6	6.85	-	4.5	89
Syenite with chalcopyrite	- -	1.1 <0.003	<0.025 <0.025	0.13 0.26	51 75	

Recent assays of samples from this property were as high as 14 ppm platinum + palladium with a median value for 12 samples of 0.45 ppm platinum and 0.36 ppm palladium (Hulbert and others, 1988).

Sappho claim, British Columbia, Canada

Pyrite and chalcopyrite mineralization is associated with Coryell syenomonzonite and shonkinite intrusions (Church, 1986). Mineralization occurs in (1) biotite shonkinite and sericitized feldspathic pegmatoids as blebs and pods; (2) skarns near the intrusive contact; and (3) shears. Production recorded from 1916 to 1918 was 112 metric tons averaging 6.06 percent copper and 197 ppm silver (Hulbert and others, 1988). Analyses of samples reported by Mutschler and others (1985) and Church (1986) indicate these ores are also enriched in platinum group elements:

Sample	Copper wt. percent	Platinum ppm	Palladium ppm	Gold ppm	Silver ppm
Pegmatitic shonkinite-monzonite with chalcopyrite	6.2 5.5	1.25 0.78	1.23 0.405	0.51 0.34	60 55
Grab sample	3.2	0.9	-	-	-

Recent assays of samples from this property were as high as 13 ppm platinum + palladium with a median value for 11 samples of 0.030 ppm platinum and 0.029 ppm palladium (Hulbert and others, 1988).

Copper King mine, Goose Lake area, Montana

Copper-rich sulfide mineralization that has been described as magmatic segregations occurs in coarse-grained syenite (syenite of Goose Lake; Elliott, 1979) at the Copper King mine (Lovering, 1929). High-grade ore exposed in a trench near the shaft house contains approximately 20 percent copper, 98 ppm silver, and up to 3 ppm platinum. Breccias and segregation veins have also been described (Simons and others, 1979). Analyses of samples of mineralized syenite from this area were reported by Simons and others (1979) and Mutschler and others (1985). These analyses and two new analyses are listed below:

Sample	Copper wt. percent	Platinum ppm	Palladium ppm	Gold ppm	Silver ppm
Stockpile, main shaft	6.8	1	0.9	0.3	37
Dump, collar of main shaft	0.16	-	-	trace	10
Stockpile, small shaft NE of main shaft	3.2	44	36	trace	102
Mineralized exposures near small shaft	minor	0.3	not detectable	trace	10 to 14
Syenite with high-grade chalcopyrite ore	9.7	2.42	1.27	0.37	38
Chalcopyrite vein in syenite	18	5.3	22.85	0.13	82
Pegmatitic syenite with chalcopyrite	22	13.6	6.43	0.19	81
Sulfide concentrates	32 31	1.66 0.165	1.355 3.967	0.83 0.043	110 100
91JH62 (massive sulfide ore)	19	5.8	4.3	0.099	68
91JH63 (chalcopyrite- rich vein)	18	0.59	1.8	0.077	68

CHAPTER H

HYDROCARBON POTENTIAL OF THE ABSAROKA-BEARTOOTH STUDY AREA: A PRELIMINARY SUMMARY

By William J. Perry, Jr., and Edward J. LaRock

The purpose of this report is to provide a qualitative assessment of the hydrocarbon potential of the Absaroka-Beartooth study area. A limited Laramide thrust overhang (hanging wall) is anticipated within the area on the primarily transpressional northern flank of the Beartooth uplift in southernmost Stillwater and Sweetgrass Counties, extending westward into central Park County (fig. H1-A; H2), a lateral distance of over 50 miles. Hydrocarbons have been trapped in small oil fields, chiefly noncommercial heavy oil/tar accumulations in Lower Cretaceous reservoirs, along the Nye-Bowler fault zone in southern Stillwater and western Carbon Counties on the Dean, MacKay, and Roscoe domes and Fiddler Creek anticline north of and partly overridden by the Beartooth front (respectively DD, M, R and F, fig. H1-A; see also fig. H3). Width of this fault zone is as much as 8 miles.

The northeastern flank of the Laramide Beartooth uplift has been thrust northeastward over the margin of the adjacent Crazy Mountains basin (fig. H1-B from Stone, 1983, fig. 6). Vertical separation along this fault system is believed to exceed 20,000 ft. This northeastward thrusting of the Beartooth block may have caused this block to override unbreached hydrocarbon reservoirs associated with the Nye-Bowler fault zone. Structures associated with the Nye-Bowler fault zone have been locally overridden by the Beartooth block. The Beartooth block was erosionally stripped to the Archean crystalline rocks during latest Paleocene and early Eocene time (Dutcher and others, 1986; Hickey and others, 1986; Geigengack and others, 1986). The maximum overthrusting occurs in the Red Lodge, Montana, area, where fault separation probably exceeds 10 miles. Petroleum has been discovered in other areas in similar situations (Gries, 1983).

The Cretaceous Thermopolis and Mowry Shales are the principal source rocks in the area. Petroleum source rocks of Paleozoic age appear to be absent

along the Beartooth front: the Phosphoria equivalent, the Shedhorn Sandstone of Permian age, is absent or thin (E.A. Maughan, USGS, oral commun., 1985; Graumann and others, 1986). Devonian Bakken Shale equivalents are likewise absent or thin in this area and here lack identified hydrocarbon source potential where present. Long distance migration of oil prior to development of the Beartooth uplift is required for oil accumulations from Paleozoic rocks to be present in the area.

Status of exploration: Southern Stillwater County and adjacent Park County have been extensively drilled during various episodes of hydrocarbon exploration. The Dean Dome, MacKay Dome, and Roscoe Dome heavy oil/tar accumulations lie within the area of the Nye-Bowler fault zone. These deposits have proven to be uneconomic to produce as the trapped oil is too viscous to flow easily (low API gravity) unless heated; the reservoirs are essentially tar sands. Only one well has been drilled in southern Stillwater County near the Beartooth Front, the now abandoned Texaco 1 Ostrum, in section 9, T. 6 S., R. 17 E., from which 15 ft of core in the Cretaceous Dakota Sandstone bled oil (fig. H1). Farther west several wells have been drilled along the northern boundary of the Beartooth frontal zone in east-central Park County, only one of which, a very shallow (2,728 ft) Pennsylvanian Amsden test, had a show of oil; all have been abandoned.

