U.S. DEPARTMENT OF THE INTERIOR
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MINERAL RESOURCE ASSESSMENT MAP FOR VEIN AND REPLACEMENT DEPOSITS OF GOLD, SILVER, COPPER, LEAD, ZINC, MANGANESE, AND TUNGSTEN IN THE BUTTE 1°×2° QUADRANGLE, MONTANA

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MAP I–2050–D

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INTRODUCTION

PURPOSE AND SCOPE

The purpose of this report is to assess the potential for undiscovered vein and replacement deposits of gold, silver, copper, lead, zinc, manganese, and tungsten in the Butte 1°×2° quadrangle. This quadrangle, in west-central Montana, is one of the most mineralized and productive regions in the United States. Its mining districts, including the world famous Butte or Summit Valley district, have produced a variety of metallic and nonmetallic mineral commodities valued at more than $6.4 billion. Because of its importance as a mineral producing region, the Butte quadrangle was selected for study by the U.S. Geological Survey under the Conterminous United States Mineral Assessment Program (CUSMAP). Under this program, new data on geology, geochemistry, geophysics, geochronology, mineral resources, and remote sensing were collected and synthesized. The field and laboratory studies were also supported by funding from the Geologic Framework and Synthesis Program and the Wilderness Program. The methods used in resource assessment include a compilation of all data into data sets, the development of a descriptive model for vein and replacement deposits in the quadrangle, and the analysis of data using techniques provided by the Geographic Information System (GIS). This map is one of a number of reports and maps on the Butte 1°×2° quadrangle. Other publications resulting from this study include U.S. Geological Survey Miscellaneous Investigations Series Maps I–2050–A (Rowan and Segal, in press) and I–2050–B (Purdy and Rowan, in press); Miscellaneous Field Studies Map MF–1925 (Wallace, 1987); and Open-File Reports 86–292 (Wallace and others, 1986) and 86–0632 (Elliott and others, 1986). Reports on mineral resource assessment for several other types of deposits in the Butte quadrangle are in preparation.

GEOGRAPHIC SETTING

The Butte quadrangle is bounded by latitudes 46° and 47° N. and longitudes 112° and 114° W. (fig. 1). The city of Butte is in the southeastern part of the quadrangle; Helena, the state capital of Montana, is on the eastern edge; and Missoula is near the northwestern corner of the quadrangle. Most of the quadrangle is in Granite, Powell, Lewis and Clark, and Jefferson Counties and smaller parts are in Missoula, Ravalli, Deer Lodge, and Silver Bow Counties. The quadrangle includes a number of major and minor mountain ranges separated by intermontane valleys. The continental divide trends nearly south through the eastern part of the quadrangle to a point near Butte, then trends generally west near the southern boundary of the quadrangle. East of the divide, drainage is to the Missouri River, and west of the divide, to the Clark Fork, which has its headwaters in the vicinity of Butte.

GEOLOGIC SETTING

The Butte quadrangle contains igneous, metamorphic, and sedimentary rocks and deposits that range in age from Proterozoic to Quaternary. Proterozoic, Paleozoic, and Mesozoic sedimentary rocks are widespread, and Cretaceous and Tertiary plutonic rocks and associated metamorphic rocks occur in the cores of most mountain ranges. Volcanic and volcaniclastic rocks of Cretaceous and Tertiary ages are found mostly in mountain ranges in the eastern and northern parts of the quadrangle. Intermontane basins are filled with Tertiary and Quaternary sedimentary rocks and deposits.

The sedimentary record begins with rocks that were deposited during Middle Proterozoic time when the Belt basin occupied the area of the Butte quadrangle; clastic and carbonate rocks of the Belt Supergroup have a total thickness of about 16,000 m in the quadrangle. Mafic dikes and sills were intruded into the Belt rocks, probably during Late Proterozoic time. During Paleozoic time, near-shore and shallow-water carbonate and carbonate-bearing clastic rocks were deposited and have a total thickness of about 2,400 m; Paleozoic strata are mainly in the north, central, and northeastern parts of the quadrangle. Mesozoic sedimentary rocks were deposited in a foreland basin in which about 6,700 m of clastic and carbonate strata accumulated in the central part of the quadrangle and about 2,400 m of equivalent strata in the northeastern part of the quadrangle.

In Late Cretaceous time, numerous stocks and several batholiths were emplaced at mesozonal and epizonal depths. The Boulder, Idaho, Sapphire, and Philipsburg batholiths, composed of monzogranite and granodiorite, and numerous smaller stocks of diorite, granodiorite, and monzogranite were formed during this time. Hydrothermal activity during and following the waning stages of magmatism resulted in a variety of mesothermal and epithermal mineral deposits. The Elkhorn Mountains Volcanics, of Late Cretaceous age, occur as roof pendants and along the margins of the Boulder batholith and probably represent early extrusive phases of the magma which later formed the Boulder batholith.

Volcanism and erosion, as well as sedimentation in intermontane valleys, took place during the Tertiary. Extensive volcanism during early and middle Tertiary time formed the Lowland Creek Volcanics in the southeastern part of the quadrangle and volcanic fields in the Garnet Range and east of Lincoln. Volcanics of equivalent age also occur northeast of Deer Lodge in the northwestern part of the Boulder Mountains. Lacustrine and fluvial deposits accumulated in intermontane valleys during mid- to late Tertiary time, concurrently, in part, with volcanism which contributed volcanic debris to the sediment. During late Tertiary time, extensive pediments formed, and gravel,

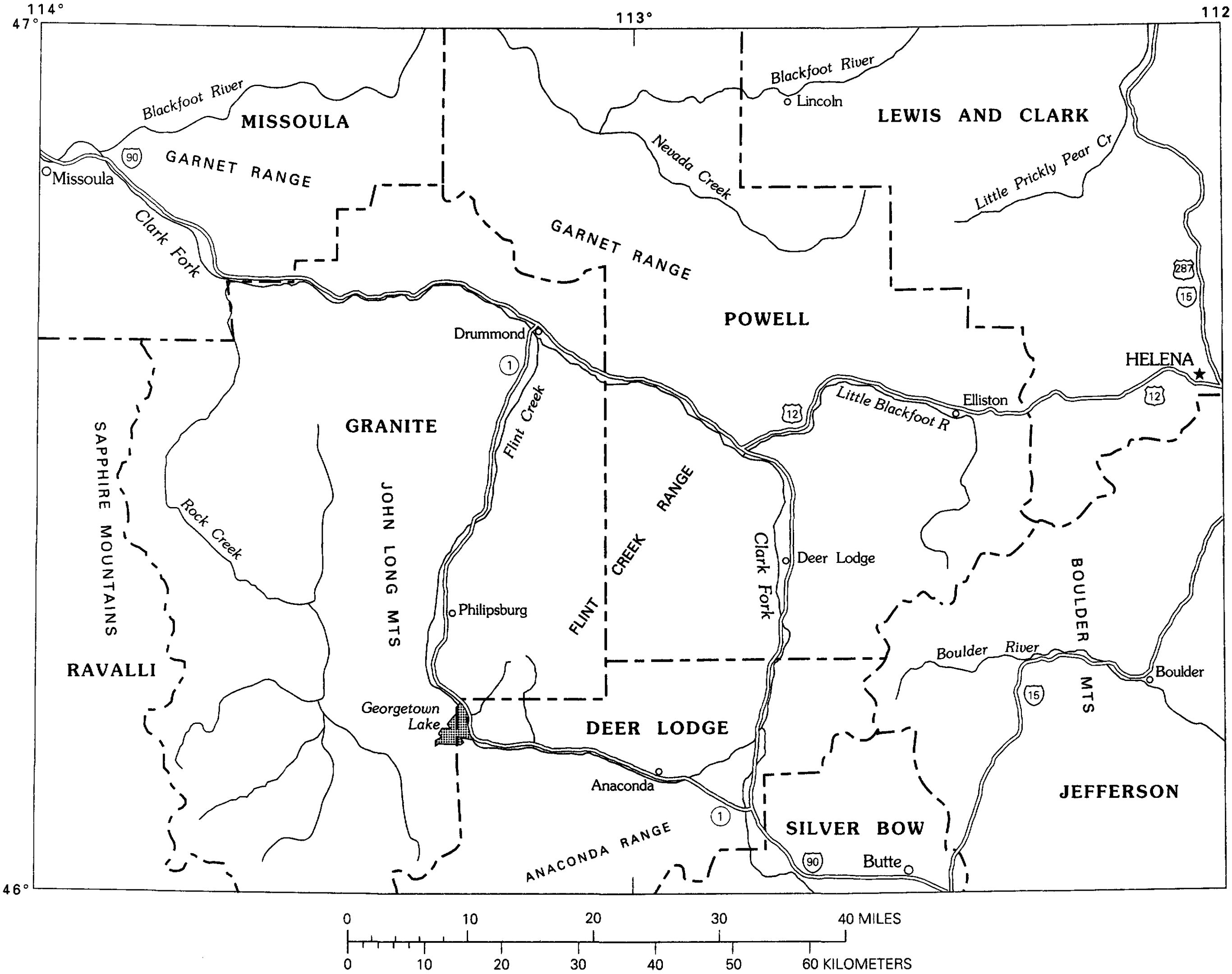

Figure 1. Index map of the Butte 1°×2° quadrangle.

some of which contains valuable placer deposits of gold, was deposited on the pediments.

Quaternary time was dominated by extensive alpine glaciation in most of the ranges in the quadrangle; icecaps occupied high areas in the Flint Creek and Anaconda Ranges and the Boulder Mountains. Four glacial events have been identified in the Flint Creek Range and multiple glacial events probably occurred in the other ranges as well. A series of glacial lakes formed during the last glacial event in the northeastern and western parts of the quadrangle. Post-glacial time was one of erosion and alluvial deposition in modern stream channels.

The principal structural elements of the Butte quadrangle are the Sapphire thrust plate, the southwestern end of the Montana disturbed belt, and strike-slip faults of the Lewis and Clark line (figure 2). The complexly folded and faulted Sapphire thrust plate occupies much of the western and central parts of the quadrangle and the Montana Disturbed Belt is in the northeastern part where it abuts faults of the Lewis and Clark line. The Lewis and Clark line consists of a broad zone of east-southeasterly to southeasterly trending faults that extends across the west-central and northeastern parts of the quadrangle. Some steeply dipping faults of the Lewis and Clark line may have originated during deposition of the Proterozoic Belt rocks; however, most faulting and folding resulted from a series of widespread late Mesozoic compressional events that formed a regional foreland basin as thrust plates moved generally from west to east. Most of the pre-Tertiary sedimentary rocks in the quadrangle have been moved to their present positions by thrust and strike-slip faults. The most intense deformation took place in the Late Cretaceous when laterally extensive thrust faults, zones of imbricate thrusts, and tight and overturned folds were formed. As a consequence of Late Cretaceous magmatism, most of which postdated the thrust and strike-slip faulting, the faulted terrane was

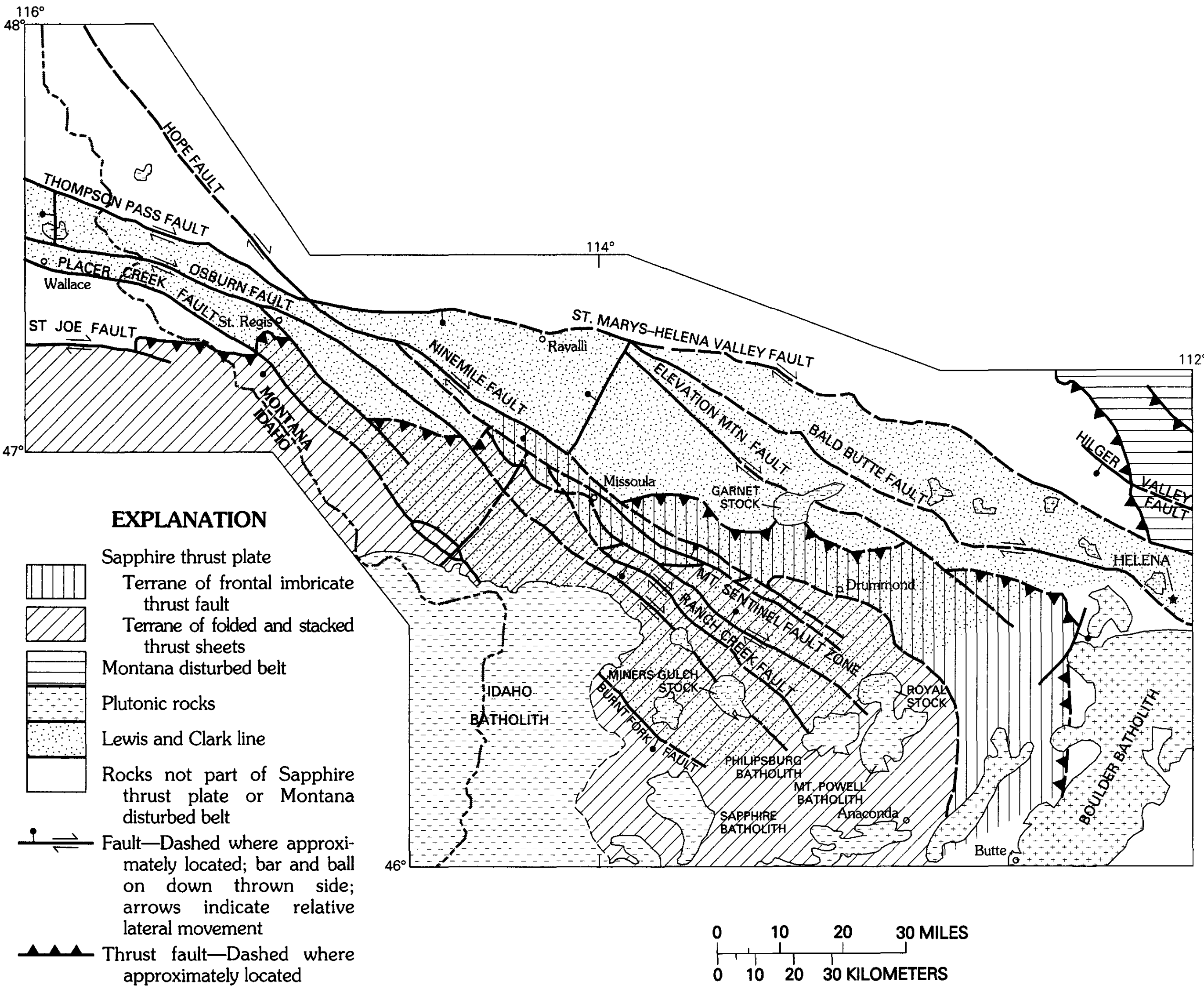

Figure 2. Principal structures and plutons of the Sapphire thrust plate.

welded into a resistant buttress that impeded further deformation. During early Tertiary time most of the present mountain ranges and drainage systems were formed by erosion in response to normal faulting. Along the east side of Deer Lodge Valley and north of Elliston, normal faulting continued into middle Tertiary time. Minor Quaternary faulting has probably continued along some normal faults and along some strike-slip faults of the Lewis and Clark line.

