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U.S. GEOLOGICAL SURVEY**

**Mineral resource assessment map for skarn deposits of gold, silver,  
copper, tungsten, and iron in the Butte 1°×2° quadrangle, Montana**

**By**

**J.E. Elliott, C.A. Wallace, G.K. Lee, J.C. Antweiler, D.J. Lidke, L.C. Rowan, W.F. Hanna, C.M.  
Trautwein, J.L. Dwyer, and S.H. Moll**

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# INTRODUCTION

## PURPOSE AND SCOPE

The purpose of this report is to assess the potential for undiscovered skarn deposits of gold, silver, copper, tungsten, and iron in the Butte 1°×2° quadrangle. Other deposit types have been assessed and reports for each of the following have been prepared: Vein and replacement deposits of gold, silver, copper, lead, zinc, manganese, and tungsten; porphyry-stockwork deposits of copper, molybdenum, and tungsten; stockwork-disseminated deposits of gold and silver; placer deposits of gold; and miscellaneous deposit types including strata-bound deposits of copper and silver in rocks of the Middle Proterozoic Belt Supergroup, phosphate deposits in the Permian Phosporia Formation, and deposits of barite and fluorite. The Butte quadrangle, in west-central Montana, is one of the most mineralized and productive mining regions in the U.S. 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 (at the time of production). 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 supported, in part, 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 an occurrence model for skarn deposits in the quadrangle, and the analysis of data using techniques provided by a 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 (USGS) Miscellaneous Investigations Series Maps I-2050-A (Rowan and Segal, 1989), I-2050-B (Rowan and others, 1991), I-2050-D (Elliott and others, in press); Miscellaneous Field Studies Map MF-1925 (Wallace, 1987a); and Open-File Reports OF-86-292 (Wallace and others, 1986) and OF-86-0632 (Elliott and others, 1986).

## 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, and 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 (map A). Proterozoic, Paleozoic, and Mesozoic sedimentary rocks are abundant and widespread as are Cretaceous and Tertiary plutonic rocks; the latter occur in the cores of most mountain ranges with associated metamorphic rocks. Volcanic and volcanoclastic 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 oldest rocks exposed in the quadrangle are the Belt Supergroup that were formed during Middle Proterozoic time when part of the Belt basin occupied the area of the Butte quadrangle; clastic and carbonate rocks of the Belt Supergroup have a total thickness of at least 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 sediments 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. About 6,700 m of clastic and carbonate Mesozoic sedimentary rocks were deposited in a foreland basin in the central part of the quadrangle, and about 2,400 m of equivalent strata were deposited in the northeastern part of the quadrangle.

In Late Cretaceous time, magmatism resulted in the formation of numerous stocks and several batholiths that were emplaced at mesozonal and epizonal depths and the formation of volcanic and volcanoclastic rocks. These plutons include the Boulder, Idaho, Sapphire, and Philipsburg batholiths, which are composed of monzogranite and granodiorite, and numerous stocks of diorite, granodiorite, and monzogranite. Hydrothermal activity during and following the waning stages of magmatism formed a variety of mineral deposits. Volcanic and volcanoclastic rocks of 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. Exten-

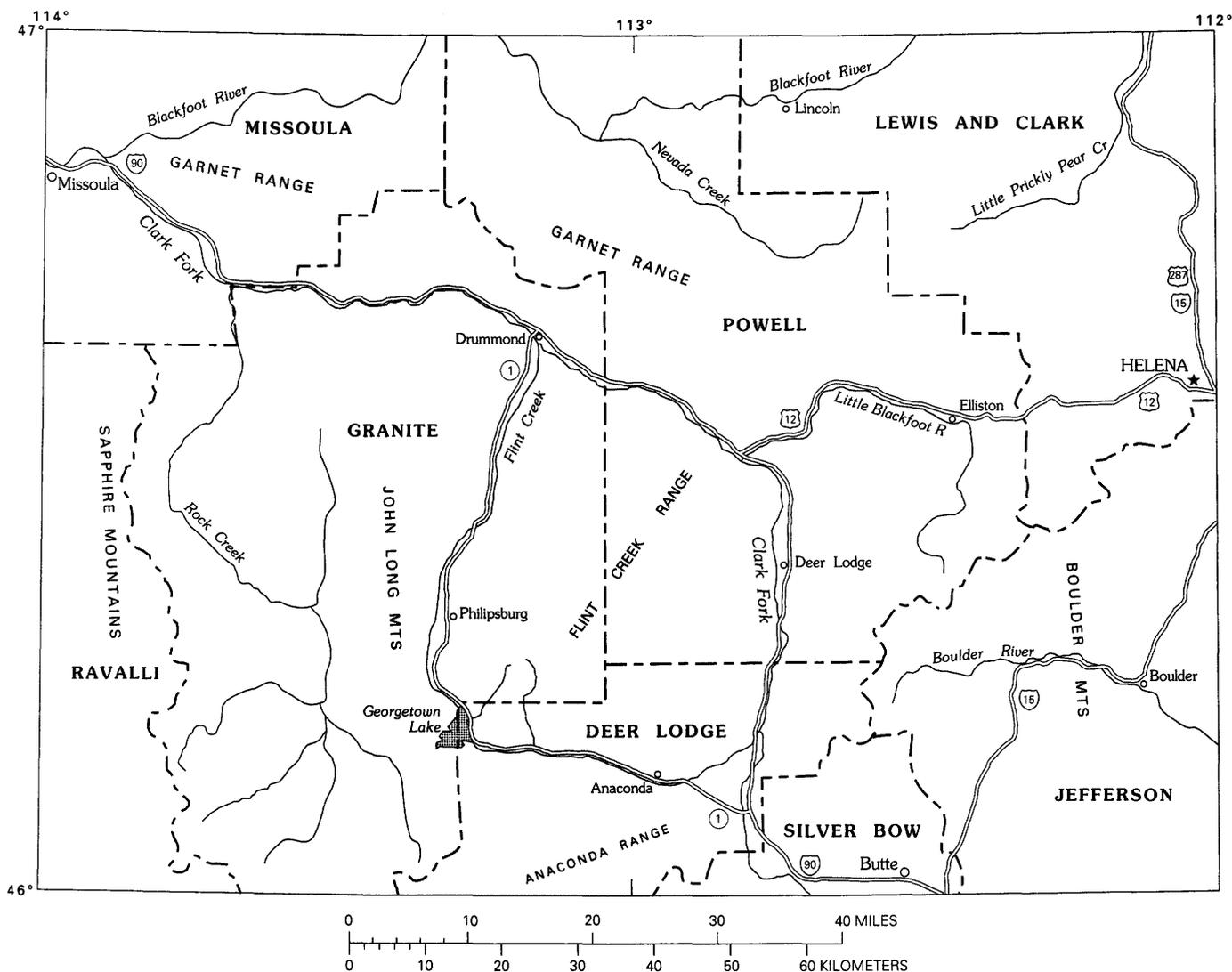


Figure 1. Index map of the Butte 1°x2° quadrangle.

sive Tertiary volcanism formed the Eocene Lowland Creek Volcanics, in the southeastern part of the quadrangle, and formed volcanic fields in the Garnet Range and east of Lincoln. Volcanic rocks 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. Concurrent volcanism contributed volcanic debris to the intermontane basins. During late Tertiary time, extensive pediments formed, and gravel, some of which contains valuable placer deposits of gold, was deposited on the pediments. Quaternary time was dominated by extensive alpine glaciation in many of the ranges in the quadrangle. Icecaps occupied the topographic crests of the Flint Creek and Anaconda Ranges and the Boulder Mountains, and valley and cirque glaciers were prevalent in these and other ranges. Four glacial events have been identified in the Flint Creek Range, and multiple glacial events probably occurred in the other ranges as well. Extensive glacial lakes repeat-

edly filled valleys in the northeastern and western parts of the quadrangle during the last glacial event. Post-glacial time was one of erosion and deposition of alluvium in modern stream channels.

The principal structural elements in 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 (fig. 2). The complexly faulted and folded 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 regional compression during late Mesozoic time. This compression formed

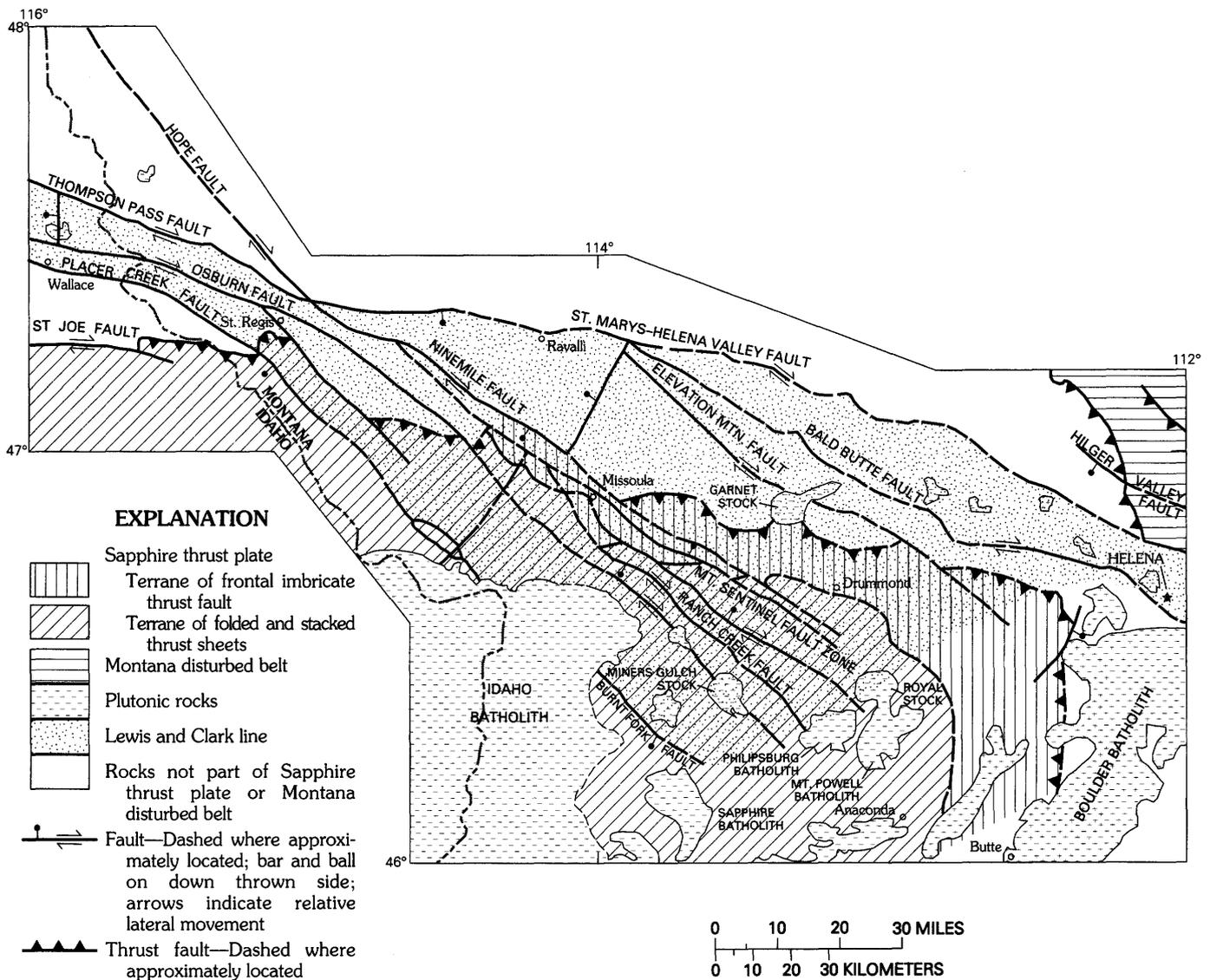


Figure 2. Principal structures and plutons of the Sapphire thrust plate (from Elliott and others, 1988).