To the east, in section 32, T. 6 S., R. 18 E., in Carbon County, exploration around and mining of the Cruse oil seeps (fig. H1-A) mark sporadic unsuccessful efforts, beginning in 1889 (Montana's first recorded oil exploration) (Ames, 1991). Farther southeast, west of Red Lodge, the Amoco 1 USA, drilled in SW $\frac{1}{4}$ SE $\frac{1}{4}$ section 19, T. 8 S., R. 20 E. to a total measured depth of 15,800 ft (TVD 14,205 ft) was completed as a dry hole in 1987 (figs. H1 and H3). This well drilled Cretaceous rocks beneath the Beartooth thrust overhang in this hole. These rocks

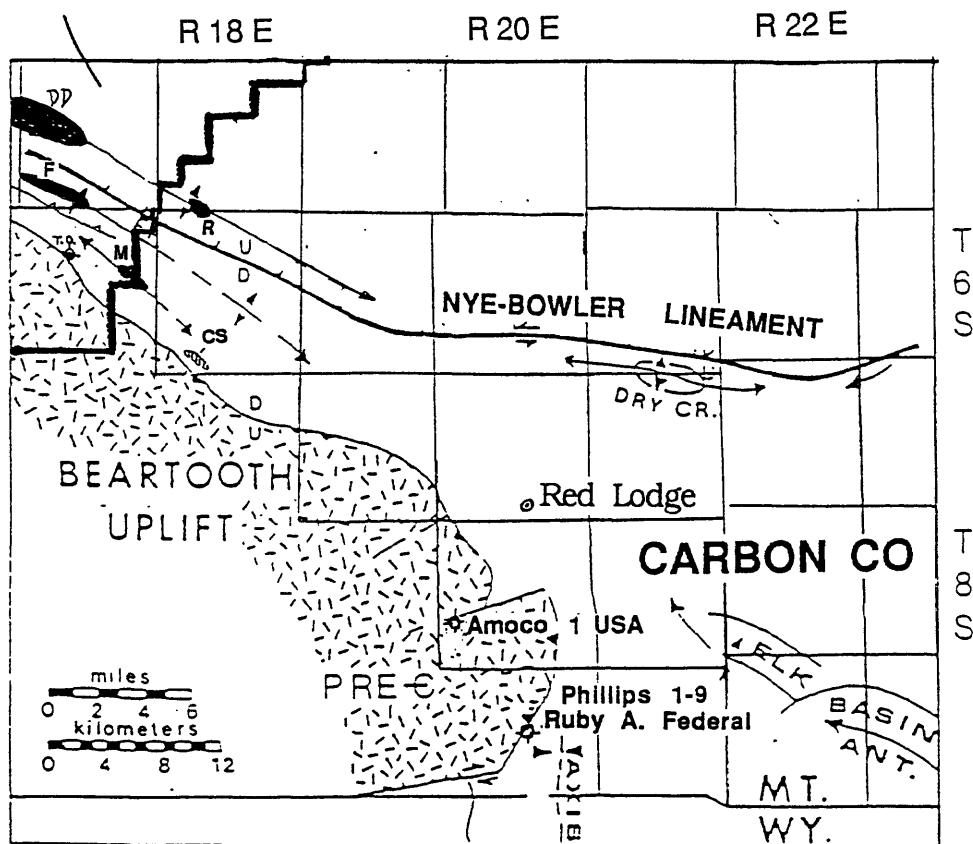
A**STILLWATER CO**

Figure H1-A.--Regional structure map on the Cretaceous Dakota Sandstone, showing structural elements associated with eastern Beartooth uplift and Nye-Bowler lineament, modified from Stone (1983). Heavy black line is boundary between Carbon and Stillwater Counties, Montana. Abbreviations: DD - Dean Dome oil field; F - Fiddler Creek oil field; M - MacKay Dome oil/tar accumulation; R - Roscoe Dome oil field; CS - Cruse seeps and oil plant, all abandoned; T.O. - Texaco 1 Ostrum drillhole.

B

SW

NE

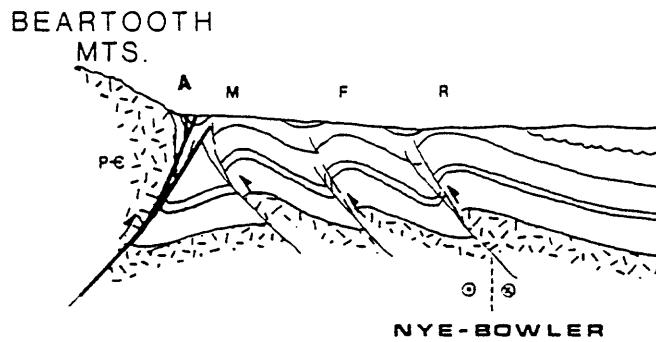


Figure H1-B.--Schematic north-south cross section near west edge of figure H1-A, showing structural relationships inferred by Stone (1983). A - area of overhang.