MINERAL DEPOSITS

Large quantities of a variety of metallic and nonmetallic mineral commodities have been produced from the Butte quadrangle during its long mining history. The Butte or Summit Valley mining district is one of the richest and most productive mining districts in the world, and the value of its metal output, more than $6 billion, is far greater than the combined total, about $400 million, of the rest of the quadrangle. The two most important types of deposits that have been mined in the quadrangle are hydrothermal vein and replacement deposits of base and precious metals and placer deposits of gold. Other important deposit types are porphyry or stockwork copper and molybdenum; skarn gold, copper, silver, and tungsten; vein and replacement manganese, tungsten, barite, and fluorite; and strata-bound phosphate.

Copper is the most important commodity produced from the quadrangle and has come mainly from the Butte district. This district also has yielded significant amounts of silver, zinc, manganese, lead, gold, cadmium, bismuth, molybdenum, selenium, tellurium, and sulfuric acid. Many other districts in the quadrangle have also been substantial producers of gold, silver, lead, zinc, and copper. The Philipsburg district was a leading producer of manganese and also has produced appreciable amounts of precious and base metals. Significant quantities of tungsten, phosphate, fluorite, barite, sapphires, limestone, and silica have also been mined from various districts in the quadrangle.

Mineral deposits and occurrences within the Butte quadrangle are of many types and ages. The oldest mineral occurrences of potential economic significance are of strata-bound copper and silver minerals in the Middle Proterozoic Belt Supergroup. Some, such as those in quartzite of the Mount Shields Formation, are similar to deposits at Troy, in northwestern Montana, which are presently being mined. Strata-bound deposits of phosphate rock hosted by the Lower Permian Phosphoria Formation have been mined in several parts of the quadrangle and are still being mined in the eastern part of the Garnet Range. The most important periods of ore deposition in the quadrangle were the Late Cretaceous and Paleocene Epochs, when most of the productive hydrothermal vein and replacement porphyry/stockwork and skarn deposits were formed. These are temporally and spatially related to plutonic rocks of Late Cretaceous age. Some younger hydrothermal deposits are associated with Eocene volcanism; a notable example is the Montana Tunnels mine, a large low-grade diatreme-hosted gold-silver deposit that is related to the middle Eocene Lowland Creek Volcanics. During Tertiary and Quaternary time, placer deposits of gold and other minerals formed by weathering of lode deposits and transportation and deposition of gold and other valuable minerals in gravel on pediments, in alluvial fans, and in stream channels.

VEIN AND REPLACEMENT DEPOSITS

Approximately 80 percent of all of the known mines and prospects in the Butte quadrangle are vein and replacement deposits containing precious and base metals. These deposits also account for most of the total production in the quadrangle. Outstanding examples are the large, high-grade copper-zinc-lead-silver veins of the Butte district, the silver veins of the Granite-Bimetallic mine (Philipsburg district), the gold-silver veins of the Drumlummon mine (Marysville district), and the silver-zinc-lead veins and replacement ore bodies of the Alta mine (Wickes district).

PRINCIPAL MINING DISTRICTS

The largest and most productive vein and replacement deposits are in the Butte district. Many Butte veins were mined mainly for their copper and silver content, but some also have produced large amounts of zinc, lead, and manganese. Other important deposits are in the Philipsburg, Black Pine, Marysville, Helena, Wickes, and Boulder districts.

Butte district

Following an early period of placer gold mining during the 1860's, the Butte district became one of the foremost silver-producing districts of the western U.S. in the 1870's. The first major discovery of copper was in 1882, when high-grade copper ore was found on the Anaconda and Colusa claims. Since then, copper has been the main product, but during several periods, the district has also been a leading producer of manganese and zinc (Miller, 1973).

The principal host rocks at Butte are monzogranite, alaskite, aplite, and pegmatite of the Cretaceous Boulder batholith. These rocks are cut by pre-mineralization quartz porphyry dikes. In the western part of the district the batholith is covered by postmineral rhyolitic rocks of the Eocene Lowland Creek Volcanics.

Most underground mining at Butte was conducted on large high-grade veins that form two principal systems, (1) the steeply dipping, east-trending veins of the Anaconda system and (2) the northwest-trending veins of the Blue system. These veins, and zones of closely spaced fractures called "horsetail ore bodies," formed during the main stage of mineralization (Meyer and others, 1968). District-wide zoning is evident in the mineralogy of the veins of the main stage of mineralization. The central zone is dominated by copper-bearing minerals; in the peripheral zone, manganese-, silver-, and zinc-bearing minerals are abundant and copper is sparse; and in the intermediate zone, between the peripheral and central zones, copper and manganese-zinc ores overlap. The main-stage veins have well-developed alteration envelopes; the thickness and type of alteration vary with stage and zone of mineralization (Meyer and others, 1968). Where veins are closely spaced, alteration envelopes coalesce to form areas of pervasive alteration, particularly in the central zone where the alteration envelopes are much thicker than in the outer zones.

The largest underground mines in the district, each of which produced more than 10 million tons of predominantly copper ore from 1875 to 1944, are the Anaconda, Leonard, Mountain Con, and West Colusa. About 25 mines produced between 1 and 10 million tons of ore each during this period and numerous mines in the district produced smaller amounts of ore (M.H. Gidel, unpub. data, on file with Montana Bureau of Mines and Geology).

Philipsburg district

The Philipsburg district is known principally for its large production of silver and manganese but has also produced significant quantities of zinc, lead, copper, and gold. Discovery of rich silver ores of the Hope mine in 1864 led to the construction of the first silver mill to be built in Montana Territory in 1867 and to the discovery of several more silver mines in the district. The most famous and productive mine in the district is the Granite-Bimetallic mine which yielded more than $32 million in silver and gold between 1882 and 1905 (Emmons and Calkins, 1913). From 1900 to about 1962 the district was a major producer of manganese ores and, following World War I, was the leading domestic source of natural battery-grade manganese dioxide (Prinz, 1967).

Mineral deposits of the district are partly in the Philipsburg granodiorite batholith of Late Cretaceous age and partly in a folded and faulted sequence of sedimentary rocks (Proterozoic to Jurassic) that is in contact with the batholith. The sedimentary rocks have been folded into a north-plunging anticline. The principal deposits are steeply dipping east- and northwest-trending quartz veins in granodiorite and Paleozoic carbonate rocks, quartz veins along bedding in Paleozoic rocks, and stratiform to irregular replacement deposits in Paleozoic carbonate rocks. Sedimentary host rocks are mainly carbonate beds of the Upper Cambrian Hasmark and Red Lion Formations and the Devonian Maywood and Jefferson Formations.

Black Pine district

The Black Pine or Combination mine, the largest mine of the district, was discovered in 1882 and was a major producer of silver and gold ore from 1888 to 1897 (Emmons and Calkins, 1913). After 1900, the mine had only sporadic production until it was developed as a modern underground mine using trackless equipment in 1974 (White, 1976). Since 1974, approximately one million tons of ore have been mined, and it is the principal underground mine in the Butte quadrangle (Waisman, 1985).

The mine has extensive underground workings along shallow-dipping quartz veins in quartzite of the Middle Proterozoic Mount Shields Formation. The veins cut bedding at a low angle (Waisman, 1985). No igneous rocks are exposed in the immediate mine area but the mineralization is probably related to an igneous source rock in the subsurface. The mineralogy and geochemistry of the ores are complex; besides silver and gold, the ores also contain copper, lead, zinc, antimony, arsenic, and tungsten.

Marysville district

The Marysville district is known principally as a gold producer but it also has had a large output of silver, lead, copper, and zinc. The most famous mine, the Drumlummon, was discovered in 1876 and produced an estimated $16 million in ore prior to 1928 (Pardee and Schrader, 1933). Base- and precious-metal vein deposits of the district are in granodiorite of the Cretaceous Marysville stock and in contact-metamorphosed Helena and Empire Formations of Middle Proterozoic age adjacent to the stock. Vein deposits are also in hornfels-facies Proterozoic rocks above and adjacent to an unexposed granite stock which has been penetrated by drill holes. The Drumlummon vein, which has been developed for 1,000 m along strike and to a depth of 490 m (Pardee and Schrader, 1933), contains lamellar quartz-calcite intergrowths, abundant manganese oxide minerals, and vuggy to brecciated textures suggestive of an epithermal origin. Gold-bearing placer deposits were mined in several streams which drain the district; the richest of these placers were found along Silver Creek, to the east of the Marysville district. An estimated $3 million in gold was produced from the Silver Creek placers prior to 1921 (Lyden, 1948).

Helena district

The Helena district is famous for rich gold placers, such as Last Chance Gulch, which was discovered in 1864, but lode gold deposits are also in the district. The lodes are vein deposits in granodiorite and vein, replacement, and skarn deposits in Paleozoic limestone at or near contacts with granodiorite. The largest lode mine, the Whitlatch-Union, was discovered in 1864, and it produced an estimated $6 million in gold prior to 1911. Most of the Whitlatch-Union mine workings are in granodiorite just south of the contact with Quadrant Quartzite of Pennsylvanian age (Knopf, 1913). The district lies along the northern margin of the Cretaceous Boulder batholith and spans the contact between granodiorite of the batholith and folded and faulted limestone, shale, and sandstone of Proterozoic, Paleozoic, and Mesozoic ages.

Wickes district

In the Wickes district, silver-lead and silver lode deposits and placer gold deposits were found almost simultaneously in 1864. One of the earliest discoveries, the Gregory lode, led to the construction of one of the first smelters in Montana Territory in 1867 (Knopf, 1913).

The Wickes district is within the Boulder batholith. In the western part of the district, many mines are in a large inlier of volcanic and volcaniclastic rocks consisting of two formations, the pre-batholithic Late Cretaceous Elkhorn Mountains Volcanics and the post-batholithic Eocene Lowland Creek Volcanics. The principal ore deposits have been base- and precious-metal vein and replacement bodies in monzogranite of the batholith and in andesitic volcanic and volcaniclastic rocks of the Elkhorn Mountains Volcanics. However, a large low-grade gold deposit, Montana Tunnels, was recently discovered in rocks of the Lowland Creek Volcanics and is now being mined (Sillitoe and others, 1985). This deposit consists of disseminated sulfide minerals and stockwork quartz-carbonate-sulfide veins in a diatreme breccia. Besides gold, the mine also produces silver, lead, and zinc. The most productive silver-lead mine in the district, the Alta mine, is credited with the output before 1893 of 1.25 million tons of ore valued at $32 million (U.S. Geological Survey, 1911). The Alta ore bodies are overlapping lenses, veins, and replacement bodies, mostly of galena, pyrite, tetrahedrite, and minor sphalerite, in a gangue of altered wall rock; they are along a steeply dipping east-trending shear zone in Elkhorn Mountains Volcanics (Becraft and others, 1963). In places, the wall rock is intensely tourmalinized and consists of nearly equal amounts of quartz, sericite, tourmaline, and pyrite (Knopf, 1913).

Boulder district

The largest mine in the district, the Comet, was discovered in 1874. It is reported to have yielded about $13 million to 1911 and has a total recorded production from 1904 to 1950 of 447,554 metric tons of ore (Becraft and others, 1963). The ore, containing gold, silver, lead, zinc, and copper, was in veins along an east-trending steeply dipping shear zone. Three main and several smaller veins consisted of galena, sphalerite, pyrite, and minor arsenopyrite, chalcopyrite, and tetrahedrite in a gangue of quartz, carbonate minerals, and altered wall rock (Becraft and others, 1963). In places, the wall rock is intensely tourmalinized and consists of nearly equal amounts of quartz, sericite, tourmaline, and pyrite (Knopf, 1913).

As in the Wickes district, the Boulder district is within the Boulder batholith and some parts of the district are underlain by volcanic and volcaniclastic rocks of the Elkhorn Mountains Volcanics and the Lowland Creek Volcanics. Most of the ore deposits are quartz-sulfide veins in monzogranite of the batholith.

METHODOLOGY OF MINERAL RESOURCE ASSESSMENT

The methods of mineral resource assessment used in this report are based in part on previous reports, such as those by Shawe (1981), Pratt and others (1984), and Harrison and others (1986b), and in part on discussions with colleagues at the U.S. Geological Survey including Jack E. Harrison and Frederick S. Fisher, coordinators of the Wallace (Idaho and Montana) and Challis (Idaho) CUSMAP projects, respectively. Most importantly, however, the methods evolved through a close cooperation with Robert C. Pearson, coordinator of the Dillon (Idaho and Montana) CUSMAP, which is immediately south of the Butte quadrangle. Although each of the previous CUSMAP mineral assessments has followed a different path, a general procedure has been developed, as follows.

1. Compilation of geologic, geochemical, geophysical, and remotely sensed data pertinent to the occurrence of mineral deposits.
2. Determination of the types of mineral deposits known to occur and that might occur in the quadrangle.
3. Apply available conceptual, descriptive occurrence models of mineral deposit types and recognition criteria for the occurrence of each type of deposit or develop models as required.
4. Evaluate the areal distribution and relative importance of various recognition criteria.
5. Assess the mineral resource potential based on the presence or absence of recognition criteria.

Much of the modeling approach and the use of favorable criteria was first applied by Pratt (1981) to the Rolla, Missouri, quadrangle. Harrison and others (1986b) adapted and expanded the methodology to the Wallace quadrangle. Pearson and others (in press, a, b) followed Harrison's lead but worked cooperatively with personnel at the Earth Resources Observations Systems (EROS) Data Center in Sioux Falls, South Dakota, in the development of GIS techniques for mineral resource assessment. These techniques added much more flexibility and innovation to the interpretation and presentation of data. This report follows closely the procedures developed for and applied to the Dillon CUSMAP.

The GIS methods for mineral resource assessment include data acquisition, data compilation and interpretation, and mineral resource assessment. For the Butte quadrangle, most of the data were acquired through new studies consisting of geologic mapping, geochemical and geophysical surveys, remote sensing and geochronologic studies, and examination of mines and prospects. These data, combined with data from previous published and unpublished sources, were compiled on maps at a scale of 1:250,000 or in tables. Interpreted and compiled data were entered into GIS. The types of mineral deposits that could be expected to occur in the quadrangle were determined, and descriptive occurrence models for these deposit types were established. Mineral resource assessment for principal mineral deposit types was accomplished on the GIS. For each deposit type, a series of submodels were developed. These submodels were based on favorable criteria, such as host rocks and associated plutonic rocks for each deposit type, on tabular and statistical summaries prepared using GIS, and on interactive processing on GIS. The completed submodels were then combined into a total score map (map K) from which a mineral resource assessment map (map A) was prepared. Map A shows the level of potential for the occurrence of vein and replacement deposits.

ACQUISITION, COMPILATION, AND INTERPRETATION OF DATA

MINERAL OCCURRENCE DATA

Mineral occurrence data for mines and prospects in the Butte quadrangle have been compiled by Elliott and others (1986). The mineral occurrence data list 1,111 mines and prospects grouped by mining districts and geographic areas. The mineralized sites are found throughout the quadrangle but 858 (78 percent) are in established mining districts and the remaining 253 (22 percent) are more widely scattered over the remainder of the quadrangle. The mines and prospects are classified into 13 deposit types. Seven hundred seventy two (69.5 percent) of these are classified as vein and replacement deposits of base and precious metals, 46 (4.1 percent) are vein and replacement manganese deposits, and 19 (1.7 percent) are vein and replacement tungsten deposits. The data on mines and prospects were compiled from many sources; the principal one was the U.S. Geological Survey (USGS) Mineral Resource Data System (MRDS). All of the MRDS records for the Butte quadrangle were checked for accuracy against original sources, revised if necessary, and updated. Additions that were made to MRDS records included data from published reports more recent than those cited in MRDS, unpublished records of the the U.S. Forest Service, and data collected during the Butte CUSMAP project and wilderness study projects conducted by the USGS and U.S. Bureau of Mines. The MRDS records are available to the public through USGS offices in Menlo Park, California, and Reston, Virginia. In the course of field work in the Butte quadrangle, during summers of 1980–1984, approximately 150 mineralized sites were visited in order to verify the data in the MRDS and other data and to collect additional information on geology, geochemistry, altered rocks, and mineral deposits.