an extensive foreland basin east of thrust plates that 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 occurred during Late Cretaceous time when laterally extensive thrust sheets, zones of imbricate thrusts, and tight and overturned folds were formed. Most Late Cretaceous magmatism postdates thrust and strike-slip faults; stocks and batholiths emplaced into the faulted terrane made the terrane more resistant to continued deformation. During early Tertiary time most of the present mountain ranges and drainage systems were formed by erosion and normal faulting along some ranges. Some normal faulting along the east side of Deer Lodge Valley and north of Elliston continued into middle Tertiary time. Minor Quaternary faulting may be related to continued

activity 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, from the rest of the quadrangle. The two most important types of deposits that have been mined in the quadrangle are (1) hydrothermal vein and replacement deposits of base and precious metals and (2) placer deposits of gold. Other important deposit

types are porphyry or stockwork copper and molybdenum; skarn gold, copper, silver, tungsten, and iron; 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 large 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.

A variety of mineral deposits and occurrences ranging in age from Proterozoic to Quaternary are found in the Butte quadrangle. The oldest 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 formation in the quadrangle were during 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-zinc-lead deposit that is related to the middle Eocene Lowland Creek Volcanics (Sillitoe and others, 1985). During Tertiary and Quaternary time, placer deposits of gold and other minerals formed as the result of the release of gold by weathering of lode deposits and transportation and deposition of gold and other valuable minerals on pediments, in alluvial fans, and in stream channels.

## SKARN DEPOSITS

The term "skarn," as used here, refers to deposits at or near contacts of carbonate-rich sedimentary rocks with intermediate to felsic plutonic rocks. Skarn deposits are characterized by a gangue that consists of "a coarse-grained, generally iron-rich, mixture of Ca-Mg-Fe-Al silicates formed by metasomatic processes at relatively high temperature" (Einaudi and Burt, 1982). Skarns have a wide range in texture and composition and have formed by the infiltra-

tion and diffusion of metasomatic fluids carrying exotic components (Einaudi and Burt, 1982). These fluids are mainly magmatic in origin, but many skarn deposits show evidence of several stages of metasomatism and alteration which indicate fluid change from early metamorphic fluids to magmatic fluids, and, in some cases, ending with late meteoric fluids (Einaudi and others, 1981). Skarn is synonymous with the terms contact-metamorphic, hydrothermal metamorphic, contact metasomatic, igneous metamorphic, and tectite (Burt, 1982).

Skarn deposits can be classified as endoskarn or exoskarn based on rock type they replace. Endoskarns are the result of replacement of intrusive rocks within the contact zone and exoskarns result from replacement of carbonate host rocks at or near the contact (Einaudi and Burt, 1982). Most of the world's economic skarn deposits are classified as calcic exoskarns, which form by replacement of limestone. Magnesian skarns, resulting from the replacement of dolomite, are less common. Garnet and pyroxene are the dominant minerals in calcic exoskarns. Skarn deposits are also classified based on the dominant economic metal they contain; the principal types are iron, tungsten, copper, zinc-lead, and tin (Einaudi and Burt, 1982). Compositional variations in garnet and pyroxene and content of sulfide minerals have also been used to separate skarns into reduced (grossularite + hedenbergite, sulfide poor) and oxidized (andradite + diopside, sulfide rich).

Skarns form over a wide range of temperature and pressure in complex magmatic-hydrothermal systems and commonly show evidence of multiple stages of recrystallization and metasomatism. The characteristic pattern of many skarns is an early stage of contact metamorphism, an intermediate stage of prograde metasomatism, and a late stage of retrograde metasomatism with associated sulfide deposition. Most skarns probably form at temperatures in the range of 300–600 °C and at moderate to shallow depths (range in pressure of 0.3 to 3 kb). Tungsten skarns and base-metal (copper, zinc, lead) sulfide skarns are most characteristic of continental-margin orogenic belts and are thought to be related to subduction-related I-type magmas. Tungsten skarns probably form at somewhat greater depths and at higher temperatures than base-metal sulfide skarns (Einaudi and others, 1981).

In the western U.S., skarns have been important producers of a variety of metals and are of particular importance as sources of tungsten. Most of the highly productive tungsten skarn deposits are in Nevada and California. Good examples are the Pine Creek and Strawberry mines in California and the Mill City and Tem Piute districts in Nevada. Skarn deposits have also been important sources of tungsten in Montana. The two most productive mines, the Calvert Hill and Brown's Lake deposits, in the Pioneer Range, were important producers of tungsten during the 1950's. These deposits are in the Dillon 1°×2° quadrangle, directly south of the Butte quadrangle. At the

Calvert mine, 102,800 tons of ore having a grade of 1.13 percent  $WO_3$  were mined during 1956–57 and an additional 10,000 tons of ore having a grade of 0.66–1.47 percent  $WO_3$  were mined in 1959 (Walker, 1963). The Brown's Lake mine produced 625,107 tons of ore having a grade of 0.35 percent  $WO_3$  during 1953–1957 (Pattee, 1960). Recent exploration in the vicinity of the Brown's Lake mine has resulted in the discovery of new orebodies having large reserves. These orebodies have an estimated 6,000,000 tons of rock having a grade of 0.57 percent  $WO_3$  (Len Garrand, 1988, written commun.). In the Dillon quadrangle, the principal host for tungsten-bearing skarns is a thinly bedded unit consisting of limestone, dolostone, sandstone, and mudstone that has been referred to as Amsden Formation of Mississippian and Pennsylvanian age (Pearson and others, in press b).

### PRINCIPAL SKARN DEPOSITS IN THE BUTTE QUADRANGLE

Skarn deposits are numerous in the Butte quadrangle; there are 49 mines and prospects which have been classified as skarn deposits (Elliott and others, 1986). Most skarns are calcic exoskarns but some magnetite-rich skarns (DeMunck, 1956), such as those in the Georgetown and Philipsburg districts, are magnetite-bearing magnesian exoskarns (Einaudi and others, 1981), which have formed by metasomatic replacement of dolomite. Most of the magnetite skarns occur in the Cambrian Hasmark Formation. Only a few of the skarns have been significant producers; the principal products have been gold, silver, and copper. Minor amounts of tungsten and iron have also been produced from skarn deposits. The iron ore has been mined at several localities and shipped to smelters for use as flux. In the Butte quadrangle, skarn deposits generally occur along or near contacts of Late Cretaceous granodiorite or monzogranite plutons with favorable limestone or dolomite beds. The most productive skarn deposits in the quadrangle are the Cable, Spring Hill, Blue Jay, Lexington, War Eagle, and Ajax mines. In addition, a subsurface tungsten-bearing skarn has been discovered by drilling in the Princeton district.

At the Cable mine, a septum of dolomite of the Cambrian Hasmark Formation that extends into the Cable granodiorite stock has been converted into several types of skarn. The two main types of skarn are (1) garnet-actinolite-magnetite-pyroxene-hematite-epidote-mica and (2) magnetite  $\pm$  calcite  $\pm$  olivine  $\pm$  diopside  $\pm$  sericite  $\pm$  pyrite  $\pm$  pyrrhotite. Gold ore occurs as large, irregular bodies which generally consist of calcite, quartz, magnetite, pyrrhotite, and gold. The gold is generally associated with coarsely crystalline calcite, quartz, and sulfide minerals (mainly pyrite and pyrrhotite) (Emmons and Calkins, 1913). The Cable mine has an estimated production of 165,000 oz of gold and 135,000 oz of silver having a gross value of \$4–6 million.

The Spring Hill mine, in the Helena district, is along the contact of limestone (Madison Group) and a small Late Cretaceous granodiorite stock. Both endoskarn and exoskarn are present in the contact zone. Gold ore is in the endoskarn, which consists of tremolite-actinolite, augite, calcite, quartz, epidote, zoisite, chlorite, phlogopite, scapolite, serpentine, monticellite, apatite, sphene, arsenopyrite, pyrite, pyrrhotite, and native gold. The exoskarn consists of calcite, diopside, dolomite, and garnet (Jones, 1934). The mine has an estimated production of 38,000 oz of gold (valued at \$760,000) for the period of 1885–1930 (estimated from data in Pardee and Schrader, 1933, p. 207).

The Blue Jay and War Eagle mines are in the Austin district. Ore, which contained copper, silver, and lead, has been mined from contact zones of limestone with andesite and monzogranite at the Blue Jay mine. The ore is oxidized and consists of hematite, limonite, chrysocolla, cerussite, azurite, and malachite. The total production is estimated to be \$300,000 (Pardee and Schrader, 1933). The War Eagle mine, located at the contact of limestone of the Madison Group with monzogranite, has produced a total of 75,000 tons of iron-rich rock for smelter flux. Small amounts of silver, as argentiferous galena, have also been reported (Pardee and Schrader, 1933).

The Lexington mine, in the Scratchgravel Hills area, produced ore that contained silver, lead, and gold having an estimated worth of \$250,000. The mine workings follow a 2-ft-wide zone of skarn that consisted of garnet-hornblende rock, although much of the production may have come from quartz veins that cut the skarn. The skarn is an inclusion in the monzonite stock of the Scratchgravel Hills (Pardee and Schrader, 1933).

