MAP I-1803-G

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

MAPS SHOWING MINERAL RESOURCE ASSESSMENT FOR COPPER AND MOLYBDENUM IN PORPHYRY AND STOCKWORK DEPOSITS AND FOR TUNGSTEN, IRON, GOLD, COPPER, AND SILVER IN SKARN DEPOSITS, DILLON 1° × 2° QUADRANGLE, IDAHO AND MONTANA

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PAMPHLET

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CUSMAP

This report is one of a series of reports that present, chiefly with maps at a scale of 1:250,000 and 1:500,000, various aspects of the geology, geochemistry, geophysics, and mineral resources of the Dillon 1°×2° quadrangle, southwestern Montana and east-central Idaho (fig. 1). These studies were made largely under the Conterminous United States Mineral Assessment Program (CUSMAP), the primary purpose of which is to determine the mineral resource potential of selected 1°×2° quadrangles by means of a multidisciplinary approach. CUSMAP is intended to provide information on mineral resources to assist Federal, state, and local governments in formulating minerals policy and land-use policy and to produce sound scientific data that may be of value to private industry and the general public in mineral exploration and development.

INTRODUCTION

This report is one of several in the series that assess the mineral resources of the Dillon quadrangle. For the purpose of the assessment, mineral deposits in the quadrangle that are either known or suspected from a knowledge of the geologic setting have been grouped into 30 deposit types on the basis of mineralogy, commodity, or structural or depositional setting. The emphasis in these assessment reports is on metallic minerals, but some important nonmetallic minerals will also be assessed. Fossil fuels are beyond the scope of this investigation; phosphate and uranium have been investigated previously (Swanson, 1970; Wodzicki and Krason, 1981); and certain nonmetallic minerals, including bulk commodities such as sand and gravel, are in large supply and thus not considered.

The mineral resource assessment discussed in this report considers two deposit types: (1) porphyry or stockwork deposits of copper and molybdenum (referred to generally in this report as porphyry deposits) and (2) skarn deposits of tungsten, iron, gold, copper, and silver. Combining copper and molybenum porphyry deposits into a single deposit type is believed necessary for this purpose mainly because the two metals are found together in most deposits in the quadrangle, a geochemical signature unique to each has not been determined, and the significant petrologic characteristics of many associated plutons are not well known, especially characteristics of subsurface plutons whose presence is inferred from geophysical data.

In assessing mineral resources, we have adopted a general philosophy similar to that of Harrison and others (1986). We attempt to identify those parts of the quadrangle that are favorable for the occurrence of mineral resources. We do not attempt to locate specific exploration targets nor to determine the quantity of reserves or resources present.

GEOLOGIC SETTING

The Dillon quadrangle comprises two major tectonic provinces: the Montana thrust belt occupies approximately the western two-thirds of the quadrangle, and the North American craton occupies the eastern one-third (fig. 2). Rocks of both provinces are similar stratigraphically and temporally and include crystalline basement, mainly of Archean age; sedimentary strata of Proterozoic, Paleozoic, and Mesozoic age; igneous rocks, both intrusive and

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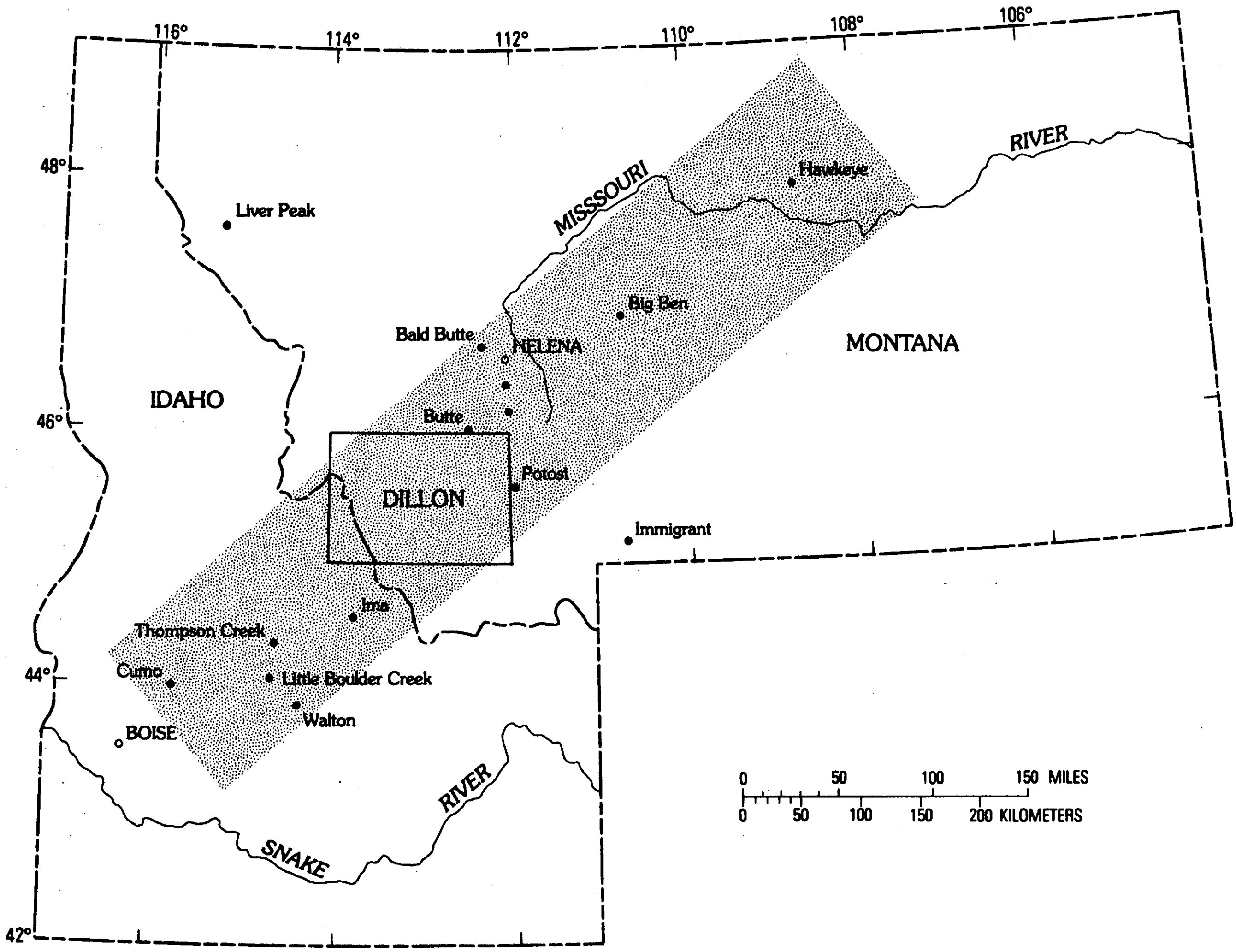

Figure 1. Index map showing location of Dillon 1°×2° quadrangle and Idaho-Montana porphyry belt and some molybdenum and (or) copper porphyry deposits (dots) outside the Dillon quadrangle. From Armstrong and others (1978) and Rostad (1978).

extrusive, mostly of late Mesozoic and early Cenozoic age; and basin-fill, glacial, and alluvial deposits of Cenozoic age.

The 1:250,000-scale geologic map shown on maps S and T is a preliminary map of the quadrangle by Ruppel and others (1983) and because of the scale does not show all of the geologic features mentioned in this report. The preliminary map was generalized, and a computer plot of the generalized map is shown as maps A and J to illustrate the digitized geology as it was used in the mineral resource assessment.

The crystalline basement is widely exposed on the craton, and, where its age has been determined, it is Archean, except for Proterozoic mafic dikes (James and Hedge, 1980). The age of crystalline basement in the Highland Mountains is not known. In the thrust belt, the basement is exposed only in the core of the Armstead anticline in the south-central part of the quadrangle, where it is probably Archean, and in small fault blocks in the northeastern Pioneer Mountains and on Bloody Dick Creek along the south boundary of the quadrangle, where U/Pb and Rb/Sr age-determination techniques indicate that the rocks are Early Proterozoic (Arth and others, 1986; R.E. Zartman, written commun., 1984). All three of these exposed masses within the thrust belt may be allochthonous.

Middle Proterozoic rocks, primarily the Belt Supergroup and Lemhi Group, are exposed mainly in the thrust belt. They are in fault contact with the crystalline basement, and hence their depositional bases are not exposed. Proterozoic intrusive rocks, in addition to the mafic dikes in the craton, are represented by granite plutons (Evans and Zartman, 1981) that intruded the Yellowjacket Formation in the Salmon River Mountains along the west side of the quadrangle.