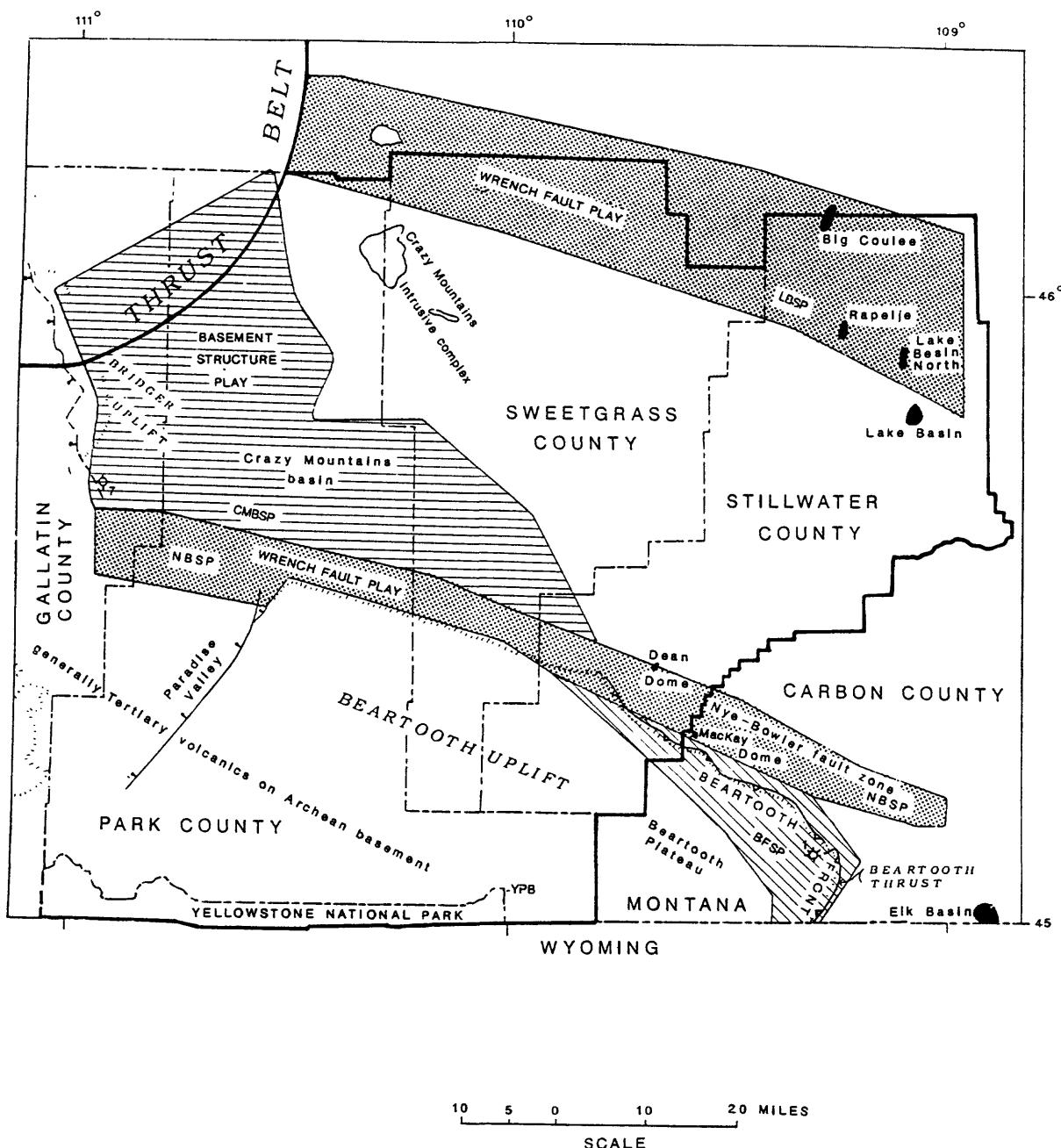


Figure H2.—Eastern part of southwest Montana oil and gas province, from Perry (1988), showing plays and subplays assessed in that report, selected drillholes, selected physiographic features, and selected tectonic features. BFSP - Beartooth front subplay of subthrust play, diagonally ruled. CMBSP - Crazy Mountains basin subplay of basement structure play, horizontally ruled. Other subplays of these two plays occur in the western part of the province (Perry, 1988). The wrench fault play is composed of LBSP - Lake basin subplay and NBSP - Nye-Bowler subplay, both shown with a screen pattern. YPB - Yellowstone Park boundary. Numbered well symbols refer to: 1, Amoco 1-USA, Carbon County, and 7, Sohio Petroleum 1-3 Moats, TD 14,041 ft, Gallatin County.

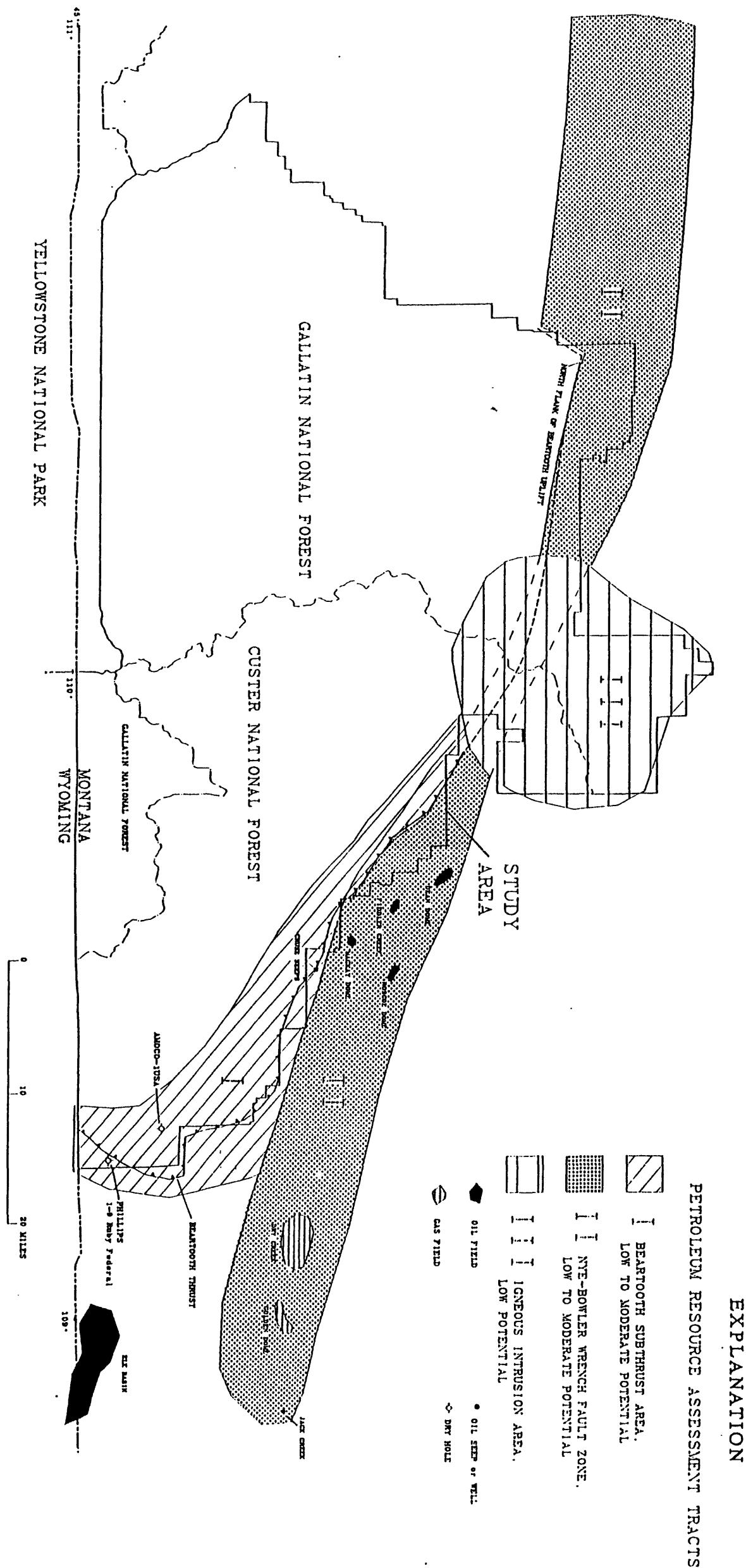


Figure H3.—Qualitative petroleum resource assessment tracts of the Absaroka-Bearooth study area.

reportedly contained shows of oil and gas (table H1, summary log of drillhole). More recently (July 18, 1990), Phillips Petroleum spudded the 1-9 Ruby A Federal drillhole in NW $\frac{1}{4}$ NW $\frac{1}{4}$ section 15, T. 9 S., R. 20 E. (figs. H1 and H3). This hole was directionally drilled back underneath the Beartooth front with its primary objective the Madison/Tensleep section beneath the thrust front. The hole was abandoned August 15, 1991, at a depth of 8,100 ft during a third sidetrack attempt. The maximum depth reached was 11,759 ft in the second sidetracked hole. No geologic information has been released. The greatest amount of displacement along the Beartooth frontal thrust zone is believed to occur south of Red Lodge, Montana, in the area of the Phillips drillhole. Here, depth to autochthonous Precambrian basement may exceed 25,000 ft.