In the Ophir district, the Ajax mine has exploited a skarn that follows the contact of Cambrian limestone with Cretaceous granodiorite of the Blackfoot City stock. The ore consists of magnetite, hematite, and garnet. The mine reportedly produced ore, which contained gold, silver, and copper, that had an estimated value of \$50,000 (Pardee and Schrader, 1933).

A tungsten-bearing skarn zone was discovered by Union Carbide Corporation in the Princeton district during the 1970's. At this prospect (called Finlay Basin or HO claims), tungsten skarn was explored by drilling. The skarn is a replacement of limestone beds of the Snowcrest Range Group and of the Madison Group. The best grades are found in skarn at the contact zone between Madison Group limestone and granodiorite of the Royal stock. This deposit contains an estimated 850,000 tons of ore that has a grade of 0.68 percent  $WO_3$  (John Trammel, written commun., 1985).

### METHODOLOGY OF MINERAL RESOURCE ASSESSMENT

The purpose of this study is to assess the potential for undiscovered skarn deposits of gold, silver, copper, tung-

sten, and iron in the Butte 1°×2° quadrangle. To accomplish this task, methods had to be adopted or developed to allow us to assess the potential for occurrence of unexposed mineral deposits. The methods used in this study involve the development of descriptive mineral deposit models and the application of these models using the technology of Geographic Information Systems (GIS). A mineral deposit model is "...the systematically arranged information describing the essential attributes (properties) of a class of mineral deposits. The model may be empirical (descriptive), in which instance the various attributes are recognized as essential even though their relationships are unknown; or it may be theoretical (genetic), in which instance the attributes are interrelated through some fundamental concept." (Cox and Singer, 1986, p. 2).

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); 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; and, most importantly, on working in close cooperation with Robert C. Pearson, coordinator of the Dillon (Idaho and Montana) CUSMAP, which is directly south of the Butte quadrangle. Although each of the previous CUSMAP mineral resource assessments has followed a different path, a general procedure has been developed, as follows:

1. Collection and compilation of geologic, geochemical, geophysical, and other data pertinent to the occurrence of mineral deposits.
2. Determination of the types of mineral deposits known to exist and that might exist in the quadrangle.
3. For each deposit type, apply available conceptual descriptive models or develop models and recognition criteria as required.
4. Evaluate the areal distribution and relative importance of recognition criteria.
5. Assess the mineral resource potential based on the presence and rank of recognition criteria.

Much of the modeling approach and the use of favorable criteria were first applied by Pratt (1981) to the Rolla quadrangle (Missouri). Harrison and others (1986b) adapted and expanded the methodology for the Wallace quadrangle (Idaho and Montana). Pearson and others (in press a, b) followed Harrison's lead and worked cooperatively with personnel at the EROS Data Center at Sioux Falls, South Dakota, in the development of GIS techniques for mineral resource assessment of the Dillon quadrangle (Idaho and Montana). 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.

For the Butte quadrangle, most of the data needed for resource assessment 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. The interpreted and compiled data were then entered into a computer-based GIS.

A GIS, consisting of computer hardware and software components, was used to develop procedures for mineral resource assessment, interpret compiled and processed data, and prepare the intermediate and final map-based products of resource assessment. Nearly all of the original data were either in map or tabular form. A generalized geologic map, mining district map, geophysical anomaly map, limonite map, and linear features map were digitized and entered into a vector subsystem of the GIS. Geochemical data and mine and prospect data were entered as tabular data in the GIS.

Several descriptive mineral deposit models were developed based on the types of mineral deposits that exist or have a high potential for existing in the Butte quadrangle. Each mineral deposit model consists of a description and a list of recognition criteria. For deposit types that are well represented in the Butte quadrangle, the recognition criteria are based mainly on observed characteristics of such deposits within the quadrangle and in the adjacent region of southwestern Montana. For some types of deposits, not present or not well represented in the quadrangle, descriptions and (or) models for deposits in other parts of the northwestern and western U.S. were used. The kinds and quantity of data available limited the number and types of recognition criteria. It was also required that the recognition criteria be applicable to the entire quadrangle, and not just selected parts of the quadrangle.

For each mineral deposit model, several GIS submodels were developed that correspond to recognition criteria of the deposit model. Within each GIS submodel, a scoring or weighting range was generated that expresses the degree of favorability for factors such as host rock, associated igneous rock, geochemical anomalies, and others. The scores are based mostly on observed or measured association of mines and prospects with certain classes of host rock, igneous rocks, geochemical anomalies, and other factors. Each submodel has several levels having scores in the range of 0 to 5. The final mineral resource assessment map (map A) is derived by combining the GIS submodels (maps D-J) into a summary GIS model (map K) and then assigning levels (low, moderate, high, very high) of mineral resource potential to the final map.

## **MINES AND PROSPECTS**

Mineral deposit data for mines and prospects in the Butte quadrangle were compiled by Elliott and others

(1986). They list 1,111 mines and prospects by mining district and geographic area. These mines and prospects are found throughout the quadrangle; 858 (77 percent) are in established mining districts and the remaining 253 (23 percent) are more widely scattered over the remainder of the quadrangle. Mines and prospects are classified into 13 deposit types. Vein and replacement deposits of base and precious metals are the most common deposit type with 772 (69.5 percent) of the mines and prospects classified as this type. Next in frequency are placer (nearly all gold but some tungsten and sapphire) deposits with 135 (12.2 percent) mines and prospects. Mines and prospects classified as skarn deposits account for 49 (4.4 percent) of the mines and prospects. The data on mines and prospects were compiled from all available published and unpublished data; the principal source 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 included data from published reports more recent than those cited in MRDS, unpublished records of 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 1980–84, approximately 150 mineralized sites were visited in order to verify the MRDS and other data and to collect additional information on geology, geochemistry, alteration, and mineralization.

## GEOLOGY

The geologic map that was digitized and used for the mineral resource assessment of the Butte quadrangle is a modified version of the generalized geologic map by Wallace (1987a). Initially, 38 geologic map units, 5 classes of faults, and axial traces of folds were digitized from the generalized geologic 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 of granodiorite were distinguished from other Late Cretaceous plutons of granodiorite, granite, and monzodiorite. Additions of these 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 where covered by younger volcanic and sedimentary rocks and surficial deposits. This allowed the mineral resource assessment of the potential for skarn deposits to be extended beneath these younger rocks and surficial deposits.

The geologic map of the Butte quadrangle portrays new map data obtained between 1975 and 1983 except for the area of the Boulder batholith, which had been mapped previously. During the period 1975–79, 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 from the Boulder batholith at 1:250,000 scale (Wallace and others, 1986; Wallace, 1987a).

The rock units that are important for the resource assessment of skarn deposits are sedimentary rocks of Proterozoic, Paleozoic, and Mesozoic age and plutonic rocks of Cretaceous and Tertiary age. Because the composition of host rocks is critical to the formation of skarn deposits, the most favorable carbonate host rocks are emphasized in the following pages, and other units having low potential as hosts for skarn deposits, such as Cretaceous and Tertiary volcanic rocks and Tertiary and Quaternary sedimentary rocks, are not discussed. Paleozoic sedimentary rocks, especially carbonate units which are susceptible to metasomatic replacement, are more important than Proterozoic and Mesozoic sedimentary rocks as hosts for skarn deposits. Plutonic rocks, especially those of granodioritic composition and of Cretaceous age, are the most probable sources of most of the hydrothermal ore-forming fluids that formed skarn deposits.

## SEDIMENTARY ROCKS

The oldest rocks in the quadrangle are part of the Belt Supergroup (Middle Proterozoic). The Belt Supergroup is dominantly a clastic sequence that consists 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. Formations of the middle Belt carbonate overlie the Ravalli Group and include two laterally equivalent rock units, each of which is estimated to be at least 3,000 m thick; the Helena Formation is present in most of the quadrangle and the Wallace Formation dominates in the westernmost part of the quadrangle. The Helena Formation is a dolomite- and limestone-rich sequence of argillite and siltite, whereas the Wallace Formation is mainly dolomitic argillite, siltite, and quartzite. The Missoula Group, which is about 10,000 m

thick in the western part of the quadrangle, forms the uppermost part of the Belt Supergroup. This dominantly clastic sequence contains, in ascending order, the Snowslip, Shepard, and Mount Shields Formations, the Bonner Quartzite, the McNamara and Garnet Range Formations, and the Pilcher Quartzite.

Paleozoic rocks range in age from Middle Cambrian to Early Permian, but the Paleozoic succession is incomplete because numerous unconformities separate formations. The Paleozoic 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 are at the top.

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

Overlying the Cambrian formations is the 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 Jefferson Formation (Upper Devonian), above the Maywood Formation, is composed mainly of black and dark-gray dolomite and limestone, which is interbedded with some shale beds near the base and has light-gray limestone and dolomite breccia near the top. North and northeast of the Sapphire thrust plate, the Three Forks Formation (Upper Devonian and Lower Mississippian) overlies the Jefferson Formation, but within the Sapphire thrust plate the Three Forks Formation is absent. The Three Forks Formation consists of brownish-gray shale, siltstone, limestone, and 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 are 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. Upper Mississippian and Lower Pennsylvanian rocks of the Snowcrest Range Group (identified by B.R. Wardlaw, oral commun., 1986), which were considered previously to be Amsden Formation (Emmons and Calkins, 1913; Kauffman and Earll, 1963; McGill, 1959; Ruppel and others, 1981), overlie rocks of the Madison Group and consist 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, vitreous, 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 and volcanoclastic rocks form a succession of shale, sandstone, limestone, tuff, bentonite, volcanoclastic conglomerate, and carbonate-bearing clastic rocks that range in age from Middle Jurassic to Late Cretaceous (Emmons and Calkins, 1913; Kauffman and Earll, 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 Ellis Group (Middle and Upper Jurassic), Kootenai Formation (Lower Cretaceous), Blackleaf Formation (Lower and Upper Cretaceous), and several formations of Late Cretaceous age. The sequence of Upper Cretaceous rocks that overlies the Lower and Upper Cretaceous Blackleaf Formation differs 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, Telegraph Creek Formation, Virgelle Sandstone, and Two Medicine Formation. In contrast, within the Sapphire thrust plate, the Blackleaf

Formation is overlain, in ascending order, by the Coberly, Jens, Carten Creek, and Golden Spike Formations (Gwinn, 1961; Gwinn and Mutch, 1965, p. 1137). Numerous unconformities separate rock units of Mesozoic age.