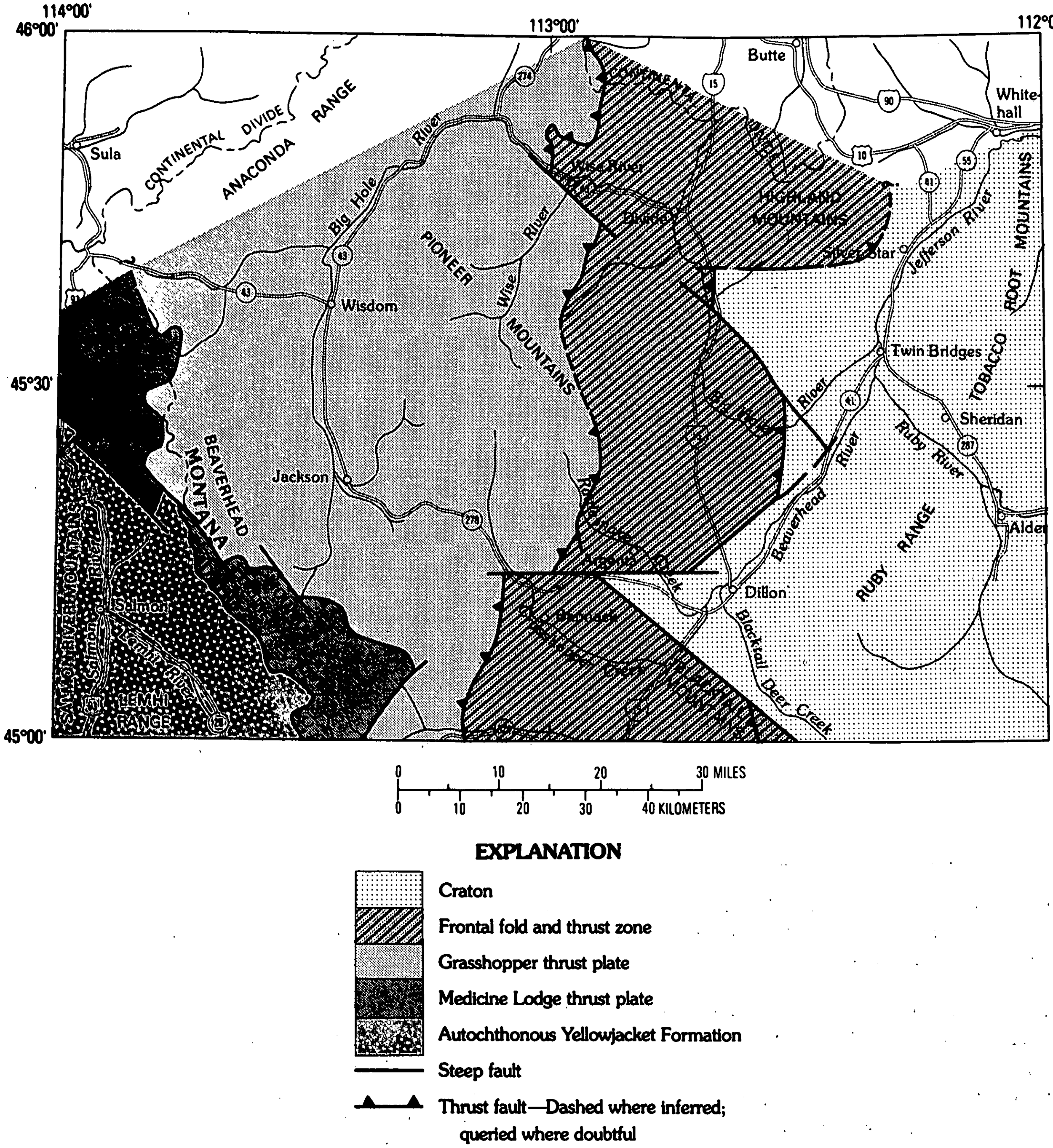

Figure 2. Tectonic province map of Dillon 1°×2° quadrangle, Idaho and Montana. Modified from Ruppel and Lopez (1984). Igneous rocks and surficial deposits not shown.

The Paleozoic and Mesozoic strata are widely distributed on the craton part of the quadrangle, where the basal unit (the Middle Cambrian Flathead Sandstone nearly everyplace) is in depositional contact with the crystalline basement, and in the eastern part of the thrust belt, where their base is in depositional contact with Middle Proterozoic strata. Changes in sedimentary facies from the craton westward into the thrust belt, especially of some of the marine Paleozoic units, are partly the result of telescoping by the thrusts.

Phanerozoic igneous rocks in the quadrangle (named according to the classification of Streckeisen, 1976) are of Late Cretaceous and Tertiary age. The Phanerozoic plutons are mainly of intermediate composition but range from hornblende gabbro, through granodiorite and monzogranite, to biotite-muscovite granite, and they have calc-alkalic affinities. They intrude all older major groups of rocks, especially in the north half of the quadrangle. The only part of the quadrangle without these plutons is the southeastern 20 percent. Cretaceous volcanic rocks are associated with the Cretaceous plutons locally in the northeastern and central parts of the quadrangle. Volcanic rocks of Tertiary age are present in isolated patches mainly in a north-trending belt through the middle of the quadrangle but also in the southwest corner, along the west edge, and as small masses in many other parts of the quadrangle.

Tertiary deposits that fill the basins and locally cap upland areas are commonly from less than one hundred to many thousands of feet thick and contain a major pyroclastic component (especially in tuffaceous mudstone); locally derived, fluvially deposited, fine to coarse epiclastic detritus; and minor lava flows.

The thrust belt has been divided into two major plates (fig. 2), the Medicine Lodge plate to the west and the Grasshopper plate to the east (Ruppel and Lopez, 1984). The eastern part of the thrust belt is called the frontal fold and thrust zone (Ruppel and Lopez, 1984), a gradational zone that has characteristics of both the thrust belt and craton. West of the Medicine Lodge plate, in the southwestern part of the quadrangle, the bedrock is largely the Middle Proterozoic Yellowjacket Formation, which is interpreted by Ruppel (1978) and Ruppel and Lopez (1984) to be autochthonous. Although sedimentary rocks as young as Late Cretaceous are involved in thrusting, all Mesozoic plutons, so far as known, are younger than thrusting.

High-angle faults are widespread in all parts of the quadrangle, and many of them belong to one or the other of two major groups. A northwest-trending group is known in the Archean terrane as well as in younger rocks; these have had movement at various times from at least as early as the Proterozoic to as late as Quaternary. Faults belonging to a north- and northeast-trending group commonly are located along and within Tertiary basins; these faults moved mainly in middle to late Tertiary time, thereby delineating the existing mountain ranges.

INTRUSIVE IGNEOUS ROCKS

Porphyry and skarn deposits in the quadrangle are associated with plutons of several batholithic or plutonic suites (maps B and K). The Boulder, Pioneer, Idaho, and Tobacco Root batholiths are the predominant suites, the Anaconda plutonic suite is prominent in the Anaconda Range (Elliott and others, 1985), and small outlying intrusive bodies, whose relationship to the batholithic suites is uncertain, are also present.

Approximately one-third of the Boulder batholith is in the Dillon quadrangle, the rest extending north and northeast of the quadrangle. The assignment of some plutons to the Pioneer or to the Boulder batholith is not clear-cut since they seem to overlap spatially in the region around Divide, Mont. Furthermore, age determinations suggest a considerable, and perhaps complete, overlap of the Boulder and Pioneer batholiths in time of emplacement, although additional modern studies of the Boulder batholith are needed. Arth and others (1986) suggest that differences in strontium isotopes in several plutons distinguish the two batholiths. Butte Quartz Monzonite of the Boulder batholith is the pre-eminent large pluton, comparable to, though considerably larger than, the Uphill Creek Granodiorite of the Pioneer batholith. The range in age of the Boulder batholith is about 70–80 Ma (Smedes and others, 1988) and, in general, the more mafic rocks are older. The range in composition among rocks of the Boulder batholith is comparable to that in the Pioneer batholith (Lambe, 1981). One difference between the two is that alaskite, aplite, and pegmatite are much more abundant in the Boulder batholith. Another difference is that some smaller satellitic bodies surrounding the Boulder batholith are low in silica, such as the hypersthene-and olivine-bearing monzonite in the Ringing Rocks stock and the olivine-bearing lamprophyre in the same general region along the east side of the batholith. No biotite-muscovite granite is present in the Boulder batholith, except that muscovite is locally present in miarolitic and pegmatitic parts of the Donald plutons; these phases also contain molybdenite. Alkali and trace-element abundances indicate that the plutons of the batholith represent two magma series: a sodic series in which $Na_2O > 3.5$ percent and $K_2O < 3.5$ percent and a "main" series in which $Na_2O < 3.5$ percent and $K_2O > 3.5$ percent (Tilling, 1973). By this division, the Butte Quartz Monzonite, Homestake pluton, alaskite, and, tentatively, Burton Park plutons constitute the main series; and Rader Creek, Climax Gulch, Donald, Hell Canyon, Moose Creek, and Moosetown plutons constitute the sodic series.

The Pioneer batholith, like the Boulder batholith, consists of one major pluton (Uphill Creek Granodiorite) surrounded or intruded by satellitic plutons. As generally understood, the Pioneer batholith includes all intrusive rocks in the Pioneer Mountains except for some small mafic and silicic Tertiary dikes. In addition, small stocks as far south as the Bannack mining district can be considered to be parts of the Pioneer batholith, although it is uncertain whether a mineralized subvolcanic plug east of Bannack should also be included. Chemically, according to Snee (1982), the Pioneer batholith rocks tend to be similar to the sodic series of Tilling (1973). Snee (1982) has shown that, in general, the more mafic rocks are older and the more silicic rocks are younger. Snee (1982) also concludes that intrusion ranged from about 80 to 65 Ma and that plutonism was nearly continuous during this time. Hornblende gabbro and minor hornblendite at about 80 Ma are the oldest and most mafic, except for an inclusion of ultramafic rock on the east side of the batholith, whose age and relation to the batholith are unknown (Zen, 1988). The most voluminous rock types of the Pioneer batholith are an intermediate-age group of plutons consisting of biotite-hornblende tonalite and granodiorite, which are mostly about 73–78 Ma. The youngest and most silicic plutons are biotite monzogranite, biotite-muscovite monzogranite and granodiorite, and porphyritic hypabyssal rhyodacite to rhyolite; these range from about 65 to 72 Ma. Molybdenum stockwork occurrences are confined to the youngest group of the more silicic plutons, but a copper porphyry prospect in a subvolcanic plug is compositionally similar to the intermediate-age group. Skarn deposits are also associated with the intermediate-age group.

Plutonic rocks in the northwest corner of the quadrangle have been assigned to the Idaho batholith by N.J. Desmarais (oral commun., 1980), who also referred (1983) to these plutons as the "Chief Joseph plutonic suite." These rocks range from foliated granodiorite of Late Cretaceous age (80 Ma) to hypabyssal dike rocks and lava flows of Eocene age (43 Ma).

The Tobacco Root batholith, in the Tobacco Root Mountains, is much smaller than either the Pioneer or Boulder batholiths; it includes satellitic plugs, stocks, dikes, and sills in addition to the large central pluton. The central pluton straddles the eastern quadrangle boundary, and most of it is outside the quadrangle. It is zoned from hornblende tonalite and diorite near the margin to biotite granite at the core, but only the mafic border phases are in the Dillon quadrangle (Smith, 1970). Small satellitic bodies include quartz monzonite, granodiorite, syenite, lamprophyre, and intrusive breccia (Johns, 1961; Burger, 1967; O'Neill, 1983a). Porphyry mineralization that affected the mafic marginal facies of the main batholith is spatially associated with younger quartz monzonite dikes (O'Neill and others, 1983).

Plutonic rocks in the Anaconda Range and northern Beaverhead Mountains, in the northwestern part of the quadrangle, range widely in age and composition (Desmarais, 1983; Elliott and others, 1985). Some of the oldest plutons were intruded syntectonically into Middle Proterozoic sedimentary rock that was regionally metamorphosed to high grade; these plutons are foliated and were evidently emplaced at considerable depth. Younger plutons that are not foliated include a batholith of biotite-muscovite granodiorite that crops out along the southeast flank of the Anaconda Range for nearly its full length and extends southwest into the Beaverhead Mountains. Smaller plutons are both older and younger than the biotite-muscovite granodiorite and are mostly equigranular to porphyritic monzogranite and granodiorite stocks and dikes that contain hornblende and biotite or biotite alone. Among the youngest intrusive rocks are a swarm of northeast-trending silicic dikes that may be related in age to the Eocene Challis Volcanics; these are porphyritic and have an aphanatic to very fine grained groundmass, indicating a hypabyssal environment. Several of the plutons in the Anaconda Range have been mineralized pervasively, and prospects and occurrences of molybdenum stockwork deposits are described by Elliott and others (1985). Although the Eocene dike swarm shows little evidence of mineralization, an intrusive center of about the same age near North Fork, Mont., has been pervasively mineralized with copper and molybdenum (Bunning and Burnet, 1981).