Resource potential of Forest Lands: Perry (1988) identified areas of potential hydrocarbon occurrence in the southwest Montana oil and gas province (fig. H2). A low to moderate potential for oil and gas would appear to be present in Cretaceous rocks along the Nye-Bowler lineament and beneath the Beartooth front in the Red Lodge area southward into Wyoming, respectively areas I and II, figure H3. Because of extensive volcanism and associated igneous intrusion along the Nye-Bowler fault zone in area III, figure H3, there would appear to be a low potential for oil in that part of the Gallatin National Forest.

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Table H1.--Summary log of Amoco 1 USA, Carbon County, Montana

[Surface location SW $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 19, T. 8 S., R. 20 E. KB elevation 6,279 ft]

Formations or structures encountered	Measured depth	Vertical depth
First hole:		
Top of crush breccia of fault zone	8,354	8,326
Base of Precambrian metamorphic rocks and top of overturned Ordovician Bighorn section attenuated/abundant faults	8,421	8,393
Base of Triassic Chugwater/top of Permian Phosphoria Fm.	8,532	8,503
Base of Lower Cretaceous Cody Shale (overturned)	10,210	10,175
Five faults - first at:	11,300	11,259
approximate top, upright sequence	12,100	12,046
Upper Cretaceous Niobrara Formation	12,140	12,085
Dakota Formation (Lower Cretaceous)	13,624	13,463
Fuson Shale (Lower Cretaceous)	13,888	13,705
TD (in Jurassic Morrison Formation?)	14,013	
Shows of oil and gas in Upper Cretaceous Niobrara Fm.	12,140-50	
Second hole (1-A) sidetracked to southwest:		
Base of granite/top Phanerozoic	8,354	8,263
Base of shear zone/top Bighorn Dolomite	8,434	8,336
Paleozoic carbonates structurally thinned/stretched/missing		
Cody Shale (Upper Cretaceous)	11,300	10,828
Fault (Cody over Thermopolis)		
Dakota Formation (Lower Cretaceous)	12,342	11,601
Dinwoody Formation (Triassic)	14,178	12,975
TD (in Jefferson Dolomite, Devonian)	15,800	14,205
Bottom hole location about 1 mile southwest of surface location.		
Above information provided by petroleum industry sources and my examination of geophysical borehole logs.		

CHAPTER I

COAL AND COAL BED METHANE RESOURCES OF THE ABSAROKA-BEARTOOTH STUDY AREA

By Jean N. Weaver and James R. Gruber, Jr.¹

SUMMARY

Possibilities do exist within the Abasaroka-Beartooth Study Area (ABSA) for minable coal resources within the Cretaceous Eagle Sandstone but not within the Tertiary Fort Union Formation. There is some potential for coal bed methane resources in both units.

INTRODUCTION

Since about 1870, coal has been mined in Montana for commercial and domestic fuel. About 35 percent of Montana is underlain by coal and, until recently, most of the coal was used to make coke for smelting copper, as fuel for railroads, and for commercial and domestic heating (Sholes, 1985). Several historically important coal deposits are peripheral to the ABSA; these are the coal beds in the Late Cretaceous Eagle Sandstone near Livingston, Gardiner, Nye, and Bridger (east of Red Lodge) and coal beds in the Paleocene Fort Union Formation near Red Lodge (Bear Creek coal field).

At the turn of the century, coal from the Eagle Sandstone was mined for commercial and domestic fuel from various exposures along the upper Yellowstone, Boulder, Stillwater, and Clarks Fork River drainages. Areal distribution and the quality of coal deposits along the Beartooth front had an influence on the location of the Northern Pacific Railway route across Montana. With a rail line in place, the more accessible coal deposits at Livingston and Bridger became commercially successful ventures.

Coal from the Fort Union Formation in the Red Lodge area was also historically important in supplying fuel for railroads. In 1895, Carbon County's

coal production stood at 184,000 st (Sholes, 1985). By 1906, the Rock Creek East mine at Red Lodge had produced over 300,000 st of coal. Also in 1906, the Yellowstone Park railroad spur was built to open and provide access to the Bear Creek coal field. In 1907, work began on the West Side mine of Red Lodge. By 1918, 1,800 miners were employed and coal production increased to nearly 1.8 million st. In 1943, the Bear Creek coal field was the site of Montana's worst coal mine disaster (Finch, 1985). On February 27, 1943, a gas and coal dust explosion killed 74 miners at the Montana Coal and Iron Company's Smith mine. Following this disaster coal production declined and, in 1953, the railroad suspended operations to the Bear Creek coal field. Coal was transported from the only remaining mine (Brophy mine, northwest of Bear Creek) to Red Lodge until the middle 1960's. In 1978, Portland General Electric attempted to reopen the Brophy mine but, because of poor roof conditions and decreasing market demands, the effort was unsuccessful.

COAL BEDS IN THE EAGLE SANDSTONE

High quality bituminous coal is present in the Late Cretaceous Eagle Sandstone around the margins of the Beartooth Mountains. This coal resource extends into the ABSA and is only partly exposed and is generally deeply buried from Livingston eastward into the Bighorn Basin in the vicinity of Red Lodge, Montana (plate 1).

The Late Cretaceous Eagle Sandstone, in this area, is an eastward-pointing wedge of nonmarine, regressive-shoreline, and shallow-water strata. The Eagle Sandstone generally consists of a basal Virgelle Sandstone Member, a middle shale, and an upper sandstone unit. The underlying Late Cretaceous

¹Bureau of Land Management, Billings, Montana.

Telegraph Creek Formation is a sequence of shallow-water marine shale, siltstone, and fine-grained sandstone that is transitional between shale of Early Cretaceous units and the Eagle Sandstone. Overlying the Eagle Sandstone along the eastern portion of the Beartooth Mountains is a transgressive wedge of Claggett Shale that thins to the west. Along the western portion of the mountains the Eagle Sandstone is unconformably overlain by sedimentary and volcaniclastic rocks of the Livingston Group, and, in the Sliderock Mountain area, by Late Cretaceous andesite lava flows and volcanic debris flows (lahars). Source material for the Eagle Sandstone was the detritus shed by erosion of Laramide foreland uplifts in western Montana and Wyoming.

The Eagle Sandstone exposed near Livingston consists of sandstone, siltstone, sandy siltstone and silty sandstone, and coal beds. The coal-bearing sequence (approximately 600 ft thick) contains roughly 70 ft of total coal ranging in thickness from a few inches up to 20 ft. This sequence also consists of lagoonal, estuarine, and terrestrial deposits laid down near ancient shorelines (Roberts, 1966). Eastward, in the vicinity of Bridger, along the Clarks Fork Valley, the Eagle Sandstone ranges from 200 to 250 ft thick. Coal near Bridger has been mined at numerous locations from bituminous beds with a maximum thickness of 7 ft (Knappen and Moulton, 1930).