## 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 intrude rocks of the Missoula Group in the northwestern part (Nelson and Dobell, 1959, 1961; Wallace and others, 1986). These dikes and sills are correlated with Middle or Late Proterozoic dikes and sills that exist elsewhere in Belt rocks (Harrison and others, 1986a; Mudge and others, 1982) because of compositional and geochemical similarity.

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 (all K-Ar ages from older publications have been recalculated using the International Union of Geological Sciences (IUGS) decay constants). 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) part of 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).

Most of the Boulder batholith, as well as several of its satellite plutons, are in the Boulder Mountains between Helena and Butte or 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). A large number of productive vein and replacement deposits, including 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, 1985, written commun.), 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 mines and prospects.

The principal plutons of the Flint Creek Range are the Philipsburg and Mount 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, 1983, oral commun.). Most plutonic rocks in the range are post-tectonic and emplaced after thrusting. However, in the eastern part of the range, older plutonic and metamorphic rocks of Racetrack Creek, which includes plutonic rocks ranging from granodiorite to diorite, are deformed by thrust faults, indicating pretectonic or syntectonic emplacement. Most mineral deposits are related to the granodiorite plutons such as the Royal and Cable stocks and the Philipsburg batholith.

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, 1982, written commun.). However, an older granodiorite-tonalite-quartz diorite plutonic complex is cut by thrust faults and may be Late Cretaceous in age (Elliott and others, 1985; Heise, 1983; J.D. Obradovich, 1982, written commun.). Few, mostly nonproductive, mineral occurrences 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, 1977, written commun.), are along the western border and in the southwestern corner of the Butte quadrangle. These plutons are part of the Idaho batholith and generally lack associated 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, Big Spring Creek, Welcome Creek, Wallace Creek, Gird Point, and Gillespie Creek stocks. The ages of most of these stocks range between 82 and 49 Ma (Wallace and others, 1986; J.D. Obradovich, 1982, oral and written commun.). 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 of probable Cretaceous age are in the southern Sapphire Mountains but their ages have not been determined. Many of the granodiorite plutons, including the Garnet, Henderson, Wallace Creek, and Miners Gulch stocks, have associated mineral deposits, whereas others, such as the Sapphire batholith, have few associated mines and prospects.

## GEOCHEMISTRY

The geochemical data used for the mineral resource assessment of the Butte quadrangle were obtained from a sampling survey conducted by the USGS during 1979–82. 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 skarn deposits were generated from the analytical data for stream-sediment and

panned-concentrate samples. 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, analyses 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 related to ore, are components of relatively insoluble heavy minerals; alluvium may be panned to concentrate these minerals to levels at which the ore-related 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 generally collected near the stream-sediment samples but from coarser-grained 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 for 31 elements 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 by atomic-absorption (AA) methods described by Ward and others (1969), Thompson and others (1968), and Viets (1978) and analyzed for tungsten by colorimetric (CM) methods (Welsh, 1983). The precision of the SES method is given by Motooka and Grimes (1976). For the resource assessment of

the Butte quadrangle, only SES and AA analyses were used, because the CM analyses had not been performed on the majority of samples.

Analytical results were entered into the Rock Analysis Storage System (RASS), which is a computerized data base maintained by the USGS in Denver, Colorado (Van Trump and Miesch, 1976). RASS contains both descriptive geologic data 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 a USGS Open-File Report (Campbell and others, 1982); however, this report is incomplete for analytical data from the eastern one-third of the quadrangle, and it contains some errors that have been subsequently corrected on the magnetic tape.

The procedures used for processing and interpretation of geochemical data are described in the Appendix.

## GEOPHYSICAL DATA

The several geophysical methods utilized in this study produce data best applied to the assessment of subsurface mineral resource potential. Magnetic and gravity data proved particularly useful in the Butte quadrangle. These data were acquired in regional surveys of the quadrangle or compiled from previous surveys. After compilation of all data onto maps at a scale of 1:250,000, the maps were examined and compared with maps of geology (Wallace, 1987a) and mines and prospects (Elliott and others, 1986). Many of the geophysical anomalies were correlated with geologic units and with the distribution of known mineral occurrences. Magnetic highs coincide with some mapped plutons, especially with those of intermediate or mafic composition and of Late Cretaceous or Tertiary age. Many mines and prospects in the quadrangle are associated with Late Cretaceous or Tertiary plutons of granodiorite and monzodiorite, thus, 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 areas of anomalously low gravity are coincident with sedimentary basins that are filled with Tertiary and Quaternary sediment, whereas other gravity lows coincide with mapped plutons, some of which have associated mineral deposits. Therefore some of the low gravity anomalies also have a positive correlation with mines and prospects of the Butte quadrangle.

The correlation of areas of anomalously high magnetism with plutons is based on two assumptions; (1) that the boundaries of a given pluton dip steeply, at least in the shallow subsurface, and (2) that the total magnetization has a direction and polarity consistent with those of the present earth's magnetic field. The first condition of steep upper

flanks of the rock mass can be proven only by drilling or other geophysical data. 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 developed that permitted the drawing of lines around regions inferred to be underlain by significantly thick masses 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 nature of the geophysical data used in this study and the specific procedures for developing an interpretive geophysical map are described in the appendix. The resulting map is shown as map H. On this map, some areas of mapped plutonic rocks, which are larger than the 1.5 km (0.9 mi) spacing of the magnetic data grids, fall outside of the areas of magnetic plutonic rocks. By inference, these rocks are either quite thin and consequently small in volume and magnetic dipole moment or they are less magnetic than most plutonic rocks. If less magnetic, these rocks may be either leucocratic or hydrothermally altered, as are some parts of the Boulder batholith. The techniques used in this study are not suitable for discriminating between hydrothermally altered plutonic rocks and other types of nonmagnetic or weakly magnetic rocks.

## REMOTE SENSING

Remote-sensing studies included the analysis of limonitic rocks from Landsat data (Rowan and Segal, 1989) and the analysis of linear features from Landsat and side-looking airborne radar (SLAR) data (Rowan and others, 1991). Exposures of anomalously limonitic rock and soil, which might be the result of hydrothermal alteration, and linear topographic and tonal features, which might be expressions of structural features, were determined from a Landsat Multispectral 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.

## LIMONITIC 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 (1989) 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. A color-ratio composite, instead of single-channel composite images, was 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 and these areas were evaluated in the field to distinguish between limonite that resulted from the weathering of hydrothermally altered rocks and limonite developed from weathering of unaltered iron-bearing rocks. In many areas of the quadrangle, dense vegetation precluded reflectance measurements using MSS image data; in these areas limonitic rocks and soils could not be detected.

## LINEAR FEATURES

Linear features were delineated by the analysis of MSS and SLAR images; the principal objective of this analysis was to determine the relationship between linear features and known mines and prospects (Elliott and others, 1986) and to apply this relationship to the 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 differences in color or shades of color. Rowan and others (1991) mapped linear features but excluded those that obviously reflected lithologic layering or cultural features and included only the linear features that were assumed to represent structures such as faults, shear zones, fractures, dikes, and alignments of fold axes. After mapping the linear features, they were digitized for subsequent analysis.

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 history and lithology. A comparison of spatial association of linear features with known 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

### THE GEOGRAPHIC INFORMATION SYSTEM (GIS)

The development of procedures for mineral resource assessment and the preparation of the final mineral resource

assessment map was expedited by the use 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; data that are already in a digital format, such as aeromagnetic data, are entered directly into the 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 GIS and 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 having large amounts of ore production from 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 the 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 and others (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 interactively display interim results of processing, and to statistically analyze spatial relations between data sets. The

procedures used for entry, processing, and interpretation of data by the GIS are explained in the Appendix.

## MINERAL RESOURCE ASSESSMENT

The procedure used in the mineral resource assessment of skarn deposits in the Butte quadrangle consisted of (1) the development of a descriptive model for skarn deposits, (2) the development of submodel maps based on favorable criteria of the descriptive model using GIS techniques, and (3) the combination of these submodel maps into a summary map showing various levels of potential for undiscovered skarn deposits. The following paragraphs define the mineral resource terms that are used in this report.

**Recognition criteria**—Geologic parameters 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, are considered to be required for the occurrence of a mineral deposit (Pratt and others, 1984).

**Permissive criteria**—Criteria that are present in some but not all 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 sufficiently large concentration of valuable or useful metal or material 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.

**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, or high levels of resource potential. This category is generally used only for areas with thick alluvium or other covering rock unit 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 in this report for the areas of highest total scores on the mineral assessment map for skarn deposits (map A). This higher rating of mineral resource potential is justified based on the quantity and quality of data available for skarn deposits and based on the existence of approximately 40 productive deposits of this type within the quadrangle. Other deposit types, such as porphyry or stockwork copper-molybdenum deposits, have potentials no higher than **HIGH** mineral resource potential because fewer deposits of these types are known within the quadrangle and there is greater uncertainty in regard to the descriptive model and the application of the available data to their assessment.

#### DESCRIPTIVE MODEL FOR SKARN DEPOSITS OF GOLD, SILVER, COPPER, TUNGSTEN, AND IRON

The descriptive model for skarn deposits of gold, silver, copper, tungsten, and iron is based on (1) known deposits in the Butte quadrangle and (2) a model for contact metasomatic tungsten-copper-gold deposits (Elliott, 1982). This model is similar to models for tungsten skarn, copper skarn, and zinc-lead skarn deposits proposed by Cox and Singer (1986).

#### Regional settings of skarn deposits

Skarns form in plutonic environments in regions of active tectonism and orogeny. Skarn deposits are common in the western United States and they are found commonly at borders of calc-alkaline batholiths, in contact zones of

satellite plutons, or in roof pendants and septa of metasedimentary rocks in plutons. Host rocks for skarns are typically shelf facies carbonate rocks. Limestone and marble are favorable hosts, but the presence of interlayered impure carbonate rocks and siliceous clastic rocks in predominantly carbonate sequences may enhance the favorability of certain formations or groups to host skarn deposits. In the Butte quadrangle, the most favorable hosts for skarn deposits are Paleozoic carbonate rocks. These are the Silver Hill, Hasmark, and Red Lion Formations of Cambrian age; the Devonian Jefferson Formation; the Snowcrest Range Group (formerly called the Amsden Formation) of Mississippian and Pennsylvanian age; and the Mississippian Madison Group. Less favorable carbonate-bearing sequences are the Helena, Wallace, and Empire Formations of the Middle Proterozoic Belt Supergroup and limestone of the Cretaceous Kootenai Formation.