Farther south in the Beaverhead Mountains, the Carmen Creek stock is almost the only exposed intrusive body except for scattered mafic to intermediate dikes. Geophysical anomalies (mainly magnetic) associated with most of the Beaverhead Mountains and a contiguous area eastward from the Beaverheads into the Big Hole Divide area have been interpreted by Hanna and others (unpub. data, 1991) to suggest subsurface plutons. A small stock near Bloody Dick Peak, in the Big Hole Divide area, overlaps the geophysical anomalies and is interpreted by Hanna and others (unpub. data, 1991) as the exposed part of a large subsurface plutonic mass.

For the purpose of assessing mineral resources in porphyry and skarn deposits, the numerous individual plutons in the quadrangle have been classified primarily by composition and age into eight groups (maps B and K) regardless of any association in a batholithic or plutonic suite.

PROCEDURE

The procedure used in the assessment of the Dillon quadrangle for mineral resources in porphyry and skarn deposits is similar to one outlined in Shawe (1981) and is a modification of those used by Harrison and others (1986), Pratt, Erickson, and others (1984), and Pratt, Walker, and others (1984). Very generally, the procedure calls for construction of a deposit model for each deposit type based on currently accepted concepts, background knowledge, and available data. Then the characteristics of the deposit type in the model are compared with the same characteristics in the study area to determine the degree of fit, and hence the favorability, of the area for the occurrence of deposits of that type. In its simplest form, the model is a list of characteristics and relationships—referred to here as "favorability criteria" (Pratt, Erickson, and others, 1984)—that are known or suspected to be associated with the deposit type. Models of porphyry copper deposits (Lowell and Guilbert, 1970; Cox, 1986b), low-fluorine molybdenum deposits (Theodore, 1986), and skarn deposits (Elliott, 1981; Cox, 1986a) provide critical details necessary for construction of deposit models for the Dillon quadrangle. In addition, a model for molybdenum deposits based on the Liver Peak deposit, about 130 mi northwest of the Dillon quadrangle (Harrison and others, 1986) provided important information. The criteria used here are those that can be applied to resource assessment at a scale of 1:250,000. They are adapted from compilations such as Theodore (1986), Harrison and others (1986), and Elliott (1981) and from published and unpublished information on the deposits listed in table 1 and in Loen and Pearson (1989).

The steps involved in the procedure are summarized as follows; these steps are listed in approximately the sequence they were performed, although some steps overlapped in time:

1. Compile existing data and collect new data on geology, geochemistry, aeromagnetics, gravity, remote sensing, and mineral deposits.
2. On the basis of our understanding of the geologic environment and mining history, determine which mineral deposit types are likely to be present in the area and define the type as closely as possible by means of current concepts and knowledge and the types and scale of data available.
3. For each deposit type, prepare a tentative list of favorability criteria, which constitutes a preliminary deposit model.
4. For purposes of computer processing, digitize the geologic map, compile other data sets in digital form, and enter the digital data into a multilayered, computer-based geographic information system (GIS).
5. Using the GIS, compare the spatial association of mines and prospects with the appropriate parts of the database to help determine the relative importance of each criterion in the model. This step assists in assigning relative scores to the criteria; however, with only 22 porphyry occurrences and 40 skarn deposits and occurrences to compare, a statistically valid correlation of deposits with favorability criteria may not be possible.
6. Subjectively assign relative scores to each favorability criterion, using relationships derived from step 5 and other subjective attributes and relationships determined from deposit models.
7. Sum the scores assigned to all favorability criteria so that each grid cell in the raster processing system of the GIS has a total score that represents its relative favorability for the deposit type being considered. Group the summed scores and classify the groups as having low, moderate, or high mineral resource potential. Plot the grouped scores to show graphically the areal distribution of these categories of resource potential.
8. As appropriate, discuss and evaluate the areas of moderate and high favorability.

DATABASE

Seven main data sets were employed in the resource assessment. These were compiled from pre-existing data, reports, maps, and other compilations and from new data gathered during the field phase of the Dillon project. Pre-existing data include geologic mapping, stream-sediment geochemistry, various gravity and aeromagnetic surveys, Landsat Multispectral Scanner (MSS) and side-looking radar (SLAR) images, and descriptions and production statistics of mines and prospects. Newly acquired data include geologic maps, data on mines and prospects, some rock and stream-sediment geochemistry, and gravity and aeromagnetic surveys for parts of the quadrangle. Much of the information was obtained since 1977 in connection with mineral resource assessments of National Forest Wildernesses and wilderness study areas made by the U.S. Geological Survey and U.S. Bureau of Mines, specifically the Anaconda-Pintlar Wilderness (Elliott and others, 1985), Middle Mountain–Tobacco Root Roadless Area (O'Neill, 1983a, 1983b; O'Neill and others, 1983), West Pioneer Mountains Wilderness Study Area (Berger and others, 1983), and eastern Pioneer Mountains area (Pearson and others, 1988; Pearson and Zen, 1985).

GEOLOGY

A preliminary geologic map was prepared at a scale of 1:250,000 by compilation of numerous sources supplemented and modified by field checking and reconnaissance mapping (mainly from 1978 to 1983) (Ruppel and others, 1983). The preliminary map was generalized, the emphasis being on geologic units and structures thought to be important for the mineral resource assessment (map A).

GEOCHEMISTRY

The regional geochemical component of the Dillon quadrangle mineral resource assessmment consists of analytical data on 1,600 stream-sediment samples and the sample-locality data for those samples. The stream-sediment sampling was done under the National Uranium Resource Evaluation (NURE) program of the U.S. Department of Energy (Broxton, 1979). The NURE analytical results were supplemented by re-analyzing splits of the 1,600 samples for As, Sb, Zn, Mo, Ca, Mg, and Zr in the laboratories of the U.S. Geological Survey.

In order to determine the suites of elements in the regional stream-sediment database that may best reflect the presence of porphyry and skarn deposits, approximately 2,500 mineralized rock samples were collected from three general deposit types in the quadrangle: (1) vein and replacement deposits of base and precious metals, (2) porphyry copper and molybdenum deposits, and (3) tungsten and base- and precious-metal skarn deposits. These samples were analyzed in laboratories of the U.S. Geological Survey, and the analytical data are given in Leatham-Goldfarb and others (1986). A discriminant-function analysis of the analytical data on the 2,500 rock samples was used to test the validity of the threefold deposit-type classification and to determine if certain suites of elements could be used to discriminate among the three deposit types (B.R. Berger and S. Leatham-Goldfarb, unpub. data, 1985). The discriminant-function analysis indicates that the suite barium-lanthanum-molybdenum-strontium is indicative of porphyry deposits, and the suite iron-manganese-scandium-vanadium is indicative of skarn deposits. Elements such as copper that might be expected in the porphyry suite are not included in the suite because they are components of other deposit types as well. Elements such as tungsten are not included in the skarn suite because tungsten was detected in so few samples that it was not amenable to statistical treatment. The element suites thus determined on mineralized rock samples were then used to determine anomalous stream-sediment samples. This approach is considered valid because many stream-sediment samples from drainage basins that are known to contain porphyry and skarn mineral occurrences are anomalous in the respective suites. Anomalous values of each element in the element suites were defined as those values that are greater than the geometric mean of the analytical values.

GEOPHYSICS

Magnetic and gravity anomaly data acquired and compiled throughout the quadrangle are regional in scale and were used to delineate occurrences of magnetic plutonic rocks (maps F and O). In this study, filtered magnetic anomaly maps of gridded data were used to derive map boundaries of these magnetic rocks through the following steps:

1. Data from six local surveys and one regional survey, all having diverse flight specifications, were merged by analytical continuation and smoothing techniques into a single gridded data set. The data and interpretations were extended 15 minutes of latitude and longitude beyond the quadrangle boundaries to reduce edge effects.
2. A pseudogravity gradient map was computed. This map illustrates the amplitude of the horizontal gradient of the aeromagnetic data. Elongate crests of the pseudogravity anomalies were contoured.
3. A reduced-to-pole map was computed. On this map, effects of the inclination of the Earth's magnetic field were removed.
4. Zero-contour lines of a bandpass-filtered second-vertical-derivative map computed from the reduced-to-pole map were plotted.
5. Regions of areal overlap of closed axial traces of crests in step 2 with closed zero-contour lines in step 4 were taken as the location of significant bodies of magnetic rocks; these bodies are assumed to be in part steep sided.

The boundary lines of these subsurface bodies were drawn objectively, but whether anomaly sources are Precambrian metamorphic rocks or Phanerozoic mafic to intermediate igneous rocks is commonly unknown. Gravity anomaly values may help to distinguish these two rock groups because gravity anomalies tend to be higher over the more dense metamorphic rocks. However, where high-density metamorphic rocks are overlain by lower density sedimentary rocks, the superposition of the metamorphic rock gravity high and the sedimentary rock gravity low may result in an ambiguous anomaly that is intermediate in value.

In the Dillon quadrangle, the combined gravity and magnetic anomaly data suggest that regions in the southeastern part of the quadrangle, covering much of the Ruby Range, Beaverhead River valley, Tobacco Root Mountains, and an area extending southward from the Tobacco Root Mountains, are underlain in large part by the Archean metamorphic rock complex. However, in and near the Tobacco Root Mountains, Cretaceous plutonic rocks of intermediate composition intrude mafic to ultramafic Precambrian metamorphic rocks, and these two groups cannot be distinguished on the basis of their magnetic characteristics. The ability to distinguish between these rock types requires higher resolution geophysical techniques or drilling.

REMOTE-SENSING DATA

Three sets of remote-sensing data were available in the analysis of the Dillon quadrangle (interpreted lineaments and linear features (Purdy and Rowan, 1990) and hydrothermally altered rocks (Segal and Rowan, 1989)), but only the data on altered rocks were used in this assessment of porphyry and skarn deposits. There is no discernible spatial association between linear features and known skarn and porphyry deposits in the quadrangle. The distribution of hydrothermally altered rocks was determined from MSS images that had been digitally processed to enhance the diagnostic reflectance characteristics of limonite. Those limonite anomalies thus detected were evaluated in the field to determine which were formed as a result of hydrothermal alteration.