GEOLOGIC DATA

The geologic map that was digitized and used for the mineral resource assessment is a modified version of the generalized geologic map of the Butte quadrangle (Wallace, 1987). Initially 38 geologic map units, 5 classes of faults, and axial traces of folds were digitized from this map. For the purpose of resource assessment, four units of the Belt Supergroup, the Garnet Range, Mount Shields, Empire, and Spokane Formations, were digitized from the detailed map of the Butte quadrangle (Wallace and others, 1986); furthermore, several Late Cretaceous plutons were distinguished from other Late Cretaceous plutons of granodiorite, granite, and monzodiorite. Addition of these map units allowed a more complete and detailed assessment of the mineral resource potential. The generalized geologic map was also modified by the extrapolation of geologic contacts and faults beneath younger deposits. This allowed the mineral resource assessment of the potential for vein and replacement deposits to be extended beneath postmineral surficial deposits.

The geologic map of the Butte quadrangle portrays new data obtained between 1975 and 1983, except for the area of the Boulder batholith. During the period 1975–1979 reconnaissance geologic mapping was completed in the northwestern and western part of the quadrangle. Between 1980 and 1983 new reconnaissance mapping was completed over the remainder of the quadrangle, and between 1979 and 1982 more detailed geologic studies were completed in six U.S. Forest Service Wilderness Study Areas. Main responsibilities for geologic mapping were shared by C.A. Wallace, who completed the western two-thirds of the quadrangle, and R.G. Schmidt (deceased), who completed the eastern third of the quadrangle and compiled the geologic information for the Boulder batholith (Wallace and others, 1986; Wallace, 1987).

The rocks most directly involved in the resource assessment of vein and replacement deposits are plutonic and volcanic rocks of Cretaceous and Tertiary ages and sedimentary rocks of Proterozoic, Paleozoic, and Mesozoic ages. Because of their association with mineral deposits, these rocks are described in some detail in the following pages, whereas postmineral Tertiary and Quaternary sedimentary rocks and deposits are not further discussed. Plutonic rocks, especially Late Cretaceous granodioritic rocks, are the most probable sources of hydrothermal fluids that formed vein and replacement deposits, as well as being hosts to vein deposits. The role of volcanic rocks is mainly as hosts for vein deposits, but in some mining districts, volcanic activity may also have been closely related to ore-forming events. Sedimentary rocks are hosts to both vein and replacement deposits. Paleozoic sedimentary rocks, especially carbonate units which are susceptible to hydrothermal and metasomatic replacement, are relatively more important hosts than Proterozoic and Mesozoic sedimentary rocks.

Sedimentary and volcanic rocks

The oldest rocks are part of the Belt Supergroup (Middle Proterozoic). The Belt Supergroup is dominantly a clastic sequence that consists in ascending order, of the Ravalli Group, the middle Belt carbonate sequence, and the Missoula Group. The Greyson, Spokane and Empire Formations of the Ravalli Group, in ascending order, are the oldest Belt rocks exposed. They have a minimum thickness of about 2,400 m in the northeastern part of the quadrangle. In general, the percentage of carbonate in argillite, siltite, and quartzite increases upward through these three formations. The middle Belt carbonate sequence includes two laterally equivalent rock units, each of which is estimated to be at least 3,000 m thick; the Helena Formation occurs over most of the quadrangle and the Wallace Formation occurs in the westernmost part of the quadrangle. The Helena Formation is a limestone-rich sequence of argillite and siltite, whereas the Wallace Formation is mainly dolomitic argillite, siltite, and quartzite. The Missoula Group is a dominantly clastic sequence that consists of, in ascending order, the Snowslip, Shepard, and Mount Shields Formations, the Bonner Quartzite, the McNamara and Garnet Range Formations, and the Pilcher Quartzite. This group is about 10,000 m thick in the western part of the quadrangle.

Paleozoic rocks range in age from Middle Cambrian to Early Permian, but the succession is incomplete because numerous unconformities separate formations. The section is about 2,800 m thick, and the formations are mainly dolomite and limestone; clastic rocks dominate in the upper part of the sequence and phosphatic beds occur at the top of the sequence.

The Middle Cambrian Flathead Quartzite, at the base of the Paleozoic section, is a fine- to coarse-grained quartzite that contains some glauconite. It overlies Belt rocks with a disconformity or slight angular unconformity, and in some places is absent. In the Sapphire thrust plate the Flathead Quartzite is overlain by the Middle Cambrian Silver Hill Formation (Emmons and Calkins, 1913). The Silver Hill has three informal members that are equivalent to the Wolsey Shale, Meagher Limestone, and Park Shale, which occur east and northeast of the Sapphire thrust plate. The lower member contains black, grayish-green, or grayish-red shale and siltstone, gray limestone, and fine- or medium-grained gray or rusty glauconitic sandstone. Phosphatic fossil debris and phosphatic oolites occur in this member. The equivalent Wolsey Shale is similar but contains more limestone. The middle member is mostly a thinly laminated, gray limestone that is mottled with orange-weathering siliceous dolomite streaks; the equivalent Meagher Limestone contains fewer thinly laminated beds. The upper member is a thin, green, waxy shale that contains some interbedded laminated limestone beds; the lateral equivalent, the Park Shale, is also a green, waxy shale that contains limestone beds mainly near the base.

Overlying the Silver Hill Formation and the Park Shale is the Middle and Upper Cambrian Hasmark Formation, which is a thinly laminated, gray and buff dolomite. The Red Lion Formation (Upper Cambrian) overlies the Hasmark Formation; a thin zone at the base of the Red Lion is composed of red shale, siltstone, and limestone, but most of the unit is gray, laminated limestone and interbedded, laminated, orange-weathering siliceous dolomite.

Overlying the Cambrian formations is the Middle and Upper Devonian Maywood Formation, which consists of grayish-red and yellowish-weathering dolomitic and calcareous shale, dolomite, limestone, carbonate-cemented sandstone, and siliceous sandstone. The Upper Devonian Jefferson Formation, above the Maywood Formation, is composed mainly of black and dark-gray dolomite and limestone interbedded with some shale beds near the base, and, near the top, light-gray limestone and dolomite breccia. North and northeast of the Sapphire thrust plate, the Upper Devonian and Lower Mississippian Three Forks Formation overlies the Jefferson Formation, but within the Sapphire thrust plate, the Three Forks is absent. The Three Forks Formation is composed of brownish-gray shale, siltstone, and limestone that contains rare sandstone beds.

Lower and Upper Mississippian rocks consist of formations of the Madison Group in most of the quadrangle, but two formations of the Tendoy Group occur near the bottom of the sequence in the western part of the Garnet Range (W.J. Sando, oral commun., 1986). Rocks of the Madison and Tendoy Groups are gray limestone, cherty limestone, and shaley limestone. The Upper Mississippian and Lower Pennsylvanian Snowcrest Range Group (identified by B.R. Wardlaw, oral commun., 1986), which was considered previously to be Amsden Formation (Emmons and Calkins, 1913; Kauffman and Earll, 1963; McGill, 1959; Ruppel and others, 1981), overlies the Madison Group and consists of reddish-gray shale, siltstone and sandstone, calcareous clastic rocks, gray limestone, and buff dolomite. The Quadrant Quartzite (Pennsylvanian) overlies the Snowcrest Range Group; it is a yellowish-gray and tan, fine-grained quartzite that contains a thin zone of dolomite at the base, north and northeast of the Sapphire thrust plate. Above the Quadrant Quartzite is a sequence of Lower Permian rocks that includes the Park City and Phosphoria Formations and the Shedhorn Sandstone, in ascending order. This succession is composed of gray and dark-gray shale, siltstone, limestone, chert, sandstone, and phosphatic rock. The Park City Formation is absent east and northeast of the Sapphire thrust plate.

Mesozoic sedimentary rocks form a succession of shale, sandstone, limestone, tuff, bentonite, volcaniclastic conglomerate, and carbonate-bearing clastic rocks that range in age from Middle Jurassic to Late Cretaceous (Emmons and Calkins, 1913; Kauffman and Earle, 1963; Gwinn, 1961; McGill, 1959; Gwinn and Mutch, 1965) and are about 8,500 m thick in the central part of the quadrangle. The principal sequences of rocks are, in ascending order, the Middle and Upper Jurassic Ellis Group, Lower Cretaceous Kootenai Formation, and Lower and Upper Cretaceous Colorado Group and Upper Cretaceous Montana Group. Upper Cretaceous rocks that overlie the Lower Cretaceous Blackleaf Formation (Colorado Group) differ in lithologic sequence in different parts of the quadrangle; in the northeastern corner of the quadrangle, in the Montana Disturbed Belt, the Blackleaf Formation is overlain sequentially by the Marias River Shale of the Colorado Group, Telegraph Creek Formation, Virgelle Sandstone, and the Two Medicine Formation of the Montana Group, whereas within the Sapphire thrust plate the Blackleaf Formation is overlain sequentially by the Coberly, Jens, and Carten Creek Formations (Gwinn, 1961) of the Colorado Group and the Golden Spike Formation of the Montana Group (Gwinn and Mutch, 1965, p. 1137; Schmidt, 1978, p. 41–43). Numerous unconformities separate the Mesozoic rock units.

Volcanic rocks in the Butte quadrangle range in composition from basalt to rhyolite and in age from Late Cretaceous (Robinson and others, 1968) to late Oligocene (R.A. Zimmermann, oral commun., 1987). The oldest volcanic rocks are mainly basalt and andesite, whereas the youngest generally are bimodal assemblages of basalt-andesite and rhyolite. The Late Cretaceous Elkhorn Mountains Volcanics (Ruppel, 1961, 1963; Smedes and others, 1962; Becraft and Pinckney, 1961; Becraft and others, 1963) form the most extensive volcanic field, mainly in the Boulder Mountains in the eastern part of the quadrangle. The rhyolitic Lowland Creek Volcanics, of middle Eocene age, occur along a northeast-trending zone in the Boulder Mountains, west of Butte and near Anaconda. Middle Eocene basalt, andesite, and rhyolite in the Garnet Range are younger than the Lowland Creek Volcanics (Carter, 1982). Other volcanic rocks of probable Eocene age include a bimodal andesite-rhyolite assemblage in the Elliston area, west of Helena, and bimodal basalt and rhyolite in the southern Sapphire Mountains. Andesite and rhyolite near Lincoln, in the northeastern part of the quadrangle, represent middle Eocene and late Oligocene eruptive sequences, respectively, according to fission track ages obtained by R.A. Zimmermann (oral commun., 1987).

Plutonic rocks

The oldest igneous event recorded in the Butte quadrangle is represented by Middle or Late Proterozoic gabbro and microgabbro dikes and sills that intrude Middle Proterozoic rocks of the Ravalli Group in the northeastern part of the quadrangle and the Missoula Group in the northwestern part (Nelson and Dobell, 1959, 1961; Wallace and others, 1986).

The greatest number of plutons and largest volume of plutonic rocks, consisting mostly of granodiorite and monzogranite, were emplaced during Cretaceous and early Tertiary time between about 100 and 46 Ma. In the eastern half of the quadrangle, these plutons include the Boulder batholith and a northwesterly trending group of stocks between Helena and Lincoln. In the western half of the quadrangle, these plutons include (1) stocks and batholiths in the Flint Creek Range, (2) stocks and a batholith in the Anaconda Range, (3) the Idaho batholith in the southwestern part of the quadrangle, (4) stocks and a batholith in the Sapphire Mountains, and (5) stocks in the John Long Mountains and the Garnet Range (fig. 2). Except for some plutons in the Flint Creek and Anaconda Ranges, all these plutons are post-tectonic and were emplaced after thrust faulting.

Most of the Boulder batholith, as well as several of its satellitic plutons, is in the Boulder Mountains between Helena and Butte and west of Helena. The batholith also extends to the east and the south, beyond the quadrangle boundaries. The principal rock types are granodiorite and monzogranite having an age range of about 78–71 Ma (Ruppel, 1961, 1963; Robinson and others, 1968; Wallace and others, 1986). Numerous productive vein and replacement deposits, including those in the Butte district, are within and near the Boulder batholith.

A group of stocks, which range in age between 97 and 52 Ma (H.H. Mehnert, written commun., 1985), are aligned along a northwesterly trend south of the St. Marys-Helena Valley fault. These stocks intrude Middle Proterozoic rocks, are principally granodiorite in composition, and are associated with numerous lode and placer deposits.

The principal plutons of the Flint Creek Range are the Philipsburg and Mt. Powell batholiths and the Royal stock. These plutonic rocks consist of granodiorite and monzogranite and range in age from about 78 to 63 Ma (Hyndman and others, 1972; Elliott and others, 1984; J.D. Obradovich, oral commun., 1983). Most mineral deposits in the range are related to granodioritic plutons such as the Royal and Cable stocks and the Philipsburg batholith. In the eastern part of the range, the older Racetrack Creek plutonic and metamorphic suite, which includes plutonic rocks ranging from granodiorite to diorite, is deformed by thrust faults, indicating a pre- or syn-tectonic emplacement of this suite.

Plutonic rocks of the Anaconda Range, in the southern part of the quadrangle, are mostly post-thrusting and Tertiary in age (about 55–46 Ma, J.D. Obradovich, written commun., 1982). However, an older granodiorite-diorite plutonic complex is cut by thrust faults and may be Late Cretaceous in age (Elliott and others, 1985; Heise, 1983; J.D. Obradovich, written commun., 1982). Few, mostly nonproductive, mineral deposits are associated with the plutonic rocks of the Anaconda Range.

Plutons of tonalite, granodiorite, and monzogranite, which range in age from about 78 to 60 Ma (Desmarais, 1983; J.D. Obradovich, written commun., 1977), occur along the western border and in the southwestern corner of the Butte quadrangle. These plutons are part of the Idaho batholith and generally lack mineral deposits (Elliott and others, 1986).

Numerous granodiorite and monzogranite plutons are scattered throughout the western part of the quadrangle in the Sapphire Mountains, John Long Mountains, and Garnet Range; these include the Miners Gulch, Garnet, Henderson Creek, Big Spring Creek, Welcome Creek, Wallace Creek, Gird Creek, and Gillespie Creek stocks. The age of most of these stocks ranges between 82 and 50 Ma (Wallace and others, 1986; J.D. Obradovich, oral and written commun., 1982). In the southern Sapphire Mountains, the Sapphire batholith (granodiorite and monzogranite) was intruded at about 73 Ma (Wallace and others, 1982). Stocks of pyroxenite and syenite occur in the southern Sapphire Mountains; these plutons are probably Cretaceous, but their ages have not been determined.

GEOCHEMICAL DATA

The geochemical data used for the mineral resource assessment of the Butte quadrangle were obtained from a sampling survey conducted by the U.S. Geological Survey during 1979–1982. A total of 3,410 stream-sediment, 2,639 heavy-mineral panned-concentrate, 2,407 rock, and 217 soil samples were collected. The maps used to formulate the geochemical submodel for the assessment of vein and replacement deposits were generated from the stream-sediment and panned-concentrate analytical data. These samples, unlike the rock and soil samples, were relatively evenly distributed throughout the quadrangle and were judged to provide the best data for the development of the geochemical submodel.