#### Deposit-orebody characteristics of skarn deposits

At the scale of a deposit or an orebody, intrusive rocks either are in direct contact with a skarn or are found a short distance away from a skarn. The intrusive rocks that are associated with contact metasomatic deposits are commonly the youngest of a series of intrusives. Skarn-related intrusions are usually equigranular and are biotite or biotite-hornblende-bearing granitoids. They usually have modal compositions of monzogranite or granodiorite. The metallogenic intrusive rocks are usually more leucocratic and quartz-rich compared to associated nonmetallogenic intrusive rocks. Skarns are commonly cut by younger (postmetasomatic) dikes and quartz veins.

Selective replacement and metasomatism is probably most effective in purer carbonates. However, thinly bedded carbonate units that are interbedded with impure carbonate and siliceous clastic rocks are more favorable than thickly bedded sequences of pure carbonate rocks for two reasons. First, during folding and (or) faulting there is a greater tendency to develop fracture zones of high permeability in the thinly bedded sequences. Thick-bedded pure carbonate rocks tend to deform plastically without developing zones of high permeability. Second, sequences of impure carbonate and siliceous beds also provide a nearby source for silica, alumina, and other constituents for the formation of calc-silicate minerals of skarn zones. In the Butte quadrangle, the Snowcrest Range Group, which consists of interbedded shale, siltstone, sandstone, calcareous clastic rocks, limestone, and dolomite, is the most favorable host for the development of skarns, especially tungsten skarns. The Snowcrest Range Group is generally a few hundred feet thick, although both the thickness and lithology change laterally in the region. Hydrothermal alteration related to the formation of skarn zones is usually more evident in carbonate host rocks than in the intrusive rocks. The most common effect is the bleaching of carbonate rocks, probably due to

removal of organic carbon, near and at the intrusive contact. Contact metamorphism commonly results in the recrystallization of carbonate to marble and the development of calc-silicate minerals such as scapolite, idocrase, and wolastonite. Skarns typically consist of iron-rich garnet, pyroxene, amphibole, and (or) epidote. Many skarns, especially gold-, silver-, and copper-bearing types, contain moderate to large amounts of sulfide minerals; the most common of which are pyrite and pyrrhotite. The weathering of skarn deposits commonly results in the development of limonitic zones.

Structures in host and intrusive rocks, the dip of bedding relative to the intrusive contact, and the configuration of the intrusive contact are important ore controls in the formation of skarns. Folds, faults, and joints provide secondary channels of higher permeability for the movement of mineralizing fluids. Places where an intrusion intersects the limb of an anticline or where a fold in the host rocks plunges towards an intrusive contact are highly favorable for the localization and formation of skarns. At places where bedding dips towards the intrusive contact, conditions are more favorable for the formation of skarn than where bedding is parallel or dipping away from the intrusive. The configuration of the intrusive contact may affect the development of skarn deposits in several ways. Troughs in the contact may aid in the movement of metasomatic fluids, and overhangs of intrusive rock over host carbonate rock in the contact zone may cause "ponding" of fluids. A shallow-dipping or flat contact is more favorable than a steeply dipping contact because the flatter contact promotes increased thermal effects and metasomatism on favorable carbonate host rocks.

The chemistry of skarn deposits is quite variable; base-metal skarns (copper, lead, zinc) generally contain more sulfide minerals than tungsten skarns, and the geochemical suite of trace and minor elements for base-metal skarns shows a greater abundance of chalcophile elements such as arsenic, bismuth, and molybdenum. Tungsten skarns contain higher concentrations of lithophile elements and have minor and trace element suites that include beryllium, tin, fluorine, and niobium.

#### Geophysical and remote sensing exploration techniques for skarn deposits

The detection of skarns by geophysical techniques is based on the following characteristics of skarns: (1) Skarn deposits are located along contacts of plutons. Many plutonic rocks are more magnetic than surrounding sedimentary rocks which they intrude and would appear as magnetic highs in regional aeromagnetic surveys. Therefore the edges of magnetic highs would be favorable places to look for skarns. (2) Skarns are composed of calc-silicate and other minerals of high specific gravity, generally in the range of 3.0 to 3.5. Minerals of the carbonate host rocks, such as

calcite and dolomite, and of associated intrusive rocks, such as quartz and feldspar, have specific gravities generally in the range of 2.6 to 2.7. Therefore a skarn deposit should be detectable as an anomalous gravity high in a gravity survey. (3) Skarn deposits commonly contain minor to major amounts of pyrrhotite and (or) magnetite. Such skarns should be detectable as anomalous magnetic highs in magnetic surveys. (4) Some skarns contain minor to major amounts of sulfide minerals, especially pyrite and pyrrhotite. Electrical methods should be useful in the detection of skarns having anomalous amounts of sulfide minerals compared to surrounding host and intrusive rocks. Only characteristic (1), above, is useful in regional surveys and is the only technique for which data are available in this study. Characteristics (2), (3), and (4) are probably useful only in detailed studies having closely spaced data points because the size of skarn deposits is generally too small to be detected in regional surveys. Detailed geophysical surveys were not attempted in this study.

Like regional geophysical surveys, remote-sensing studies would not be particularly useful for the discrimination of actual skarn deposits because the target size is very small. However, since most skarn deposits contain iron-rich minerals including silicates, oxides, and sulfides, the weathering of skarns can result in areas of limonite that might be detected and mapped using Landsat images. These areas of limonite might indicate the presence or potential for skarn as well as other types of mineral deposits. The mapping of linear features by remote-sensing techniques can be useful in the discrimination of structures which may control the localization of skarn deposits. For this study, both limonite and linear feature maps were prepared for the purpose of mineral resource assessment of the Butte quadrangle.

#### Recognition criteria for skarn deposits

The recognition criteria listed below for skarn deposits in the Butte quadrangle are based mainly on known deposits within the quadrangle or in the adjacent Dillon quadrangle. These criteria are restricted to the kinds of data available, mainly as a result of CUSMAP studies. To be useful as recognition criteria, a set of data (geochemical, aeromagnetic, and other data) should be complete, or nearly so, for the quadrangle as a whole and amenable to GIS treatment; for example, 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.

The favorable recognition criteria for skarn deposits are

1. Favorable host rock, such as carbonate-bearing sequences, preferably of Paleozoic age.
2. Plutonic rocks of suitable age and composition, such as granodiorite of Late Cretaceous age.
3. Geochemical anomalies in stream-sediment sam-

ples, especially multiple-element anomalies containing tungsten, gold, copper, lead, zinc, iron, manganese, molybdenum, tin, beryllium, silver, arsenic, and (or) bismuth.

4. Limonite formed by weathering of iron-bearing minerals in hydrothermally altered or metasomatized rocks.

5. Geophysical anomalies which may indicate the existence of magnetic plutonic rocks in the subsurface.

6. Favorable faults and (or) folds in host rocks.

7. Favorable linear features.

Criteria 1, 2, and 3 can be considered diagnostic criteria and 4, 5, 6, and 7 can be considered permissive criteria. A negative criterion would be the interior areas of exposed plutonic rocks, because skarns are formed along the margins of plutons and usually only in the exocontact zone.

#### PROCEDURE USING THE GEOGRAPHIC INFORMATION SYSTEM

The recognition criteria for the descriptive deposit model were used to develop seven submodels using the GIS; each submodel is representative of a recognition criterion (maps D-J). Each submodel was assigned a point score in the range of 0–5 to indicate the degree of favorability of geologic, geochemical, or geophysical environments or factors for the occurrence of skarn deposits. Diagnostic criteria such as host rocks, plutonic rock association, and geochemical anomalies have maximum scores of 5; permissive criteria such as structure, alteration, geophysics, and linear features have maximum values of 2 or 3. The final model (map K) is derived by overlaying and summing all of the scores of individual submodels. 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 host rock submodel is based on (1) the observed association between known skarn deposits and geologic units in western Montana and (2) the well-documented favorability of carbonate sedimentary rocks as hosts to skarn deposits in other regions of the U.S. and the world. The largest tungsten skarn deposits in Montana, such as Brown's Lake and Calvert mines in the Dillon quadrangle, are metasomatic replacements of the Amsden Formation (Pearson and others, in press b). In the Butte quadrangle, rocks of similar lithology to the Amsden Formation have been mapped as the Snowcrest Range Group. Based on an analogy with host rocks for skarn deposits in the Dillon quadrangle, the Snowcrest Range Group is considered the most favorable host in the Butte quadrangle. On the generalized map (map A) the Snowcrest Range Group is not shown separately but is combined with other stratigraphic units of Permian, Pennsylvanian, Mississippian, and Devonian age (unit PDs). The Madison Group and Jefferson

Formation, also known to be favorable hosts for skarns, are included in the same map unit (unit PDs) as the Snowcrest Range Group. Other favorable host units in the Butte quadrangle are the Silver Hill and Hasmark Formations of Cambrian age; these are combined with other Cambrian units and shown on the generalized geologic map as a single unit (unit Cs).

A tally of skarn deposits shows that 44.9 percent are in Devonian to Permian sedimentary rocks (unit PDs) and 38.8 percent in Cambrian sedimentary rocks (unit Cs). Nearly all of the remaining deposits (16.3 percent) are hosted by Proterozoic sedimentary rocks. The association of skarn deposits with a particular geologic map unit is determined by the calculation of normalized mine density, which is defined as the percent of total mineral occurrences divided by the percent of total map area for a map unit (percent mines/percent area). For example, if 70 of a total of 700 mineral occurrences are in a map unit which occupies 5 percent of the map, then the percent mines is  $70/700=0.1$  or 10 percent. 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 densities than the average respectively. Normalized mine densities were calculated for known skarn deposits versus geologic map units. The highest density was 10.8 for Cambrian sedimentary rocks and the second highest was 4.36 for Devonian to Permian sedimentary rocks.

Another measure of the favorability of host rocks is the relationship between size of deposit and host rock. The size of production from skarn deposits was compared with the age of the host rock, and it was found that more of the larger deposits are in Devonian to Permian sedimentary rocks than in Cambrian sedimentary rocks. The Calvert and Brown's Lake mines in the Dillon quadrangle and the Spring Hill and Finlay Basin skarn deposits in the Butte quadrangle are all in Devonian to Permian sedimentary rocks.

