U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MAPS SHOWING MINERAL RESOURCE ASSESSMENT FOR PORPHYRY AND STOCKWORK DEPOSITS OF COPPER, MOLYBDENUM, AND TUNGSTEN AND FOR STOCKWORK AND DISSEMINATED DEPOSITS OF GOLD AND SILVER IN THE BUTTE 1° × 2° QUADRANGLE, MONTANA

BY

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MISCELLANEOUS INVESTIGATIONS SERIES

MAP I–2050–F

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INTRODUCTION

PURPOSE AND SCOPE

This report documents the assessment for potential occurrences of undiscovered porphyry and stockwork deposits of copper, molybdenum, and tungsten (porphyry Cu-Mo-W) and stockwork and disseminated deposits of gold and silver (disseminated Au-Ag) in the Butte 1°×2° quadrangle. The Butte quadrangle, in west-central Montana, is one of the best known mineral producing regions in the U.S. Mining districts in the quadrangle, 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 this resource assessment for porphyry Cu-Mo-W and disseminated Au-Ag deposits in the quadrangle include a compilation of all data, the development of descriptive occurrence models, and the analysis of data using techniques provided by a Geographic Information System (GIS).

This map is one of several maps on the Butte 1°×2° quadrangle. Other deposit types have been assessed for the Butte quadrangle, and maps (U.S. Geological Survey (USGS) Miscellaneous Investigation Series Maps) for each of the following have been prepared: Vein and replacement deposits of gold, silver, copper, lead, zinc, manganese, and tungsten (Elliott, Wallace, and others, 1992a) and skarn deposits of gold, silver, copper, tungsten, and iron (Elliott and others, 1992b). Other publications resulting from this study include linear features map (Rowan and others, 1991); limonite and hydrothermal alteration map (Rowan and Segal, 1989); mineral occurrence maps (Elliott and others, 1986; Elliott, Loen, and others, 1992); and geologic maps (Wallace, 1987; Wallace and others, 1987).

GEOGRAPHIC SETTING

The Butte quadrangle is bounded by latitudes 46° and 47° N and longitudes 112° and 114° W (fig. 1). 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 several 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 approximately 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 near Butte.

GEOLOGIC SETTING

The Butte quadrangle contains igneous, metamorphic, and sedimentary rocks and surficial deposits that range in age from Proterozoic to Quaternary (map C). Proterozoic, Paleozoic, and Mesozoic sedimentary rocks are abundant and widespread as are Cretaceous and Tertiary plutonic rocks; the latter are present, along with associated metamorphic rocks, in the cores of most mountain ranges. Volcanic and volcaniclastic rocks of Cretaceous and Tertiary ages are found mostly in mountain ranges in the eastern and northern parts of the quadrangle. Intermontane basins are filled with Tertiary and Quaternary sedimentary rocks and deposits.

The oldest rocks exposed in the quadrangle are Belt Supergroup rocks that were deposited 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 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 sediment was deposited. The Paleozoic strata have a thickness of about 2,400 m and are mainly in the north, central, and northeastern parts of the quadrangle. About 6,700 m of clastic and carbonate Mesozoic sedimentary rocks are in the central part of the quadrangle, and about 2,400 m of equivalent strata are in the northeastern part of the quadrangle. These strata were deposited in foreland basins.

In Late Cretaceous time, magmatic processes resulted in the emplacement of numerous stocks and several batholiths at mesozonal and epizonal depths and the eruption and deposition of volcanic and volcaniclastic rocks. These Upper Cretaceous plutons include the Boulder, Idaho, Sapphire, and Philipsburg batholiths, which are composed chiefly of monzogranite and granodiorite, and numerous stocks of diorite, granodiorite, and monzogranite. Hydrothermal activity during and following the waning stages of magmatism formed many types of mineral deposits. Upper Cretaceous volcanic and volcaniclastic rocks of the Elkhorn Mountains Volcanics exist as roof pendants and along the margins of the Boulder batholith and probably represent early extrusive phases of the Boulder batholith.

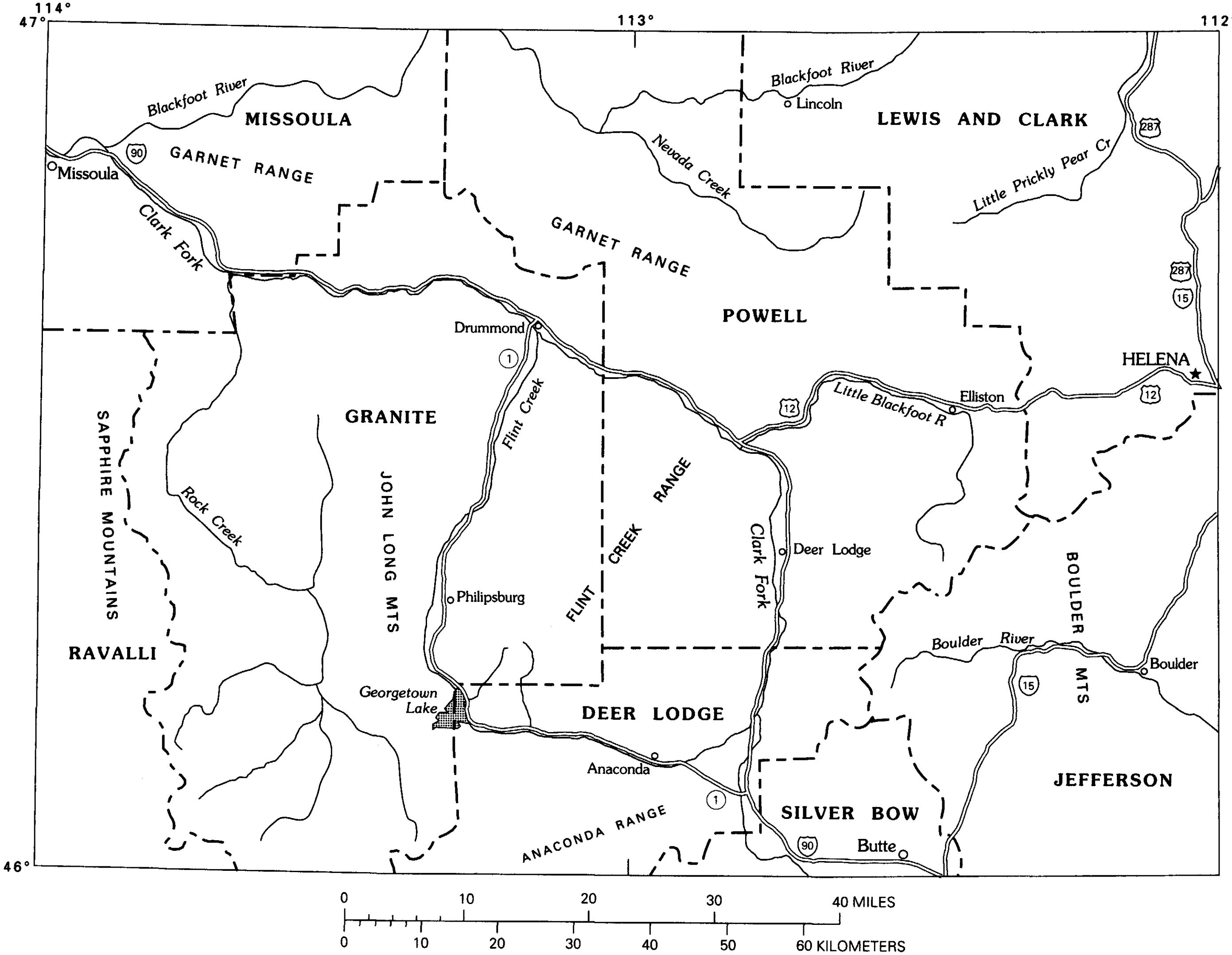

Figure 1. Index map of the Butte 1°×2° quadrangle.

Volcanism and erosion, as well as sedimentation in intermontane valleys, took place during Tertiary time. Extensive early and middle Tertiary volcanism formed the Lowland Creek Volcanics in the southeastern part of the quadrangle, volcanic fields in the Garnet Range and east of Lincoln, and minor volcanic rocks 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 mountain ranges in the quadrangle. Icecaps occupied the topographic crests of the Flint Creek and Anaconda Ranges and the Boulder Mountains (Ruppel, 1962), and valley and cirque glaciers were also prevalent in these and other mountain ranges of the quadrangle. 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 repeatedly 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.

Figure 2 shows the principal structural elements in the Butte quadrangle: these are the Sapphire thrust plate (Ruppel and others, 1981), the southwestern end of the Montana disturbed belt (Mudge, 1972), and strike-slip faults of the Lewis and Clark line (Wallace and others, 1990). 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 of the quadrangle 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 striking 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 an extensive foreland basin east of thrust plates that moved predominantly 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 magmatic events post-date thrust and strike-slip faults; stocks and batholiths emplaced into the faulted terrane probably made the terrane more resistant to continued compressional deformation. Normal faulting during early Tertiary time and subsequent erosion controlled the development of some of the present mountain ranges and drainage systems. 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 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 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 (3) porphyry or stockwork copper and molybdenum; (4) skarn gold, copper, silver, tungsten, and iron; (5) vein and replacement manganese, tungsten, barite, and fluorite; and (6) strata-bound phosphate.

Many commodities, both metallic and nonmetallic, have been produced from the quadrangle but the principal value of production has been in metals, especially copper, gold, and silver. Copper is the most important commodity and has come mainly from the Butte district (map D). 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 including Black Pine, Philipsburg, Marysville, Rimini, and Wickes districts (map D), also have been substantial producers of gold, silver, lead, zinc, and copper. The Philipsburg district was a leading producer of manganese as well as a producer of large amounts of precious and base metals. Large quantities of tungsten, phosphate, fluorite, barite, sapphires, limestone, and silica have also been mined from various districts in the quadrangle.