MINES AND PROSPECTS

Many mines throughout the quadrangle were examined. The geologic setting, character of mineralization, and deposit type were determined where possible, and samples were collected for analysis. These newly acquired data were compiled together with information from the U.S. Geological Survey's Mineral Resource Data System (MRDS) (previously known as the Computerized Resource Information Bank (CRIB)). Because much of the MRDS file was derived from old reports that did not reflect modern geologic concepts or terminology, the contents of the file were checked against original sources and updated where possible. The MRDS format was then recast by Loen and Pearson (1989) into a simplified tabular format that contained information expected to be of use in the resource assessment. Of the 829 mines, prospects, and significant mineral occurrences described in the quadrangle, 22 are classified as porphyry and 40 as skarn.

THE GEOGRAPHIC INFORMATION SYSTEM

A computer-based geographic information system (GIS) was used to develop and apply the deposit models, evaluate the resultant mineral resource assessment, and prepare the mineral resource assessment maps. A GIS provides a means of comparing and inter-relating various kinds of data that can be referenced geographically. An analogy to GIS processing may be made with a stack of transparent maps of the same area that are superimposed and registered, each map showing a particular kind of data. For example, one map might show surface geology (geologic map) and another map might show location of mines and prospects. If one wished to compare visually the distribution of mines and prospects of a certain mineral deposit type with the distribution of a certain geologic map unit, each of these subsets of data would have to be made readily identifiable, and only a qualitative estimate of spatial relationships could generally be made. However, when the data are digitized and entered into a GIS, spatial relationships between any two (or more) data sets can be compared quantitatively throughout the map area by the use of arithmetic and other statistical operations. Thus, the effects of two or more data sets at any point can be considered simultaneously. For some comparisons of two or three simple data sets, the GIS may be superfluous, but where the number of data sets is large and the variables are categorically and topologically complex, the manual or visual approach can treat the analysis objectively and uniformly only with the expenditure of large amounts of time, if at all. The manual approach to CUSMAP mineral assessment was used by Pratt, Erickson, and others (1984) and by Harrison and others (1986), but the potential advantages of the GIS technique were demonstrated by Pratt, Walker, and others (1984). Some technical aspects of the GIS are described in the following paragraphs.

The GIS used in this study consists of (1) three main subsystems, (2) interfaces between the subsystems, and (3) capabilities for a variety of manipulative, mathematical, and plotting functions. The three subsystems are a relational database management subsystem (RDBMS), a vector subsystem, and a raster subsystem. All three are needed because the diverse data, as described in the preceding section, are in tabular, gridded, and map form, each of which requires different treatment. The subsystems provide capabilities for data entry, data manipulation, surface generation, contouring, statistical analysis, and the generation of tabular, statistical, and cartographic products. The interfaces provide the additional capabilities to edit, reformat, and transfer data 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. The data types used in this study include maps, text, tables, gridded data, and previously digitized information. Initially, all data were entered into the RDBMS, into the vector subsystem, or into both. After editing and reformatting, the data were transferred to the raster subsystem, which was used for model development and resource assessment.

The RDBMS deals with tabular data and provides powerful techniques for editing, combining, and subsetting tables of categorical, analytical, and spatial attributes. RIM (Relational Information Manager) and INFO were the RDBMS packages used.

The vector subsystem treats data as either points, lines, or polygons (areas bounded by lines) and maintains information on the topologic relationships among them. This subsystem is suitable for very detailed analysis of spatial data, for processing data sets that include features described by multiple attributes, and for processing composite data sets that include features described spatially as points, lines, or polygons. The vector subsystem used in this investigation is ARC/INFO.

The raster subsystem, which treats all data as a matrix of geographically referenced grid cells, is much faster than the vector subsystem for many types of analysis. It is useful for processing continuous data represented as gridded surfaces. Spatial resolution, once the grid-cell size has been selected, is fixed for any given surface. The raster subsystem used is IDIMS (Interactive Digital Image Manipulation System).

All spatial data sets must be geographically coregistered in both coordinate units and map projection. The base map used for data compilation is the Dillon 1°×2° quadrangle (1955 edition, revised 1977), which uses the Transverse

Mercator projection. Hence all data sets were transformed to this projection. Important parameters include a central meridian of 113° and a scale factor of 0.9996. Other parameters were a latitude of origin of 45° and no false easting or northing. The 1927 North American Datum, based on the Clarke 1866 ellipsoid (Snyder, 1982, p. 15–16), was used throughout. To minimize the potential error in digitally coregistering maps, all projection changes were performed using the General Cartographic Transformation Package (GCTP), which is incorporated in the vector subsystem and the RDBMS but not in the raster subsystem.

Developing and applying the deposit model was accomplished primarily in the raster-based subsystem (IDIMS) of the GIS. All resident data sets within the GIS were reformatted as grid-cell arrays containing 559 rows and 789 columns. Each coregistered grid cell represents a ground area of 200 × 200 m. Cell size was selected on the basis of 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 126 m. The minimum resolvable line (two points) and polygon (three points) adds to the overall locational error, and co-locating points during the overlay process multiplies the errors. Thus, a cell size of 200 × 200 m reflects a compromise between accurate feature location and reasonable detail. Furthermore, computer processing time becomes inordinately long as array size is increased by decreasing the cell size.

Various forms of the data were treated in different ways for GIS processing:

Maps.—Hand-drafted maps included (1) a generalized geologic map containing 25 rock units and 7 types of structures (used to generate maps A and J), (2) an interpretive geophysical map showing extent of principal magnetic rock bodies (used to generate maps F and O), (3) maps showing some geochemical sample and mineral-occurrence localities, and (4) maps showing limonitic rocks interpreted from remote-sensing data (used to generate maps G and P). Geologic structures were treated as lines, geochemical-sample and mine and prospect localities as points, and other data as polygons. These data were digitized by marking points and tracing lines that define the respective features from the original map or from a photographically enlarged copy of the original map. Each type of feature was assigned a unique numeric code (class value) that could be used to access, edit, manipulate, and display specific variables, associations, and relationships within the database. The geologic map units, geologic structures, and geophysical interpretive map required several iterations of digitizing and editing, chiefly to add detailed information requisite to the deposit models but not present on the earlier versions of the generalized geologic map and to account for reinterpretations of the geophysical data. After editing, these maps were converted to a raster format for entry into IDIMS.

Tables and text.—Two data sets (stream-sediment geochemistry and mines and prospects) were nominally tabular but were treated differently prior to conversion to raster format.

The stream-sediment geochemical data were received on magnetic tape in U.S. Geological Survey Statpac tabular format. Output from the Statpac program is as 80-character records with one or more header records describing the contents and size of ensuing records (Kork and Miesch, 1984). A program was written that reads the header and then generates a relation (a table maintained by the RDBMS). The header information is used to generate the schema (the name, order, and size of attributes in each record of the relation). Next, another program loads the data into the relation, decoding Statpac qualifying flags and modifying the data accordingly as it runs. After reprojecting sample-site coordinates from geographic to Transverse Mercator coordinates, the analytical data were subjected to a minimum-curvature surface-generation algorithm (Briggs, 1974; Webring, 1981) to produce a raster map for each element that had been determined to be indicative of mineralization (the element suites described in a preceding section). By means of the raster subsystem of the GIS, values in each raster map were transformed to logarithms, divided by the geometric mean (defined as the anomalous threshold value) of the analytical values for each element, and normalized by assigning background values to zero and linearly rescaling the anomalous values to the range 1–100.

The normalized raster maps of all elements in each geochemical suite (porphyry suite and skarn suite) were further processed in the raster subsystem to produce a composite-anomaly map and an anomalous-assemblage map that were used to develop a geochemical submodel for each deposit type. These maps, as such, are not included in this report, but a modification of the composite-anomaly maps, as discussed in a later section, are presented as maps E and N. The composite-anomaly maps present a summation of the four single-element maps. They were prepared by digitally overlaying and summing the normalized maps of all elements in a suite. The anomalous-assemblage maps show which element or elements contribute to the anomaly in each geochemically anomalous area; they were prepared by reassigning the anomalous values in each normalized map to a new number, digitally overlaying the reassigned maps of all elements in a suite, and summing the new numbers. The new numbers were chosen using powers of 2 (1, 2, 4, 8) so that sums in any combination of the four elements are unique numbers. For example, in the porphyry suite, all grid cells anomalous in barium are coded 1, all grid cells anomalous in lanthanum are coded 2, and so on.

Data on mines and prospects were received on magnetic tape as a text file containing tables with pertinent data embedded in the text. The text required extensive editing to extract and reformat the tables prior to entry into the RDBMS. After further editing of the tables in the RDBMS, site coordinates were extracted and processed to create a point data set in the vector subsystem. This data set was then reprojected from geographic to Transverse Mercator coordinates and rejoined with the attribute information. These reprojected data were then queried and plotted according to required combinations of attribute values. A vector-to-raster conversion step was necessary to create raster images of selected combinations for further analysis.

Gridded data.—Data sets available in gridded formats on magnetic tape but not used directly in the resource assessment are Landsat Multispectral Scanner (MSS) data, residual aeromagnetic anomalies, Bouguer gravity anomalies, and a digital elevation model (DEM). The DEM data were put into the raster subsystem and processed to create a topographic shaded-relief image that could be used for display and interpretation.

PORPHYRY DEPOSITS OF COPPER AND MOLYBDENUM

Porphyry deposits of copper and molybdenum have been discovered in the Dillon quadrangle but have not been mined. Mineralized zones that contain copper or molybdenum minerals or are recognized as prospective for copper and molybdenum because of hydrothermally altered and quartz-veined rock were found mainly in the 1960's, 1970's, and early 1980's during a period of concentrated exploration by mining companies. A few prospective areas were discovered during the field phase of the Dillon project or during concurrent mineral resource assessments of wilderness study areas (Pearson and Berger, 1980; Pearson and others, 1988). A brief description of 22 deposits and prospects that are known in the quadrangle is given in table 1.

Molybdenum is the principal metal sought in most of these deposits and prospects, but two are known to contain appreciable copper as well as some molybdenum. The Cannivan Gulch deposit (table 1; map S, No. 20) is the one most explored and developed, and it contains mostly molybdenum and very little copper.

The only porphyry copper deposit that has been mined in Montana is the famous Berkeley pit at Butte, 1 mi north of the Dillon quadrangle. Copper is the principal metal produced at Butte, but molybdenum production has also been important in recent years. This deposit is atypical of porphyry copper deposits in that large numbers of high-grade veins were mined before large-tonnage open-pit mining of low-grade ore began. Its geologic setting is also unusual in that it is in a moderate-size batholith rather than being associated with a small stock or plug, as is typical of most porphyry copper deposits in the southwestern United States. The Butte deposit is typical in that the ore mined from the open pit was largely in supergene chalcocite. Likewise, only one porphyry deposit has been mined in Idaho: the Thompson Creek deposit near Challis, Idaho, began producing molybdenum in 1982.