COAL AND COAL GAS RESOURCES OF THE EAGLE SANDSTONE

Although notable quantities of high quality coal exist in the Eagle Sandstone along the margins of the Beartooth uplift and within the ABSA, it is unlikely that this resource will ever be mined because of its thin lenticular nature, depth of burial, and complex geologic setting. Ironically, the characteristics that deem Eagle coal unminable enhance its potential as a coal gas resource. Estimates of methane in coal from the Eagle Sandstone Formation, at a depth of 1,000 ft, using Kim's (1977) equation, indicate volumes of gas up to 450 cubic-ft per st. Tectonics and volcanic activity, such as in the Sliderock Mountain area, may have resulted in increased metamorphism (higher rank coal) and overpressuring, which could increase the volume of gas per ton of coal even more significantly suggests that this potential resource should be examined more closely.

COAL BEDS IN THE FORT UNION FORMATION

The following discussion is a brief overview of the Paleocene Fort Union Formation and its coal resources in the northern Bighorn Basin of south-central Montana. The middle member of the Fort Union Formation contains economic coal deposits. However, the coal-bearing sequence encroaches near but does not enter the ABSA. Due to the close proximity (approximately 1 mile) of the coal deposits to the ABSA boundary, the Bear Creek coal field is discussed below.

The Bear Creek coal field, Montana, (fig. I1) contains an 850-ft section of the Lower Paleocene Fort Union Formation. Coal beds of previous economic importance have been found within the Fort Union in the Bear Creek coal field, east of the ABSA. Eight to ten coal beds, with thicknesses of 4 to 11 ft, are present in the Fort Union Formation, approximately 7 miles east of Red Lodge. At Red Lodge mine adits are present, but no coal of economic importance has been mined since the early 1900's. Quaternary gravel terraces on the west side of Rock Creek provide a thick cap over the Fort Union Formation. These thick gravels have deterred the mining of coal on the west side of Rock Creek. The thrust faults on the eastern edge of the ABSA have displaced the Fort Union Formation such that coal-bearing sequences have been cut off and no coal of any current or future economic importance is present within the ABSA.

The Fort Union reaches thicknesses of approximately 10,000 ft in part of the Bighorn Basin (Rawhins, 1986). The formation dips slightly (3° to 4°) to the southwest until it abuts the Beartooth Mountain uplift at the base of the mountain range (fig. I2). The southwest dip of the Fort Union and increased elevations due to the proximity of the mountains, explains the westward increase in depth of the coal beds. The Fort Union is laterally extensive and encircles the east sides of the Beartooth Mountains and ABSA. The Fort Union Formation on the west side of the Bighorn Basin ranges up to 8,540 ft thick and thins to the east, northeast, and southeast. East of Red Lodge, the Fort Union consists of: a lower barren sequence (5,000 ft), an intermediate coal-bearing sequence (800 ft), and an upper barren sequence which approaches 2,000 ft in thickness (fig. I2) (Rawhins, 1986). This upper barren sequence correlates with the conglomerates along the present Beartooth Mountain front

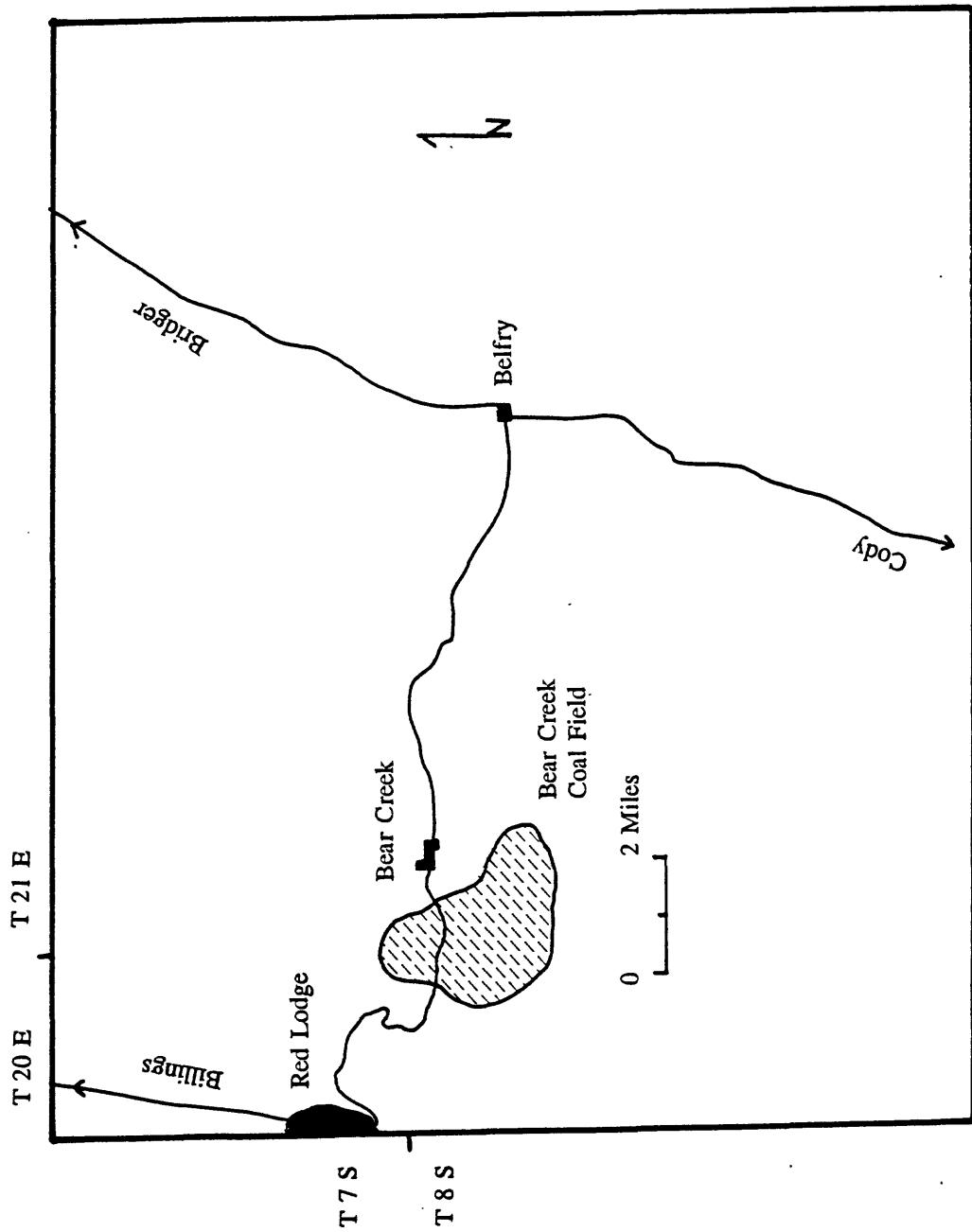


Figure II.—Location of the Bear Creek coal field. (Modified from Yuretich and Hicks, 1986.)