Mineral deposits and occurrences in the Butte quadrangle range in age from Precambrian to Quaternary. The oldest occurrences of potential economic significance are of strata-bound copper and silver minerals in the Middle Proterozoic Belt Supergroup. Some occurrences, such as those in quartzite of the Mount Shields Formation, are similar to the Troy deposits, in northwestern Montana, that are currently being mined. Strata-bound deposits of phosphate rock in the Lower Permian Phosphoria Formation have been mined in several parts of the quadrangle and are 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

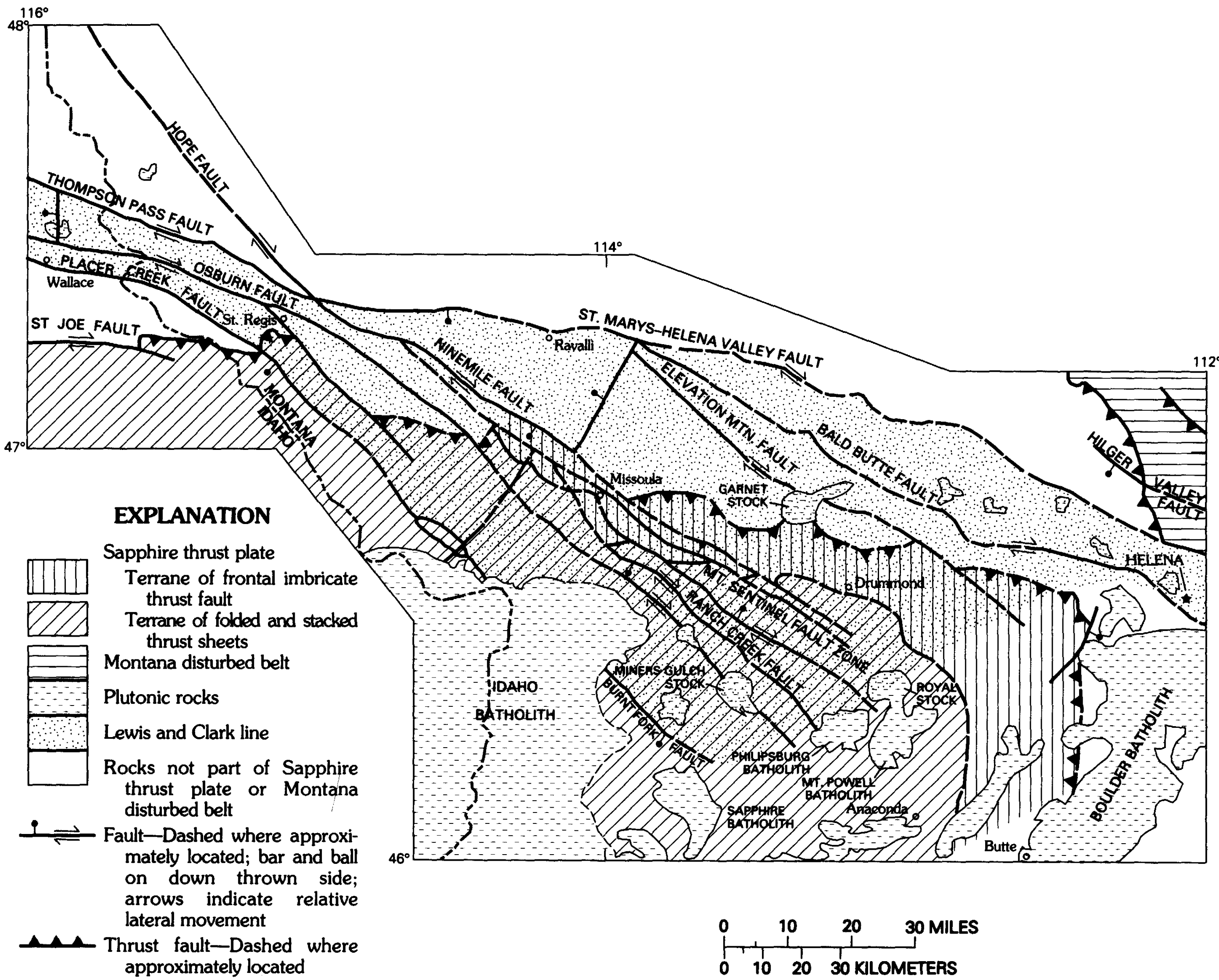

Figure 2. Principal structures and plutons of the Sapphire thrust plate (from Elliott and others, 1988).

younger hydrothermal deposits are present in Eocene volcanic rocks; a notable example of which is the Montana Tunnels mine in the Wickes district (map D). This mine exploits a large low-grade diatreme-hosted gold-silver-zinc-lead deposit that is in 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.

PORPHYRY/STOCKWORK DEPOSITS OF COPPER, MOLYBDENUM, AND TUNGSTEN

Porphyry Cu-Mo-W deposits consist of concentrations of copper-, molybdenum-, and (or) tungsten-bearing minerals as disseminated grains or as numerous thin veins or veinlets that form stockwork zones in favorable host rocks. As used here, this deposit type includes porphyry copper (or copper-molybdenum), porphyry molybdenum (including Climax type), and stockwork tungsten deposits. Porphyry-type deposits are commonly gigantic (100 to 1,000 million tonnes of ore; Cox and Singer, 1986) hydrothermal-petrogenetic systems related to intrusive stocks in plutonic-volcanic fields. The intrusives are typically porphyritic rocks, commonly including epizonal or hypabyssal dacite, latite, quartz latite, and rhyolite porphyries but also including their plutonic, phaneritic equivalents such as quartz diorite, monzonite, quartz monzonite, and granite (Guilbert and Park, 1986). Porphyry deposits commonly show concentric zoning both in the types and concentration of metals and in facies of alteration. The alteration includes pyritic, argillic, phyllic, and potassic types.

The Butte quadrangle is transected by the northeasterly trending "Idaho-Montana porphyry belt" (Rostad, 1978). This belt is similar to the Colorado mineral belt (Tweto and Sims, 1963) in that it is the locus of many porphyry-type molybdenite and copper deposits and prospects. Examples of porphyry molybdenum deposits in Idaho are Little Boulder Creek (White Cloud), Thompson Creek, and Cannivan Gulch (Rostad, 1978). Examples of porphyry molybdenum deposits in Montana are Bald Butte and Big Ben (Rostad, 1978). Well-known porphyry copper-molybdenum deposits are Butte (Meyer and others, 1968) and Heddleston (Miller and others, 1973). Most of these molybdenum or copper-molybdenum systems in Idaho and Montana are associated with calc-alkalic plutonic rocks, but the Bald Butte deposit may be a transitional type to alkalic-calcic rocks and Big Ben may be a Climax-type occurrence (Westra and Keith, 1981). The porphyry-type deposits exist in several tectonic settings including locations in the Cordilleran orogenic belt in central Idaho and locations in the craton in central Montana. The ages of deposits in the porphyry belt range from about 86 to 41 Ma (Rostad, 1978).

The porphyry Cu-Mo-W deposits appear to be related to Cretaceous and possibly Tertiary hypabyssal or plutonic rocks of monzogranitic and granodioritic composition. Typically the ore-related intrusive rocks are porphyritic and have multiple phases of intrusion and brecciation. Although cogenetic volcanic rocks are not found with porphyry-type systems in the Idaho-Montana porphyry belt, in other regions porphyry/stockwork deposits are typically associated with volcanic centers and have slightly older or cogenetic volcanic rocks. In some districts, as in the Butte district, vein and replacement deposits may be the upper parts of porphyry systems.

The largest porphyry-type deposits in the Butte quadrangle are in the Butte district. At Butte, zones of stockwork veins, disseminated copper and molybdenum minerals, and supergene enrichment have been mined by block caving and open-pit methods. In several aspects the so-called porphyry deposits at Butte are atypical because porphyritic intrusive rocks are rare, evidence for a volcanic center at Butte is weak, and widespread cogenetic volcanism is lacking. However, much of the Butte ore is stockwork in form and includes both copper and molybdenum dominant zones, especially in the deeper parts of the hydrothermal system. The stockwork, disseminated, and supergene-enriched mineralized zones at Butte have enormous value, having produced several billion dollars in copper, zinc, lead, silver, gold, and other metals.

Although no other porphyry or stockwork deposits in the quadrangle are comparable in worth to Butte, considerable exploration effort has been expended for these deposits and several low-grade copper and molybdenum systems have been drilled or explored in a systematic way. A molybdenum mineralized zone has been found at Bald Butte in the Marysville district (Rostad, 1969), a porphyry copper deposit (Beavertown prospect) is known in the Wickes district, and disseminated molybdenum and tungsten minerals have been identified in the Henderson Creek stock in the Henderson Creek area.

The Henderson Creek area is unusual because of the presence of scheelite in the Henderson Creek stock. Near the head of Henderson Creek, the scheelite is present within and around the contacts of a granodiorite stock of probable Late Cretaceous age. The scheelite exists as disseminated grains and stockwork veinlets in the granodiorite stock and in surrounding contact metamorphosed metasedimentary rocks of Middle Proterozoic age. Based on results from trenching and sampling by the U.S. Bureau of Mines, it estimated that a large tonnage of scheelite-bearing rock averaging 0.03 percent WO_3 is present in the area (Hundhausen, 1949). The area also has anomalous concentrations of molybdenum and the Henderson Creek stock has been explored for a molybdenum porphyry system by trenching and drilling by mining companies but no economic deposits were found.

Despite the relative scarcity of identified porphyry Cu-Mo-W deposits or prospects in the Butte quadrangle, they are exploration targets of great importance. The presence of porphyry Cu-Mo deposits in the Butte district and others such as the Cannivan Gulch and Heddleston deposits in nearby areas indicate that geologic conditions are favorable for the occurrence of undiscovered deposits of this type in the Butte quadrangle.

STOCKWORK/DISSEMINATED DEPOSITS OF GOLD AND SILVER

Disseminated Au-Ag deposits are a major exploration target of many mining companies at present and several deposits are being mined in Montana and within the Butte quadrangle. These deposits include the Basin Creek and Montana Tunnels mines within the quadrangle, the Golden Sunlight and Beal Mountain mines in the Dillon quadrangle to the south, and the Zortman-Landusky mine in central Montana. Ore minerals in these deposits are both structurally controlled (stockwork veins, breccias, and fault zones) and disseminated.

Breccia bodies are major features at both the Montana Tunnels (Sillitoe and others, 1985) and Golden Sunlight mines (Porter and Ripley, 1985). At the Montana Tunnels mine, the ore minerals are in a large diatreme (approximately 600×1,200 m) in the Lowland Creek Volcanics (middle Eocene). The gold and some of the silver are present as electrum within an assemblage of sulfide minerals (sphalerite, galena, pyrite, chalcopyrite, and acanthite) that are found as disseminated grains in the matrix of the diatreme breccia, as mineralized clasts in the breccia, as multidirectional veins in the breccia, and as open-space fillings in masses of brecciated volcanic and volcaniclastic rocks. Gold ore at the Golden Sunlight mine is within and around a pipe-shaped breccia that cuts Proterozoic sedimentary rocks and latite porphyry sills. Gold and associated minerals are present both as disseminated grains in breccia clasts and matrix and in sulfide veins.

At the Basin Creek mine, gold is in Tertiary (late Eocene) rhyolitic flows and ignimbrites that overlie monzogranite of the Boulder batholith. The ore bodies are in fracture-controlled quartz veins, zones of silicified stockwork veins, shear zones, and zones of disseminated minerals in volcanic and volcaniclastic rocks. The mineralized zones are controlled by northeasterly and northwesterly trending faults and shear zones.

The Zortman-Landusky mine is in the Little Rockies of north-central Montana. The Little Rockies is a dome-shaped feature of about 230 km^2 that consists of Paleocene laccoliths of calc-alkalic to alkalic composition, Precambrian amphibolite and gneiss, and Paleozoic and Mesozoic sedimentary rocks. The Paleocene intrusive rocks range in composition from diorite to granite but the majority of these rocks are syenite, quartz latite, and rhyodacite (Hastings, 1988). The gold ore bodies at the Zortman-Landusky mine are structurally controlled by major north-northwest- and northeast-trending faults (Hastings, 1988). The ore bodies are epithermal deposits that are zoned from surface and shallow low-grade oxidized stockwork veins, breccias, and intensely fractured sheeted fissure zones to deeper higher-grade narrow veins and zones of stockwork veins.