The Dillon quadrangle is within a region of geology favorable for porphyry deposits, a tectonic mobile belt that has been intruded by many plutons of intermediate composition. Rocks in the thrust belt part of the quadrangle, mainly sedimentary rocks of Middle Proterozoic, Paleozoic, and Mesozoic age, have been deformed mainly by thin-skin thrusting. The eastern one-third of the quadrangle, part of the stable craton, has been deformed by structures that involved crystalline basement to a major degree. The plutons are concentrated in the north half of the quadrangle, but they extend south of the Pioneer Mountains into the south-central part of the quadrangle, and geophysical studies indicate that plutons are more abundant in the subsurface in the southwestern part than surface exposure suggests.

No clear structural control of porphyry deposits is evident. Because porphyry deposits are generally spatially associated with plutons and theoretically are genetically related to plutons, any structural control would be secondary and relate to the structural control that affected intrusion of the plutons themselves. The plutons all seem to be later than thrusting, as no examples of the involvement of plutons with thrusting are known, and many examples of plutons are known that intrude thrusts. Where they intrude thrusts, the plutons generally cut the thrusts sharply. One exception is the fine-grained granodiorite near the New Departure mine, in the Blue Wing district southwest of Dillon, which evidently was intruded along the thrust fault that extends from Bannack northward for many miles (Lowell, 1965). About half of the flat-bottomed klippe (0.5×1 mi) at the New Departure mine is probably underlain by this intrusive rock, and an irregular sill-like part of this same pluton extends along this thrust for almost 3 mi to the west and south. The view that, in general, the emplacement of plutons was not controlled by thrusts differs from the conclusions of Ruppel (1978) for east-central Idaho and of Ruppel and Lopez (1984) for the Pioneer Mountains and other parts of the Dillon quadrangle. According to these alternative interpretations, the magmas ascended, mostly as steep-sided stocks, to the major thrusts, where they were diverted along imbricate thrusts to form sheets that did not

Table 1. *Porphyry, stockwork, and disseminated deposits and prospects of copper and molybdenum in the Dillon 1°x2° quadrangle, Idaho and Montana*

[Plutonic-rock names are those generally used in referenced reports; rock classification varies and is commonly unknown]

No. on map	Name(s) and location (lat N., long W.)	Geologic setting	Mineralization and alteration	Discovery and exploration	References
1	Granite Peak (45 34 00, 112 02 00)	Tobacco Root batholith, a zoned pluton (7 x 19 mi) elongated northwest-southeast and composed of a mafic rim (tonalite and minor hornblende diorite) and a granite core; quartz monzonite dikes cut tonalite; batholith is 72-77 Ma, intrudes Archean high-grade gneiss, and is cut by regional northwest-trending high-angle faults.	Quartz-vein stockwork in quartz monzonite dikes and surrounding tonalite; limonite staining in area 1 mi in diameter; pyrite, chalcopyrite, and molybdenite present.	Drilling at 7 sites in 51-claim block by U.S. Steel Corp.	O'Neill, 1983a; O'Neill and others, 1983.
2	Donald (45 51 00, 112 26 00)	Donald pluton of Boulder batholith is equigranular leucocratic granite, locally biotitic; commonly miarolitic and pegmatitic.	Quartz veins and miarolitic cavities contain euhedral quartz, muscovite, pyrite, molybdenite, and traces of chalcopyrite.	Numerous old prospect pits. Exploration by Burlington Northern, Inc.	Smedes and others, 1973.
3	April claims (Crystal Butte) (45 35 58, 112 28 25)	Biotite quartz monzonite stock (0.3 x 0.6 mi) and adjacent diorite stock (0.1 x 0.6 mi) intrude Archean gneiss.	Quartz monzonite altered to greisen-like vuggy aggregate of muscovite, quartz, locally K-feldspar, and sporadic clots and disseminated grains of pyrite and molybdenite; same minerals except muscovite in quartz veins; secondary biotite(?) present locally. In diorite, quartz veinlets contain pyrite and very minor molybdenite and are bordered by sericite.	Two core holes (1,134; 1,163 ft) in 1982 by U.S. Steel Corp. Core on file at Montana Bureau of Mines and Geology, Butte, Mont.	Sahinen, 1939; this study.

Table 1. *Porphyry, stockwork, and disseminated deposits and prospects of copper and molybdenum in the Dillon 1°x2° quadrangle, Idaho and Montana*--Continued

No. on map	Name(s) and location (lat N., long W.)	Geologic setting	Mineralization and alteration	Discovery and exploration	References
4	McCartney Mountain (45 31 10, 112 35 35)	Biotite granodiorite stock (2.5 mi diameter) and dikes of quartz-eye porphyry and rhyodacite or andesite intrude hornfelsed Upper Cretaceous mudstone and sandstone; some hornfels contains calc-silicate minerals.	Veinlets contain calcite, quartz, minor pyrite, and local molybdenite and chalcopyrite.	Two core holes (2,400; 2,500 ft) in 1980-81 by Freeport Minerals, Inc. Core on file at Montana Bureau of Mines and Geology, Butte, Mont.	This study.
5	Cold Spring (Grasshopper) (45 09 20, 112 55 00)	Dacite porphyry plug (75 Ma) about 0.7 mi diameter intrudes volcanic dome of similiar composition.	Quartz-vein stockwork; chalcopyrite, molybdenite(?), and gold in veins and as disseminated grains.	Discovered in 1977 by Cities Service Corp.; three rotary holes (370-555 ft) in 1978; one 2,500-ft core hole in 1979 by Molycorp, Inc.	Meyer, 1980.
6	Old Tim (45 24 00, 113 12 36)	Altered quartzite of Missoula Group (Middle Proterozoic) intruded by small quartz porphyry dike.	Quartz-vein stockwork.	Exploration drilling by mining companies.	This study.
7	Pear Lake (Monaghan Prospect, Birch Creek) (45 26 10, 112 59 38)	Within Pioneer batholith (Uphill Creek Granodiorite, 75 Ma) and associated dikes and small, irregular intrusive bodies of fine-grained to aphanitic porphyritic rhyodacite; phenocrysts are quartz, plagioclase, K-feldspar, and biotite.	Quartz veins, greisen-like vuggy pockets and bunches, and propylitically altered breccia pipe. Molybdenite and minor pyrite associated with quartz and muscovite. Galena, sphalerite, and chalcopyrite present very locally in quartz veins. Quartz veins trend mainly northeast within northeast-trending belt of mineralization and alteration.	Claimed prior to 1943; claimed by AMAX, Inc., about 1978.	Kirkemo and others, 1965; Pearson and others, 1988; Willis, 1978; this study.

Table 1.--*Porphyry, stockwork, and disseminated deposits and prospects of copper and molybdenum in the Dillon 1°x2° quadrangle, Idaho and Montana*--Continued

No. on map	Name(s) and location (lat N., long W.)	Geologic setting	Mineralization and alteration	Discovery and exploration	References
8	Dubois Creek (45 27 45, 112 53 05)	Intrusion breccia (68.4 Ma) consisting of various intrusive rock types as fragments in minor to major proportion of silicic igneous matrix. Breccia intrudes Uphill Creek Granodiorite (75 Ma).	Minor quartz veins and disseminated pyrite (altered to limonite). Geochemical anomalies of copper, molybdenum, lead, tungsten, and tin.	Discovered by L.W. Snee in 1978.	Pearson and others, 1988; Snee, 1978.
9	Crystal Park (Hot Springs Creek, Price Creek) (45 28 35, 113 05 50)	Fine-grained to aphanitic, porphyritic rhyodacite in dikes and small, irregular intrusive bodies that intrude Uphill Creek Granodiorite.	Quartz veins and greisen-like alteration of rhyodacite and granodiorite; altered rock consists of muscovite, quartz, minor rutile, and sporadic pyrite and molybdenite.	Recognized by USGS in 1979; drilling by Utah International in 1980 and Cominco American in 1981.	Pearson and Berger, 1980.
10	Elkhorn district (45 39 24, 114 02 20)	In Uphill Creek Granodiorite 3 mi from contact; adjacent to Comet fault.	Numerous quartz veins on the 1,000 level of the Elkhorn mine contain muscovite and molybdenite and average several centimeters wide. About 200 quartz veins were cut in the first 2,000 ft of the adit but not all contain molybdenite.	The 1,000-level adit was driven between 1913 and 1921. Interest in the mine as a molybdenum prospect developed in the early 1980's.	Geach, 1972; Pearson and others, 1988.
11	Jacobson Meadow (45 31 30, 113 02 40)	In Uphill Creek Granodiorite and porphyritic dikes similar to those at Crystal Park and Pear Lake.	Quartz-vein stockwork. Pyrite disseminated in wallrock; veins contain pyrite, magnetite, K-feldspar, muscovite, biotite, chlorite, and rutile. Molybdenite is sparse in veins.	Recognized by USGS in 1978.	Pearson and Berger, 1980; Pearson and others, 1988.
12	Armor Creek (Odell claims) (45 32 18, 113 10 27)	Mainly in quartzite of Missoula Group (Middle Proterozoic) and minor biotite granodiorite and quartz-eye porphry.	Quartz vein stockwork. Pyrite and molybdenite in veinlets. Intrusive breccia.	Discovered by Cyprus Mines, Inc., in 1968(?). Molycorp, Inc., as joint venture partner, drilled six holes 715-1,831 ft deep in 1970's.	Berger and others, 1983.
13	Wyman Creek (45 33 45, 113 07 30)	Quartzite of Missoula Group (Middle Proterozoic).	Quartz-vein stockwork.	Recognized by USGS in 1980.	Berger and others, 1983.

Table 1.--*Porphyry, stockwork, and disseminated deposits and prospects of copper and molybdenum in the Dillon 1°x2° quadrangle, Idaho and Montana*--Continued

No. on map	Name(s) and location (lat N., long W.)	Geologic setting	Mineralization and alteration	Discovery and exploration	References
14	Odell Lake (45 35 00, 113 15 00)	Quartzite, argillite, and calc-silicate rock of Missoula Group (Middle Proterozoic) intruded by batholithic pluton of biotite-hornblende granodiorite (Uphill Creek Granodiorite) and a stock (0.5 x >2 mi) of medium- to fine-grained porphyritic biotite granodiorite of Odell Lake; contact breccia common.	Mineralized intrusive breccia in which sedimentary fragments are altered to quartz and sericite; breccia is sulfide bearing. Anomalous molybdenum, copper, and zinc in stream sediments.	Recognized by USGS in 1980.	Berger and others, 1983.
15	Baldy Lake (45 35 56, 113 16 00)	Quartzite of Missoula Group (Middle Proterozoic) intruded by biotite granodiorite of Odell Lake.	Sulfide-bearing intrusive breccia affected by quartz-sericite alteration; sulfide-bearing quartz veins surrounding breccia. Molybdenum, copper, and zinc in stream sediments.	Recognized by USGS in 1980.	Berger and others, 1983.
16	Stone Creek (Stone-Horse, Cob claims) (45 41 20, 113 12 10)	Quartzite of Missoula Group (Middle Proterozoic) intruded by biotite-hornblende tonalite of Pattengail Creek and porphyritic biotite granodiorite of Stone Creek. Small felsic dike present.	Sulfide-bearing quartz-vein stockwork. Molybdenite in quartz veinlets found in drill core. Molybdenum, copper, and zinc in stream-sediment samples. Altered quartz-eye porphyry dike.	Staked by Bear Creek Mining Co. in early 1970's. Cob claims staked by Utah International, Inc., in late 1970's. Several drill holes.	Berger and others, 1983.
17	Moose Creek (45 38 00, 113 03 00)	Quartzite of Missoula Group (Middle Proterozoic) separated from Clifford Creek Granite on east by northeast-trending Fourth of July fault.	Quartz-vein stockwork; veins contain minor limonite; known mainly from veined float in area of thick soil.	Recognized by USGS in 1979.	Pearson and others, 1988.