In the resource assessment of skarn deposits we assigned a higher favorability to Devonian to Permian sedimentary rocks than to Cambrian sedimentary rocks because we think the size of productive deposits is more important than the normalized density of mines and prospects. Other geologic map units have lower favorabilities than either Devonian to Permian or Cambrian sedimentary rocks. Map D shows the ranked favorabilities of host rock submodel with Devonian to Permian sedimentary rocks scored as 5 and Cambrian sedimentary rocks as 4. Other carbonate-bearing units are scored 1, 2, or 3 based on the distribution of known deposits. Noncarbonate units are scored 0. Mapped exposures of plutonic rocks are displayed as gray because, in this report, they are treated only as source rocks and not as hosts for skarns. Endoskarns can occur in some plutonic rocks but, if present, they are expected to be small and generally associated with larger exoskarns in the adjacent sedimentary rocks. This submodel

also can not account for skarn deposits in inclusions or roof pendants within plutons if these inclusions and roof pendants are not shown on the generalized geologic map.

#### Plutonic rock submodel

The plutonic rock submodel (map E) is based on the normalized mine densities of known skarn deposits proximate to contacts of plutons and on some subjective judgments based on age and composition of plutons. The normalized mine densities of skarn deposits were measured in successive 1-km-thick bands around plutons, extending outward to 6 km away from contacts. Based on the normalized mine densities, the optimum zone for the occurrence of skarn deposits is from the contact to 2 km away from the intrusive contact. The scoring of zones is based on the age and composition of plutonic rocks; the scores are 5, 3, 2, or 1 (map E). No plutons were scored as 4 because of a considerable gap in mine densities between plutons scored as 5 (average density of 9.2) and those scored as 3 (average density of 0.9). The highest scored plutons (5 points) are all Late Cretaceous in age and mostly granodiorite; they include the Boulder and Philipsburg batholiths and the Royal, Scratchgravel Hills, Marysville, and Cable stocks as well as some other plutons of granodioritic to dioritic composition. The lowest ranked plutons (1 point) include Tertiary or Tertiary or Cretaceous monzogranite, granodiorite, gabbro, syenite, and pyroxenite; these units are found in the Anaconda Range and in the southern part of the Sapphire Mountains.

#### Geochemical submodel

The selection of elements and suites of elements for the geochemical submodel was based on (1) chemical composition of known skarn deposits and (2) association of single-element anomalies with known deposits. The data for the geochemical characterization of known deposits was obtained by 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 (from Elliott and others, 1986) on anomaly maps and calculating the normalized mine density in areas of anomalously high concentrations for each element. This normalized mine density is the percentage of all the skarn mines and prospects in the quadrangle that are in geochemically 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 density of 1.0 is the average value for the total area of the map, those single-element anomaly maps having densities of greater than 1.0 were selected for the geochemical

submodel. The elements selected for inclusion in the geochemical submodel were tungsten, gold, copper, lead, zinc, iron, manganese, molybdenum, tin, beryllium, silver, arsenic, and bismuth.

The total number of anomaly maps were reduced and simplified by arithmetically combining some single-element maps into multielement maps. These maps show combined anomalies for groups of two or three elements such as lead and zinc or molybdenum, tin, and beryllium. The final set of anomaly maps included maps for an accessory suite I (lead-zinc), accessory suite II (iron-manganese), accessory suite III (molybdenum-tin-beryllium), accessory suite IV (silver-arsenic-bismuth), and single elements (tungsten, gold, and copper). For the anomaly maps of these suites, each anomalous area represents an anomalously high concentration of one or more of the constituent elements of the suite.

The geochemical submodel for skarn deposits is a combination of the four geochemical suite anomaly maps (lead-zinc, iron-manganese, molybdenum-tin-beryllium, and silver-arsenic-bismuth) and three single-element maps (tungsten, gold, and copper). In the resultant submodel, any pixel (200×200 m cell) having a nonzero value represents the summation of one to seven individual nonzero (anomalous) pixels from the constituent single-element or suite anomaly maps. To keep track of suite and single-element anomaly images for the purpose of weighting the results in the final map, numbers in the series, 1, 2, 4, 8, 16, 32, 64, and so on, were assigned to the maps. All nonzero (anomalous) pixels on the tungsten map were assigned a value of 1; on the gold map, 2; on the copper map, 4; on the lead-zinc map, 8; on the iron-manganese map, 16; on the molybdenum-tin-beryllium map, 32; and on the silver-arsenic-bismuth map, 64. 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), and so on, original components of any pixel can be readily determined. Therefore, a pixel on the composite map that has a value of 15, for example, consists of a combination of anomalies for accessory suite I (lead-zinc = 8) and three single elements (copper = 4, gold = 2, and tungsten = 1), and any pixel having a value of 127 is the sum of 1 + 2 + 4 + 8 + 16 + 32 + 64, which indicates an area where all of the components (suites plus tungsten, gold, and copper) are present in anomalous concentrations.

In the final step, all 127 possible assemblages of anomalies for suites of elements and for single elements (composite anomalies) were ranked and assigned favorability scores of 1 to 5 (table 1, map F). This ranking was based on the calculation and comparison of normalized mine densities as previously done for the single-element anomalies, but in this case, areas of composite anomalies were used in place of single-element anomalies. The areas of composite anomalies having normalized mine density values greater than 1.0 are listed in table 1. Of the 49 skarn

Table 1.—Favorable assemblages in the geochemical submodel for mineral resource assessment for skarn deposits of Au, Ag, Cu, W, and Fe in the Butte 1°×2° quadrangle, Montana

[Values of nonzero (anomalous) pixels are as follows: W=1; Au=2; Cu=4; Pb-Zn=I=8; Fe-Mn=II=16; Mo-Sn-Be=III=32; Ag-As-Bi=IV=64.]

Assemblage	Total value of pixel	Normalized mine density factor (number of deposits)	Favorability score
W+Au+Cu+III+IV	112	24.46(1)	5
Au+Cu+II+III+IV	118	23.88(1)	5
W+Au+Cu+II+III+IV	119	NA(0)	5
Au+II+III+IV	114	17.59(4)	5
W+Au+II+III+IV	115	NA(0)	5
W+Cu+I+III	45	17.28(1)	5
W+II+III+IV	113	13.92(1)	5
W+Au+I+IV	75	9.64(1)	4
W+Au+Cu+I+III+IV	111	9.09(3)	4
W+Au+Cu+I+IV	79	6.94(2)	4
Cu+II+III+IV	116	6.19(1)	4
W+Cu+II+III+IV	117	NA(0)	4
I+IV	72	5.38(3)	4
I	8	3.87(4)	3
Au+I	10	3.34(2)	3
W+Au+I	11	NA(0)	3
Au+Cu+I+III+IV	110	3.27(1)	3
Cu+I	12	3.15(1)	3
W+Au+Cu+I	15	NA(0)	3
W+IV	65	2.82(3)	3
W+Au+IV	67	NA(0)	3
Au	2	2.12(6)	2
W	1	1.85(3)	2
Au+Cu+I+IV	78	1.73(1)	2
others	4-7,9,13,14,16-22,32-44, 46,48-50,64,66,68-71,73, 76,77,80-87,96-102, 104-109,112,120	n.a. n.a. n.a. n.a.	1 1 1 1

mines and prospects in the quadrangle (Elliott and others, 1986), 87.8 percent are within areas of anomalous geochemistry and 87.2 percent are within areas of anomalous geochemistry where the normalized mine densities are greater than 1.0.

#### Alteration submodel

The alteration submodel is based on a map that shows areas of known and inferred limonitic, hydrothermally altered rock (Rowan and Segal, 1989). Scores are assigned based on the observed association of the altered areas with known deposits. Dense vegetation in many parts of the quadrangle precluded the discrimination of some altered areas on Landsat images and some uncertainty is involved in distinguishing limonite related to hydrothermal activity from limonite caused by weathering of unaltered

iron-bearing rocks. Therefore a maximum score of 3 points is assigned to the alteration submodel. Altered areas have a very high normalized mine density (22.0) and were assigned a score of 3 points in the alteration submodel (map G). One kilometer-wide zones around altered areas have a density of 5.8 and were assigned a score of 2 points each. Zones 1-2 km away from altered areas have a density of 2.9 and were assigned 1 point each. The remainder of the quadrangle was assigned a score of 0 points.

#### Geophysical submodel

The geophysical submodel (map H) is based on an interpretative map that displays the surface and subsurface distribution of magnetic plutonic rocks. This interpretative map is derived through the analysis of regional magnetic and gravity data. On map H, outcropping plutons are shown

as areas of gray and the predicted subsurface extensions of these magnetic plutonic rocks are shown in blue. The areas of subsurface magnetic plutonic rock were compared with the distribution of known skarn deposits and normalized mine densities were calculated. For the areas in blue on map H, the density is 1.45. This density is quite low and suggests only a weak correlation between skarn mines and prospects and the areas of predicted subsurface magnetic plutonic rock. Normalized mine densities were also calculated for one-km-wide zones extending 6 km outward from the outer edge of subsurface magnetic plutonic rock. For a zone 2 km wide (shown in green on map H) that surrounds the subsurface magnetic plutonic rock, a normalized density of 3.48 was calculated; this 2-km-wide zone was assigned a score of 2 points. A score of 1 point was assigned to the areas of subsurface magnetic plutonic rock. The remainder of the quadrangle was assigned 0 points.

#### Structure submodel

Both faults and folds were analyzed for spatial association with skarn mines and prospects. Five classes of faults, normal, thrust, strike-slip, oblique-slip, and unclassified, were digitized from the generalized geologic map of the Butte quadrangle. The axial traces of anticlines and synclines were also digitized from the generalized geologic map. The spatial association of skarn mines and prospects with faults and folds was tested by calculating the normalized mine densities in successive 0.2-km-wide zones outward from faults and axial traces of folds. Based on the normalized mine densities, the spatial association of mapped faults with mines and prospects is weak; densities greater than 1.0 (average for quadrangle) were recorded only for thrust and normal faults. The optimum zone for normal faults is a zone 2 km wide on both sides of the fault traces. The normalized mine density for this zone is 2.15. For thrust faults the optimum zone is 1 km wide on both sides of fault traces. The normalized mine density for this zone is 1.59. Since the density is higher for normal faults than for thrust faults, normal faults are assigned a higher score. Thus zones which are 4 km wide (2 km on either side) along normal faults are assigned 2 points and zones which are 2 km wide along thrust faults are assigned 1 point (map I). The skarn deposits show a stronger correlation with folds than with faults. Normalized mine densities were calculated for axial traces of synclines, anticlines, and combined synclines and anticlines in 1-km-wide zones as much as 6 km away from axial traces. Because both synclines and anticlines showed similar normalized mine densities, no distinction is made between zones associated with anticlines and zones associated with synclines. The areas 0–1 km away from axial traces of folds have a density of 5.30, those from 1 to 2 km have a density of 2.75, and those from 2 to 3 km have a density of 0.73. These areas were assigned 3, 2, and 1 points, respectively (map I). For the compilation of

map I, the pixel scores for faults and those for folds were compared and only maximum scores were retained.