The Beal Mountain mine is approximately 25 km southwest of Butte and south of the Butte 1°×2° quadrangle. The geology and genesis of the deposit have been described by Hastings and Harrold (1988). Gold ore bodies at the Beal Mountain mine are in thermally metamorphosed Upper Cretaceous clastic sedimentary rocks, and this deposit was probably formed at higher temperatures than deposits discussed above. Gold and associated minerals were deposited at a temperature of about 230–325 °C, based on fluid inclusion studies. The age of ore deposition is probably Late Cretaceous, based on a K-Ar isotopic age of 71.8 Ma for adularia from a quartz-adularia vein. The gold ore bodies are along the borders of a diorite stock that has an age of 74.8 Ma. Gold is present with sulfide minerals either as disseminated grains in metasedimentary rocks and diorite or in narrow quartz-chlorite-calcite veins. The disseminated ore minerals are controlled by favorable horizons, the more favorable units are metaconglomerate beds.

METHODOLOGY OF MINERAL RESOURCE ASSESSMENT

The primary goal of the Butte CUSMAP studies was to assess the mineral resource potential of the Butte 1°×2° quadrangle. The methods used in the assessment involved the development of descriptive mineral deposit models and the application of these models using the computer-based spatial data processing 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:

1. Collection and compilation of geologic, geochemical, geophysical, and other data pertinent to the occurrence of mineral deposits.
2. Determination of both the types of mineral deposits present and the types that could 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 relative importance 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 (1992a, 1992b) followed Harrison's lead but worked cooperatively with personnel at the Earth Resources Observations Systems (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 and 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 map-based products of resource assessment (see Appendix). Nearly all of the original data were either in map or tabular form. Maps, which include a generalized geologic map, mining district map, geophysical anomaly map, limonite map, and linear features map, were digitized and entered into a vector graphics subsystem of the GIS. Geochemical data and mine and prospect data were entered as tabular data in the GIS.

Descriptive mineral deposit models were developed based on the types of mineral deposits that are present or could exist 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 deposits in the quadrangle and in adjacent regions of southwestern Montana. For some deposit types that are 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 for the Butte quadrangle limited the number and types of recognition criteria for each mineral deposit model. The recognition criteria are also limited to data that apply to the entire and not just selected parts of the quadrangle.

For each mineral-deposit model, 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 other factors. The scores are based mostly on observed or measured association of mines and prospects with certain classes of host rock, igneous rocks, geochemical anomalies, etc. Each submodel has several levels with scores in the range of 0 to 5. The final mineral resource assessment maps (maps A and B) are derived by combining the GIS submodels into summary GIS models (maps L and R) and then assigning levels (low, moderate, high) of mineral resource potential to the final maps.

DESCRIPTION OF DATA SETS

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 of Wallace (1987). Initially, 38 geologic map units, 5 classes of faults, and axial traces of folds were digitized from the generalized geologic map. For 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, 1987); furthermore, several Late Cretaceous granodiorite plutons were distinguished from other Late Cretaceous granodiorite, granite, and monzodiorite plutons. 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 beneath younger Tertiary and Quaternary sedimentary rocks and surficial deposits. This allowed the mineral resource assessment of the potential for porphyry Cu-Mo-W and disseminated Au-Ag deposits to be extended beneath post-mineralization sedimentary rocks and surficial deposits.

Except for the Boulder batholith in the southeastern part of the quadrangle that had been mapped in detail, the geologic map of the Butte quadrangle portrays new map data obtained between 1975 and 1983. During the period 1975–1979, reconnaissance geologic mapping was completed in the northwestern and western part of the quadrangle. Between 1980 and 1983 new reconnaissance mapping was completed over the remainder of the quadrangle and between 1979 and 1982 more detailed geologic studies were completed in six U.S. Forest Service Wilderness Study Areas. Main responsibilities for geologic mapping were shared by C.A. Wallace, who coordinated the mapping in the western two-thirds of the quadrangle, and R.G. Schmidt (deceased), who coordinated the mapping in the eastern third of the quadrangle and compiled the geologic information from the Boulder batholith at 1:250,000 scale (Wallace and others, 1987; Wallace, 1987). Details and references to the above mapping can be found in Wallace and others (1987).

Sedimentary rocks—The oldest rocks in the quadrangle are part of the Belt Supergroup (Middle Proterozoic), which 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. This group has 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 the three formations of the Ravalli Group. 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 occurs over most of the quadrangle and the Wallace Formation occurs in the westernmost part of the quadrangle. The Helena Formation is a dolomite- and limestone-rich sequence of argillite and siltite, and 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 formations in the lower and middle parts of the section consist mainly of dolomite and limestone; clastic rocks dominate in the upper part of the sequence and phosphatic beds occur at the top.

At the base of the Paleozoic section, the Middle Cambrian Flathead Quartzite is a fine- to coarse-grained quartzite that overlies Belt rocks with a disconformity or slight angular unconformity, and, in some places, it is absent. Within the Sapphire thrust plate (fig. 2) 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 occurs east and northeast of the Sapphire thrust plate. The lower member 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, phosphatic fossil debris, and phosphatic oolites. The Wolsey Shale contains similar rock types, but it contains more limestone than the lower member of the Silver Hill Formation. The middle member of the Silver Hill Formation is mostly a thinly laminated, gray limestone that is mottled with orange-weathering siliceous dolomite streaks. The Meagher Limestone is similar to the middle member of the Silver Hill Formation but contains fewer thinly laminated beds. 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 waxy, green shale that contains limestone beds mainly near the base. Overlying the Silver Hill Formation and the Park Shale is the Middle and Upper Cambrian Hasmark Formation, which is a thinly laminated, gray- and tan-weathering dolomite. The Upper Cambrian Red Lion Formation overlies the Hasmark Formation; most of the unit is gray, laminated limestone and interbedded, laminated, orange-weathering siliceous dolomite, but the unit has a thin basal zone of reddish-gray shale, siltstone, and limestone.

Overlying the Cambrian formations is the Middle and Upper Devonian Maywood Formation, which consists of grayish-red- and yellowish-weathering dolomitic and calcareous shale, dolomite, limestone, carbonate-cemented sandstone, and siliceous sandstone. The Upper Devonian Jefferson Formation, which overlies the Maywood Formation, is composed mainly of dark-gray dolomite and limestone that is interbedded with some shale beds near the base, and it 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 on the Sapphire thrust plate the Three Forks Formation is absent. The Three Forks Formation is a brownish-gray shale, siltstone, and limestone with rare sandstone beds.

Lower and Upper Mississippian sedimentary rocks consist of the Madison Group in most of the quadrangle, but two formations of the Tendoy Group occur near the bottom of the sequence in the western part of the Garnet Range (W.J. Sando, oral commun., 1986). Rocks of the Madison and Tendoy Groups are gray limestone, cherty limestone, and shaly 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; McGill, 1959; Kauffman, 1963; 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 on the Sapphire thrust plate, but this unit contains a thin zone of dolomite at the base, north and northeast of the thrust plate. Above the Quadrant Quartzite is a sequence of Lower Permian rocks that includes, in ascending order, the Park City and Phosphoria Formations and the Shedhorn Sandstone. This succession is composed of gray and dark-gray shale, siltstone, limestone, chert, sandstone, and phosphatic rock. The Park City Formation is absent east and northeast of the Sapphire thrust plate.

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

Plutonic rocks—The oldest igneous event known 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 rocks of the Missoula Group in the northwestern part (Nelson and Dobell, 1959, 1961; Wallace and others, 1987). Based on compositional similarity and stratigraphic position, these dikes and sills are correlated with Middle or Late Proterozoic dikes and sills that are in Belt rocks in areas adjacent to the Butte quadrangle (Mudge and others, 1982, Harrison and others, 1986a).

Most plutons and the 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 with the decay constant of Steiger and Jäger, 1977). 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 (figs. 1 and 2) include (1) stocks and batholiths in the Flint Creek Range; (2) stocks and a batholith in the Anaconda Range; (3) the Idaho batholith in the southwestern part of the quadrangle; (4) stocks and a batholith in the Sapphire Mountains; and (5) stocks in the John Long Mountains and the Garnet Range.

Most of the Boulder batholith, as well as several of its satellitic plutons, are in the Boulder Mountains between Helena and Butte and west of Helena. The batholith also extends to the east and the south, beyond the quadrangle boundaries. The principal rock types are granodiorite and monzogranite with an age range of about 78–71 Ma (Ruppel, 1961, 1963, Robinson and others, 1968; Wallace and others, 1987). Many productive vein and replacement deposits, including those of the Butte district, are within and near the Boulder batholith.

A group of stocks, which range in age between 97 and 52 Ma (H.H. Mehnert, written commun., 1985), are aligned along a northwesterly trend northwest of Helena and south of the St. Marys-Helena Valley fault (fig. 2). These stocks intrude Middle Proterozoic rocks, are principally granodiorite in composition, and numerous mines and prospects are associated with them.

The principal plutons of the Flint Creek Range are the Philipsburg and Mt. Powell batholiths and the Royal stock. These plutonic rocks consist of granodiorite and monzogranite and range in age from about 78 to 61 Ma (Hyndman and others, 1972; J.D. Obradovich, oral commun., 1983; Elliott and others, 1984; Marvin and others, 1989). Most plutonic rocks in the range are post-tectonic and were emplaced after thrusting. However, in the eastern part of the range, the older plutonic and metamorphic suite of Racetrack Creek, which includes plutonic rocks ranging from granodiorite to diorite, is deformed by thrust faults indicating pretectonic or syntectonic emplacement of probable Late Cretaceous age. Most mineral deposits are related to the granodiorite plutons such as the Royal stock 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, written commun., 1982). However, in the northeastern part of the range, an older granodiorite-tonalite-quartz diorite plutonic complex is cut by thrust faults and may be Late Cretaceous in age (J.D. Obradovich, written commun., 1982; Heise, 1983; Elliott and others, 1985). 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 (J.D. Obradovich, written commun., 1977; Desmarais, 1983), occur along the western border and in the southwestern corner of the

Butte quadrangle. These plutons are part of the Idaho batholith and usually 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 Creek, Big Spring Creek, Welcome Creek, Wallace Creek, Gird Creek, and Gillespie Creek stocks. The ages of most of these stocks range between 82 and 49 Ma (Wallace and others, 1987; J.D. Obradovich, oral and written communs., 1982). In the southern Sapphire mountains the Sapphire batholith (granodiorite and monzogranite) was intruded at about 73 Ma (Wallace and others, 1982). The ages of stocks of pyroxenite and syenite in the southern Sapphire Mountains have not been determined. Mineral deposits are in and near many of the granodiorite plutons, including the Garnet, Henderson Creek, Wallace Creek, and Miners Gulch stocks but others such as the Sapphire batholith have few associated mines and prospects.