Table 1. *Porphyry, stockwork, and disseminated deposits and prospects of copper and molybdenum in the Dillon 1°x2° quadrangle, Idaho and Montana*--Continued

No. on map	Name(s) and location (lat N., long W.)	Geologic setting	Mineralization and alteration	Discovery and exploration	References
18	Stine Creek (45 43 25, 113 02 00)	Pluton of Stine Creek (1.5 x 4.0 mi) is even-grained biotite-hornblende granodiorite; muscovite is present in altered granodiorite near an aplitic dike.	Area of quartz-sericite alteration is in north-central part of stock. Molybdenite was noted in dike.	Recognized by USGS in 1980.	Berger and others, 1983.
19	Black Lion (45 27 52, 113 00 41)	Clifford Creek Granite (65 Ma) is biotite-muscovite granite in a stock (2.5 x 4.0 mi) that intrudes Paleozoic sedimentary rocks.	Closely spaced molybdenite-bearing quartz veins in a large altered zone within southeastern part of Clifford Creek Granite stock; widespread muscovite and pyrite. Veins trend north to northeast.	Discovered by Cyprus, Mines, Inc., about 1968. Drilled by Cyprus in 1970's and 1980's.	Pearson and others, 1988.
20	Cannivan Gulch (45 39 17, 112 57 20)	Cannivan stock is a small (1,500 x 2,500 ft) calc-alkaline intrusive body that comprises two principal phases, older granodiorite and younger quartz monzonite. The quartz monzonite is itself a composite of at least two separate phases. The stock intruded Cambrian and Devonian carbonate rocks forming calc-silicate skarn.	Quartz-vein stockwork in two partially overlapping ore shells within the quartz monzonite and calc-silicate skarn.	Discovered by Cyprus Exploration Co. in 1968. Exploratory drilling of 55 holes from 1969 to 1980; additional drilling after 1980; 2,371-ft adit dug in 1980-1981.	Schmidt and Worthington, 1979; Hammitt and Schmidt, 1982.
21	Lower Seymour Lake (45 50 50, 113 11 05)	Batholitic pluton of biotite-muscovite granodiorite (about 50 Ma) on northwest side of regionally extensive northeast-trending fault that bounds northwest side of Big Hole basin. Granodiorite commonly has uneven to pegmatoid texture and is locally sheared and silicified.	Quartz vein stockwork in biotite-muscovite granodiorite, which is variably altered to quartz, sericite, and clay minerals. Igneous texture destroyed by silicification and (or) shearing locally. Quartz veins, which are as much as 1 ft thick, contain limonite after pyrite, molybdenite, ferrimolybdite, and fluorite.	Recognized by USGS in 1981.	Elliott and others, 1985.

Table 1 -*Porphyry, stockwork, and disseminated deposits and prospects of copper and molybdenum in the Dillon 1°x2° quadrangle, Idaho and Montana*--Continued

No. on map	Name(s) and location (lat N., long W.)	Geologic setting	Mineralization and alteration	Discovery and exploration	References
22	Bobcat Gulch (45 21 23, 113 59 27)	Stocks and numerous dikes ranging from quartz diorite to rhyolite intrude Middle Proterozoic Yellowjacket Formation. Largest stock (0.7 x 1.5 mi) is mostly granodiorite. Most intrusive rocks are porphyries with plagioclase, quartz, and biotite phenocrysts. Extrusive rhyolite is several hundred feet north of the largest stock and also near a smaller stock just west of the Dillon quadrangle.	Copper and molybdenum minerals are in veinlets, fracture coatings, and disseminations associated with several intrusive phases. Quartz latite dikes are the most consistently altered and mineralized. An older quartz-pyrite-molybdenite phase of mineralization is associated with quartz diorite. Highest copper grades are in supergene chalcocite blanket.	Several drill holes by Cominco American from about 1977 to 1981.	Bunning and Burnet, 1981.

penetrate the upper plates very far. Only rarely can either of these interpretations be confirmed owing to restricted vertical exposures. The many high-angle faults in the quadrangle likewise show no clear association with plutons, in part because many of them are younger than the plutons.

The Dillon quadrangle is intersected by a regional northeast-trending concentration of intrusive rocks and various types of mineral deposits, including porphyry deposits, referred to by Jerome and Cook (1967) as the "transverse porphyry belt," by Rostad (1978) as the "Idaho-Montana porphyry belt," and by Armstrong and others (1978) and Armstrong and Hollister (1978) as the "White Cloud-Cannivan porphyry molybdenum belt." An approximate outline of the belt and the location of the porphyry deposits in the belt are shown on figure 1. By Rostad's definition, the belt extends about 450 mi from the vicinity of the Boise Basin in central Idaho to the Little Rocky Mountains in north-central Montana. The principal porphyry deposits along the belt are the Little Boulder Creek and Thompson Creek deposits in Idaho and the Cannivan Gulch, Butte, and Big Ben deposits in Montana (fig. 1 and map S, No. 20). Many other deposits and prospects in the Dillon quadrangle are within the belt, but some, in both Idaho and Montana, are outside the belt as defined. O'Neill and Lopez (1985) describe major structural features that are parallel with, or are contained within, parts of the belt.

HOST ROCKS

Brittleness, which permits a stockwork of quartz veins to form, is the chief characteristic of a favorable host for porphyry deposits. The principal host rocks for known porphyry deposits and prospects in the Dillon quadrangle are Upper Cretaceous and lower Tertiary intrusive igneous rocks. Other host rocks are Middle Proterozoic sedimentary rocks and, at the Cannivan Gulch deposit, Phanerozoic sedimentary rocks. At least some of the plutonic rocks that host the deposits are probably genetically related to the mineralization process. The silicic nature of quartzitic and silicate rocks may exert some compositional control as well by providing a source of SiO_2 to the ore-forming fluid. The Middle Proterozoic sedimentary rocks that are host to porphyry mineralization are mainly quartzite of the Mount Shields Formation and Bonner(?) Quartzite of the Belt Supergroup, which is extensively exposed in thrust sheets in the Pioneer Mountains and Anaconda Range. In the Salmon River Mountains, the Middle Proterozoic Yellowjacket Formation, consisting of fine-grained argillitic quartzite, siltite, and argillite, is also a host. Both the Mount Shields and Yellowjacket were recrystallized regionally to low-grade metamorphic rocks; the original clay matrix of the quartzite was converted to white mica and locally to chlorite and biotite also. Near plutons, contact metamorphism produced higher grade mineral assemblages that result in brittler host rock.

The Phanerozoic sedimentary rocks at Cannivan Gulch (mainly Devonian Jefferson Dolomite and Cambrian Hasmark Formation) were probably favorable hosts only because they had been converted to brittle calc-silicate skarn prior to molybdenum mineralization (Hammitt and Schmidt, 1982).

ASSOCIATION WITH PLUTONS

Porphyry deposits and prospects are in most parts of the quadrangle where Phanerozoic intrusive igneous rocks are present; this is true mainly for the north half of the quadrangle. As illustrated on map B, the deposits and prospects are mostly in the Pioneer Mountains in the central part of the quadrangle, where the association is with plutons of the Pioneer batholith (Zen and Dutro, 1975; Snee, 1978, 1982; Arth and others, 1986). Other occurrences are associated with the Tobacco Root batholith along the east boundary of the quadrangle, with the Boulder batholith in the northeastern part, with a small intrusive center on the west boundary that is believed to be related to Challis Volcanics, and with several types of plutons in the Anaconda Range in the northwestern part. Most of the plutons in the northwestern part of the quadrangle have been considered by N.J. Desmarais (oral commun., 1980) to be part of the Idaho batholith. A few porphyry prospects in the Pioneer Mountains are not associated with stocks or batholiths, but a few small silicic dikes are present at these places, suggesting that a related larger pluton is beneath each of them.

THE DEPOSIT MODEL

The preceding descriptions and discussion of characteristics of porphyry deposits and the data available for this assessment lead to the following condensed mineral deposit model used in the mineral resource assessment. The individual items that constitute the model are referred to as favorability criteria, which are those characteristics and relationships that best localize porphyry deposits geologically and geographically and for which data are available.

Mapped faults, remotely sensed linear features, and other structural data were not used in this assessment because no clear association of the structural features with porphyry deposits is evident.

Spatial association with plutons

Most known porphyry deposits and prospects are at least partly within plutons, and thus the plutons in the quadrangle are counted as favorable loci for undiscovered deposits (map B). Plutons at the surface can be located from the geologic map. A possible limitation of the generalized geologic map is that an unknown number of small plutons are not shown because they were not found during reconnaissance mapping. Such small plutons could be very significant as exemplified by the compound stock at Cannivan Gulch (map S, No. 20), which is only 1,000×2,000 ft at the surface (Hammitt and Schmidt, 1982), and by the circular plug about 2,000 ft in diameter at the Grasshopper prospect (map S, No. 5; Meyer, 1980); both of these plutons are extensively mineralized.

The deposits that are not localized within plutons are probably above the tops or on the flanks of cupolas or cylindrical plutons (Cox, 1986b). Subsurface plutons may be identified by interpretation of geophysical data if they are large enough, contain enough magnetite, and provide a contrast with the country rock in magnetic or gravity properties. The relatively more mafic composition of plutonic rocks may be estimated if hydrothermal alteration is not too severe. Smaller plutons not detected with the reconnaissance geophysical techniques could be especially important in the search for porphyry deposits. A map showing the distribution of plutons based on the interpretation of geophysical data (map F) was digitized and entered into the GIS.

Some porphyry deposits in the country rock surrounding plutons are either the result of mineralization associated with the exposed pluton or with a subsurface pluton that may have intruded along the contact between the exposed pluton and the country rock. For this reason, a zone 1 km wide surrounding exposed plutons is also considered favorable; the 1-km width was selected arbitrarily.