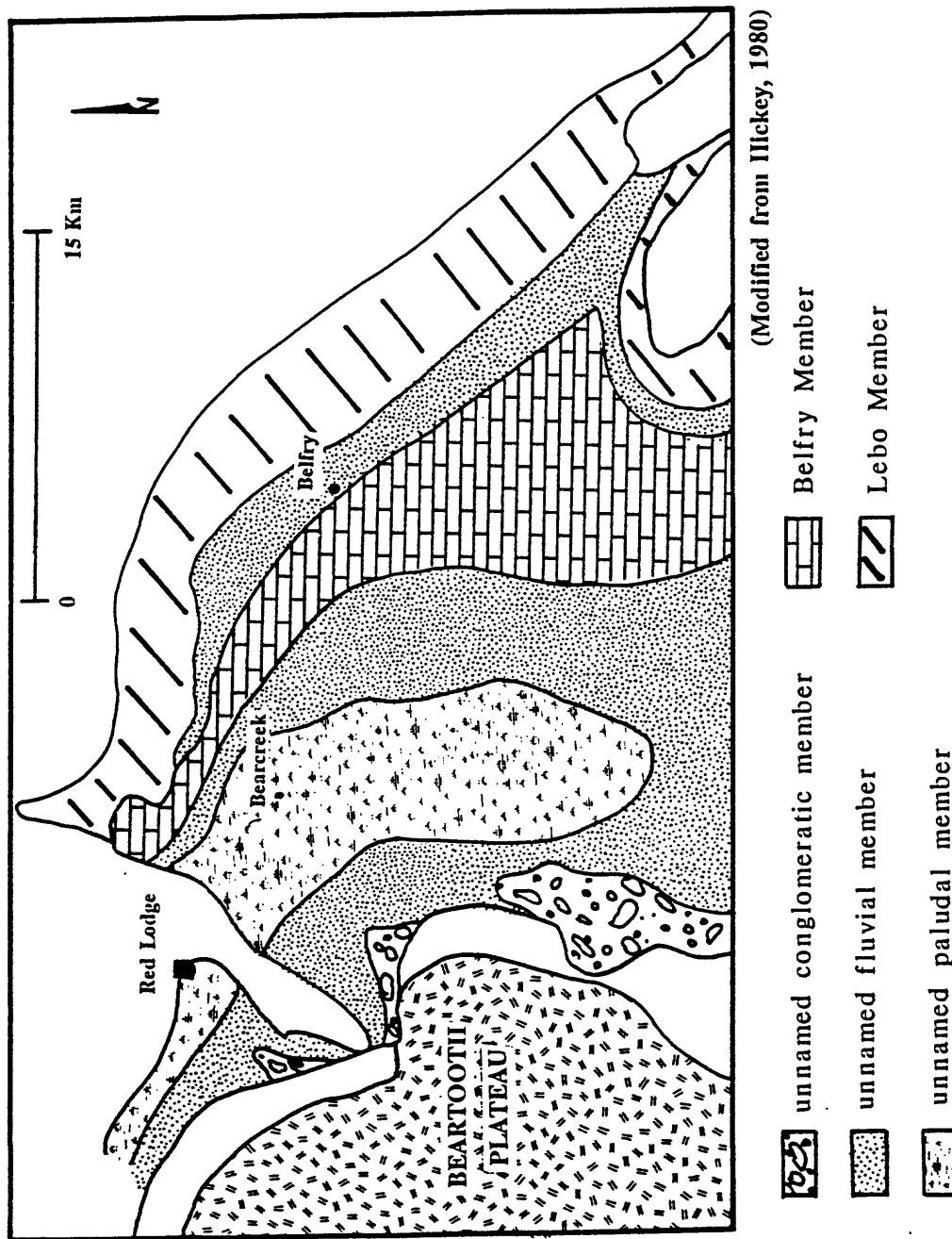


Figure 12.—Depositional systems within the Fort Union Formation near Red Lodge.

(Hickey, 1980; Flueckinger, 1972; Woodruff, 1907). These conglomerates, as well as the late Paleocene sediments that lack coal, reflect a change from paludal deposition to high energy fluvial deposition in this part of the basin following a major episode of structural deformation along the Beartooth thrust fault.

The Fort Union Formation in the Bear Creek coal field consists of conglomerates, sandstones, shales, and lignites which accumulated in a subsiding basin as a molasse-type deposit. Lacustrine and paludal environments were present along low lying areas of the basin axis (figs. I2 and I3). The Belfry Member of the Fort Union Formation represents the lacustrine facies and the unnamed paludal member represents the coal-bearing facies. The conglomerates were deposited along the mountain fronts on alluvial fans (Flueckinger, 1972; Jobling, 1974; Rea and Barlow, 1975). Along the northeastern flank of the Beartooth Mountains, the conglomerates grade basinward into sandstones, carbonaceous shales, and lignites. Subsurface data show that some of the major coal beds are laterally extensive within the Bear Creek coal field. The cyclic development of the coals reflects intermittent periods of long term basin stability. Alternating dominance of the sandstones suggests that their influx and distribution were controlled through episodic uplift of the nearby Beartooth Mountains (Weaver and Gruber, 1991). Fresh water limestones appear further east and southeast of the town of Bear Creek indicating lacustrine deposition. Along the eastern margin of the ABSA, the Fort Union Formation that is present is primarily the conglomeratic facies of the formation and thus is unlikely to host coal deposits of current economic potential. No coal beds have been reported from this area.

COAL AND COAL BED METHANE RESOURCES IN THE FORT UNION FORMATION

Resources in the Bear Creek coal field have been estimated to be 3,000,000 st in place (Rawlins, 1986); coal rank ranges from sub-bituminous B to sub-bituminous A and Btu values (British Thermal Units) range from 10,000 to 11,000 per pound (Rawlins, 1986). Coal analyses indicated high ash (10 to 12 percent) and high sulfur (1.2 to 3 percent). Average moisture content is between 10 to 11 percent, volatiles 36 percent and fixed carbon 42 percent (Rawlins, 1986). During 1990 to 1992, there was interest in drilling for coal bed methane in the Bear Creek coal

field. To date (December 1992), no discoveries of methane have been reported.