MINES AND PROSPECTS

Mineral-occurrence data for mines and prospects in the Butte quadrangle have been compiled by Elliott, Loen, and others (1992). This compilation describes more than 1,100 mines and prospects in the mining districts and geographic areas in the quadrangle. Mines and prospects are present throughout the quadrangle; 78 percent are in established mining districts and the remaining 22 percent are more widely scattered in the quadrangle. Mines and prospects have been assigned to 13 deposit types. Vein and replacement deposits of base and precious metals are the most common deposit type and they constitute or make up 70.2 percent of the mines and prospects. Next in abundance are placer deposits (nearly all gold, but some tungsten and sapphire) that constitute 12.6 percent of the mines and prospects. Mines and prospects classified as porphyry Cu-Mo-W and disseminated Au-Ag deposits account for only 10 and 5 sites respectively. However, the small number of porphyry deposits is compensated by their very large contribution to production of mineral wealth of the quadrangle. 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 and revised if necessary. Additions included data from published reports more recent than those cited in MRDS, from unpublished records of the U.S. Forest Service, and from 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 Mineral Information Offices in Washington, D.C.; Spokane, Wash.; Reno, Nev.; and Tucson, Ariz. During field work in the Butte quadrangle, between 1980 and 1984, approximately 150 mineralized sites were visited to verify the MRDS and other data and to collect additional information on geology, geochemistry, and mineral deposits.

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 (McDanal and others, 1985). Geochemical maps used to prepare the geochemical submodels for the assessment of porphyry Cu-Mo-W and disseminated Au-Ag deposits were developed from the stream-sediment and panned-concentrate analytical data. These data, unlike that from 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, 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 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 was saved for analysis.

Panned-concentrate samples were normally collected near the stream-sediment sample localities but from coarser-grained material (usually containing gravel-size particles). This coarse detritus represents a high-energy depositional environment in the stream channel where a natural concentration of heavy minerals is most likely to occur. Heavy minerals were concentrated 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). In addition, many samples were analyzed for gold, arsenic, copper, lead, zinc, silver, bismuth, cadmium, and antimony by atomic-absorption (AA) methods described by Thompson and others (1968), Ward and others (1969), and Viets (1978), and they were also analyzed for tungsten by colorimetric (CM) methods (Welsch, 1973). 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.

Analytical results were entered into the Rock Analysis Storage System (RASS), which is a computerized data base maintained by the USGS in Denver, Colo. (Van Trump and

Miesch, 1976). RASS contains both descriptive geologic data and analytical data. The data are available on magnetic tape from the National Technical Information Service (McDanal and others, 1985). Most of the data are also available in a USGS Open-File Report (Campbell and others, 1982); however, analytical data for the eastern one-third of the quadrangle are incomplete and the report contains some errors which were later corrected in McDanal and others (1985).

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

GEOPHYSICS

Magnetic and gravity data were used to assess subsurface mineral resource potential. New gravity and magnetic surveys were completed for the Butte quadrangle during the CUSMAP project. The gravity survey consisted of 2,325 observations within and directly adjacent to the quadrangle (Hassemer, 1981; 1984a,b; 1986); 1,900 of which are new, 262 were made previously by the USGS, and 163 were obtained from nonproprietary data files of the U.S. Department of Defense. All gravity data were obtained using high-precision Lacoste and Romberg geodetic gravimeters. The aeromagnetic survey represents total-field measurements along 70 east-west flight lines spaced 1 mi apart at an average elevation of 9,000 ft above mean sea level (USGS, 1984). Gravity and magnetic data were supplemented by the measurements of densities and magnetization of 823 rock samples from the quadrangle; these measurements were made on a wide range of rock types that varied in density and magnetization.

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 of the quadrangle are associated with exposed Late Cretaceous or Tertiary plutons of granodiorite and monzodiorite; thus, there is a 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 coincide with sedimentary basins that are filled with Tertiary and Quaternary sediment, and other gravity lows coincide with mapped plutons, some of which have associated mineral occurrences. Therefore, some of the low gravity anomalies also have a positive correlation with mines and prospects of the Butte quadrangle.

Buried plutons are inferred to underlie many areas of anomalously high magnetism. This inference 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 assumption of steep contacts of a buried pluton might be determined by drilling or inferred by 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 rock. The interpreted thicknesses of the magnetic plutonic rock vary widely, perhaps in the range of 0.5 to 10 km. The geophysical data used for this study and the specific procedures for developing an interpretive geophysical map (map K) are described in the appendix. In this interpretive map some areas of mapped plutonic rocks are outside the areas of interpreted magnetic plutonic rocks. By inference, these bodies of rocks are either quite thin and thus small in volume and magnetic dipole moment or they are less magnetic than most plutonic rocks. If these rocks are thin plutonic units such as sills and dikes, then they probably have low potential for undiscovered mineral deposits. If less magnetic, these rocks may have lower contents of magnetic minerals or be hydrothermally altered, as are some parts of the Boulder batholith. If the magnetism is low because of hydrothermal alteration, then the potential for undiscovered mineral deposits is high. 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 surface 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 with westward illumination and a spatial resolution of approximately 10 m (recorded during December, 1979).

Hydrothermally altered rocks—Limonite, which is a combination of ferric iron oxide minerals, can be identified on MSS digital images because of its diagnostic spectral reflectance in the wavelength region of 0.4–1.1 micrometers. Rowan and Segal (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 identified as having anomalously high limonite 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 weathering of hydrothermally altered rocks and limonite that resulted 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 identified by analysis of MSS and SLAR images; the principal objective of this analysis was to determine the relation between linear features and known mines and prospects and to apply these relations 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 also may represent differences in color or shades of color. Rowan and others (1991) excluded linear features 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 the linear features were located on maps, they were digitized for later 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 six domains based on patterns of linear features and the relations of linear features to structures and lithology. A comparison of spatial association of linear features with known mines and prospects resulted in the subdivision of the 6 domains into 16 subdomains (map H). 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 showed 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 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). Different types of spatial data can be referenced and compared both in quality and quantity using a GIS. A GIS can 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 and another shows the locations of mines and prospects. To compare the distribution of mines and prospects with geologic map units without using a GIS, both maps would have to be prepared as transparencies at the same scale and superimposed. Visual and qualitative comparisons would then be made about 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 a GIS, the maps are digitized and entered into the 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 with arithmetic operations and statistics. Thus, the effects of two or more data sets at any particular location are analyzed simultaneously and both quantitative and qualitative relationships can be quickly determined. Using the example of the comparison of mines and prospects with geologic map units, relations such as the percentage of gold deposits associated with sedimentary units of Paleozoic age, the percentage of mines with large production found in intrusive rocks, or the density of mines in Precambrian rocks are calculated with ease and speed.

For some studies, in which only two or three data sets of low complexity are used, GIS may not be advantageous, but where the number of data sets is large and the kinds of data are more complex, the GIS method offers many benefits in speed, objectivity, and reproducibility over manual methods. The manual method 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 method was made by Pratt and others (1983). The results of this comparison indicated that the GIS method had many advantages over the manual method while producing similar conclusions.

For the mineral resource assessment of the Butte quadrangle, GIS technology and procedures offered many advantages because of the numerous data sets and the complexity 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 three-dimensional surfaces from point data, to display interim results of interactive processing sessions, and to statistically analyze spatial relations among data sets. The procedures used for entry, processing, and interpretation of data by the GIS are explained in the Appendix.

RESOURCE ASSESSMENT

The procedure used in the mineral resource assessment of porphyry/stockwork Cu-Mo-W and stockwork/disseminated Au-Ag deposits in the Butte quadrangle consisted of (1) the development of descriptive models, (2) the use of GIS techniques to develop submodels based on recognition criteria of the descriptive model, and (3) the combination of these submodels into a map that shows various levels of potential for the occurrence of undiscovered deposits.

Terminology used in this report is adapted from Pratt and others (1984) and Goudarzi (1984). The mineral resource terms from Pratt and others (1984) are:

Recognition criteria—Geologic, geophysical, and geochemical features that determine the favorability for the occurrence of a mineral deposit.

Diagnostic criteria—Criteria that are present in all or nearly all known deposits and, in most cases, that are considered required for the occurrence of a mineral deposit.

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

Negative criteria—Criteria normally equated with the known absence of diagnostic criteria.

The following definitions are from Goudarzi (1984):

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

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

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

Mineral resource potential—The likelihood for the occurrence of undiscovered mineral resources in a defined area. Mineral resource potential is preferred in the description of an area; favorability is best applied to a specific rock mass (or type) or geologic environment. The levels of resource potential can be specified as high, moderate, low, no, and unknown (Goudarzi, 1984).

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 was not 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 usually used only for areas overlain by thick alluvium or other covering rock units and where geophysical and geochemical data are not adequate to determine the level of resource potential.

DESCRIPTIVE MODEL FOR PORPHYRY AND STOCKWORK DEPOSITS OF COPPER, MOLYBDENUM, AND TUNGSTEN

Porphyry Cu-Mo-W deposits are large, low-grade deposits that are usually amenable to bulk mining methods (open pit or block caving). The ore minerals occur as disseminated grains, in zones of stockwork veining, or as supergene enrichment zones of secondary minerals. Such deposits occur throughout the Rocky Mountain and Basin and Range regions of the western U.S. These deposits are major sources of copper and molybdenum and many other metals that are produced as byproducts. Although there are no porphyry/stockwork tungsten deposits that produce tungsten as a primary product in the U.S., tungsten has been produced as a byproduct from the porphyry Mo deposit at Climax, Colorado, and porphyry/stockwork tungsten deposits are known in other parts of the world such as in China and Canada. Applicable models from Cox and Singer (1986) are porphyry Cu, porphyry Cu-Mo, Climax Mo, and porphyry Mo (low F). No model for stockwork W deposits is presented by Cox and Singer (1986).

Regional setting—In the Butte quadrangle, the most favorable rocks for the occurrence of porphyry Cu-Mo-W deposits are Late Cretaceous or Tertiary granitic (rhyolitic) to granodioritic (dacitic) plutonic, hypabyssal, and volcanic rocks. The presence of volcanic centers, with plutonic and (or) hypabyssal porphyritic rocks in the same area as pre- or syn-volcanic rocks, may be especially favorable to the occurrence of porphyry Cu-Mo-W deposits, and regional structures commonly control the location of these deposits. The Boulder batholith with its associated ore deposits including the porphyry-type deposits in the Butte district is along a regional structure called the Great Falls tectonic zone (O'Neill and Lopez, 1985). At the scale of districts or mines, faults are commonly important controls for ore deposition.