Kind and age of plutonic rock

Copper porphyry deposits are generally associated with intermediate intrusive rocks (Cox, 1986b). In the Dillon quadrangle these are mostly hornblende-biotite monzogranite, granodiorite, tonalite, or quartz diorite. Molybdenum porphyry deposits are generally associated with more silicic rocks (Theodore, 1986), which are represented in the Dillon quadrangle by biotite granite and biotite-muscovite granite and granodiorite. Most plutons in the quadrangle are equigranular and medium grained, and some are megacrystic or porphyritic. Relatively few are fine-grained porphyries, consisting of abundant phenocrysts and chilled fine-grained groundmass. The most abundant plutonic rock in the quadrangle is hornblende-biotite granodiorite that constitutes Butte Quartz Monzonite, Uphill Creek Granodiorite, and many smaller plutons. Both Tertiary and Cretaceous plutons are mineralized and hence no distinction can be made according to age; rocks of both ages are considered here to be equally favorable.

Of the 29 porphyry deposits and prospects in the quadrangle (22 of which are listed in table 1 and located on map S), 15 are within or near plutons of Cretaceous biotite granodiorite and granite (unit Kbgg on maps S and T). For this reason, this unit is considered the most favorable on the basis of composition for the occurrence of porphyry molybdenum deposits. The next most favorable is Cretaceous hornblende-biotite granodiorite, quartz diorite, and tonalite (unit Kghb), which is favorable mainly for copper, as 9 of the 29 deposits and prospects are within or near plutons of this unit. Less favorable are biotite-muscovite granodiorite and granite (unit Tgg) and Tertiary granodiorite (unit Tgd), both of which are locally mineralized. All other intrusive rocks have still lower, though significant, favorability except for Proterozoic granite and gabbroic and ultramafic rocks of various ages, which have essentially no favorability for this deposit type.

Kind of host rock

On the basis of abundance of deposits and prospects in the Dillon quadrangle and of estimates of physical properties (mainly brittleness), the map units considered most favorable as host rocks for porphyry deposits are hornblende-biotite granodiorite, quartz diorite, and tonalite (Kghb); biotite granodiorite and granite (Kbgg); biotite-muscovite granodiorite and granite (Tgg); and granodiorite and other intermediate rocks (Tgd). On the same basis, another group of rocks is considered to have intermediate favorability; these include all other bedrock units except those that are predominantly carbonate. Units that are predominantly carbonate (upper and lower Paleozoic rocks (PMs, D€s) and Archean marble (Ac)) make up a third group that has low favorability, despite the fact that the Cannivan Gulch deposit is partly in one of these units (D€s). Surficial units of Quaternary and Tertiary age (Qa, Tt, and Tb) are not favorable as host rocks.

Stream-sediment geochemistry

Although the suite Ba, La, Mo, Sr was determined by discriminant function analysis to be similar chemically to mineralized rock from porphyry deposits and prospects, as discussed earlier in this report, a comparison of the deposits and prospects map (map B) with geochemical anomalies consisting of all four elements showed that the deposits and prospects were concentrated in anomalies that contain molybdenum and not concentrated in anomalies that do not contain molybdenum. This comparison was made by means of the GIS using the anomalous-assemblage map, which illustrates the variation in elemental make-up of the several anomalous areas. A measure of the concentration, or density, is the number of deposits and prospects per unit area of the quadrangle that is anomalous. The density was calculated as the percent of the total number of deposits and prospects that are within anomalous areas divided by the percent of the area of the quadrangle that is anomalous. With this calculation, a density of 1.0 would be expected if the deposits and prospects were evenly distributed, on a per-unit-area basis, between anomalous and non-anomalous areas. Considering only anomalies with molybdenum-bearing assemblages, the density is 4.8; considering only anomalies from which molybdenum is absent, the density is 0.45.

The composite-anomaly map was analyzed in a similar manner. Using the results of these analyses, we excluded anomalous areas not characterized by molybdenum-bearing assemblages (they were given a score of zero) in preparing the composite-anomaly map (map E), and we grouped the remaining anomalies (those that contain molybdenum) into three levels of favorability depending on their density, as shown on map E. In order of increasing favorability, the anomalies were assigned scores of 1 (densities 1.0 to 1.88), 2 (densities >1.88 to 2.75), or 3 (densities >2.75).

A comparison of the composite-anomaly map for porphyry deposits with a similar map for vein and replacement deposits (Pearson and others, in press) indicates similarities between the two. Hence, the geochemical map prepared for vein and replacement deposits may also be useful in describing, by means of geochemistry, environments favorable for porphyry deposits. In conjunction with supporting field observations, the two maps could perhaps be used together to detect or describe vertically telescoped or superposed geochemical signatures of porphyry mineralization.

Limonitic alteration

Limonite anomalies can be evidence of hypogene mineralization. Limonite may form from weathering of iron-bearing sulfide, oxide, and carbonate minerals. A map showing the field-checked limonite anomalies was digitized. Because the map areas of limonitic rocks are very small at 1:250,000 scale, their effect has been enlarged by 1 km outward so that most of the resulting anomalies (map G) are about 2–3 km in diameter. This enlargement is justified because vegetation commonly restricts the extent of visible limonite and because hydrothermal alteration was likely more extensive than the recognized limonite.

ASSESSMENT SCHEME

The preceding favorability criteria were subjectively evaluated to determine their relative significance for the localization of porphyry deposits. The kind of plutonic rock is judged to be the most significant criterion. Host rock and geochemistry are second in importance, and geophysical interpretation and remotely sensed limonite are of least importance. The criteria were ranked and given scores (fig. 3), depending on their association with known porphyry deposits and prospects. Each grid cell then had a favorability score of 0–14 of a possible score of 15 (no grid cell had a score equal to a maximum possible for each criterion (map H). The summed rating scores were grouped into three levels of mineral potential for porphyry deposits: high (12–14), moderate, (8–11), and low (1–7) (map S). The grouping and breakpoints take into consideration the distribution of known porphyry occurrences within areas described by the combined model score of 0–15. The terms "high," "moderate," and "low" are relative and encompass the entire range of possible scores.

DISCUSSION

As expected from the rating scores assigned to the favorability criteria, areas of high potential shown on map S are associated with plutonic rocks. Conversely, most exposed plutons received a rating of moderate or high. In general, the areas of high potential are surrounded by areas of moderate potential, and these, in turn, are surrounded by areas of low potential. The largest areas of high potential are in the region of plutonic rocks of the Pioneer and Boulder batholiths, but several very small stocks and plugs also have high potential. The biotite-muscovite granodiorite batholith in the Anaconda Range is the only large pluton that has (in part) low potential. This rating is the result of low favorability assigned to the plutonic rock itself and a low score attributed to geophysical data because of the low magnetic susceptibility of this rock. Some large regions where subsurface plutons are inferred on the basis of geophysical data have low potential, such as large parts of the Beaverhead Mountains and Big Hole Divide area. Large areas of the Tertiary basins were given a score of 0. In general, the Tertiary and Quaternary deposits are too thick in these basins for them to be considered to have any potential even though porphyry deposits formed prior to those deposits and could exist beneath the young sediments.

The distribution of the 22 porphyry prospects and occurrences described in table 1 and shown on map S illustrates their relationship to areas of high, moderate, and low mineral resource potential. Of the 22, 9 are at least partly within areas of high potential, 9 others are at least partly within areas of moderate potential, and 3 are in areas of low potential. This relationship is taken as a validation of the model, the data, and the assessment technique at a scale of 1:250,000, although limitations of all three are recognized.

However, most of the areas of high and moderate potential cover broad regions that are known to include much (perhaps mostly) fresh, unaltered and unmineralized rock that has very little chance of containing porphyry deposits. This dichotomy between the apparent success of the technique in including the known porphyry

Favorability criteria	Favorability scores					Maximum possible score
	5	4	3	2	1	
Association with plutons (area of pluton and 1 km outside pluton)	Biotite granodiorite and granite (Kbgg[1])	Hornblende-biotite granodiorite (Kghb)	Biotite-muscovite granite (Tgg) and biotite granodiorite (Tgd)	All other intrusive rocks		5
Host rocks[2]			Major plutonic rocks (Kghb, Kbgg, Tgg, Tgd)	All other bedrock units except carbonate rock units	Principal carbonate rock units (PMs, D€s, KTRs)	3
Stream-sediment geochemical anomalies			Highly anomalous	Moderately anomalous	Weakly anomalous	3
Subsurface plutons inferred from geophysical anomalies				Area of anomaly		2
Limonitic alteration				Area of anomaly and 1 km around anomaly		2

Total maximum score 15

[1]Symbols refer to geologic map units; see map S.
[2]Surficial deposits given score of 0.

Figure 3. Diagram summarizing favorability criteria and scores for porphyry deposits, Dillon 1°×2° quadrangle, Idaho and Montana.

occurrences in areas rated as having high and moderate potential and its failure to eliminate large regions that are almost certainly unmineralized is ascribed mainly to deficiencies in the data. Much of the aeromagnetic data is at a 2-mi flight-line spacing; the geochemical database is of a reconnaissance nature (approximately one sample per 4 sq mi), and the geologic map is not detailed, in part because it is 1:250,000-scale reconnaissance and in part because it was generalized to a degree thought practical for digitizing. An improvement in any of these or other data sets would make the assessment more specific and probably eliminate many unmineralized tracts from the high and moderate potential ratings.

SKARN DEPOSITS

Skarn deposits in the Dillon quadrangle have produced most of the tungsten that has been mined in Montana, the greatest part during the 1950's, when prices established during a U.S. Government purchasing and stockpiling program made the mining of low-grade ores economical. In addition to tungsten, substantial amounts of gold, modest amounts of copper and silver, and small amounts of iron have been mined from deposits that have been classified previously as contact metasomatic, tactite, or skarn. This classification may not be correct, however, for some of these deposits, especially some of the gold deposits in which the ore may have formed in hydrothermal vein and replacement deposits within or adjacent to, but later than, the skarn itself.

The principal tungsten deposits in the quadrangle are the Browns Lake (Ivanhoe pit), Lost Creek, and Calvert deposits, all in the Pioneer Mountains (Map T; Pattee, 1960). Of the smaller occurrences of tungsten, most are in the Pioneer Mountains, and a few are in the Anaconda Range and the Tobacco Root Mountains. The Browns Lake deposit, the largest in Montana, produced about 625,000 short tons of ore averaging 0.35 percent WO_3 from 1953 to 1957 (Pattee, 1960). During this same period, the Calvert mine in the western Pioneer Mountains produced more than 100,000 short tons of ore averaging more than 1.0 percent WO_3. Mining of small tonnages of ore from the Calvert continued after 1957 (Geach, 1972). The Lost Creek mine, about 3 mi south of the Browns Lake deposit, produced more than 20,000 tons of ore averaging 0.18 percent WO_3 from 1952 to 1956 (Pattee, 1960). The Lentung deposit is a new discovery in the Storm Park area, between the Browns Lake and Lost Creek deposits along the east contact of the Pioneer batholith; it is evidently a significant tungsten deposit, but it has not yet been developed or mined.