Sampling methods

Stream-sediment samples consist of a mixture of detritus derived from rocks and surficial deposits upstream from the sample locality; therefore, analysis of these samples gives a measure of the chemical composition of the source materials. Some metals, such as copper, lead, and zinc, which are common constituents of hydrothermal mineral deposits, show appreciable solubility in the zone of weathering and during transportation by fluvial processes. These and other soluble metals tend to be concentrated in the fine fraction of stream sediment as the result of adsorption and precipitation under favorable chemical conditions. Other metals, some of which may be ore related, occur in relatively insoluble heavy minerals; alluvium may be panned to concentrate these minerals to levels at which the metals may be measured by chemical analysis.

Stream-sediment samples, which consisted predominantly of silt-size material from alluvium, were collected from most first-order (unbranched) drainages and from all second-order and larger streams. At each sample locality, a composite sample of fine-grained material was collected and placed in a metal-free paper envelope. Each sample was air dried and sieved using an 80-mesh (0.17 mm) stainless steel screen, and the minus-80-mesh fraction of the sample was saved for analysis.

Panned-concentrate samples were collected near the stream-sediment samples but from coarser material usually containing gravel-size particles. This coarse detritus represents a higher energy depositional environment in the stream channel where a natural concentration of heavy minerals is most likely to occur. Concentrates were prepared by panning, usually at the sample locality, and placed in a plastic bag. Each sample was air dried and saved for analysis.

Analytical methods

All samples were analyzed to determine 31 elements by using a semiquantitative, direct-current arc emission spectrographic (SES) method (Grimes and Marranzino, 1968). Many samples were also analyzed for gold, arsenic, copper, lead, zinc, silver, bismuth, cadmium, and antimony using atomic-absorption (AA) methods described by Ward and others (1969), Thompson and others (1968), and Viets (1978) and for tungsten by colorimetric (CM) methods (Welsch, 1983). The precision of the SES method is given by Motooka and Grimes (1976). For the resource assessment of the Butte quadrangle, only the SES and AA analyses were used because the CM analyses had not been performed on the majority of samples.

All analytical results were entered into the Rock Analysis Storage System (RASS), a computerized data base maintained by the USGS in Denver, Colorado (Van Trump and Miesch, 1976). RASS contains both descriptive geological information and analytical data. The data are available on magnetic tape (McDanal and others, 1985) from the National Technical Information Service. Most of the data are also available from the USGS for 30-minute subdivisions of the Butte quadrangle in an open-file report (Campbell and others, 1982); however, this is a preliminary report that is incomplete for the eastern one-third of the quadrangle and contains some errors that have been subsequently corrected on the magnetic tape.

Data processing and interpretation

Analytical data from RASS were converted into binary form by data management and statistical reduction (STATPAC) programs (Van Trump and Miesch, 1976). Magnetic tape files of the data were created and sent to the EROS Data Center.

In many samples the concentration of one or more elements was outside the limits of determination for the analytical method used, there was interference which prevented the determination of the concentration of element(s), or the element(s) was not determined. In such cases the limits of determination were reported with one of the following qualifiers; N, not detected; L, detected but at less than the lower limit of determination; G, greater than the upper limit of analytical determination; B, not analyzed; or H, interference. The analytical data that contain qualified values are incomplete (truncated). These truncated data sets can create significant problems in the preparation of statistical summaries, in estimating the thresholds for anomalies, and in the preparation of geochemical maps. In order to avoid problems inherent in dealing with truncated data sets, the values qualified by "B" or "H" were eliminated and those qualified by "N", "L", and "G" in the analytical data were replaced by real numbers. The substitutions were as follows: values qualified by "N" were replaced by 0.3 times the lower limit of analytical determination for each element; values qualified by "L" were replaced by 0.7 times the lower limit of analytical determination; and values qualified by "G" were replaced by 1.5 times the upper limit of determination.

After substitutions for and removal of qualified values, the analytical data were converted into gridded (raster) files and geochemical "surfaces" were interpolated using a minimum curvature algorithm (Briggs, 1974). By scaling the chemical concentrations associated with the grid cells to correspond to brightness levels of pixels on a computer monitor screen (gray levels of 0 to 255), images of the interpolated geochemical surfaces were generated. The dynamic range (maximum minus minimum values) of actual data values was much greater than 255 for some elements and considerable compression of the data was needed to fit the 0–255 range. To reduce this effect, the gridded chemical concentration values for each element were transformed logarithmically, which results in smoothing of each geochemical surface and reduction of its relief. The images created by this transformation are probably more accurate representations of the distributions of the chemical concentrations because most minor and trace elements have approximate log normally distributed populations.

The percentage of data that is valid (unqualifed) for certain elements differs greatly between sample media (panned concentrate versus stream sediment) and (or) analytical methods (SES versus AA). The images derived from data having fewer qualified value substitutions were found to be more meaningful than those from data with substantially more replacements. Consequently, not all analytical methods and sample types were included for each element; the sample type(s) and analytical method(s) for elements used in the geochemical submodel for vein and replacement deposits are shown in table 1.

Geochemical thresholds (table 1), which represent the highest background concentrations, were selected for each of the single-element geochemical surfaces based on statistical distributions (histograms and percentiles) of the data, consideration of average crustal abundances of elements (Rose and others, 1979), and interactive processing of the geochemical surface images using video displays. An anomaly map was constructed for each element by reassigning a gray level greater than zero to pixels with brightness values corresponding to chemical concentrations above the threshold and zero to those at or below the threshold.

GEOPHYSICAL DATA

Geophysical studies indicate that magnetic and gravity data are applicable to mineral resource assessment of the Butte quadrangle. These data were acquired in regional surveys of the quadrangle or compiled from previous surveys. After compilation of all data to maps at a scale of 1:250,000, the maps were examined and compared with geologic (Wallace, 1987) and mines and prospects (Elliott and others, 1986) maps. It was evident that many of the geophysical anomalies could be correlated with geologic units and with the distribution of known mineral occurrences. Magnetic highs show a close spatial association with some plutons, especially with those of granodioritic, monzodioritic, or alkalic composition and of Late Cretaceous or Tertiary age. Since many mines and prospects of the quadrangle are associated with Late Cretaceous or Tertiary plutons of granodiorite and monzodiorite, there is an apparent positive correlation between magnetic plutonic rocks and mines and prospects. Examination of gravity data and comparison of these data to the geologic map indicated that several of the gravity lows are associated with sedimentary basins which are filled with Tertiary and Quaternary sediments, while other gravity lows coincide with mapped plutons, some of which have associated mineral occurrences. Therefore some of the gravity anomalies also have a positive correlation with mines and prospects of the Butte quadrangle. The important correlation of magnetic highs to mapped plutonic rocks can be objectively shown if it is assumed that the boundaries of a given plutonic rock mass dip steeply, at least in the shallow subsurface, and if it is assumed that the total magnetization has a direction and polarity consistent with those of the present earth's magnetic field. While the first condition of upper steep flanks of the rock mass can be proved only by drilling or other geophysical data, or both, the second condition of normally directed and polarized total magnetization is supported by rock magnetic data (Hanna, 1967, 1969, 1973a, 1973b, 1977, 1978; Hassemer and Lidke, 1986). A procedure was used which permitted the drawing of lines which encircle regions inferred to be underlain by a significantly thick mass of plutonic or geophysically similar rock. The thicknesses of the rock masses vary widely, perhaps in the range of 0.5 to 10 km. The specific procedure for drawing the lines will be described, following comments about the nature of the geophysical data.

The greatest utility of the geophysical data was its use as a tool for the assessment of mineral potential in the subsurface.

Magnetic anomaly data used in the study (U.S. Geological Survey, 1984) are based on total-field measurements made along 70 flight lines in an east-west direction, spaced 1.6 km (1 mi) apart at an average elevation of 2.7 km (9,000 ft) above mean sea level. Data along these flight lines were adjusted or controlled using data acquired along 11 north-south tie lines flown at the same elevation but with variable spacing. Anomalies were computed by subtracting the International Geomagnetic Reference Field (IGRF) 1983.65 from the adjusted total-field data. The IGRF is a reference field updated to the time of the survey and corrected for flight elevation. The resulting anomaly data

Table 1.—*Sample types and analytical methods used in the mineral resource assessment of polymetallic vein and replacement deposits*

[ppm, parts per million; pct, percent]

Element	Sample type	Analytical method	Threshold*
As	concentrate	spectrographic	200 ppm
Ag	concentrate	spectrographic	10 ppm
	sediment	spectrographic	2 ppm
	sediment	atomic absorption	3 ppm
Au	concentrate	spectrographic	20 ppm
	concentrate	atomic absorption	1 ppm
B	concentrate	spectrographic	300 ppm
	sediment	spectrographic	200 ppm
Ba	concentrate	spectrographic	7,000 ppm
	sediment	spectrographic	1,500 ppm
Bi	concentrate	spectrographic	10 ppm
	sediment	atomic absorption	7 ppm
Cu	concentrate	spectrographic	150 ppm
	sediment	spectrographic	100 ppm
	sediment	atomic absorption	200 ppm
Fe	concentrate	spectrographic	30 pct
	sediment	spectrographic	7 pct
Mn	concentrate	spectrographic	3,000 ppm
	sediment	spectrographic	2,000 ppm
Pb	concentrate	spectrographic	300 ppm
	sediment	spectrographic	200 ppm
	sediment	atomic absorption	150 ppm
Sb	concentrate	spectrographic	200 ppm
	sediment	atomic absorption	15 ppm
W	concentrate	spectrographic	50 ppm
Zn	concentrate	spectrographic	500 ppm
	sediment	spectrographic	300 ppm
	sediment	atomic absorption	500 ppm

*Highest levels of normal background concentrations.

were compared with data from 11 smaller surveys covering parts of the quadrangle (Johnson and others, 1965; U.S. Geological Survey, 1966, 1980a, 1980b, 1981; Mudge and others, 1968; Kleinkopf and Mudge, 1972; Douglas, 1973; Hanna, 1978; Lidke and others, 1983; Madson and others, 1983), many of which had been shown (Hassemer and Hanna, 1982) to exhibit inconsistencies relative to one another. This comparison of data sets served to verify the existence and locations of several important anomalies.

Although gravity anomaly data were not used directly for the drawing of lines outlining inferred plutonic rocks, these data were useful in some places for confirming occurrences of plutonic rocks, whether as lows over plutonic rocks intruded into high-density country rock or as highs over plutonic rocks flanked and (or) covered by low-density Tertiary and Quaternary sedimentary deposits. The gravity data used in the study include 2,325 observations within and immediately adjacent to the quadrangle (Hassemer, 1984, 1986), of which 1,900 are new, 262 were previously made by the U.S. Geological Survey, and 163 were acquired from the nonproprietary data files of the U.S. Department of Defense.

The procedure of drawing lines involved many steps, the first of which required processing and projecting the contractor flight-line data in preparation for gridding. The projected data were then gridded at a 1.5 km interval using a minimum curvature algorithm (Webring, 1981; Briggs, 1974). This interval corresponds approximately to the flight-line spacing and is conservative in the sense that interpolation errors are safely kept to a minimum. This data grid was then extended 15 minutes of latitude and longitude beyond the quadrangle boundaries in order to attenuate unwanted edge effects which inevitably result from further mathematical operations on the grid. This grid enlargement was accomplished by merging similarly projected and gridded data sets immediately adjacent to the quadrangle using analytical continuation and smoothing techniques, including application of an algorithm for splining under tension (Cline, 1974; Bhattacharyya and others, 1979; Hildenbrand, 1983).

Three sets of lines which tended to outline regions of relatively thick occurrences of plutonic rocks were generated by mathematical operations on values of the enlarged grid. No single set or pair of sets of these lines was sufficiently continuous to be used alone; thus all sets were used in combination. The various grid operators used to generate these sets of lines are types of two-dimensional wave-number filters which include derivatives, analytical continuation, spatial bandpass operators, reduction to north pole, and pseudogravity transformations. The mathematical procedure used was as follows: The gridded data were transformed first from the space domain to the wave-number domain by means of the computationally efficient Fast Fourier Transform (FFT); the Fourier coefficients were then multiplied by the particular wave number response of the appropriate digital filter, such as the pseudogravity filter; and finally the resulting Fourier coefficients were inversely transformed from the wave-number domain back into the space domain, yielding the desired filtered data. The sets of lines consist of either contours of the filtered gridded data or crest lines atop elongate contoured highs of a type of filtered gridded data.

The first set of lines was derived in many steps. First, the total-field data were transformed to pseudogravity anomalies by calculating the gravity field from magnetic-field measurements by means of Poisson's relation, which states that for bodies having uniform magnetization and density contrast, the magnetic potential is directly proportional to the derivative of the gravity potential in the direction of magnetization. Second, the magnitude of the horizontal gradient of these pseudogravity anomalies was computed, keeping in mind that the gradient is steepest—that is maximum—directly over the edges of steep-sided causative bodies. Third, the resulting grid of these gradient amplitudes was automatically contoured and elongated highs were noted. Last, crest lines atop the most conspicuous elongate highs were drawn automatically by computer. These resulting lines may be referred to as pseudogravity gradient crests.

The second set of lines was derived in a single step. The total-field data were transformed to reduced-to-pole anomalies. This transformation, like part of the pseudogravity transformation, removes the dependence of the total-field data on the angle of magnetic inclination. That is, the data which have been recorded in the earth's inclined magnetic field are converted to what the data would have looked like if the magnetic field had been vertical. The transformation removes anomaly asymmetry caused by inclination and thereby locates anomalies directly above the causative bodies. In the present study, after the reduced-to-pole anomalies had been automatically contoured, it was noted that zero contour lines tend to outline many exposures of plutonic rocks. This observed relationship is not generally to be expected; in the Butte data set, these zeros-of-pseudogravity anomalies presumably in many places correspond to inflection points of the anomalies where the curvature of the anomalies changes algebraic sign. This second set of lines thus consists of zero contour lines of reduced-to-pole anomalies.

The third set of lines was derived by computing the second vertical derivatives of reduced-to-pole anomalies and contouring these derivatives. Because the contoured derivatives displayed some obviously artificial wavelength features, these derivatives were bandpass filtered prior to automatic contouring. The third set of lines thus consists of zero contours of bandpass-filtered second vertical derivatives of reduced-to-pole anomalies.

The three sets of lines were integrated by initially drawing the first set where those lines approximately coincided with lines of the second set. At discontinuities, a combination of lines of the second and third sets were used to connect the lines of the first set. The resulting composite boundaries were last compared with mapped geology and Bouguer gravity anomalies.

Some areas of mapped igneous rocks which are larger than the 1.5-km spacing of the magnetic data grids fall outside of the areas of magnetic plutonic rocks shown on map H. It is inferred that these rocks are either quite thin and consequently small in volume and magnetic dipole moment or that they are relatively nonmagnetic. If relatively nonmagnetic, these rocks may be either leucocratic containing low amounts of mafic minerals or altered as are some parts of the Boulder batholith. The techniques used in this study are not suitable for discriminating altered igneous rocks.