#### Linear features submodel

The analysis of linear features demonstrated that some, but not all, linear features are related to mineral occurrences. The degree of relationship was determined by calculating the normalized density of all metallic mines and prospects (Elliott and others, 1986) in zones along linear features and circular areas enclosing intersections of linear features 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 are centered on linear features and intersections of linear features, and then selecting widths and radii of zones that had the highest normalized mine densities. For linear features, favorable zones had widths of 0.2–1.4 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, linear features and intersections of linear features were selected which show a close association with mines and prospects. Because the higher densities were associated with intersections of linear features, scores of 2 points were assigned to 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.

### MINERAL RESOURCE ASSESSMENT FOR SKARN DEPOSITS OF TUNGSTEN, COPPER, GOLD, SILVER, AND IRON

The submodels for host rocks, plutons, geochemistry, alteration, geophysics, structures, and linear features (maps D–J) were combined using overlay analysis (see appendix for explanation). Because the structures and linear features submodels are both expressions of structure and are, in part, nonadditive, only maximum values from one or the other were used for the total scores. The sum of submodels yielded total scores shown on map K. This map consists of polygons that are ranked between 0 and 22; the maximum possible score is 23. The mineral resource assessment map for skarn deposits (map A) groups polygons from map K into 4 classes of low (1 to 7 points), moderate (8 to 12 points), high (13 to 17 points), and very high (18 to 23 points) potential for undiscovered skarn deposits of tungsten, copper, gold, silver, and iron. The percentage of map area, percentage of known skarn mines and prospects, and normalized density of skarn mines and prospects for each class of potential are shown in table 2. Also shown on map A are the boundaries of mining districts and geographic areas and five skarn deposits that are ranked as medium (\$50,000 to \$499,000) or large (\$500,000 to \$5,000,000)

Table 2.—Percentage of map area, percentage of known skarn mines and prospects, and normalized density of skarn mines and prospects for areas of very high, high, moderate, and low potential

Potential	Percentage of map area	Percentage of mines*	Normalized mine density
Very high	0.4	26.5	66.3
High	2.3	32.7	14.2
Moderate	11.4	8.2	0.7
Low	62.7	4.1	0.1

\*14 mines or prospects are in areas mapped as plutonic rocks. These mines or prospects are either in inclusions or roof pendants of carbonate rock in plutonic rocks or at the contact of sedimentary rocks with plutonic rocks. The roof pendants and inclusions are too small to show at a map scale of 1:250,000, and because of generalization of units and contacts at a scale of 1:250,000, some mines and prospects appear to be within rather than outside of contacts of plutonic rocks with sedimentary rocks.

producers. Map B is an association map that shows the combinations of submodels that determined the final resource assessment map.

## SUMMARY AND SUGGESTIONS FOR EXPLORATION

All the areas of very high potential for skarn deposits (map A) are in mining districts and are at or near the contacts of stocks with sedimentary rocks. This is predetermined, in part, by the use of skarn mines and prospects in the assignment of scores to submodels. Map B shows the association of submodels that determine the mineral resource potential of each of the areas. Most of the areas of high potential are also restricted to mining districts, although many of these areas do not have productive skarn deposits. All of these areas of high and very high potential are highly favorable for exploration for undiscovered deposits. The districts and areas of very high potential are described in the following paragraphs.

1. Garnet and Top O'Deep districts and Bear Creek area in the northwestern part of quadrangle—Middle Proterozoic and Paleozoic sedimentary strata have been folded and faulted and intruded by stocks of Late Cretaceous granodiorite. Most of the production, mainly of gold, silver, and copper ores, has come from vein and replacement deposits in limestone, quartzite, hornfels, and granodiorite. A few skarn deposits are along granodiorite-limestone contacts. One, the Blue Moon, is a tungsten prospect and another, the Pearl mine, is a small (less than \$50,000) producer of gold and copper ore. Several small areas of very high potential in the Garnet district and the adjacent Bear Creek area are enclosed by a larger area of high potential, which borders the Late Cretaceous Garnet stock. The area of high potential extends from the Coloma district, which is on the west side of the stock, through parts of the Garnet and

Top O'Deep districts and parts of the Bear Creek and Garnet Range areas. The association map (map B) shows that these areas of high and very high potential result from the association H+P+C+G+SFL, which stands for host (H) + pluton (P) + geochemistry (C) + geophysics (G) + structure (SFL), and the association H+P+C+SFL.

2. Princeton district in the west-central part of the quadrangle—The Princeton district is underlain by complexly folded and faulted sedimentary rocks of Middle Proterozoic through Cretaceous ages which have been intruded by two major Cretaceous plutons: the Royal stock to the northeast and the Philipsburg batholith to the south. In addition, a major batholith, the Mount Powell biotite-muscovite monzogranite, is near the southeastern part of the Princeton district. The district has produced gold, silver, lead, copper, and zinc, mainly from vein and replacement deposits. Skarn zones exist in the Princeton district where granodiorite of the Royal stock is in contact with Paleozoic carbonate rocks. The Finlay Basin prospect is a tungsten skarn which has a large tonnage of subeconomic resources (John Trammell, 1985, personal commun.). Several small areas of very high potential are enclosed by a larger area of high potential that covers much of the Princeton district and extends south toward the Red Lion district along a septum of Paleozoic rocks that separates the Philipsburg and Mount Powell batholiths. Most of these areas of very high and high potential are determined by the associations H+P+C+G+SFL+A, H+P+C+G+SFL, H+P+SFL (area south of Princeton district), and H+P+C+SFL.

3. Philipsburg district in west-central part of the quadrangle—Middle Proterozoic to Jurassic sedimentary rocks have been folded into a north-plunging anticline, cut by several faults, and intruded by the Philipsburg granodiorite batholith of Cretaceous age. The district has been a major producer of manganese, silver, zinc, lead, copper, and gold from vein and replacement deposits. The district has several skarn deposits which have produced small amounts

of iron, manganese, and silver ore. Areas of very high and high potential cover much of the Philipsburg district and extend northeast and southwest of the district. Much of the central part of the district has very high potential as a result of the association H+P+C+G+SFL+A, where the Philipsburg batholith is in contact with Paleozoic carbonate rocks. Areas of very high and high potential to the northeast and south of the central part of the district have the associations H+P+C+G+SFL and H+P+C+SFL.

4. Georgetown district in the south-central part of the quadrangle—A thrust- and normal-faulted sequence of Middle Proterozoic to Paleozoic rocks was intruded by granodiorite of the Cretaceous Cable stock in this district. The Georgetown district has been a major producer of gold, silver, and copper ore from vein and replacement deposits. Gold-bearing magnetite skarns and small irregular masses of magnetite skarn are found at or near the contacts of Hasmark Formation with the Cable stock. The Cable stock, in the center of the district, is enclosed by areas of high and very high potential for skarn deposits. The association H+P+C+G+SFL+A determines the area of very high potential. The area of high potential that borders the Cable stock results from the associations H+P+C+G+SFL and H+P+C+G+SFL+A. The area of very high potential contains the Cable mine, a skarn/replacement deposit having a large (approximately \$3.5 million) production of gold-silver ore. An irregular area of high potential extends to the northeast of the Cable stock into the Johnson Basin district. Three associations, H+P+C+G+SFL, H+C+G+SFL, and H+P+C+SFL, give rise to this area of high potential.

5. Olson Gulch district in south-central part of the quadrangle—Complexly folded and faulted sedimentary rocks of Middle Proterozoic and Paleozoic ages have been intruded by post-tectonic Cretaceous granodiorite and diorite. The district has been a small producer of silver, gold, and copper ore, mostly from vein and replacement deposits. Several tungsten and magnetite skarns are known but only small amounts of tungsten ore and iron ore have been produced from them. Areas of high and very high potential surround a small body of Cretaceous diorite. A small pluton of Cretaceous granodiorite is also exposed in the southwest part of the district, adjacent to an area of very high potential. Nearly all of the areas of high and very high potential result from either the association H+P+C+G+SFL+A or H+P+C+G+SFL.

6. Helena and Austin districts and Stemwinder Hill area in the northeastern part of the quadrangle—From northwest to southeast, the Austin district, Stemwinder Hill area, and Helena district are along a contact zone of the Cretaceous Boulder batholith. The batholithic rocks, consisting of granodiorite and monzogranite, are in contact with a sequence of Middle Proterozoic to Mesozoic sedimentary rocks. The Austin and Helena districts and the Stemwinder Hill area have produced gold, silver, lead, copper, zinc, tungsten, and iron ore from vein, replacement, skarn, and

placer deposits. Skarn deposits include the Spring Hill mine, a large (approximately \$760,000) producer of gold ore in the Helena district, and the Blue Jay and War Eagle mines in the Austin district, which are medium (\$50,000 to \$500,000) producers of copper, lead, silver, and iron ore. A continuous zone of high potential extends through the Austin and Helena districts and Stemwinder hill area. In addition, two areas of very high potential are in the Austin and Helena districts. In the Austin district the area of very high potential is the result of the association H+P+C+G+SFL+A. In the Helena district most of the area of high potential plus the area of very high potential is due to the association H+P+C+G+SFL. In both the Austin and Helena districts, some parts of the high potential area have either the association H+P+G+SFL+A or H+P+G+SFL.

7. Marysville district in the northeastern part of the quadrangle—Limestone, siltite, and argillite of the Middle Proterozoic Helena and Empire Formations were folded, cut by normal and strike-slip faults, and intruded by the Late Cretaceous Marysville granodiorite stock and early Tertiary granite stocks (Rostad, 1978; Blackwell and others, 1974). A wide zone of contact metamorphosed rocks occurs around the Marysville stock and above unexposed granite stocks. The district was a major producer of gold, silver, lead, copper, and zinc mainly from vein and replacement deposits. Walker (1963) reported tungsten skarns in the district. The Marysville stock is completely enclosed by areas of high and very high potential. All of the very high potential area and some of the high potential area result from the association H+P+C+G+SFL+A. Nearly all of the remaining area of high potential has the association H+P+C+G+SFL.