Deposit characteristics—These deposits are commonly associated with large zoned areas of altered rocks and usually show a zoned distribution of metals and minerals in and around porphyry deposits. The Butte district is an outstanding example of zoned metals and minerals with central, intermediate, and peripheral zones (Meyer and others, 1968). The central zone is dominated by copper ore, the intermediate zone by copper and zinc ore, and the peripheral zone by manganese, silver, and zinc. Geochemically, copper and molybdenum are the most important pathfinder elements for locating copper and copper-molybdenum deposits. Other elements that are commonly found in anomalous concentrations, particularly in outer zones of porphyry deposits are zinc, gold, silver, lead, and manganese. Molybdenum, tungsten, tin, and possibly beryllium are important pathfinders for Climax-type Mo and porphyry/stockwork W deposits. Many porphyry-type deposits are found in districts that also have precious- and base-metal vein and replacement deposits. Skarn deposits, especially Cu-Au bearing skarns, also may exist in the same districts as porphyry Cu or Cu-Mo deposits.

Geophysics and remote sensing—Favorable areas for the occurrence of porphyry Cu-Mo-W deposits, such as areas of exposed or subsurface plutonic rocks and (or) volcanic centers, may be indicated by the presence of magnetic highs as determined from aeromagnetic surveys. Areas of altered rock that are indicated by the presence of limonitic rocks may be discriminated by remote sensing studies. Favorable regional structures might be located by the mapping of linear features from satellite and radar imagery.

Recognition criteria—

(1) Plutonic and hypabyssal porphyritic rocks of Late Cretaceous and Tertiary age; commonly with prevolcanic or synvolcanic rocks in the same area.

(2) Presence of hydrothermally altered rocks.

(3) Geochemical anomalies of copper, molybdenum, gold, silver, lead, zinc, tungsten, tin, beryllium, and (or) manganese.

(4) Geophysical anomalies that indicate the presence of subsurface bodies of magnetic plutonic rocks.

(5) Presence of hydrothermal deposits, including vein, replacement, and skarn deposits.

(6) Proximity to major structural features, especially to intersections of faults or lineaments.

DESCRIPTIVE MODEL FOR STOCKWORK/ DISSEMINATED DEPOSITS OF GOLD AND SILVER

Stockwork and disseminated deposits of gold and silver (disseminated Au-Ag deposits) are large, low-grade, bulk-minable deposits in which the ore minerals occur in thin veins, stockwork veins, open-space fillings, or disseminated grains in sedimentary and igneous rock. Gold is the principal product of such deposits but silver is usually recovered as a byproduct, and other metals such as copper, lead, and zinc may be important byproducts. As discussed earlier in this report, several disseminated Au-Ag deposits are presently being mined in Montana and in other western states such as Nevada and California.

Regional setting—Disseminated Au-Ag deposits usually are found in association with shallow plutonic, hypabyssal, or volcanic rocks and most of these deposits may be epithermal. The Beal Mountain deposit, south of the Butte quadrangle, may be an exception because there is evidence in the form of thermal metamorphism of the deposit having formed in a somewhat deeper environment (Hastings and Harrold, 1988). Host rocks for disseminated Au-Ag deposits include Archean metamorphic rocks, Proterozoic and Cretaceous sedimentary rocks, Cretaceous and Tertiary intrusive rocks, and Cretaceous and Tertiary volcanic and volcaniclastic rocks. The locations of these deposits appear to be controlled by regional and district-scale faulting.

Deposit characteristics—Although there is a great diversity of geologic and geochemical characteristics of known deposits, some features, common to several deposits, define the deposit type. Most disseminated Au-Ag deposits are found in districts that had a history of gold mining, where gold is in gold- and silver-bearing veins or in placers. In disseminated Au-Ag deposits, most ore bodies are structurally controlled by faults and breccia zones. Shear and breccia zones are common. Typically, rocks within or adjacent to ore bodies are altered, and argillic, pyritic, and (or) sericitic alteration of the host rocks is common. Secondary potassium feldspar is present in some deposits and silicified zones may be present (for example, the silica cap rock at the Golden Sunlight deposit). Gold usually occurs as native gold or electrum but some exists in telluride minerals. Sulfide minerals associated with gold include galena, sphalerite, chalcopyrite, arsenopyrite, pyrrhotite, and molybdenite. Gold and silver are the most important pathfinder elements for geochemical exploration. Other elements commonly present in anomalously high concentrations are zinc, lead, manganese, arsenic, antimony, mercury, barium, tellurium, fluorine, and bismuth. In the Butte CUSMAP studies, analyses were not available for mercury, tellurium, or fluorine so these were not included in the mineral resource assessment. Iron was included as a pathfinder element because anomalies in drainage samples apparently correlate with areas containing hydrothermally altered rocks and mineral deposits.

Geophysics and remote sensing—Most disseminated Au-Ag deposits are spatially associated with intrusive or extrusive rocks, and these igneous rocks commonly appear as magnetic highs in regional aeromagnetic surveys. In addition, magnetic lows in areas of igneous rocks may indicate zones of hydrothermal alteration. The Montana Tunnels mine is associated with a prominent magnetic low within a larger magnetic high that marks the location of the diatreme. The Au-Ag-Zn-Pb ore bodies at the Montana Tunnels mine are in sericitic and argillic zones of altered rock in the diatreme.

Two common features of disseminated Au-Ag deposits that can be detected by remote sensing methods are (1) altered areas and (2) regional structures. Remote sensing studies are useful in delineating areas of limonitic rocks and in mapping of linear features and intersections of linear features.

Recognition criteria—

(1) Presence of Tertiary and Cretaceous volcanic and hypabyssal rocks, especially those of rhyolitic, dacitic, and latitic composition.

(2) Presence of areas of magnetic plutonic rocks or magnetic lows within larger magnetic highs.

(3) Geochemical anomalies of gold, silver, lead, zinc, copper, arsenic, antimony, bismuth, manganese, iron, and barium.

(4) Presence of gold-silver lode or gold placer deposits.

(5) Presence of altered areas and regional structures.

GIS SUBMODELS FOR PORPHYRY AND STOCKWORK COPPER, MOLYBDENUM, AND TUNGSTEN DEPOSITS

The following submodels were developed for and apply only to porphyry and stockwork deposits of copper, molybdenum, and tungsten (porphyry Cu-Mo-W deposits).

Hydrothermal deposits submodel—Zones within 2 km of known hydrothermal deposits, including all deposit types except placer, strata-bound, and nonmetallic deposits (Elliott and others, 1986), were delineated and are shown on map D. These zones are more favorable for the occurrence of undiscovered deposits of porphyry Cu-Mo-W and are assigned a score of 2. The remainder of the map area outside of selected zones is assigned a score of 0. Also shown on map D are the locations of known porphyry-stockwork Cu-Mo-W mines or prospects.

Plutonic and volcanic rock submodel—The plutonic and volcanic rock submodel for porphyry Cu-Mo-W deposits (map I) is a modification of the plutonic rock submodel used for the mineral resource assessment of vein and replacement deposits (Elliott, Wallace, and others, 1992). For porphyry Cu-Mo-W deposits, areas underlain by volcanic and hypabyssal units or adjacent to these units were added to the plutonic rock submodel that was used for vein and replacement deposits.

In the previous case for vein and replacement deposits, the association between plutonic rocks and known vein and replacement deposits was determined empirically by superimposing the locations of mines and prospects on the geologic map and calculating the "normalized mine density." The normalized mine density is defined as the percent of total mines in the entire quadrangle that are within a designated area, such as a map unit, divided by the percent of the total map area occupied by that map unit (percent mines/percent area). For example, if 70 of a total of 700 mines are in a given map unit, then the percent of mines is 70/700=0.1 or 10 percent. If that unit covers 5 percent of the map, then the normalized mine density is 0.1/0.05=2.0. The average normalized mine density for the entire quadrangle would be 1.0 and any value greater or less than 1.0 would indicate either higher or lower than average density, respectively.

The spatial association between vein and replacement mineral occurrences and plutonic map units was tested by calculating normalized mine densities for concentric bands both inside and outside of mapped contacts of 17 plutonic units. Using this approach it was found that the most favorable area for the occurrence of vein and replacement deposits was a 4-km-wide band extending from 1 km inside the contact to 3 km outside the contact. Known porphyry Cu-Mo-W deposits in the Butte quadrangle also show a close spatial association with plutonic rocks. However these deposits are mostly found within but near the margins of intrusives rather than in the rocks bordering intrusives. Therefore, for porphyry Cu-Mo-W deposits, the most favorable zone is closer to or within intrusive contacts compared with vein and replacement deposits. A 4-km-wide band extending from 2 km inside the intrusive contacts to 2 km outside contacts was defined as favorable for porphyry Cu-Mo-W deposits compared to 1 km inside to 3 km outside contacts for vein and replacement deposits.

Types of plutonic rocks in the Butte quadrangle were ranked in order of favorability based on the density of known vein and replacement mines in 4-km-wide bands. The most favorable plutons, which have normalized mine densities in the range of 2.2 to 10.3, were assigned 5 points. These plutons are Cretaceous stocks and batholiths of granodiorite, monzogranite, and gabbro and include the Philipsburg and Boulder batholiths, the Royal, Cable, Scratchgravel Hills, and Marysville stocks, and small bodies of gabbro, alaskite, aplite, and pegmatite. The next most favorable group of plutons had substantially lower densities that ranged between 0.7 to 1.6, and these were given scores of 3 to emphasize the much lower mine densities as compared to the higher mine densities in the most favorable plutons. Cretaceous granodiorite and monzogranite and Tertiary granodiorite are the principal pluton types in this second group. Other types of plutonic rocks were assigned lower scores based on normalized mine densities. Plutons with densities of 0.3–0.6 were given 2 points, and the least favorable plutons, which had no mines in the 4-km-wide zones, are assigned 1 point.

Construction of the plutonic rock submodel showed that relations between plutons of different ages cause complications for the point scores. For example, if a Tertiary pluton (3 points for 4-km-wide zone) intruded a Cretaceous granodiorite pluton (5 points for 4-km-wide zone) and the zone surrounding the granodiorite, part of the older rock would be consumed and a new contact zone would be superimposed (see fig. 3). Part of the 4-km-wide zone associated with the older pluton (5 points) would be removed by stoping or assimilation and a new 4-km-wide zone (3 points) associated with the younger pluton would be formed. However, where this new zone was superimposed on the 4-km-wide zone of the older pluton, the point value of the older pluton (5 points) would be retained. All such age relations were evaluated and scored (map I) using GIS procedures described in the Appendix.