REMOTELY SENSED DATA

Remote sensing studies included the mapping of limonitic and hydrothermally altered rocks from an analysis of Landsat data (Rowan and Segal, in press) and the mapping of linear features from an analysis of Landsat and side-looking airborne radar (SLAR) data (Purdy and Rowan, in press). Exposures of anomalously limonitic, possibly hydrothermally altered rock and soil, and linear topographic and tonal features, which may be expressions of structural features, were determined from a Landsat Multi-spectral Scanner (MSS) image (no. 2553–27331, recorded on July 28, 1976). Linear features were also mapped from a proprietary X-band SLAR image mosaic (recorded during December, 1979) with westward illumination and a spatial resolution of approximately 10 m.

Hydrothermally altered rocks

Limonite, which is a combination of ferric iron oxide minerals, can be identified on MSS digital images because of its diagnostic spectral reflectance in the wavelength region of 0.4–1.1 micrometers. Rowan and Segal (in press) processed the MSS image data, which covered nearly all of the Butte 1°×2° quadrangle, to display the characteristic limonite spectral reflectance and to distinguish limonite from dry vegetation, which has similar spectral reflectance. Color-ratio composite, instead of single-channel composite images, were used to subdue albedo and topographic illumination effects. Areas that were identified as having limonite anomalies were transferred from the color-ratio composite image to topographic maps. Subsequently these areas were evaluated in the field to distinguish between limonite that resulted from the weathering of hydrothermally altered rocks and limonite that developed from weathering of unaltered iron-bearing rocks. In many areas of the quadrangle, dense vegetation precluded reflectance measurements using MSS image data and, therefore, the discrimination of limonitic and hydrothermally altered rocks was prevented.

Linear features

The analysis of MSS and SLAR images was undertaken to delineate linear features, to relate MSS and SLAR data to known mines and prospects, and to develop criteria for mineral resource assessment. Linear features are defined as distinct linear to slightly curvilinear mappable elements; these generally represent linear segments of streams, ridges, and aligned terminations of topographic features. However, linear features may also represent tonal distributions. Purdy and Rowan (in press) excluded linear features that obviously reflect lithologic layering or cultural features and only mapped the linear features that were assumed to represent structures, such as faults, shear-zone fractures (open or filled with dikes or veins), and alignments of fold axes. After mapping, the linear features were digitized for subsequent computer-based data processing.

Initial analysis of the linear features indicated complex patterns with variations of length, density, and trends in different parts of the Butte quadrangle. Therefore the quadrangle was subdivided into 6 geologic domains based on patterns of linear features and their relation to areas of similar structural histories and lithology. A comparison of spatial association of linear features with known vein and replacement mines and prospects (Elliott and others, 1986) resulted in the subdivision of the 6 domains into 16 subdomains. Within each subdomain, the distribution of mineralized sites was compared with linear trends of six azimuthal ranges, N. 0°–29° E., N. 30°–59° E., N. 60°–90° E., N. 0°–29° W., N. 30°–59° W., and N. 60°–90° W. This comparison demonstrated that some linear features and intersections of linear features show close spatial associations with known mines and prospects and that others do not. Those associated with mineralized sites were used in the mineral resource assessment.

COMPUTER-BASED DATA PROCESSING

DESCRIPTION OF THE GEOGRAPHIC INFORMATION SYSTEM (GIS)

The development of procedures for mineral resource assessment and the preparation of the final mineral resource assessment map was facilitated by the utilization of a computer-based Geographic Information System (GIS). Various kinds of data that can be referenced geographically can be compared both qualitatively and quantitatively using a GIS. In a hypothetical case, GIS would be applied to an area for which there exists a set of maps, each of which contains a particular kind of data. For example, one map shows surface geology (geologic map) and another map shows the locations of mines and prospects. To compare the distribution of mines and prospects with geologic map units without using GIS, both maps would be prepared as transparencies at the same scale and superimposed. Visual and qualitative comparisons would then be made as to the association of mines and prospects with particular geologic map units. Quantitative relations could be derived but their derivation would be very time consuming particularly when three or more maps (data sets) are involved. With GIS, the maps are digitized and entered into GIS or, where data are already in a digital format such as aeromagnetic data, are entered directly into GIS. The relations between sets of data are compared quantitatively throughout the map area by the use of arithmetic operations and statistics. Thus the effects of two or more data sets at any particular location are analyzed simultaneously and both quantitative and qualitative relationships can be quickly determined. Using the example of the comparison of mines and prospects with geologic map units, relations such as the percentage of gold deposits associated with sedimentary units of Paleozoic age, the percentage of mines with large production in intrusive rocks, or the density of mines in Precambrian rocks are easily and quickly calculated. For some studies, where there are only two or three data sets of low complexity, GIS may not be advantageous, but where the number of data sets is large and kinds of data are more complex, the manual or visual approach can analyze these data objectively and uniformly only with the expenditure of large amounts of time if at all. The manual approach to CUSMAP mineral assessment was used by Pratt (1981), Pratt and others (1984), and Harrison, Leach, and Kleinkopf (1986b), and a comparison of manually derived results with those obtained using a GIS-based approach was made by Pratt and others (1983). For the mineral resource assessment of the Butte quadrangle, GIS technology and procedures offered great advantages because of the large number of data sets, the complexity of the data, and the lack of personnel and time to perform manual analyses of the data. Fundamental capabilities of the GIS include data entry, feature and attribute manipulation, overlay analysis, and the generation of tabular, statistical, and cartographic products. Additional features of the GIS that were useful in this study included capabilities to generate surfaces, to interactivly display interim results of processing, and to statistically analyze spatial relations between data sets.

The computers and software used in this study consist of three main subsystems—tabular, vector, and raster—for processing the diverse types of geographically referenced data. The principal software components of these subsystems are Relational Information Manager (RIM), ARC/INFO, and Interactive Digital Image Manipulation System (IDIMS).

The vector subsystem treats data as either discrete points, lines, or polygons (areas bounded by lines) and maintains information on the topologic relations among them. This subsystem is suitable for digitally encoding data presented on thematic maps and for processing those data sets that include features requiring representation as points, lines, or polygons. The vector subsystem used in this investigation is ARC. Both RIM and INFO software are designed for processing tabular data and provide powerful techniques for editing and combining tabular data and for preparing subsets of tabular data. Although used primarily for processing attribute and analytical data, spatial data can also be entered and processed by these software packages in the tabular subsystem. The raster subsystem, which treats all data as an array of grid cells, is much faster than the vector subsystem for many functions. It is useful for the treatment of surfaces and, once the grid-cell size has been selected, its resolution is fixed for any given surface. The raster subsystem uses IDIMS software. Interfaces between subsystems are of major importance; these provide the ability to edit, reformat, and transfer data sets from one subsystem to another.

Data were provided for computer processing in a variety of formats, each having its own requirements for entry into the GIS. Initially, most data were entered into the vector subsystem, a tabular subsystem, or into both. After manipulation, the data were reformatted and entered into the raster subsystem, in which most of the model development and resource assessment procedures were performed.

PROCEDURES USED FOR DATA ENTRY AND PROCESSING

All spatial data were referenced to a common map projection and coordinate system in order to be processed within the GIS. Data for the Butte quadrangle were compiled using the Butte 1°×2° National Topographic Mapping Series (NTMS) quadrangle (1958 edition, revised 1977) as the base map, which is a Transverse Mercator projection based on the Clarke 1866 ellipsoid and the 1927 North American Datum (Snyder, 1982). The principal elements are a central meridian of 113°, a scale factor of 0.9996, a latitude of origin of 46°, and no false easting or northing. All data used in this study were geometrically transformed to this projection, and to minimize the potential error in coregistering maps, all projection changes were performed using the General Cartographic Transformation Package (GCTP), which is incorporated in the vector and tabular subsystems of the GIS.

The data for the Butte CUSMAP included maps, tables, gridded data, and previously digitized information. Maps were digitized and entered into the vector subsystem. Tables were entered into the tabular subsystem. Gridded data grids were entered into the raster subsystem and previously digitized information was entered into the vector subsystem. Geologic structures (faults and traces of axial planes) were treated as lines; geochemical sample localities and mines and prospects were treated as points; and other data, such as geologic map units and boundaries of mining districts were treated as polygons.

Maps

Maps used for the mineral resource assessment included (1) a generalized geologic map that contained 38 rock units and 7 types of structures, (2) a map that showed the boundaries of 70 mining districts and other areas with mines and prospects, (3) a map that showed the surface and subsurface extent of principal magnetic rock bodies (plutonic rocks) interpreted from geophysical data, (4) a map that showed areas of limonitic alteration interpreted from Landsat data, and (5) a map that showed subdomains of linear features interpreted from Landsat and SLAR data. The line and polygon data from these maps were digitized using ARC/INFO. Each feature was numerically encoded with a unique identifier that could be used to access it as an individual spatial entity as well as with a class value that could be used to access it and all other features of the same type. The codes were subsequently used to edit, manipulate, and display specific map variables, associations, and relations. The geologic map required several iterations of digitizing and editing to add units and concealed contacts and to redefine units. This process of adding detail to the geologic map was very important for the mineral resource assessment of specific types of mineral deposits. After editing, these maps were converted to a raster format for entry into IDIMS.

Tables

Two sets of data, (1) stream geochemistry and (2) mines and prospects, were both initially in tabular form but were treated differently during data entry.

The stream geochemistry, which consisted of data from panned-concentrate and minus-80-mesh stream sediment samples, was reformatted from USGS STATPAC tabular format (Kork and Miesch, 1984) to RIM format. Information on location (latitude and longitude) were reprojected from geographic to Transverse Mercator coordinates and processed to produce raster maps. In this operation the analytical data were subjected to a minimum-curvature surface-generation algorithm (Briggs, 1974; Webring, 1981) to produce a raster map for each required element.

Data on mines and prospects were entered into INFO. Site coordinates were extracted from the tabular subsystem and processed to create a point map in the vector subsystem. This map was then reprojected from geographic to Transverse Mercator coordinates and rejoined with the attribute information in the INFO system. The data were then plotted according to required combinations of attribute values and converted from vector to raster images.

Gridded data

The only data in gridded format used in the development of the mineral assessment model was the digital elevation model (DEM) for the Butte quadrangle. The DEM data were entered into the raster subsystem and processed to create a topographic shaded-relief image, which was used as a base for display and interpretation of other data sets.

Previously digitized data

Linear features interpreted from remote sensing data consisted of geographic coordinates of the start and end of the line segments and the length and azimuth of each segment. The data were subdivided into six files based on ranges of azimuth. The data were reformatted to generate a geographic-coordinate file and an attribute file which were entered into the vector subsystem. After reprojecting into Transverse Mercator coordinates, all linear features were converted to raster files.

Data analysis

The development and application of procedures for mineral resource assessment were accomplished primarily in the raster subsystem (IDIMS) of the GIS. All data sets in the GIS were reformatted as gridded arrays containing 559 rows and 775 columns. Each cell in the arrays represents a ground area of 200 m by 200 m. Cell size was selected to be equivalent to the national map accuracy standards, which state "...for maps on publication scales of 1:20,000 or smaller,...not more than 10 percent of the points tested shall be in error by more than 1/50 inch" (Thompson, 1979, p. 104). At 1:250,000 scale, 1/50 in. equals 127 m. The minimum resolvable line (two points) and polygon (three points) adds to the overall locational error, and registering of points during the overlay process multiplies the errors. Thus a cell size of 200 m x 200 m is a compromise between accurate feature location and reasonable detail. Furthermore, computer-processing time required for a raster data set is directly related to array size; consequently, if the chosen cell size is very small, processing the resultant large array can require a considerable amount of computer time.

MINERAL RESOURCE ASSESSMENT

The procedure used in the mineral resource assessment of polymetallic vein and replacement deposits in the Butte quadrangle consisted of (1) the development a descriptive model for vein and replacement deposits, (2) the use of GIS techniques to develop submodels based on recognition criteria of the descriptive model, and (3) the combination of these submodels into a map that shows various levels of potential for the occurrence of vein and replacement deposits. The mineral resource terms used in this section are defined as follows:

Recognition criteria—Geologic features that determine the favorability for the occurrence of a mineral deposit (Pratt and others, 1984).

Diagnostic criteria—Criteria that are present in all or nearly all known deposits and, in most cases, that are considered to be required for the occurrence of a mineral deposit (Pratt and others, 1984).

Permissive criteria—Criteria that are present in some known deposits; their presence is considered to favor the occurrence of a mineral deposit but they are not required (Pratt and others, 1984).

Negative criteria—Criteria generally equated with the known absence of diagnostic criteria (Pratt and others, 1984).

The following definitions are from Goudarzi (1984):

Mineral assessment—An evaluation of the likelihood for the occurrence of undiscovered resources in an area.

Mineral occurrence—A place where a useful mineral or material is present; this term has no resource or economic connotation.

Mineral deposit—A concentration of valuable or useful metal or material sufficiently large that extraction at a profit may be feasible under current or future conditions.

Mineral resource potential—The likelihood for the occurrence of undiscovered mineral resources in a defined area. Mineral resource potential is preferred in the description of an area; favorability is best applied to a specific rock mass (or type) or geologic environment. The levels of resource potential can be specified as HIGH, MODERATE, LOW, NO, and UNKNOWN (Goudarzi, 1984) and VERY HIGH (this study).

LOW mineral resource potential—Assigned to areas where geologic, geochemical, and geophysical characteristics define a geologic environment in which the existence of resources is unlikely. Use of the low potential category requires specific positive knowledge; it should not be used as a catch-all category for areas lacking adequate data.

MODERATE mineral resource potential—Assigned to areas where geologic, geochemical, and geophysical characteristics and the application of mineral deposit models indicate a geologic environment favorable for occurrence of mineral deposits.

HIGH mineral resource potential—Assigned to areas where geologic, geochemical, and geophysical characteristics and the application of mineral deposit models indicate a geologic environment with a high likelihood for the occurrence of mineral deposits and where evidence indicates that mineral concentration has taken place.

UNKNOWN mineral resource potential—Assigned to areas where information is inadequate to assign low, moderate, high, or very high (see below) levels of resource potential. This category is generally used only for areas overlain by thick alluvium or other covering rock units and where geophysical and geochemical data are not adequate to determine the level of resource potential.

NO mineral resource potential—Assigned to areas of negative criteria; areas in which diagnostic or permissive criteria are known to be absent. This category should be reserved for a specific type of resource in a well-defined area. For example, it is appropriate to say that there is no oil potential in an area where the only rocks present are unfractured Precambrian granite.

In addition to these terms, VERY HIGH mineral resource potential is used for the areas of highest total scores on the mineral assessment map for vein and replacement deposits (map A). This rating is based on the quantity and quality of data available for vein and replacement deposits and on the occurrence of a great number of productive deposits of this type within the quadrangle.

DESCRIPTIVE MODEL FOR VEIN AND REPLACEMENT DEPOSITS OF GOLD, SILVER, COPPER, LEAD, ZINC, TUNGSTEN, AND MANGANESE

Vein and replacement deposits of gold, silver, copper, lead, zinc, tungsten, and (or) manganese are the most abundant type of deposits in the Butte quadrangle. Vein and replacement deposits include deposits previously classified as fissure-filling or fissure vein, hydrothermal vein, mesothermal vein, fracture filling, mineralized shear zone, vein-/shear zone, replacement vein, replacement, and stratabound replacement. The recognition criteria for this model are based on the characteristics of deposits that occur within the Butte quadrangle. Many of these characteristics are similar to those of models described by Cox and Singer (1986), including those for tungsten vein, polymetallic replacement deposit, polymetallic vein, and replacement manganese.