8. Ophir district in the northeastern part of the quadrangle—In this district, the Late Cretaceous Blackfoot City stock has intruded folded sedimentary rocks of Middle Proterozoic through Cretaceous ages. The district is a large producer of gold (approximately \$4.1 million), mainly from placer deposits. Gold, silver, copper, lead, and minor tungsten have been produced from lode deposits. Several lode deposits are gold-silver-copper skarns, which are at the contact of the granodiorite stock with Paleozoic carbonate rocks such as the Jefferson Formation and Madison Group. Areas of very high and high potential border the Blackfoot City stock along the north, east, and south contacts. The association of H+P+C+G+SFL accounts for all of the very high potential areas and some of the high potential areas. Some of the high potential areas are the result of the combination H+P+G+SFL.

Several other areas of high potential and significant size (approximately 1 mi<sup>2</sup> or larger) are not associated with known skarn occurrences, but these areas are also very favorable for exploration for undiscovered deposits; these areas are described in the following paragraphs.

9. Stemple-Gould district in the northeastern part of the quadrangle—An area of high potential encircles the Cretaceous Granite Butte stock (granodiorite) in the south-

eastern part of the district. The stock intruded sedimentary rocks of Middle Proterozoic age. The principal mine, the Jay Gould mine, was a large producer of gold-silver ore (more than 95 percent of the production was gold) (Pardee and Schrader, 1933). The district has also produced silver, copper, and lead. The known occurrences are vein and replacement deposits in granodiorite and in calcareous argillite, siltite, and quartzite of the Empire and Helena Formations. The area of high potential is the result of the associations H+P+C+G+SFL and H+P+C+G. The Empire and Helena Formations are moderately favorable (score = 2 points) for the occurrence of skarn deposits.

10. Scratchgravel Hills area in the northeastern part of the quadrangle—Areas of high potential are within and adjoin the west and east sides of the Scratchgravel Hills area. The high ranking of the western side is the result of the association H+P+C+G+SFL+A, whereas that of the eastern side is determined by the association P+C+G+SFL. The central part of the Scratchgravel Hills area is composed of the Scratchgravel Hills monzonite stock (Cretaceous). This stock intruded Proterozoic rocks that include the Spokane and Empire Formations and diorite sills. The district has produced gold, silver, lead, and copper from skarn, vein, and replacement deposits. Most of the mines are small (less than \$50,000) or medium (\$50,000 to \$500,000) producers of silver or gold ore. The western area of high potential coincides with exposures of Helena and Empire Formations, which are moderately favorable for the occurrence of skarns. However, these formations are not in contact with the Scratchgravel Hills stock at the surface, so any potential skarn zone would be expected only in the subsurface where these formations are in contact with the stock. In the eastern area, most of the Middle Proterozoic rocks are covered by Quaternary surficial rocks, but a contact zone of monzonite with the Empire Formation is expected at a shallow depth.

11. North Boulder Mountains area in the eastern part of the quadrangle—A small area of very high potential enclosed by a larger area of high potential is in the North Boulder Mountains area just north of the Elliston district. The associations of submodels that determine these ratings are H+P+C+G+SFL, H+P+C+SFL, and H+P+G+SFL. Although much of this area is covered by Quaternary surficial rocks, a contact zone between Paleozoic carbonate rocks and the Boulder batholith is predicted at a shallow depth.

12. Flint Creek Range area in the central part of the quadrangle—An area of high potential is in the northeastern part of the Flint Creek Range area and adjacent to the Royal stock. This Cretaceous granodiorite intruded Paleozoic and Mesozoic sedimentary rocks. The area of high potential is the result of the associations H+P+C+G+SFL and H+P+G+SFL. The most favorable part of this area is where the stock is in contact with carbonate rocks of Paleozoic age, such as the Madison Group and the Snowcrest Range Group.

13. Red Lion district in the south-central part of the quadrangle—A very small area of very high potential is enclosed in a larger area of high potential in the north-central part of the Red Lion district. The associations which determine these ratings are H+P+C+G+SFL+A, H+P+A+G+SFL, and P+C+A+G+SFL. In this part of the district, Cambrian and Middle Proterozoic sedimentary rocks are in contact with the Philipsburg batholith. The Middle Proterozoic rocks, consisting of quartzite of the Missoula Group, overlie the Cambrian rocks and are separated from them by a thrust fault. The contact zone between Cambrian carbonate rocks and granodiorite is the most favorable part of the area for skarn deposits. The geologic setting of this area is very similar to that of the Cable mine in the Georgetown district.

14. Silver Lake district in the south-central part of the quadrangle—In the southwestern part of the Silver Lake district the combination of all submodels, H+P+C+G+SFL+A, define an area of high potential. In this area, folded and thrust-faulted Paleozoic sedimentary rocks are in contact with a Cretaceous granodiorite-diorite intrusive complex. Contact zones of this intrusive with carbonate rocks of Cambrian, Devonian, Mississippian, and Pennsylvanian age are favorable for skarn deposits.

15. Sapphire Mountains area in the southwestern part of the quadrangle—Several small areas of high potential are along the west side of the Sapphire batholith in the southern part of the Sapphire Mountains area. The rating of high potential is the result of the association H+P+C+G+SFL. Although no skarn deposits and very few mineral occurrences of any type are known in this part of the Sapphire Mountains area, the age and composition of the intrusive rocks of the Sapphire batholith are similar to metallogenic plutons in other parts of the Butte quadrangle. The host for potential skarn deposits in the areas of high potential is the Middle Proterozoic Wallace Formation (western equivalent of the Helena Formation).

#### TESTING MINERAL RESOURCE ASSESSMENT PROCEDURE

One test of the method of mineral resource assessment developed and used in this study is its effectiveness in locating and outlining areas where skarn mines and prospects are known to exist. Map A and table 2 show that the method meets this test in that nearly all of the areas of very high and high potential are in mining districts which have skarn mines and prospects. The normalized mine density for areas of very high potential is 66.3 and for areas of high potential is 14.2. The success of the method in locating known skarn deposits is not too surprising because the method is based on (1) characteristics of known skarns and (2) the scores of submodels are based on normalized mine densities of known skarns. However, the actual presence or absence of skarns in a particular district or area is not a

criterion in the assignment of level of potential. The areas of very high and high potential are generally larger than areas of known deposits and in many cases, such as in the Philipsburg district, extend beyond the boundaries of the mining district. Thus, in most districts, the area that is favorable for exploration for undiscovered skarn deposits is much larger than the area of known skarn deposits. In addition, some areas of high potential are in districts or areas, such as the Stemple-Gould and Silver Lake districts and part of the North Boulder Mountains area, where there are no known skarns. Such areas are also favorable for exploration for undiscovered skarn deposits.

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## APPENDIX

### PROCEDURES USED FOR PROCESSING AND INTERPRETATION OF GEOCHEMICAL DATA

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 USGS Earth Resources Observations Systems (EROS) Data Center where they were reformatted and entered into a relational data base.

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. To avoid problems inherent in dealing with truncated data sets, the qualifiers "B" or "H" were eliminated and "N," "L," and "G" in the analytical data were replaced by numbers. The substitutions were as follows: values qualified by "N" were replaced by 0.3 times the lower limit of analytical determination; 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 qualifiers, 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 reported concentrations was much greater than 255 for some elements and considerable compression of the data was needed to fit the 0-255 range. To compress the data, the gridded chemical concentrations for each element were transformed logarithmically. This resulted in the smoothing of each geochemical surface. 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 normal distributed populations.

The percentage of data that is valid (unqualified) 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 with 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 skarn deposits are shown in table 3.

Geochemical thresholds (table 3), which represent the highest background concentrations, were selected for each of the single-element geochemical surfaces on the basis of 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 on 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 a gray level equal to zero to those at or below the threshold.

### PROCEDURES USED FOR THE PROCESSING AND INTERPRETATION OF GEOPHYSICAL DATA

Magnetic anomaly data used in this study (USGS, 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 2,700 m (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 having 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 were compared with data from 11 smaller surveys covering parts of the quadrangle (Johnson and others, 1965; USGS, 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 the surveys were shown (Hassemer and Hanna, 1982) to exhibit inconsistencies relative to one another. This comparison of data sets served to verify the existence and location of several significant anomalies.

Although gravity anomaly data were not used directly for the drawing of lines that outline inferred plutonic rocks, the gravity data were useful in some places for confirming the existence of plutonic rocks, both as gravity lows over plutonic rocks which intruded higher-density country rock or as gravity highs over plutonic rocks which are flanked and (or) covered by low-density Tertiary and Quaternary sedimentary deposits. The gravity data used in this study

Table 3.—*Sample types and analytical methods used in the mineral resource assessment for skarn deposits of Au, Ag, Cu, W, and Fe in the Butte 1°×2° quadrangle, Montana*

[ppm, parts per million; pct, percent]

Element	Sample type	Analytical method	Anomaly 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
Be	Concentrate	Spectrographic	7 ppm
	Sediment	Spectrographic	7 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	3000 ppm
	Sediment	Spectrographic	2000 ppm
Mo	Concentrate	Spectrographic	30 ppm
	Sediment	Spectrographic	10 ppm
Pb	Concentrate	Spectrographic	300 ppm
	Sediment	Spectrographic	200 ppm
	Sediment	Atomic absorption	150 ppm
Sn	Concentrate	Spectrographic	50 ppm
W	Concentrate	Spectrographic	50 ppm
Zn	Concentrate	Spectrographic	500 ppm
	Sediment	Spectrographic	300 ppm
	Sediment	Atomic absorption	500 ppm

include 2,325 observations within and immediately adjacent to the quadrangle (Hassmer, 1984, 1986), of which 1,900 are new, 262 were previously made by the USGS, and 163 were acquired from the nonproprietary data files of the Department of Defense.

The procedure of drawing lines that outline areas of inferred plutonic rocks 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 (0.9 mi) 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 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 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; 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 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. As a result, 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 relationship is not generally 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.

#### DESCRIPTION OF THE GEOGRAPHIC INFORMATION SYSTEM AND PROCEDURES USED FOR DATA ENTRY AND PROCESSING

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.

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 in 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 has 38 rock units and 7 types of structures, (2) a map that shows the boundaries of 70 mining districts and other areas having mines and prospects, (3) a map that shows the surface and subsurface extent of principal magnetic rock bodies (plutonic rocks) interpreted from geophysical data, (4) a map that shows areas of limonitic alteration interpreted from Landsat data, and (5) a map that shows 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 and were in digital format. 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

55 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.