Many porphyry-type deposits show an association with volcanic and hypabyssal rocks, so a volcanic rock submodel was developed and added to the plutonic rock submodel. This volcanic rock submodel was developed by including all volcanic and hypabyssal rocks (Tertiary and Cretaceous) and by using the GIS to include areas within 2 km of

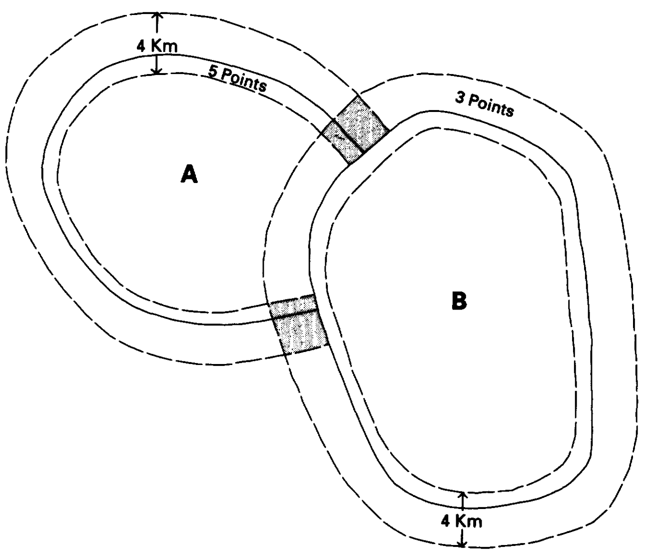

Figure 3. Sketch showing age relationships and scoring of plutons. Older pluton A (outer 4-km-wide zone is 5 points) cut by younger pluton B (outer 4-km-wide zone is 3 points). Part of A's zone retains 5-point value and B's 3-point zone is superimposed on A.

mapped volcanic and hypabyssal rocks. A score of 3 was assigned to the volcanic units more favorable to contain porphyry Cu-Mo-W deposits. These units are the Tertiary Lowland Creek Volcanics and the Cretaceous Elkhorn Mountain Volcanics. The other less favorable volcanic units were assigned a score of 2, and a score of 1 was assigned to the areas within 2 km of all volcanic and hypabyssal rocks. This submodel was added to the plutonic rock model and the 2-km-wide areas around older volcanic units (such as the Cretaceous Elkhorn Mountain Volcanics) were removed where intruded by younger plutonic units (map I).

Geochemical submodel—The geochemical submodel for porphyry Cu-Mo-W deposits is based on anomaly maps (see Appendix) for copper, molybdenum, silver, gold, lead, zinc, tungsten, tin, beryllium, and manganese. To reduce the number of anomaly maps and thereby simplify the analytical procedures used in the construction of the geochemical submodel, some single-element maps were arithmetically combined into multi-element maps. These maps show combined anomalies for groups of two or three elements. The geochemical submodel for porphyry Cu-Mo-W deposits (map J) is a combination of the three geochemical suites anomaly maps (silver-gold, lead-zinc, and tungsten-tin-beryllium) and three single-element maps (copper, molybdenum, and manganese). In the resultant submodel, any pixel (grid cell on a computer screen with a brightness in the range of 0–255 levels of brightness and representing an area of 200m×200 m) having a nonzero (greater than zero) value represents the summation of one to six individual pixels from the constituent single-element or geochemical suites anomaly maps. To identify the source of suite and single-element anomaly images, numbers in the series, 1, 2, 4, 8, 16, and 32, were assigned to the maps. All nonzero (anomalous) pixels on the copper map were assigned a value of 1; on the molybdenum map, 2; on the silver-gold map, 4; on the lead-zinc map, 8; on the tungsten-tin-beryllium map, 16; and on the manganese map, 32. Because the sum of any two or more of these numbers yields a unique number not found in the series, 1, 2, 4, and so on, 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 the lead-zinc (8), silver-gold (4), molybdenum (2), and copper (1) maps, and any pixel having a value of 63 is the sum of 1 + 2 + 4 + 8 + 16 + 32, which identifies an area that contained all the components (geochemical suites plus copper, molybdenum, and manganese) in anomalous concentrations.

In the final step, all 63 possible assemblages of anomalies (composite anomalies) for geochemical suites and for single elements were ranked and assigned favorability scores of 1 to 5 (table 1). The distribution of known porphyry Cu-Mo-W deposits was compared to the areas of anomalies by calculating normalized mine densities; however, because of the low number of known occurrences (10) the results are not very credible. The following scores were assigned based on the geochemistry of known porphyry Cu-Mo-W deposits. A score of 5 was assigned to assemblages that include copper and molybdenum plus a combination of at least three of the geochemical suites and (or) manganese. A score of 4 is assigned to assemblages that include (1) copper and molybdenum combined with two of the geochemical suites and (2) copper or molybdenum plus a combination of at least three of the geochemical suites and (or) manganese. A score of 3 is assigned to assemblages that include (1) copper and molybdenum with no or one geochemical suite or manganese and (2) copper or molybdenum plus two of the geochemical suites and (or) manganese. A score of 2 is assigned to assemblages that include copper or molybdenum with no or one geochemical suite or manganese. A score of 1 is assigned to all other nonzero classes (any single element or suite map or combinations not included above).

Geophysical submodel—The geophysical submodel for porphyry Cu-Mo-W deposits (map K) is based on an interpretative map that displays the surface and inferred subsurface distribution of magnetic plutonic rocks. This interpretative map was derived from the analysis of regional magnetic and gravity data and from the generalized geologic map. This submodel is the same as that used for the mineral

Table 1.--*Favorable assemblages of elements in the geochemical submodel for porphyry/stockwork deposits of copper, molybdenum, and tungsten in the Butte 1°X 2° quadrangle, Montana*

[Values for nonzero (anomalous) pixels are as follows: Cu=1; Mo=2; Ag and (or) Au=Pm=4; Pb and (or) Zn=PZ=8; W and (or) Sn and (or) Be=WSB=16; Mn=32]

Assemblage	Total value of pixel	Favorability score
Cu+Mo+Pm+PZ+WSB+Mn	63	5
Cu+Mo+PZ+WSB+Mn	59	5
Cu+Mo+Pm+WSB+Mn	55	5
Cu+Mo+Pm+PZ+Mn	47	5
Cu+Mo+Pm+PZ+WSB	31	5
Cu+Mo+Pm+PZ	15	4
Cu+Mo+Pm+WSB	23	4
Cu+Mo+PZ+WSB	27	4
Cu+Mo+Pm+Mn	39	4
Cu+Mo+PZ+Mn	43	4
Cu+Mo+WSB+Mn	51	4
(Cu or Mo)+Pm+PZ+WSB+Mn	61,62	4
(Cu or Mo)+PZ+WSB+Mn	57,58	4
(Cu or Mo)+Pm+WSB+Mn	53,54	4
(Cu or Mo)+Pm+PZ+Mn	45,46	4
(Cu or Mo)+Pm+PZ+WSB	29,30	4
Cu+Mo+Mn	35	3
Cu+Mo+WSB	19	3
Cu+Mo+PZ	11	3
Cu+Mo+Pm	7	3
Cu+Mo	3	3
(Cu or Mo)+Pm+PZ	13,14	3
(Cu or Mo)+Pm+WSB	21,22	3
(Cu or Mo)+PZ+WSB	25,26	3
(Cu or Mo)+Pm+Mn	37,38	3
(Cu or Mo)+PZ+Mn	41,42	3
(Cu or Mo)+WSB+Mn	49,50	3
(Cu or Mo)+Mn	33,34	2
(Cu or Mo)+WSB	17,18	2
(Cu or Mo)+PZ	9,10	2
(Cu or Mo)+Pm	5,6	2
Cu or Mo	1,2	2
Others	4,8,12,16,20,24,28,32, 36,40,44,48,52,56,62	1

resource assessment of vein and replacement deposits (Elliott, Wallace, and others, 1992). The areas of magnetic plutonic rock were compared with the distribution of known vein and replacement mines and prospects, and normalized mine densities were calculated. The areas of magnetic plutonic rock exposed at the surface and those inferred in the subsurface have a very low normalized mine density of 1.4, which suggests only a weak correlation between known mines and prospects and the areas of magnetic plutonic rock. In the submodel shown on map K, a score of 2 points is assigned to the areas of magnetic plutonic rock and a score of 1 point is assigned to 2-km-wide zones around those areas. The other parts of the quadrangle are assigned a score of 0 points.

GIS SUBMODELS FOR STOCKWORK AND DISSEMINATED GOLD AND SILVER DEPOSITS

The following submodels were developed for and apply only to stockwork and disseminated gold and silver deposits (disseminated Au-Ag deposits).

Gold-silver mineral occurrence submodel—Disseminated Au-Ag deposits are commonly in areas or districts where gold and (or) silver are known in lode or placer deposits. The gold-silver mineral occurrence submodel includes all sites (Elliott and others, 1986) that have occurrences of gold or silver. Zones within 2 km of these occurrences were defined and assigned a score of 2 (map N). Also shown on map N are the locations of known disseminated Au-Ag deposits in the quadrangle.

Volcanic rock submodel—The volcanic rock submodel (map O) for disseminated Au-Ag deposits is similar to that used for porphyry Cu-Mo-W deposits. A score of 3 is assigned to more favorable volcanic units, 2 to less favorable volcanic units, and 1 to areas within 2 km of mapped volcanic and hypabyssal rocks.

Geochemical submodel—The geochemical submodel for disseminated Au-Ag deposits is based on anomaly maps for gold, silver, copper, lead, zinc, arsenic, bismuth, antimony, iron, manganese, boron, and barium; this submodel is very similar to that used for precious- and base-metal vein and replacement deposits (Elliott, Wallace, and others, 1992). Some single-element maps were arithmetically combined into multi-element or geochemical suites maps that show combined anomalies for groups of two or three elements. The geochemical submodel (map P) is a combination of four geochemical suites anomaly maps (gold-silver, copper-lead-zinc, arsenic-bismuth-antimony, and iron-manganese) and two single-element maps (boron and barium). Any pixel (grid cell) with a nonzero (value greater than zero) represents the summation of one to six individual nonzero pixels. All nonzero (anomalous) pixels in the gold-silver map were assigned a value of 1; those in the copper-lead-zinc map, 2; in the arsenic-antimony-bismuth map, 4; in the iron-manganese map, 8; in the boron map, 16; and in the barium map, 32.

All aggregate anomalies of the 63 possible combinations of anomalies were ranked and assigned favorability scores of 1 to 5 (table 2). This ranking is based primarily on the normalized mine densities for known precious- and base-metal vein and replacement deposits in the quadrangle (Elliott, Wallace, and others, 1992) but is also based, in part, on the comparison of anomalous areas with the location of the five known disseminated Au-Ag deposits.

Geophysical submodel—The geophysical submodel for stockwork Au-Ag deposits (map Q) is a combination of the previous geophysical interpretative map that shows the extent of magnetic plutonic rocks and a map of magnetic lows that occur within, or adjacent to, areas of volcanic and hypabyssal rocks. Magnetic lows, such as the one present at the Montana Tunnels mine, could indicate areas of altered volcanic or hypabyssal rocks. The map of magnetic lows was prepared by overlaying the aeromagnetic map for the quadrangle on the geologic map and selecting all closed magnetic lows that occur within or partly overlapping volcanic and hypabyssal units. This magnetic low map was then combined with the magnetic plutonic rock map and the resulting map was compared with the distribution of known disseminated Au-Ag deposits. Zones within 4 km of the geophysical interpretative map of magnetic plutonic rocks were delineated. The areas of the magnetic plutonic rocks plus the 4-km-wide buffer zone around them is assigned a score of 2 in map Q. Magnetic lows that are within this area are assigned a score of 4, and magnetic lows outside the areas of magnetic plutonic rocks and 4-km-wide buffer zones are assigned a score of 2.