Geology

Vein and replacement deposits are closely associated with plutonic rocks, particularly with stocks and batholiths of monzogranitic to granodioritic composition and of Late Cretaceous age. An association with volcanic rocks of intermediate to felsic composition and of Late Cretaceous to early Tertiary age is less common. A few veins are associated with early Tertiary granitic rocks.

Vein and replacement deposits occur in favorable host rocks generally along the margins of plutons or in plutonic rocks near the sides and tops of plutons. Examples of districts whose deposits are mostly outside of but near contacts with plutons are Philipsburg, Marysville, Garnet, and Georgetown. Districts in which deposits are mostly within intrusive rocks are Butte, Rimini, Basin, Boulder, and Clancy. The close association of these deposits with plutonic rocks indicates that the plutons were a source of heat, and probably metals, for hydrothermal ore-bearing solutions that circulated around the margins of plutons during the later stages of magmatic crystallization and deposited vein and replacement deposits under favorable physical and chemical conditions.

Veins are contained in a variety of host rocks; the most favorable are brittle rocks such as Proterozoic quartzite, Cretaceous metavolcanic and metavolcaniclastic rocks, or plutonic rocks. Replacement deposits are mainly in carbonate-rich sedimentary formations; the most favorable are those of Paleozoic age, such as the Silver Hill, Hasmark, and Jefferson Formations and the Madison Group.

The favorability of a rock as a host for vein and replacement deposits depends on its potential for fracturing and on its chemical and mineral composition. Fracture potential, or the tendency of a rock to fracture under stress and to retain through-going fractures, is a function of brittleness. In contrast, the favorability of a rock as a host for replacement deposits is mainly a function of its composition; however, secondary permeability due to fracturing may also promote replacement. Pure carbonate rocks are the most chemically reactive to hydrothermal ore-forming solutions, whereas pure silica rocks are the least reactive.

The movement of hydrothermal fluids through rocks is primarily a function of permeability which, in turn, includes both the original permeability and the superimposed structures (Guilbert and Park, 1986, p. 73) such as faulting and folding. The Butte quadrangle is in a region of compressional tectonics, and nearly all of the vein and replacement deposits are structurally controlled. In some districts, such as Butte and Philipsburg, vein systems are along definite trends that clearly are structurally controlled. Fissure veins in the Boulder batholith probably resulted from regional east-west compressional stress during the Laramide (Late Cretaceous and early Tertiary time) (Woodward, 1986). Many of the most productive vein deposits are in east-trending fractures that are parallel to the axis of maximum stress and thus appear to be tension fractures. Many smaller, less productive deposits are along northeast- and northwest-trending fractures that probably represent conjugate shear of the compressional stress field (Woodward, 1986).

Many vein and replacement deposits have distinctive wall-rock alteration patterns and minerals. In the Butte district, veins are commonly enveloped successively outward by potassic, sericitic, and argillic zones (Sales and Meyer, 1948; Meyer, 1950, 1965). Similar types and zones of alteration are also found in other districts. Many vein and replacement deposits throughout the quadrangle also have silicic and pyritic alteration zones. Wall-rock alteration varies from thin envelopes along individual veins to broad zones adjoining large replacement deposits or groups of veins along which alteration zones overlap. Most vein and replacement deposits typically have some gossan or limonitic rocks associated with them. This limonite is due mainly to the weathering and oxidation of pyrite that was deposited from hydrothermal solutions during alteration and mineralization.

Vein deposits are generally tabular, whereas replacement bodies vary in shape from tabular to podiform or irregular. Frequently, replacement bodies such as the manganese ore bodies of the Philipsburg district are adjacent to veins.

The mineralogy of veins and replacement deposits is very complex. The most common ore minerals for precious- and base-metal deposits are chalcopyrite, galena, sphalerite, tetrahedrite, and native gold; less common are pyrargyrite-proustite, enargite, boulangerite, chalcocite, and a variety of secondary carbonate and oxide minerals. Other sulfide minerals, generally not ore, include pyrite, arsenopyrite, stibnite, and bismuthinite. Common gangue minerals include quartz; carbonates such as calcite, siderite, and ankerite; barite; and tourmaline. Tungsten vein and replacement deposits typically consist of scheelite and tetrahedrite in a gangue of quartz and calcite. A few tungsten deposits consist of wolframite or huebnerite with or without sulfide minerals and quartz. One tungsten deposit consists of quartz, scheelite, wolframite, and fluorite. In manganese deposits, the principal hypogene manganese minerals are rhodochrosite and manganoan dolomite; weathering and supergene enrichment of these minerals produces a variety of manganese oxide minerals.

Geochemistry

Vein and replacement deposits in the Butte quadrangle vary greatly in the kinds and abundance of metals present. The principal metals that occur in most deposits are combinations of gold, silver, copper, lead, and zinc. In some deposits, silver is the main economic constituent, in others gold or copper is the most important, and in many deposits, combinations of metals, such as gold and silver, or copper, lead, and zinc, are recoverable as coproducts. Other metals of economic value, such as manganese and tungsten, are of major importance in some deposits or are minor or accessory components in others. Still other elements occur in combination with the above metals but are not usually present in high enough concentrations to be recovered economically; these include iron, arsenic, antimony, bismuth, barium, and boron. Nevertheless, the presence of anomalous concentrations of these elements in samples collected in geochemical surveys may be useful in the detection of concealed vein and replacement deposits.

Ages of mineralization

Data on the ages of mineralization in the Butte quadrangle are very sparse. Only a few deposits in or near the quadrangle have been dated directly, and the limited data available for associated plutonic rocks permit only maximum and minimum limits on ages of mineralization. Vein and replacement deposits probably are no older than Late Cretaceous and may be as young as Eocene.

At least two ages for hydrothermal mineral deposits have been established, but three and possibly more ages are suggested by some data. At Butte, where mineralization is younger than the crystallization of the Boulder batholith of Late Cretaceous age, the age of main-stage veins is probably Paleocene, based on the age of sericite (57.5 Ma by K-Ar method, Meyer and others, 1968) in alteration envelopes. A gold-silver-zinc-lead-bearing diatreme breccia at the Montana Tunnels mine is Eocene, based on the age of intramineralization dikes (45–50 Ma; Sillitoe and others, 1985). Mineralization of the Black Pine mine is Late Cretaceous, based on the age of sericite (63.9 Ma) in a vein (Waisman, 1985). Several stocks, including those at Miners Gulch, Garnet, Blackfoot City, and Marysville, have ages in the range of 76–82 Ma as determined by the K-Ar method on hornblende and biotite (H.H. Mehnert, unpub. data, 1985; J.D. Obradovich, unpub. data, 1983). Mineral deposits and related alteration are spatially associated with these stocks and are later than the crystallization of the plutons; thus, they are of Late Cretaceous age or younger. North of the Butte quadrangle, in the Heddleston district, the age of alteration of intrusive rocks that is associated with copper and molybdenum mineralization is 44.5 Ma (Miller and others, 1973). A Tertiary age of mineralization is also indicated for molybdenum mineralization in and around a concealed 48 Ma stock at Bald Butte (Rostad, 1978), in the Marysville district, and for precious- and base-metal deposits in veins above the stock.

Geophysics/remote sensing

Vein and replacement deposits are associated spatially with positive magnetic anomalies, many of which are coincident with mapped plutonic rocks, especially granodiorite of Late Cretaceous age. Many of the larger bodies of plutonic rocks also coincide with areas of low gravity. Therefore, the combination of magnetic highs with gravity lows can be used to predict the subsurface extent of magnetic plutonic rocks. In some districts, such as Butte and Wickes, mineral deposits are associated with magnetic lows, which may indicate areas of alteration of normally magnetic rock or masses of less magnetic volcanic or plutonic rock.

Comparison of linear features from Landsat images and side-looking radar with the distribution of vein- and replacement-type mines and prospects shows strong positive correlations between some of these features and the location of mineralized sites (Purdy and Rowan, in press).

Limonite is common in the weathered zone of many deposits. In some cases, the limonite is limited to the actual deposit and in others, it is distributed over broad zones adjacent to veins or vein zones. The limonite is the result primarily of the oxidation of pyrite, which occurs in alteration zones or with other sulfide minerals in vein or replacement deposits. Under optimal conditions of exposure and topography, limonitic zones can be recognized on Landsat images (Rowan and Segal, in press).

Genesis

The majority of vein and replacement deposits worldwide probably are mesothermal in the modified Lindgren classification (Ridge, 1972). In the Butte district, vein deposits probably formed over the range of hypothermal-1 to telethermal (Ridge, 1972). Some veins, such as the lamellar quartz-calcite veins of the Drumlummon mine in the Marysville district (Knopf, 1913) and the quartz-carbonate-sulfide veins of the Emery district, have textures and minerals suggestive of formation under epithermal conditions.

Only broad limits can be placed on the age of mineralization in the Butte quadrangle. Nearly all vein and replacement deposits are younger than the plutonic rocks of Late Cretaceous age. Some deposits may be Late Cretaceous but many, such as those at Butte, are probably early Tertiary (Paleocene and Eocene) in age.

The close spatial association of vein and replacement deposits with plutonic rocks strongly suggests a genetic relationship. The plutons could have acted either as a source of heat for geothermal convection cells and (or) a source of metals and other constituents for the formation of mineral deposits. These convection cells and the associated hydrothermal solutions would be developed along the margins and tops of a cooling and crystallizing pluton. The resulting mineral deposits would likewise be formed along the contacts of the pluton both as exocontact and endocontact deposits. Where substantial numbers of deposits are entirely within plutonic bodies, such as in the northern part of the Boulder batholith, studies (Pinckney, 1965) indicate that they formed near the top of the pluton.

Recognition criteria

The recognition criteria listed below for vein and replacement deposits in the Butte quadrangle are based, as much as possible, on known deposits within the quadrangle. These criteria are also based on the kinds of data available, mainly those resulting from CUSMAP studies. To be useful as recognition criteria, data should be complete for the entire quadrangle and amenable to GIS treatment. Some types of data, such as mineralogy of ores and gangue, did not seem to be particularly amenable to GIS techniques, especially considering the incompleteness of the data for all known mines and prospects.

1. Presence of favorable host rock such as Paleozoic carbonate rock for replacement deposits and Proterozoic quartzite for vein deposits.
2. Presence of plutonic rocks of suitable age and composition such as granodiorite of Late Cretaceous age.
3. Presence of geochemical anomalies in stream-sediment samples, especially multiple-element anomalies containing gold, silver, copper, lead, zinc, arsenic, antimony, bismuth, boron, iron, manganese, and (or) barium.
4. Presence of limonite formed by weathering of pyrite in hydrothermally altered rocks.
5. Presence of geophysical anomalies which may indicate magnetic plutonic rocks.
6. Presence of favorable fault zones and intersections of faults.
7. Presence of favorable linear features.

Criteria 1–3 are considered diagnostic. Criteria 4–7 are considered permissive. In some areas, significant thicknesses of post-Eocene sedimentary rocks cover older rocks. Although such cover is not a negative criterion, it would be extremely difficult in such areas to find and exploit vein and replacement deposits in the older rocks.

GIS SUBMODELS

The recognition criteria for the descriptive deposit model were used to develop a series of seven submodels in

GIS; each submodel expresses a single recognition criterion (maps B–J). Each submodel is assigned a range of values (0–5) to indicate the degree of favorableness of its respective criterion for the occurrence of vein or replacement deposits. The diagnostic criteria—host rocks, plutonic rock association, and geochemical anomalies—have maximum values of 5; the permissive criteria—faults, alteration, geophysics, and linear features—have maximum values of 2 or 3. The composite model (map K) is derived by overlaying and summing all of the scores of individual submodels. Finally, the mineral assessment map (map A) is obtained by grouping the numerical scores and assigning four levels of mineral resource potential.

Host-rock submodel

The favorableness or predisposition of a geologic map unit to host a vein or replacement deposit is the result of many factors. In this study, the factors that were considered in the ranking of host rocks included fracture potential, composition, contact metamorphism, distribution of mines and prospects, and size of mine production.

I. Fracture potential

The favorableness of a rock to host vein deposits is based on its fracture potential. The tendency for host rocks to fracture under stress and to retain through-going fractures is primarily the result of brittleness. In general, brittleness is a function of fabric, lithification, and quartz content.

Fabric characteristics that determine fracture potential are brittleness and anisotropism. Grain shapes and sizes, uniformity of grain sizes, and intergrain relationships all affect the brittleness of a rock. Igneous rocks are commonly more brittle than sedimentary rocks because of interlocking grains of various shapes. Metamorphism may increase the brittleness of rocks by the growth of new minerals or recrystallization of previously existing minerals. The tendency to develop and maintain fractures is also influenced by anisotropism. Anisotropic fabrics include bedding, foliation, joints, flow banding, and others.

In sedimentary rocks, compaction, cementation, and other processes, usually referred to as lithification, contribute to brittleness. In general, the degree of lithification is a function of age; older rocks are generally harder and more brittle than younger rocks.

In sedimentary and metasedimentary rocks, quartzite is the most brittle and pure carbonate rock, at the other end of the spectrum, is the least brittle. Therefore the percentage of quartz sandstone or quartzite in a sedimentary sequence or formation is used as a measure of brittleness. Likewise in igneous rocks, brittleness increases with the quartz and silica content.

All igneous and sedimentary rocks, except for Quaternary surficial deposits (map unit Qs) and Tertiary sedimentary deposits and rocks (Ts), were subjectively ranked in order of fracture potential and assigned scores in the range of 1 for the lowest to 10 for the highest. The highest ratings are assigned to the Garnet Range and Mount Shields Formations of the Middle Proterozoic Missoula Group (Ymi). The lowest in rank are sedimentary formations of Devonian to Permian age (PDs) and andesitic and basaltic volcanic rocks of Late Cretaceous or early Tertiary age (TKab).

II. Composition

The predisposition of a rock to host replacement deposits is a function of its composition. Pure carbonate rocks are the most chemically reactive to hydrothermal ore-forming solutions and pure silica rocks are the least reactive. Geologic units can be ranked in order of their content of chemically reactive minerals. Carbonate minerals, calcite and dolomite, are the most reactive and quartz is the least reactive. Common rock-forming minerals and mineral groups with intermediate values are olivine, pyroxene, amphibole, biotite, plagioclase, and potassium feldspar. Based on carbonate content, the sedimentary map units most favorable for replacement deposits are Devonian to Permian age (PDs) and Cambrian and Cambrian or Middle Proterozoic age (₵s and ₵Ys). The least favorable are the Garnet Range and Mount Shields Formations of the Middle Proterozoic Missoula Group (Ymi). All map units were subjectively ranked from 1 for the lowest to 10 for the highest in carbonate content.

III. Contact metamorphism

Many of the geologic units are within contact aureoles of plutons. Contact metamorphism may increase a host rock's receptiveness to the formation of vein and replacement deposits. Contact metamorphism results in an increase in brittleness and a change in fabric through recrystallization of previously existing minerals and the formation of new minerals. Metasomatism is considered to be a separate process but contact metamorphism may also involve minor bulk chemical changes. One of the most common is silicification, which also tends to increase the brittleness of affected rocks. The changes induced by contact metamorphism are generally considered to be favorable for the occurrence of mineral deposits. Since contact aureoles were not mapped during the CUSMAP field studies, an assumption must be made regarding the average width of such aureoles. A zone 2 km wide around mapped plutons is proposed as a reasonable estimate of the extent of contact metamorphism, and map units or parts of units which are within 2 km of mapped plutons are ranked higher than the same units outside of the 2-km-wide zone.