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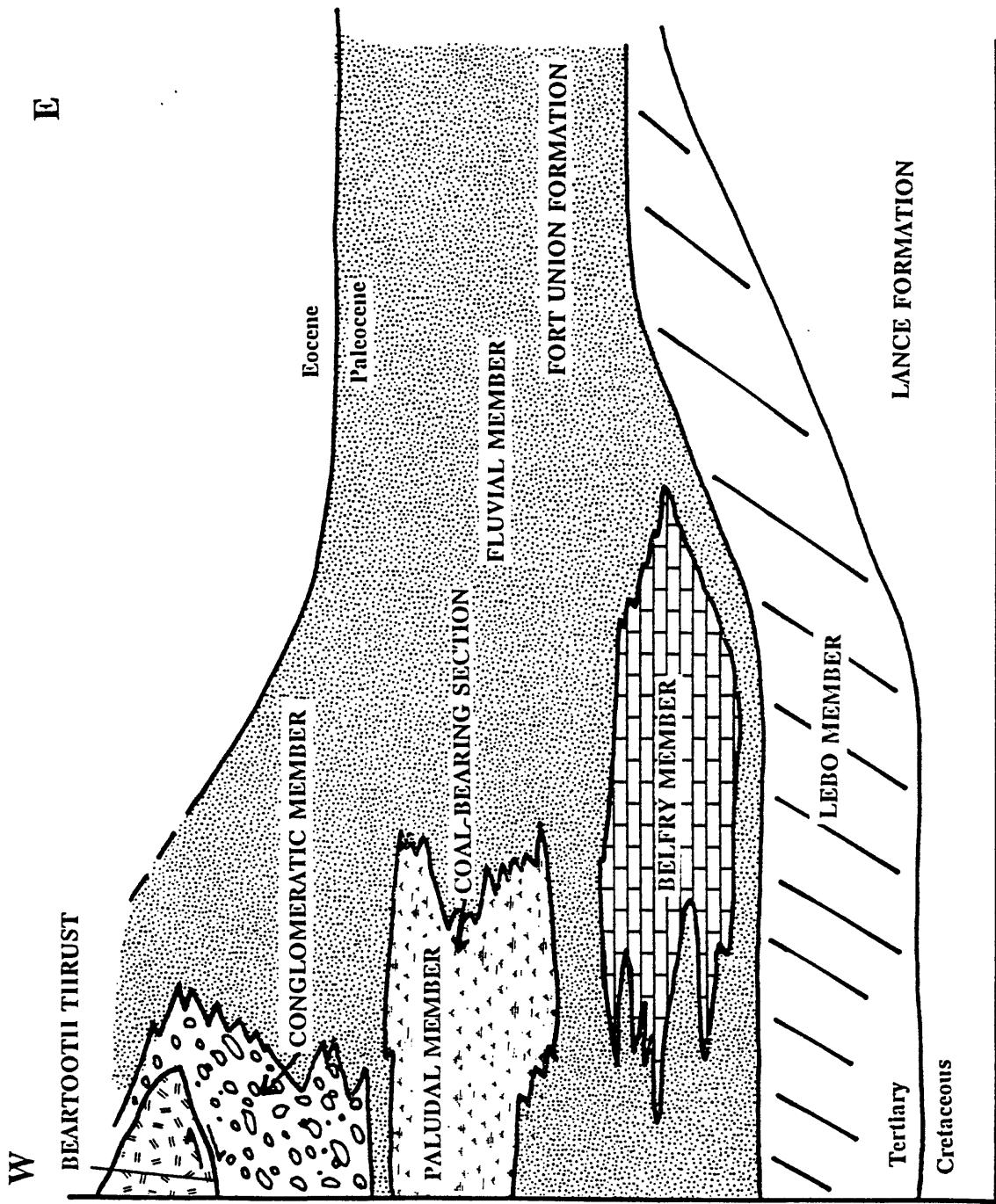


Figure 13.—Diagrammatic cross section of the Fort Union Formation, northern Big Horn Basin.

CHAPTER J

SUMMARY OF ESTIMATES OF UNDISCOVERED RESOURCES

By Jane M. Hammarstrom and Michael L. Zientek

QUALITATIVE ASSESSMENT

LOCATABLE MINERALS

Evaluation of available geologic, geochemical, geophysical, exploration, and mineral occurrence data indicates that undiscovered mineral deposits may be present in the Absaroka-Beartooth study area (ABSA). The most significant mineral deposit types present in the study area are the platinum-group-element (PGE) and chromium deposits associated with the Stillwater Complex, the gold-copper-silver skarn deposits in the New World district, and the Archean lode gold deposit in the Jardine district. Exploration for these deposit types is likely to continue, both in areas adjacent to identified resources and in other permissive or favorable areas that are open to mineral entry. Undiscovered deposits are likely to be similar to deposit types that are presently mined (for example, the Archean lode gold deposit at the Mineral Hill mine and the PGE-bearing ores in the J-M reef at the Stillwater mine), deposit types that have been discovered recently (such as the gold-copper-silver skarns in the New World district), and deposit types that have been mined in the past (placer gold deposits in the Emigrant district; polymetallic base metal vein deposits in the New World district). Deposits mined or explored in the past for copper (such as the Copper King mine at Goose Lake) and molybdenum (Emigrant district) are likely to be reexamined for precious-metal (gold and (or) platinum) potential. Reworking of old placers and reevaluation of previously delineated placer areas may be expected.

Other mineral deposit types present in the study area, such as Red Lodge chromite deposits, Stillwater nickel-copper deposits, and iron ores in magnetite skarn and banded iron formation deposits are less prospective at the present time because of economic factors (that is, below grade or tonnage levels considered economic). The potential for supergene

copper-rich zones related to porphyry copper deposits is low because of a history of extensive glaciation of the study area. Porphyry copper deposits in the ABSA may be too low grade (depending on trends in copper prices) to be mined for copper, but may be prospective for other commodities such as gold and for related deposit types such as skarns and breccia pipes.

Nine mineral resource tracts shown in plates 16-18 delineate areas that are permissive for the occurrence of various types of mineral deposits. Within the Stillwater Complex (plates 14 and 15), permissive tracts are delineated for Stillwater nickel-copper, Bushveld chromitite, Merensky Reef PGE, and PGE-enriched stratiform chromite deposits (plates 14 and 15; plate 16, subtract IVa). Favorable areas within some permissive tracts delineate areas most likely for exploration and discovery of ore deposits in the reasonably foreseeable future. Favorable areas within permissive tracts are indicated for Archean lode gold deposits (plate 16, area Ia1), for Algoma or Superior type banded iron formation deposits (plate 16, area Ib1), for porphyry copper-gold-molybdenum deposits (plate 17, areas Va1-Va5 and Vb1), and for polymetallic vein deposits (plate 18, areas VIIIa1-VIIIa5). The relative importance of these areas to the minerals industry depends largely on economic, rather than geologic factors. Many of these areas have been intensively explored in the past (Chapter E). Many areas that were explored in the past, mainly for copper, molybdenum, and (or) chromium, were not thoroughly evaluated for their gold or platinum (platinum-group elements) potential. Gold and platinum are the only metal commodities actively mined at the present time. Other commodities are present (nickel, copper, molybdenum, arsenic, lead, zinc, silver, and iron) in ore concentrations that are too small, too laterally discontinuous, metallurgically complex, too low-grade, or too inaccessible to be economic at the present time. Steep slopes (rugged topography) in some areas and glacial

overburden pose difficulties for some types of geophysical and geochemical prospecting and may hinder exploration and development of deposits.