GIS SUBMODELS FOR BOTH PORPHYRY AND STOCKWORK COPPER, MOLYBDENUM, AND TUNGSTEN AND STOCKWORK AND DISSEMINATED GOLD AND SILVER DEPOSITS

The following submodels apply to both the porphyry Cu-Mo-W and disseminated Au-Ag deposits.

Host-rock submodel—The favorableness or predisposition of a formation to serve as a host for porphyry Cu-Mo-W or disseminated Au-Ag deposits depends, in part, on fracture potential of the host rock. Fracture potential is the tendency for host rocks to fracture under stress and to retain throughgoing fractures. Fracture potential is primarily the result of brittleness, which is a function of fabric, lithification, and quartz content.

Fabric characteristics that determine fracture potential are brittleness and anisotropism. Grain shapes and sizes, uniformity of grain sizes, and intergrain relationships all affect the brittleness of a rock. Many igneous rocks are more brittle than sedimentary rocks because they are composed of interlocking grains of many shapes. Metamorphism may increase the brittleness of rocks by growth of new minerals or recrys-

Table 2.--*Favorable assemblages of elements in the geochemical submodel for stockwork/disseminated gold-silver deposits in the Butte 1° X 2° quadrangle, Montana*

[Values for nonzero (anomalous) pixels are as follows: Ag and (or) Au=Pm=1; Cu and (or) Pb and (or) Zn=BM=2; As and (or) Bi and (or) Sb=A1=4; Fe and (or) Mn=A2=8; B=16; Ba=32]

Assemblage	Total value of pixel	Favorability score
PM+BM+A1+A2+B+Ba	63	5
PM+BM+A1+A2+B	31	5
PM+BM+A1+A2	15	5
PM+BM+A1	7	5
BM+A1+A2	14	4
PM+BM+A1+B	23	4
PM+A2+B	25	4
BM+A2+B	26	4
PM+BM+A1+Ba	39	4
PM+BM+A1+A2+Ba	47	4
PM+BM+A1+B+Ba	55	4
PM+BM+A2	11	3
A2+B	24	3
BM+A2+Ba	42	3
PM+A1	5	2
BM+A1	6	2
PM+A2	9	2
PM+A1+B	21	2
PM+BM+A2+B	27	2
PM+A1+A2+B	29	2
BM+A1+A2+B	30	2
BM+A1+Ba	38	2
BM+B+Ba	50	2
Others	1-4,8,10,12,13,16-20,22,28, 32,33-37,40,41,43-46,48,49, 51-54,56-62	1

tallization of previously existing minerals. The tendency to develop and maintain fractures is also influenced by anisotropism. Anisotropic fabrics include bedding, foliation, joints, and flow banding.

In sedimentary rocks, brittleness is a function of lithification. Although there are many exceptions, in general, the degree of lithification is a function of age, and older rocks tend to be more brittle than younger rocks. Brittleness is also a function of rock type. In sedimentary and metasedimentary rocks, quartzite is the most brittle, and pure carbonate rock, at the other end of the spectrum, is the least brittle. Therefore, the percentages of quartz sandstone in a sedimentary sequence and quartzite in metamorphic rocks are used as measures of brittleness. Likewise, in igneous rocks, brittleness increases with the quartz and silica content.

Igneous and sedimentary rocks, except Quaternary surficial deposits (map unit Qs) and Tertiary sedimentary deposits and rocks (Ts), were subjectively ranked in order of fracture potential and assigned scores in the range of 1 for the lowest to 5 for the highest. The highest ratings are assigned to the Garnet Range and Mount Shields Formations of the Middle Proterozoic Missoula Group (Ymi). The lowest in rank are sedimentary formations of Devonian to Permian age (PDs) and andesitic and basaltic volcanic rocks of Late Cretaceous or early Tertiary age (TKab). Map E shows host rock favorability based on fracture potential.

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 vein and replacement deposits rather than known porphyry Cu-Mo-W and disseminated Au-Ag deposits because we have identified so few examples of the latter two types in the Butte quadrangle. 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. Due to this uncertainty of discrimination and lack of complete coverage, a maximum score of 3 points was assigned for the alteration submodel. The areas of limonitic, hydrothermally altered rock have a very high normalized mine density for vein and replacement deposits (22.0) and were assigned a score of 3 points in the alteration submodel (map F). One kilometer-wide zones around altered areas have a normalized mine 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 parts of the quadrangle more distant than 2 km from limonitic, altered areas were assigned a score of 0 points.

Fault submodel—Five classes of faults (normal, thrust, strike-slip, oblique-slip, and unclassified) were digitized from the generalized geologic map of the Butte quadrangle (Wallace, 1987). Since so few porphyry Cu-Mo-W and disseminated Au-Ag mines and prospects are present in the Butte quadrangle, the method of using normalized mine densities to rank favorableness of faults is probably not valid. However, because porphyry Cu-Mo-W and disseminated Au-Ag deposits commonly occur in the same district or in association with vein and replacement deposits, we used the association of vein and replacement deposits with faults as a measure of the favorableness of faults in controlling the location of porphyry Cu-Mo-W and disseminated Au-Ag deposits. The association of vein and replacement mines and prospects with faults was determined by calculating the normalized mine densities in successive zones of 0.2 km width for 1 km away from each class of fault. Based on the mine densities, there is no apparent correlation between mapped faults and known mines and prospects. The mine densities are 0.9 for occurrences within 1 km of all faults and 1.1 for occurrences more than 1 km from mapped faults. However, some classes of faults show a much stronger association with mines than other classes of faults, and the highest densities are associated with intersections of faults. The normalized density of mines within 1 km of unclassified faults is 1.3 and the mine density within 1 km of an intersection of normal and thrust faults is 1.9. The mine densities near faults show a sharp break at 0.6 km for most classes of faults; higher densities are found within 0 to 0.6 km than from 0.6 to 1.0 km away from faults. Based on the normalized mine densities, the fault submodel shown on map G consists of 1.2-km-wide zones (0.6 km on each side) along mapped faults. Because of the weak association between faults and mines, the maximum score for more favorable faults is 2 points. This score is assigned to normal and unclassified faults and to intersections of these faults with one another and with other classes of faults. A score of 1 is assigned to thrust, strike-slip, and oblique-slip faults, and intersections of these faults with one another. Parts of the quadrangle more than 0.6 km away from faults are assigned a score of 0 points.

Linear features submodel—The analysis of linear features demonstrated that some features are related to mineral occurrences. The degree of correlation was determined by calculating the normalized mine density of all metallic mines and prospects that are in zones along linear features and in circular areas that enclose intersections of linear features for 16 subdomains. The widths of zones and the 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 linear 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 that showed a close association with mines and prospects. Because the higher densities were associated with areas surrounding intersections of linear features, scores of 2 points were assigned to circular areas surrounding intersections and only 1 point was assigned to zones associated with favorable linear features. The resulting submodel for linear features is shown on map H.

COMPOSITE MINERAL RESOURCE ASSESSMENT MODEL FOR PORPHYRY AND STOCKWORK COPPER-MOLYBDENUM-TUNGSTEN DEPOSITS

The submodels for hydrothermal deposits, host rocks, alteration, faults, linear features, plutonic and volcanic rocks, geochemistry, and geophysics (maps D–K) and were combined using overlay analysis on the GIS. Because submodels of fault and linear features are both expressions of structure and are in part nonadditive, only maximum values from either submodel were added to other submodels. The sum of submodels yielded the total scores shown on map L. This map consists of polygons that are ranked between 0 and the highest score of 23. The mineral resource assessment map for porphyry Cu-Mo-W deposits (map A) groups polygons from map L into three classes of low (0–9 points), moderate (10–15 points), and high (16–23 points) potential for the occurrence of undiscovered porphyry Cu-Mo-W deposits. Also shown on map A are the boundaries of mining districts and geographic areas (see map D for names) and the locations of 10 porphyry Cu-Mo-W mines or prospects. Map A also locates areas of unknown potential where potential host rocks for porphyry Cu-Mo-W are covered by thick younger Tertiary and Quaternary rocks and surficial deposits. Relatively thin Quaternary surficial deposits such as alluvium and glacial deposits are not shown.

Map M is a map that shows the several combinations of submodels that determine final polygon scores in map L. For example, the point scores of areas in map L shown as H + P/V + C + G + F/L + M + A result from the combination of host rock, plutonic and volcanic rock, geochemistry, geophysics, fault, linear features, hydrothermal deposits, and alteration submodels, and other areas such as those shown as H + P/V result from the combination of host rock and plutonic-volcanic rock submodels.

COMPOSITE MINERAL RESOURCE ASSESSMENT MODEL FOR STOCKWORK AND DISSEMINATED GOLD-SILVER DEPOSITS

The submodels for host rocks (map E), alteration (map F), faults (map G), linear features (map H), gold-silver mineral occurrences (map N), volcanic rocks (map O), geochemistry (map P), and geophysics (map Q) were combined using overlay analysis on the GIS. Fault and linear features submodels were compared and only maximum values from either submodel were added to other submodels. The sums yielded the total scores shown on map R, which consists of polygons that are ranked between 0 and the highest score of 22. The mineral resource assessment map for disseminated Au-Ag deposits (map B) groups polygons from Map R into three classes of low (0–8 points), moderate (9–14 points), and high (15–22 points) potential for the occurrence of undiscovered disseminated Au-Ag deposits. Also on map B are the boundaries of mining districts and geographic areas (see map D for names), locations of known disseminated Au-Ag mines or prospects, and areas of unknown potential where potential host rocks for disseminated Au-Ag deposits are covered by thick post-mineralization Tertiary and Quaternary rocks and surficial deposits. Map S is a map that shows the combinations of submodels that determine final polygon scores in map R.

SUMMARY

The main purpose of this mineral resource assessment is to determine the potential for the occurrence of undiscovered resources in the study area. The mineral resource assessment maps A and B each show three levels of the mineral resource potential for porphyry Cu-Mo-W deposits (map A) and disseminated Au-Ag deposits (map B). On these maps, the areas shown as moderate and high potential are favorable for the occurrence of the respective deposit types. For map A, the areas of high potential cover 5.1 percent of the quadrangle and areas of moderate potential cover 23.9 percent of the quadrangle; 29.0 percent of the quadrangle is favorable for the occurrence of porphyry Cu-Mo-W deposits. For map B, the areas of high potential cover 2.3 percent of the quadrangle and areas of moderate potential cover 32.7 percent of the quadrangle; 35.0 percent of the quadrangle is favorable for the occurrence of disseminated Au-Ag deposits.