IV. Distribution of mines and prospects

The distribution of mines and prospects (hereafter referred to as "mines") relative to geologic map units was measured using GIS statistical techniques. A useful measure of the relative distribution of mines among various geologic map units is obtained by calculating the normalized density of mines. The normalized density is defined as the percent of total mines in the entire quadrangle that are within a given map unit, divided by the percent of the total map area occupied by that map unit (percent mines/percent area). For example, if 70 of a total of 700 mines are located in a given map unit, then the percent of mines is 70/700=0.1 or 10 percent. If that unit covers 5 percent of the map, then the normalized mine density is 0.1/0.05=2.0. The average normalized mine density for the entire quadrangle would be 1.0 and any value greater or less than 1.0 would indicate either higher or lower than the average density, respectively. This measure of the distribution of mines is extremely useful in the ranking of the favorableness of host rocks as well as in the rankings in all other submodels. Throughout the procedures of resource assessment, this technique was used to design and test submodels and final models.

The highest normalized densities of mines (range of 2.9 to 44.8) are found in Late Cretaceous granodioritic, quartz monzodioritic, and gabbroic rocks such as Scratchgravel Hills, Marysville, Cable, and Royal stocks; the Butte Quartz Monzonite; sedimentary rocks such as the Middle Proterozoic Empire Formation of the Ravalli Group (Yra); and sedimentary rocks of Cambrian and Cambrian or Middle Proterozoic age (Ꞓs and ꞒYs). These data support observations based on field studies and published reports. The lowest normalized densities (less than 0.25) are found in some Tertiary and Upper Cretaceous (Tgd, TKmg, TKgb, TKa) plutonic rocks, Tertiary rhyolitic rocks (Trv), and some Middle Proterozoic sedimentary rocks (Ymb, Ymi). All map units were ranked in order of normalized densities and assigned values in the range of 1 for the lowest and 10 for the highest densities.

V. Size of mine production

A rock unit containing a few highly productive mines is considered a more important host than a unit with many prospects and mines that have little or no production. Likewise, for two units containing equal numbers of deposits, the one that hosts more productive mines is more favorable. By these criteria, the most favorable map units are the Upper Cretaceous Butte Quartz Monzonite and Elkhorn Mountains Volcanics. Other highly favorable units include Cambrian sedimentary rocks (Ꞓs); Middle Proterozoic middle belt carbonate (Yc); and Cretaceous plutonic rocks such as the Philipsburg batholith, Royal stock, and Cable stock of the Flint Creek Range (Kgd), and aplitic, alaskitic, and pegmatitic rocks of the Boulder batholith (Kmg). The least favorable map units include several Tertiary and Upper Cretaceous plutonic rocks (Tgd, TKmg, TKgb, TKa); some Middle Proterozoic sedimentary rocks (Ymb, Ymi); and Middle or Late Proterozoic mafic dikes and sills (ZYg). All map units were ranked in order from 1, for the lowest, to 10 for the highest, in order of favorableness for hosting productive mines.

VI. Summary host-rock submodel

Host-rock-unit scores (1 to 10) based on fracture potential and composition were summed and rescaled to a range of 1 to 5. Likewise, host-rock-unit scores based on mine densities and on productive mines were summed and rescaled to a range of 1 to 5. Then these scores of (1) fracture potential and composition and (2) mine density and productive mines were summed and rescaled to a range of 1 to 4. Finally a value of 1 point was added to parts of map units that occurred within contact aureoles of plutons. Map B shows the areas of host rock favorability, which are one or combinations of two or more geologic map units and have scores in the range of 1 to 5. The area assigned a value of 0 is covered by considerable thicknesses of Tertiary and Quaternary sedimentary rocks and deposits and is not believed to have any favorable host rocks at shallow depth.

Plutons submodel

Throughout the Butte quadrangle, vein and replacement mineral occurrences show a spatial association with plutonic rocks. The deposits occur commonly near the contact of plutons with older igneous and sedimentary rocks. They occur both within the plutonic rock and outside the contact in the country rocks. The spatial association between vein and replacement mineral occurrences and plutonic map units was tested by calculating normalized densities for these occurrences in concentric bands both inside and outside of mapped contacts of 17 plutonic units. Using this approach it was found that the most favorable area for the occurrence of deposits was a 4-km-wide band extending from 1 km inside the contact to 3 km outside the contact. A 4-km-wide zone around plutons was also used in the assessment of vein and replacement deposits in the Dillon quadrangle (Pearson and others, in press a), but in that area the most favorable zone extends from the contact to 4 km outward from the contact.

Plutonic rocks in the Butte quadrangle were ranked in order of favorability according to the density of known vein and replacement mines in zones that extend from 1 km inside the plutons to 3 km outside. The most favorable plutons, with normalized mine densities in the range of 2.2 to 10.3, were assigned 5 points. These plutons are Cretaceous stocks and batholiths of granodiorite, monzogranite, and gabbro and include the Philipsburg and Boulder batholiths; the Royal, Cable, Scratchgravel Hills, and Marysville stocks; and small bodies of gabbro, alaskite, aplite, and pegmatite. The next most favorable group of plutons, with considerably lower densities from 0.7 to 1.6, include Cretaceous granodiorite and monzogranite and Tertiary granodiorite. These were given scores of 3, to emphasize the much lower mine densities compared to the most favorable plutons. Plutons with densities of 0.3–0.6 were given 2 points, and the least favorable plutons, which had no mines in the 4-km-wide zones, are assigned 1 point. Areas more

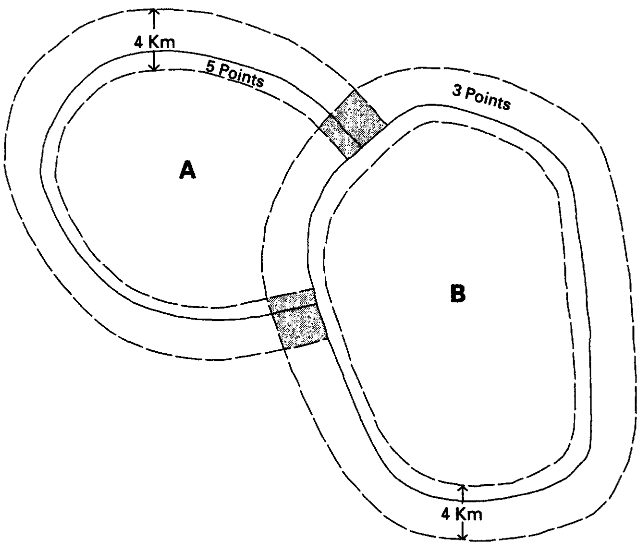

Figure 3. Sketch showing age relationships and scoring of plutons. Older pluton A (outer 4-km-wide zone is 5 points) cut by younger pluton B (outer 4-km-wide zone is 3 points). Part of A's zone retains 5-point value and B's 3-point zone is superimposed on A.

than 1 km inside or more than 3 km outside of contacts have a score of 0. The resulting plutonic submodel is shown on map E.

In the construction of the plutonic rock submodel it was soon realized that relationships between plutons of different ages would cause complications in the point scores. For example, where a Tertiary pluton (3 points for 4-km-wide zone) intruded a Cretaceous granodiorite pluton (5 points for 4-km-wide zone) and the zone surrounding the granodiorite, part of the older rock would be consumed and a new contact zone would be superimposed on it (see fig. 3). Part of the 4-km-wide zone associated with the older pluton (5 points) would be removed by stoping or assimilation and a new 4-km-wide zone (3 points) associated with the younger pluton would be formed. However, where this new zone was superimposed on the 4-km-wide zone of the older pluton, the point value of the older pluton (5 points) would be retained. All of these age relationships were evaluated and scored using IDIMS functions (map E).

Rocks that are younger than the plutonic rocks but are within the 4-km-wide zone in and adjacent to the plutons cannot contain any pluton-related mineralization. Therefore the parts of 4-km-wide zones underlain by postplutonic rock units were assigned a value of 0. These postmineralization units included rhyolitic volcanic rocks (Trv), andesitic and basaltic volcanic rocks (Tab), and Lowland Creek Volcanics (Tlc), all of Tertiary age. However, these units do host vein deposits in some parts of the quadrangle; such mineralization must be related to volcanism or to buried plutons of younger age than plutonic rocks that are exposed at the surface.

Geochemical submodel

The selection of elements and suites of elements for the geochemical submodel was based on (1) geochemistry of known vein and replacement deposits and (2) association of single-element anomalies with known deposits. The geochemical characterization of known deposits was obtained by the analysis of samples of altered and mineralized rock collected from mine dumps and workings and from a compilation of commodity data on mines and prospects (Elliott and others, 1986). The association of known deposits with single-element anomalies was determined empirically by superimposing the location of known deposits (Elliott and others, 1986) on anomaly maps and calculating the normalized density of mines in areas of anomalous geochemistry for each element. This normalized density is the percentage of all the vein and replacement mines and prospects in the quadrangle that occur in anomalous areas, divided by the percentage of the total area of the quadrangle represented by the anomalies (percent mines/percent area of anomalous geochemistry). Because a mine density of 1.0 is the average value for the total area of the map, those single-element anomaly maps with mine densities of greater than 1.0 were selected for geochemical submodels. Based on the two aforementioned criteria, the following elements were selected for inclusion in the geochemical submodel: silver, arsenic, gold, boron, barium, bismuth, copper, iron, manganese, lead, antimony, tungsten, and zinc.

To reduce the total number of anomaly maps and thereby simplify the analytical procedures used in the construction of geochemical submodels, some single-element maps were arithmetically combined into multi-element maps. These maps show combined anomalies for groups of two or three elements, such as gold and silver, copper, lead, and zinc, and other combinations of elements that show close geochemical associations in vein and replacement deposits. The final set of anomaly maps included maps for a precious metals suite (gold-silver), base metal suite (copper-lead-zinc), accessory suite I (arsenic-antimony-bismuth), accessory suite II (iron-manganese), and for single elements (boron, barium, and tungsten). For anomaly maps of these suites, each anomalous area represents an anomaly in a single element or combinations of anomalies of two or three elements.

I. Precious- and base-metal vein and replacement deposits

Four geochemical suite anomaly maps (gold-silver; copper-lead-zinc; arsenic-antimony-bismuth; iron-manganese) and two single element anomaly maps (boron, barium) were combined into a geochemical submodel for precious- and base-metal deposits. In the resultant map, any pixel with a nonzero gray level represents the summation of one to six individual nonzero pixels. In order to keep track of suite and single element anomaly maps for the purpose of

Table 2.—*Favorable geochemical assemblages in the geochemical submodel for vein and replacement precious- and base-metal deposits*

[PM, gold and (or) silver; BM, copper and (or) lead and (or) zinc; Al, arsenic and (or) bismuth and (or) antimony; A2, iron and (or) manganese; B, boron; Ba, barium]

Assemblage	Normalized density	Score
PM+BM+A1+A2+B+Ba	21.25	5
PM+BM+A1+Ba	19.79	5
PM+BM+A1+A2+Ba	9.48	5
PM+BM+A1+A2+B	9.36	5
BM+A2+B	8.33	4
PM+A2+B	6.65	4
PM+BM+A1+A2	6.48	4
PM+BM+A1+B+Ba	6.26	4
PM+BM+A1+B	4.38	4
BM+A1+A2	4.13	4
A2+B	3.74	3
PM+BM+A1	3.29	3
PM+BM+A2	2.63	3
BM+A2+Ba	2.14	3
PM+A1+A2+B	1.95	2
PM+BM+A2+B	1.82	2
BM+A1+A2+B	1.61	2
PM+A1+B	1.51	2
PM+A1	1.37	2
BM+B+Ba	1.35	2
BM+A1	1.34	2
PM+A2	1.29	2
BM+A1+Ba	1.14	2
Others		1

weighting the results in the final map, numbers in the series, 1, 2, 4, 8, 16, 32, etc., were assigned to images. All nonzero (anomalous) pixels in the gold-silver map were assigned to a brightness value of 1, those in the copper-lead-zinc map to 2, in the arsenic-antimony-bismuth map to 4, in the iron-manganese map to 8, in the boron map to 16, and in the barium map to 32. Because the sum of any two or more of these numbers yields a unique number not found in the sequence itself, such as 3 (2+1), 7 (4+2+1), 42 (32+8+2), etc., the original components of any pixel can be readily determined. For example, any pixel in the composite map that has a gray level of 15 consists of a combination of anomalies from accessory suite II (iron-manganese = 8), accessory suite I (arsenic-antimony-bismuth = 4), base-metal suite (copper-lead-zinc = 2), and precious metal suite (gold-silver = 1). Similarly, any pixel or group of pixels with a brightness value of 63 is the sum of 1+2+4+8+16+32, which indicates an area where all of the components (suites plus barium and boron) are anomalous.

In the final step, all existing aggregate anomalies of the 63 possible combinations of anomalies were ranked and assigned favorability scores of 1–5 (table 2). This ranking was based on the calculation and comparison of normalized mine densities for areas of composite anomalies as previously done for single-element anomalies. The areas of combined anomalies with density values greater than 1.0 are listed in table 2. Of the 772 known vein and replacement precious- and base-metal mines and prospects in the quadrangle (Elliott and others, 1986), 92.3 percent are within areas of anomalous geochemistry and 67.0 percent are within areas of anomalous geochemistry in which the normalized density of mines is greater than 1.0.

Table 3.—*Favorable gechemical assemblages in the geochemical submodel or vein replacement manganese deposits*

[PM, gold and (or) silver; BM, copper and (or) lead and (or) zinc; A1. arsenic and (or) bismuth and (or) antimony; Fe, iron; Mn, manganese; B, boron; Ba, barium]

Assemblage	Normalized density	Score
Mn+PM+BM+A1+Ba	69.44	5
Mn+PM+BM+Ba	52.91	5
Mn+PM+BM+A1	38.63	4
Mn+PM+BM+A1+Fe	21.86	4
Mn+PM+BM+A1+B	11.11	3
PM+BM+A1+Fe	8.32	3
Mn+PM+BM	7.11	3
PM+BM+A1	1.17	2
Others		1

II. Vein and replacement manganese deposits

The geochemical submodel for vein and replacement manganese deposits was based on nearly the same suites and elements as the vein and replacement precious- and base-metal deposit type, except that iron and manganese were not combined but kept as separate maps. Areas of anomalous iron concentrations on the iron map were assigned a value of 8 and those on the manganese map a value of 64. A composite map was created using procedures identical to those previously discussed.

Normalized densities were calculated and favorability scores were assigned as shown in table 3. Of the 45 known occurrences of vein manganese deposits in the quadrangle (Elliott and others, 1986), 43 (95.6 percent) fell within areas of the composite anomaly map having mine densities greater than 1.0.

III. Vein and replacement tungsten deposits

The geochemical submodel for vein and replacement tungsten deposits was derived in similar fashion to the preceding two submodels. In this submodel, however, a single-element tungsten map with anomalous areas assigned a gray level of 64 was added to the composite map from the vein and replacement precious- and base-metal deposit submodel.

Normalized densities were calculated as before and favorability scores were assigned as shown in table 4. The Butte quadrangle has 20 known mines and prospects of this type (Elliott and others, 1986) and 18 (90.0 percent) of these occur in geochemically anomalous areas which have mine densities greater than 1.0.