LEASABLE AND SALABLE MINERALS

Permissive rocks for oil and gas, coal, and coal bed methane are present along the northern and eastern periphery of the Absaroka-Beartooth study area. There is a low to moderate resource potential for oil and gas in Paleozoic and Mesozoic sedimentary rocks and for coal and coal bed methane in Cretaceous sedimentary rocks. There is some undetermined potential for coal bed methane resources in the Tertiary Fort Union Formation within the study area.

Potential sources of dimension stone (Archean granites and granitic gneisses) and stone for industrial use (massive carbonate rock units) are present in the study area, but have not been exploited in the past and are more readily accessible outside of the study area. Travertine is mined near Jardine; other travertine occurrences within the study area are too small to be of commercial interest.

SEMIQUANTITATIVE ASSESSMENT

Three types of estimates are used to provide a semiquantitative assessment of undiscovered mineral resources in the Absaroka-Beartooth study area:

(1) probabilistic estimates of ore and metal contained in undiscovered deposits based on estimates of numbers of undiscovered deposits combined with grade and tonnage models for well-characterized deposits elsewhere (Singer and Cox, 1987);

(2) appraisal of geologic resources in the Stillwater Complex based on available exploration data and projections compatible with observed structures;

(3) estimates of undiscovered mineral resources for Red Lodge chromite deposits from previous studies.

Estimates of numbers of undiscovered deposits for four deposit types were combined and processed by computer simulation to provide an estimate of the total amount of ore and metals remaining to be found in the study area (table J1). Deposit types considered are (1) Archean lode gold deposits for gold and silver; (2) Algoma or Superior type iron (banded iron formation) deposits for iron and phosphorous; (3) porphyry copper deposits for copper, gold, silver, and molybdenum; and (4) gold-bearing skarn deposits for

gold, silver, and copper. Other commodities such as lead, zinc, tungsten, arsenic, and platinum-group elements may be present in these deposits or in other types of undiscovered deposits within the study area. Lack of availability (through under-reporting or lack of occurrence) of grade data for by-product metals and lack of appropriate models for some deposit types precludes assessment of all of the commodities that may be present in undiscovered deposits.

No attempt is made to allocate numbers of undiscovered deposits to individual Forests because Forest boundaries split some tracts into areas too small for the purposes of estimating deposits. For land-use planning however, mean ore and metal tonnage estimates based on probability distributions for geologically-constrained areas within tracts are allocated to each Forest by considering the relative areal proportion of each Forest within the tract. Percentile (such as median values) estimates cannot be allocated in this fashion. Mean values are additive and sums of mean metal and ore tonnage estimates for individual tracts (Chapter G) are equal to the totals for the Absaroka-Beartooth study area reported in table J1.

Estimates of geologic resources associated with three types of mineral deposits in the Stillwater Complex, summarized in table J2, are based on the synthesis of exploration data, calculations, and sets of assumptions described by Zientek in Chapter F of this report.

Chromite deposits near Red Lodge (table J3) were thoroughly evaluated in the 1940's (James, 1946) and restudied by Simons and others (1979). Both of these studies emphasized that these deposits are inferior in grade and tonnage to the chromite deposits in the Stillwater Complex and are unlikely to be attractive for development in the reasonably foreseeable future.

Most of the undiscovered deposits in the ABSA are likely to be present in the Gallatin National Forest, with the notable exceptions of parts of the Stillwater Complex and New World district. These two areas cross National Forest boundaries. The quantities of undiscovered resources reported in this assessment represent an estimate of in-place ore. The potential value of any exploitable commodities represented by these undiscovered resource estimates is contingent on an evaluation of economic factors, such as costs of exploration and development and commodity prices, because these and other factors determine whether or not a mineral deposit is an ore deposit.

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Table J1.—Summary of results of probabilistic estimates of in-place geologic resources in selected types of undiscovered mineral deposits in the Absaroka-Beartooth study area

[Results are reported in metric tons, rounded to 2 significant figures; see Chapter G for explanation of methods]

Results of computer simulation	Percentile values for the entire study area				Mean values	
	90th (more likely)	50th (median)	10th (less likely)	National Forest	Gallatin National Forest	Absaroka-Beartooth study area
Gold	20	90	400	164	16	280
Silver	50	700	5,000	1,600	290	1,900
Copper	500,000	3,100,000	17,000,000	5,500,000	1,000,000	6,500,000
Molybdenum	0	35,000	300,000	110,000	20,000	130,000
Iron	1,600,000	62,000,000	1,300,000,000	650,000,000	0	650,000,000
Phosphorous	0	3,000	640,000	280,000	0	280,000
Total ore	250,000,000	1,000,000,000	5,200,000,000	2,900,000,000	170,000,000	3,000,000,000

Table J2.--Geologic appraisal of resources associated with the Stillwater Complex

[Resource estimated to elevation of 520 m above sea level. Reported in metric tons of metal, rounded to 2 significant figures. See Chapter F for explanation of methods]

Area	Custer National Forest			Gallatin National Forest			Total
Estimate type	1	2	3	1	2	3	2+3
Deposit type	Stillwater low-grade copper-nickel deposits						
Nickel	550,000	1,200,000	230,000	27,000	--	--	1,430,000
Copper	530,000	1,200,000	220,000	15,000	--	--	1,420,000
Deposit type	Bushveld chromitite deposits						
Chromium as Cr₂O₃	4,300,000	4,000,000	6,500,000	--	--	--	10,500,000
Deposit type	Merensky Reef platinum-group element deposits (J-M Reef)						
Palladium	1,000	1,100	--	600	1,300	--	2,400
Platinum	310	320	--	180	390	--	710
Gold*	19	19	--	11	24	--	43
Rhodium*	11	11	--	6	13	--	24
Copper*	19,000	20,000	--	11,000	24,000	--	44,000
Nickel*	27,000	28,000	--	16,000	35,000	--	63,000

* By-product metal resources estimated from smelter ratios derived from data in R.W. Wallace (written commun., 1990) for concentrate and smelter products of the Stillwater mine. (Thompson, 1987; Naldrett, 1989).

Estimate type 1: Resource constrained by surface sampling, drilling, and underground exploration. Numbers for the J-M Reef are geologic resources thought to be present between surface outcrops and proposed adit levels.

Estimate type 2: Resource potential for extensions of identified deposits.

Estimate type 3: Resource potential for undiscovered deposits.

Table J3.--Estimates of chromium associated with Red Lodge chromite deposits

[Resource estimates reported in metric tons, rounded to 2 significant figures. Based on previous studies by James, 1946, and Simons and others, 1979]

Estimate type	1	2
Chromium as Cr ₂ O ₃	9,000	12,000
Ore	70,000	91,000

Estimate type 1: Estimated ore remaining in identified deposits (Simons and others, 1979); amount of chromium based on an average ore grade of 12.8 percent Cr₂O₃.

Estimate type 2: Estimated ore in undiscovered deposits (James, 1946); amount of chromium based on an average ore grade of 12.8 percent Cr₂O₃.