MINERAL RESOURCE POTENTIAL FOR PORPHYRY AND STOCKWORK DEPOSITS OF COPPER, MOLYBDENUM, AND TUNGSTEN

The largest areas of favorable potential for porphyry Cu-Mo-W deposits are found in the eastern part of the quadrangle, especially in the region of the Late Cretaceous Boulder batholith, the host for many mineral deposits. The largest areas of high potential are in the Elliston, Rimini, Basin, Wickes, Boulder, Amazon, Big Foot, Butte, and Pipestone districts and in parts of the South Boulder Mountains area. Large areas of high potential are also associated with plutonic rocks that are present along a northeasterly trend between Helena and Lincoln. These areas include most or large parts of the Scratchgravel Hills area and the Marysville and Stemple-Gould districts.

In the central and south-central parts of the quadrangle, favorable areas of moderate and high potential for porphyry Cu-Mo-W deposits are associated with districts and areas in the Flint Creek and Anaconda Ranges. The largest areas of high potential are in the Rose Mountain, Princeton, Philipsburg, Red Lion, and Georgetown districts, all of which are in the Flint Creek Range.

In the northwestern part of the quadrangle, areas of moderate and high potential are related to granodioritic stocks. Areas of high potential for porphyry Cu-Mo-W deposits are found in and adjacent to the Clinton, Coloma, and Garnet districts.

In the western and southwestern parts of the quadrangle, areas of mostly moderate potential and some areas of high potential are related to granodiorite and monzogranite stocks. The areas of high potential, mostly small, are in the Black Pine and Frog Pond Basin districts and in and adjacent to the Henderson Creek area.

MINERAL RESOURCE POTENTIAL FOR STOCKWORK AND DISSEMINATED DEPOSITS OF GOLD AND SILVER

The largest areas of favorable potential for the occurrence of disseminated Au-Ag deposits are in the eastern and southeastern parts of the quadrangle, mainly in well-known districts and in areas that were extensively hydrothermally altered and mineralized. The largest areas of high potential are in the Elliston, Rimini, Basin, Wickes, and Boulder districts, and they are associated with plutonic rocks of the Late Cretaceous Boulder batholith and Late Cretaceous and Eocene volcanic rocks. Areas of high potential are also in the Butte, Big Foot, and Orofino districts and parts of the South Boulder Mountains area.

In the remainder of the quadrangle, areas of favorable potential consist mainly of smaller and widely scattered areas of moderate potential. Many of the areas of moderate potential are associated with plutonic rocks, especially Late Cretaceous granodiorite stocks, but other areas of moderate potential appear to be unrelated to those stocks. In the northeast, small areas of high potential are found in and adjacent to the Scratchgravel Hills area and the Marysville and Austin districts. In the northwest part of the quadrangle, areas of high potential are in the Coloma and Garnet districts and along the northeastern boundary of the Clinton district. In the central and south-central parts of the quadrangle, areas of high potential are found (1) in and adjacent to the Black Pine district; (2) in the Philipsburg, Princeton, Red Lion, and Georgetown districts; (3) in and adjacent to the Lost Creek district; and (4) in the eastern part of the Anaconda Range area.

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APPENDIX

PROCEDURES FOR PROCESSING AND INTERPRETATION OF GEOCHEMICAL, GEOPHYSICAL, AND OTHER DATA

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 EROS Data Center where they were reformatted and entered into a relational database.

For many samples the analytical data were incomplete and needed adjustments before they could be processed by computer methods and interpreted. These data included "qualifiers" that indicated that (1) the concentration of one or more elements was outside of the limits of determination for the analytical method used, (2) there was interference, which prevented the determination of the concentration of element(s), or (3) 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 0–255), images were created of the interpolated geochemical surfaces. The dynamic range (maximum minus minimum concentrations) of the data was much greater than 255 for some elements and the data was compressed to fit the 0–255 range. To compress the data, the gridded chemical concentrations for each element were transformed to logarithms. This operation smoothed each geochemical surface. The images created by this transformation are probably more accurate representations of the distributions of the chemical concentrations because the populations of most minor and trace elements have approximately lognormal distributions.

The percentage of data that is reported (unqualified) compared with that substituted (qualified) 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 substitutions were judged to be more credible than those from data with significant numbers of replaced concentrations. 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 submodels for porphyry Cu-Mo-W and disseminated Au-Ag deposits are shown in table 3.

Geochemical anomaly thresholds (table 3), which represent the highest background concentrations, were selected for each of the single-element geochemical surfaces based on statistical distributions (histograms and percentiles) of the data, consideration of average crustal abundances of elements (Rose and others, 1979), and interactive processing of the geochemical data using the GIS. An anomaly map was constructed for each element by reassigning a gray level to pixels with brightness values corresponding to chemical concentrations above the threshold and black to those at or below the threshold.

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 with variable spacing. Anomalies were computed by subtracting the International Geomagnetic Reference Field (IGRF) 1983.65 from the adjusted total-field data. The IGRF is a reference field updated to the time of the survey and corrected for flight elevation. The resulting anomaly data 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 which had been shown (Hassemer and Hanna, 1982) to exhibit inconsistencies relative to one another. This comparison of data sets served to verify the existence and location of several significant anomalies.

Although gravity anomaly data were not used directly to draw lines outlining inferred plutonic rocks in the subsurface, the gravity data were used in some places to interpret the presence of plutonic rocks. Some gravity lows may indicate the presence of plutonic rocks that intruded higher-density country rock or some gravity highs may indicate plutonic rocks that are flanked and (or) covered by low-density Tertiary and Quaternary sedimentary deposits. The gravity data consisted of 2,325 observations in and directly adjacent to the quadrangle (Hassemer, 1984a, 1984b, 1986), of which 1,900 observations 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 used to outline areas of inferred plutonic rocks in the subsurface required that the flight-line aeromagnetic data be processed, projected, and gridded. The data were 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 to attenuate unwanted edge effects that will result from further mathematical operations on the grid. This grid enlargement was accomplished by merging similarly projected and gridded data sets directly 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 were generated by mathematical operations on the enlarged grid and these lines outlined regions of relatively thick occurrences of plutonic rocks. 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 grid operators used to generate these sets of lines are types of two-dimensional wave-number filters that 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 the 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 derivation of the first set of lines involved four computational steps. First, the total-field data were transformed to pseudogravity anomalies by calculating the gravity field from magnetic field measurements using 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. Third, the resulting grid of these gradient amplitudes was automatically contoured and elongated highs were selected. Last, crest lines atop the most conspicuous elongate highs, called "pseudogravity gradient crests," were drawn automatically by computer.

Table 3.--*Sample types, analytical methods, and anomaly thresholds used for the mineral resource assessment of porphyry/stockwork deposits of copper, molybdenum, and tungsten, and stockwork/disseminated deposits of gold and silver in the Butte 1° X 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
B	Concentrate	Spectrographic	300 ppm
	Sediment	Spectrographic	200 ppm
Ba	Concentrate	Spectrographic	7,000 ppm
	Sediment	Spectrographic	1,500 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	3,000 ppm
	Sediment	Spectrographic	2,000 ppm
Mo	Concentrate	Spectrographic	30 ppm
	Sediment	Spectrographic	10 ppm
Pb	Concentrate	Spectrographic	300 ppm
	Sediment	Spectrographic	200 ppm
	Sediment	Atomic absorption	150 ppm
Sb	Concentrate	Spectrographic	200 ppm
	Sediment	Atomic absorption	15 ppm
Sn	Concentrate	Spectrographic	50 ppm
W	Concentrate	Spectrographic	50 ppm
Zn	Concentrate	Spectrographic	500 ppm
	Sediment	Spectrographic	300 ppm
	Sediment	Atomic absorption	500 ppm

The second set of lines was derived by transforming the total-field magnetic data 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. The data that have been recorded in the earth's inclined magnetic field are converted to a vertical magnetic field. The transformation removes anomaly asymmetry caused by inclination and it locates anomalies directly above the causative bodies. After the reduced-to-pole anomalies had been automatically contoured, the zero contour lines tended to outline many exposures of plutonic rocks. This relation is not generally expected; in many places, in the Butte data, these zeros-of-pseudogravity anomalies correspond presumably to inflection points where the curvature of the anomalies changes algebraic sign. The second set of lines thus consists of zero contour lines of reduced-to-pole anomalies.

Computation of the second vertical derivatives of reduced-to-pole anomalies and contouring of these derivatives resulted in a third set of lines. 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.

A final set of lines that show the outlines of inferred magnetic plutonic rock was generated by integrating the previously discussed three sets of lines. This final set consists of (1) a combination of the first and second sets of lines where they approximately coincide and (2) a combination of the second and third sets of lines where the first and second sets differ. The final set of lines was then compared with the generalized geology map (Wallace, 1987) and Bouguer gravity anomalies, and adjustments were made so that the interpretative map showing the outlines of mapped and inferred magnetic plutonic rocks conformed to the geology and gravity maps.

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 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 on thematic maps and for processing data sets that require representation as points, lines, or polygons. The vector subsystem used in this investigation is ARC. Both RIM and INFO software are designed to process tabular data and to provide powerful techniques to edit and combine tabular data and to prepare subsets of tabular data. Although used primarily to process 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. The raster subsystem 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 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 were entered into the raster subsystem and previously digitized information was entered into the vector subsystem. Geologic structures (faults and axial traces of folds) 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.

I. Maps

Maps used for the mineral resource assessment included (1) a generalized geologic map that contained 38 rock units and 7 types of structures, (2) a map that showed the boundaries of 70 mining districts and other areas containing mines and prospects, (3) a map that showed the outlines of principal magnetic rock bodies (plutonic rocks) exposed at the surface and inferred in the subsurface as interpreted from geophysical and geological map data, (4) a map that showed areas of limonitic alteration interpreted from Landsat data, and (5) a map that showed subdomains of linear features interpreted from Landsat and SLAR data. The line and polygon data from these maps were digitized using ARC/INFO. Each feature was numerically encoded with a unique identifier that could be used to access it as an individual spatial entity as well as with a class value or attribute that could be used to access it and all other features of the same type. The identifier 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 define units that were essential to resource assessment. 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.

II. Tables

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

The geochemistry of stream sediment, 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 maps in raster form. In this operation the analytical data were subjected to a minimum-curvature surface-generation algorithm (Briggs, 1974; Webring, 1981) to produce maps for each required element in raster form.

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

III. Gridded data

The only data in gridded format used for 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.

IV. 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 digital files based on ranges of azimuth. The data were reformatted to generate a geographic-coordinate file and an attribute file which were entered into the vector subsystem. After reprojecting into Transverse Mercator coordinates, all linear features were converted to raster form.

V. Data analysis

The development and application of procedures for the preparation of submodel and assessment maps (maps A–S) were accomplished primarily in the raster subsystem (IDIMS) of the GIS. All data sets in the GIS were reformatted as gridded arrays containing 559 rows and 775 columns. Each cell in the arrays represented 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 by 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.

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