IV. Summary geochemical submodel

The geochemical submodels for vein and replacement deposits of precious and base metals, manganese, and tungsten are similar in that areas with the same scores are coincident or overlapping in all three submodels. Because of these similarities and because the manganese and tungsten deposit types are represented by a relatively small number of known deposits, all three submodels were combined into one composite geochemical submodel which indicates favorability for precious- and base-metals, manganese, and tungsten vein and replacement deposits. This composite image was produced by comparing the gray (brightness) levels of pixels in all three submodels and selecting the maximum value for each pixel location. If, for example, the gray levels at a given pixel position in the submodels were 1, 4, and 3, respectively, the maximum value, or 4, would be assigned to that pixel position in the composite image. The composite geochemical submodel (map F) has scores ranging from 1 to 5.

Alteration submodel

The alteration submodel is based on a map that shows the distribution of limonitic, hydrothermally altered rock (Rowan and Segal, in press). Scores were assigned based on

Table 4.—*Favorable geochemical assemblages in the geochemical submodel for vein and replacement tungsten deposits*

[PM, gold and (or) silver; BM, copper and (or) lead and (or) zinc; A1, arsenic and (or) bismuth and (or) antimony; A2, iron and (or) manganese; B, boron; W, tungsten]

Assemblage	Normalized density	Score
W+PM+BM+A1+A2+B	76.92	5
W+PM+BM	11.47	4
W+BM	8.87	4
W+PM+BM+A1	7.84	4
W+A2	7.81	4
A1	6.22	3
A1+A2	5.24	3
BM	5.15	3
W+PM+BM+A1+A2	4.05	2
W	3.96	2
W+A1	3.27	2
Others		1

the observed association of the altered areas with known deposits. A maximum score of 3 points was assigned to the alteration submodel instead of the maximum score of 5 points for the host rock, pluton, and geochemical submodels, because the alteration data are limited in areal coverage and have greater uncertainty than the data on which the other submodels are based. In many areas of the quadrangle, dense vegetation precluded the discrimination of altered areas on Landsat images. Some uncertainty is involved in distinguishing limonite related to hydrothermal activity from limonite produced by weathering of unaltered iron-bearing rocks. The combined altered areas have a very high normalized density (22.0) of known vein and replacement mines and prospects and were assigned a score of 3 points in the submodel (map G). One-km-wide zones around altered areas have a mine prospect density of 5.8 and were assigned a score of 2 points. Zones 1–2 km away from altered areas have a mine density of 2.9 and were assigned 1 point. The remainder of the quadrangle was assigned a score of 0 points.

Geophysical submodel

The geophysical submodel is based on an interpretive map that displays the surface and subsurface distribution of magnetic plutonic rocks. The interpretive map is based on the analysis of regional magnetic and gravity data. The composite of areas of magnetic plutonic rock was compared with the distribution of known vein and replacement mines and prospects and normalized densities were calculated. The areas of interpreted magnetic plutonic rock at the surface and in the subsurface have a very low normalized mine density of 1.4, which suggests only a weak correlation between known mines and prospects and the geophysical interpretive map. In the submodel shown on map H, a score of 2 points is assigned to the areas of magnetic plutonic rock and a score of 1 point is assigned to 2-km-wide zones around these areas. The remainder of the quadrangle is assigned a score of 0 points.

Fault submodel

Five classes of faults—normal, thrust, strike-slip, oblique-slip, and unclassified—were digitized from the generalized geologic map of the Butte quadrangle (Wallace, 1987). The association of vein and replacement mines and prospects with faults was determined by calculating the normalized mine densities in successive zones of 0.2 km width for 1 km away from each class of fault. Based on the mine densities, the spatial association of mapped faults and known mines and prospects is weak; the densities are 0.9 for occurrences within 1 km of all faults and 1.1 for occurrences more than 1 km from mapped faults. However, some classes of faults show a much stronger association with mines than other faults, and the highest densities are associated with intersections of certain classes of faults. The density of

Table 5.—*Percentage of map area and normalized densities of vein and replacement mines for areas of very high, high, moderate, and low potential and areas covered by Tertiary sedimentary rocks and deposits*

[Leaders (---) indicate no data]

Area	Percentage of map	Percentage of mines	Normalized density
Very high	1.04	11.57	11.12
High	5.13	24.38	4.75
Moderate	24.14	48.01	1.99
Low	53.75	15.30	0.29
Covered	15.95	---*	---

*Six mines are in areas shown as covered on map A. These mines are actually in pre-Tertiary rocks whose exposures are too small to show at the map scale of 1:250,000.

mines within 1 km of unclassified faults is 1.3 and the mine density within 1 km of an intersection of normal and thrust faults is 1.9. The mine densities near faults show a sharp break at 0.6 km for most classes of faults; higher densities are found within 0 to 0.6 km than from 0.6 to 1.0 km away from faults. Based on the normalized mine densities, the fault submodel shown on map I consists of 1.2-km-wide zones (0.6 km on each side) along mapped faults. Because of the weak observed association between mapped faults and mines, the maximum score for more favorable faults is 2 points. This score is assigned to normal and unclassified faults and to intersections of these faults with one another and with other classes of faults. A score of 1 is assigned to thrust, strike-slip, and oblique-slip faults, and intersections of these faults with one another. The remainder of the quadrangle is assigned a score of 0 points.

Linear feature submodel

The analysis of linear features demonstrated that some linear features are related to mines and others are not. The degree of relationship was determined by calculating the normalized density of all metallic mines and prospects in zones along linear features and circular areas enclosing intersections of trends for 16 subdomains. The widths of zones and radii of circular areas were determined empirically by calculating normalized mine densities in 0.2 km increments in zones that were centered on linear features and circular areas that were centered on intersections and then selecting widths or radii of areas that had the highest densities. For linear features, the favorable zones had widths of 0.2 to 1.4 km on each side of the feature and the mine densities varied from 1.25 to 2.56. For intersections of linear features the radii varied from 0.8 to 1.8 km and densities from 2.47 to 5.50. Within each of 16 subdomains, selections of linear features and intersections of linear features were based on close spatial associations with higher densities of mines. Because the higher densities were associated with intersections of linear features, scores of 2 points each were assigned to areas surrounding intersections and only 1 point was assigned to zones associated with favorable linear features. The resulting submodel for linear features is shown on map J. The remainder of the quadrangle was assigned a score of 0 points.

COMPOSITE MINERAL RESOURCE ASSESSMENT MODEL FOR VEIN AND REPLACEMENT DEPOSITS OF GOLD, SILVER, COPPER, LEAD, ZINC, MANGANESE, AND TUNGSTEN

The submodels for host rocks, plutons, geochemistry, alteration, geophysics, faults, and linear features (maps D–J) were combined using overlay analysis on IDIMS. Because the fault and linear features submodels are both expressions of structure and are in part nonadditive, only maximum values from one or the other were added to other submodels. The sum of submodels yielded total scores shown on map K. This map consists of polygons that are ranked between 0 and the maximum possible score of 22. The mineral resource assessment map for vein and replacement deposits (map A) groups polygons from map K into 4 classes of low (0–8 points), moderate (9–14 points), high (15–18 points), and very high (19–21 points) potential for the occurrence of undiscovered vein and replacement deposits of gold, silver, copper, lead, zinc, tungsten, and manganese. Also shown on map A are the boundaries of mining districts and geographic areas and the locations of 14 mines classified as vein or replacement deposits that have the largest production (more than $5 million each) in the quadrangle. Map B is an association map that shows the several combinations of submodels that determine the final resource assessment map.

SUMMARY AND SUGGESTIONS FOR EXPLORATION

The main purpose of mineral resource assessment is to determine the potential or likelihood for the occurrence of undiscovered resources in the study area. The summary map (map A) shows four levels of potential for the occurrence of undiscovered resources in polymetallic vein and replacement deposits in the Butte quadrangle. Areas of unknown potential (in gray) are covered by significant thicknesses of postmineral surficial deposits, mainly Tertiary sedimentary rocks. Thin Quaternary units, such as alluvium, are not shown. The percentage of map area for each level of potential, and normalized mine densities for each level, are shown in table 5. The areas of moderate, high, and very high potential are all favorable for the occurrence of vein and replacement deposits. Approximately 30 percent (sum of moderate, high, and very high areas) of the Butte quadrangle is favorable for the occurrence of these deposits, and about 84 percent of the known occurrences are within these areas. Three of the mines having very large production (map A) are in areas of very high potential, two are in areas of high potential, and nine in areas of moderate potential. For 30 mines having production in the range $500,000 to $5 million, the map shows a much closer correlation with areas of very high and high potential. Seven of these mines are in areas of very high, 12 in areas of high, and 7 in areas of moderate potential.

As expected, most of the areas of very high potential coincide with known mining districts (map C), which have numerous highly productive vein and replacement deposits. The largest areas of very high potential occur in the following places:

(1) Eastern part of the Butte district
(2) Central and western parts of the Wickes district
(3) Central and northwestern parts of the Basin district
(4) Central part of the Elliston district
(5) Most of the Philipsburg district
(6) Most of the Marysville district

The areas of very high and high potential in the Basin and Elliston districts are aligned along a northwesterly trend. Those in the Wickes district have an easterly trend, which, to the west, intersects the northwesterly trend in the Basin district. Although favorable host rocks and plutons contribute to these trends, the most important factors determining these trends are the alignment of altered areas (map G) and geochemically anomalous areas (map F).

Most of the highly productive central part of the Butte district (map A) has moderate potential based on the procedures used in this study; it was expected that most of the district would be ranked as high to very high based on the past history of production and present exploration and production from the district. The ranking of moderate potential results from lower than expected scores in the geochemical, alteration, and geophysical submodels. These lower scores result from several conditions: (1) Fewer geochemical samples were collected from the Butte district, as compared to similar size areas in other parts of the quadrangle, because many of the natural drainages have been disturbed and contaminated by mining activities, and the results of analyses of such samples would be suspect. If more uncontaminated samples could have been collected, the geochemical submodel may have had a higher score, (2) The extensive disturbance of the surface by mining activities and cultural development in much of the Butte district hampered accurate and complete interpretation of the limonitic alteration and linear features. If the district had been undisturbed, higher scores on alteration may have been obtained, and (3) The geophysical submodel is not valid for the Butte district. A large magnetic low is centered on the Butte district; this may be due to alteration which has removed magnetite from the granitic plutonic rocks and (or) due to the occurrence of a large mass of younger nonmagnetic intrusive rock below the Butte district. Therefore, the central part of the Butte district is scored as 0 points on the geophysical submodel, even though the presence of the magnetic low may be a very favorable factor.

Other mining districts that coincide with smaller but distinct areas of very high and high potential for vein and replacement deposits are the Big Foot, Austin, Princeton, and Georgetown districts and the Scratchgravel Hills area (map A).

Of particular interest for mineral exploration are areas of high or very high potential which have few or no mines and prospects. A comparison of map A with map C identifies several such areas; the principal ones are

(1) Anaconda Range area—An area of high potential (about 3 sq mi) is in the vicinity of Mount Howe and Mount Evans in the Anaconda Range. This area was also identified as one of high mineral resource potential by a mineral survey of the Anaconda-Pintlar Wilderness (Elliott and others, 1985). The principal rock types in the area are metasedimentary rocks—schist and quartzite—of the Middle Proterozoic Missoula Group and part of a Cretaceous quartz diorite stock. The area is bordered on the east and south by a Tertiary granodiorite-monzogranite stock and is cut by numerous dacite porphyry dikes. Molybdenite-bearing quartz-sulfide veins are common. Intense limonitic alteration is widespread and resulted from the oxidation of disseminated pyrite in metasedimentary rocks, in dikes, and in quartz veins. The high rating is due to a combination of all submodels (maps D–J).

(2) Flint Creek Range area—Three areas of high potential (about 0.5–2 sq mi each) are aligned northeasterly

between the Red Lion and Princeton districts. These areas occur along the eastern edge of the Philipsburg batholith and along a septum of Paleozoic sedimentary rocks which lie between the Philipsburg batholith and the younger Mount Powell batholith. The Paleozoic rocks in this region are strongly deformed by folding and thrust faulting. The high rating is the result of the association of host rock, plutons, geochemistry, geophysics, faults, and linear-features submodels.

(3) Scratchgravel Hills area—Areas of high and very high potential extend beyond the borders of the Scratchgravel Hills area along the northwest, north, and northeast sides. The principal rock types underlying these areas are metasedimentary units of the Middle Proterozoic Ravalli Group, mainly calcareous siltite and argillite, and Proterozoic diorite sills. These areas are in the contact zone of a Cretaceous monzodioritic stock and are cut by several normal faults. The high rating is achieved from the combination of host rock, pluton, geochemistry, geophysics, faults, and linear-features submodels.

(4) Helena district—Several small areas of high potential (about 0.5–3 sq mi each) occur in the western part of the Helena district. These areas are underlain by sedimentary rocks of Proterozoic and Paleozoic age, which occur along the northern edge of granodiorite of the Cretaceous Boulder batholith. The high potential ratings result from host rock, pluton, geochemistry, geophysics, faults, and linear-features submodels.

(5) North Boulder Mountains area—Several areas of high and very high potential (as much as 9 sq mi each) are just north of the Rimini district. The principal rock units in these areas are Late Cretaceous Elkhorn Mountains Volcanics and metasedimentary rocks of Jurassic and Cretaceous age near the northern edge of the Boulder batholith. Several normal faults have been mapped in the largest of the areas. The ratings of these areas are determined by the combination of host rock, pluton, geochemistry, geophysics, faults, and linear-features submodels.

(6) South Boulder Mountains area—Several areas of mostly high potential (0.5–4 sq mi each) are east and northeast of the Orofino district. These areas are underlain mainly by contact-metamorphosed Elkhorn Mountains Volcanics, which were intruded by granodioritic rocks of the western margin of the Boulder batholith. The high rating results from the combination of host rock, pluton, geochemistry, and geophysics submodels.

(7) South Boulder Mountains area—A large area (approximately 20 sq mi) of both high and very high potential is north and northeast of the Butte district. The area is underlain by granodioritic and granitic rocks of the Cretaceous Boulder batholith and is cut by numerous north-northeasterly and northeasterly normal and strike-slip faults. The area of very high potential results from the combination of all submodels. The remainder of the area consists of (a) combinations of all submodels, (b) combined host rock, pluton, geochemistry, geophysics, faults, and linear-features submodels, or (c) combined host rock, pluton, geochemistry, and geophysics submodels.

(8) South Boulder Mountains area—A large area (about 25 sq mi) of mostly high potential but including small areas of moderate and very high potential is east of the Pipestone district and south of the Big Foot district. The area is along the eastern margin of the Boulder batholith and is underlain mainly by granodioritic rocks of the batholith and Late Cretaceous Elkhorn Mountains Volcanics, which were intruded by the batholith. The high potential ratings are determined mainly by the combination of host rock, pluton, geochemistry, alteration, and geophysics submodels.

(9) South Boulder Mountains area—An area of mostly high potential (about 12 sq mi) is in the Bull Mountain area, east of the Big Foot district. The area is along the eastern margin of the Boulder batholith and is underlain mainly by Elkhorn Mountains Volcanics. Several normal faults have been mapped in the area. The high rating is due to (a) combinations of all submodels, (b) combined host rock, pluton, geochemistry, geophysics, faults, and linear-features submodels, or (c) combined host rock, pluton, geochemistry, and geophysics submodels.

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