Other than tungsten, the most significant deposits in skarn (or in rocks containing calc-silicate minerals) in the quadrangle are probably gold deposits in the Silver Star district and possibly in the deeper parts of the Butte Highlands mine in the Highland district. The Broadway and Hudson mines at Silver Star produced more than 58,000 oz of gold and about the same amount of silver (Sahinen, 1939) from ore that averaged nearly 1.5 oz gold per short ton. Much of this mining was done before 1880. Although most of the Butte Highlands orebody seems to have been a replacement of carbonate rock, that the deeper parts contain calc-silicate minerals mixed with gold-bearing sulfides (Newcomb, 1941; Sahinen, 1950) suggests a pluton not far below the lowest mining level. Some of the gold (and minor silver and base metals) deposits in the Bannack district are closely associated with skarn, but some of the Bannack deposits are in recrystallized limestone just beyond a skarn envelope or at varying distances from the pluton where skarn is absent (Shenon, 1931); these relationships suggest that some of the Bannack deposits should be classified as skarn and some as vein or replacement deposits.

Copper deposits associated with skarn include the Johnston-Moffet mine in the Tidal Wave district and the Indian Queen mine in the Birch Creek district. The Johnston-Moffet, which has had rather small production, seems clearly to be a skarn deposit as it is in inclusions of calc-silicated carbonate rock within a small stock. About 23,000 tons of ore mined from the Indian Queen since 1902 contained 1,729,000 pounds of copper and 42,000 oz of silver (Geach, 1972). Winchell (1914) describes the ore as in irregular shoots and bunches along a fault that separates the pluton from skarn and also within limestone. These relationships suggest that mineralization may have been later than skarn development, but lacking more definitive information, the Indian Queen is included here among the skarn deposits.

About 0.5 mi southwest of the Indian Queen is a small skarn magnetite deposit on the Jumbo claim that was mined as smelter flux; it evidently produced several hundred tons (Geach, 1972).

GEOLOGIC SETTING

Skarn deposits are formed by metasomatic replacement of carbonate host rocks at or near a contact with intrusive igneous rocks. Tungsten skarn deposits are characterized by a gangue assemblage of calcium, magnesium, and iron silicates such as garnet, epidote, amphibole, pyroxene, and locally by boro-silicates such as axinite. The tungsten mineral is usually scheelite. Skarn deposits are commonly pod-shaped or are irregular; they have rather sharp contacts between ore and waste. In size, they are rarely more than 1 million tons.

The associated igneous body is plutonic rather than hypabyssal or subvolcanic, being typically a batholith, large stock, or cupola above a larger body. Its texture is generally medium grained and equigranular, and its composition is generally biotite or hornblende-biotite granodiorite or monzogranite. Hydrothermal alteration of the pluton is usually absent or restricted to a narrow zone (as much as a few feet thick) adjacent to the contact. Gold-bearing skarn deposits in the Dillon quadrangle also seem to have the same gangue minerals and the same kinds of associated plutonic rock as tungsten skarns. Magnetite-rich skarns are generally associated with more mafic intrusive rocks, but this is not the case at the Jumbo claim, where the pluton is the same granodiorite body as at the Indian Queen, Browns Lake, and Lost Creek skarn deposits.

Plutonic rocks in the Dillon quadrangle that are known to be accompanied by significant skarn deposits are Uphill Creek Granodiorite and a small tonalite stock, both in the Pioneer Mountains. Uphill Creek Granodiorite is exposed over a large area of the eastern Pioneer Mountains and also extends across the west Pioneer Mountains as a narrowing protrusion a few miles wide (map K) (Snee, 1978; Zen, 1988). The Uphill Creek is predominantly hornblende-biotite granodiorite, is medium grained, and is equigranular to megacrystic. The Calvert deposit is in an inclusion of sedimentary rock within a tonalite stock that is only about 0.5 mi wide.

HOST ROCKS

Host rocks for skarn deposits are almost exclusively carbonate sedimentary rocks. Characteristics of a particular sedimentary sequence that make it more favorable than another sequence are thin bedding and the interbedding of carbonate and noncarbonate rocks. Both of these characteristics probably promote permeability, which enhances access by mineralizing fluids (Elliott, 1981). The most favorable beds are of limestone that is interbedded with siliciclastic or pelitic beds.

In the Dillon quadrangle, the predominant host for tungsten deposits is a stratigraphic unit that in the past has been referred to as Amsden Formation of Mississippian and Pennsylvanian age. The Amsden, as the name has been used in this area, consists of well-bedded gray to red limestone (some of which is silty or sandy), gray dolostone, gray to tan sandstone and calcareous sandstone, and red calcareous and noncalcareous mudstone. As mapped on the east flank of the Pioneer Mountains (Myers, 1952; Zen, 1988), its thickness is commonly a few hundred feet, although both thickness and lithology change laterally. Stratigraphic studies in the Blacktail Mountains south of Dillon, Mont. (map R) and elsewhere to the south and east of the Dillon quadrangle have resulted in modifying the stratigraphic nomenclature of strata between Mississippian Madison Group and Pennsylvanian and Mississippian Quadrant Formation. These strata, formerly referred to as Amsden Formation or Big Snowy Group, or locally included in the Madison Group, have been redefined by Wardlaw and Pecora (1985). This largely Upper Mississippian sequence is now included in the Snowcrest Range Group and consists in ascending order of Kibbey Sandstone, Lombard Limestone, and Conover Ranch Formation. The Conover Ranch Formation is approximately equivalent to Amsden Formation, as the term has been used in this area in the past. These units are present in the Blacktail Mountains, the type locality of the Conover Ranch Formation, and in areas in the south-central part of the quadrangle from the Bannack district northward at least to Argenta. Whether these newly defined units are applicable farther north at the Browns Lake and Lost Creek mines along the east side of the Pioneer batholith or at the Calvert mine in the northwestern Pioneer Mountains is uncertain.

Compared to the post-Madison Group Upper Mississippian strata, other carbonate stratigraphic units in the quadrangle contain only minor amounts of skarn. The magnetite deposit in the Birch Creek district is in dolostone assigned to Cambrian Pilgrim Dolomite by Myers (1952). The Cambrian Meagher Limestone is host to the Butte Highlands deposit. Mission Canyon Limestone of Mississippian age contains minor amounts of skarn in the Bannack district, in the Baldy Mountain district, at the Johnston-Moffet mine in the southwestern Tobacco Root Mountains, in the Silver Star district, and possibly at the Perry tungsten prospect on the northwest flank of the Tobacco Root Mountains (map T). Carbonate beds in the Lower Cretaceous Kootenai Formation have been converted into skarn locally adjacent to the Mount Fleecer stock. At the Cayuga prospect, about 2 mi northwest of Divide, Mont., but not shown on map T, copper-bearing lodes in the Kootenai have been explored that may be in skarn, judging from the description by J.T. Pardee (in Winchell, 1914, p. 167). Few skarn deposits are in the Kootenai, despite the apparent favorableness of limestone beds in the Kootenai, because that formation is not in contact with plutonic rocks at very many places in the Dillon quadrangle. Marble layers in the Archean rocks of the Tobacco Root Mountains and Ruby Range and calcareous strata in the Middle Proterozoic Newland Limestone in the northeastern part of the quadrangle are not known to contain skarn.

STRUCTURAL CONTROL

The structure of the host rocks has a significant bearing on the formation of skarn deposits. Bedding is of primary importance. Massive or thick-bedded sequences of limestone rarely contain much skarn, presumably because of low permeability. On the other hand, thin-bedded sequences, especially those that are interbedded clastic and carbonate rocks, were probably more brittle and hence have the potential for greater inter-bed and fracture permeability, which is enhanced by faulting and folding. These attributes probably explain why the Amsden Formation and at least parts of the Snowcrest Range Group are the best hosts for ore in skarn. Where beds dip down into the pluton, the mineralizing fluids have a better opportunity to penetrate the strata than if the beds dip away. For the same reason, discordant intrusive contacts offer improved opportunities for contact of the fluids with favorable beds. Concordant vertical beds do not provide these opportunities and afford the poorest structural relationship. Irregularities in the pluton contact also result in increased surface area of contact, and overhangs of country rock above the pluton may promote ponding of fluids and the slow percolation of fluids into reactive host rocks. This kind of structural information is available only locally in the Dillon quadrangle where individual deposits have been studied, and it is of little value in assessing the resource potential of the entire quadrangle.

DEPOSIT MODEL

Characteristics of skarn deposits discussed in the preceding section and the applicable and available data in the database leads to the following condensed mineral deposit model that was then used in the mineral resource assessment.

Spatial association with plutons

Skarn deposits are, in general, adjacent to plutons (map K), few being found more than 100 m from them. Because of the possibility of subsurface deposits at contacts that do not correspond to the mapped contact of the pluton—that is, the pluton contact is irregular or dips outward with depth—the favorable zone around plutons is assumed here to be 1 km wide, in plan (map L). Boundaries of exposed plutons were obtained from the digital geologic map.

Kind and age of plutonic rock

The general association of skarn deposits with plutonic rocks of intermediate composition shows that the most favorable plutonic rock unit in the Dillon quadrangle is Cretaceous hornblende-biotite granodiorite (Kghb), which is also the most abundant intrusive igneous rock type present. Biotite granodiorite and granite (Kbgg) is a unit considered less favorable because of its uncommon association with calc-silicate skarns in the quadrangle. All other intrusive rocks in the quadrangle, many of which are hypabyssal, probably have low favorability for the presence of associated skarns. Favorable plutonic rocks are shown on map L.

Kind and age of host rock

The favorableness of a particular carbonate formation or map unit probably differs depending upon the specific type of skarn deposit. Tungsten, copper, and gold mineralization, for example, seem to have favored different stratigraphic units. Tungsten and copper are predominantly in Mississippian strata (part of map unit PMs, map T). The same strata may be hosts for gold, but the principal gold skarns are in Cambrian carbonate strata (part of map unit D€s, map T). The single known magnetite skarn is so small and localized that its host rock cannot be assumed to be specifically suited to the development of this type of deposit. Favorable host rocks are shown on map M.

Stream-sediment geochemical data

The composite-anomaly map and anomalous-assemblage map of the geochemical suite iron-manganese-scandium-vanadium, discussed in a preceding section of this report, were used in conjunction with a map of known skarn deposits and prospects to select and rank geochemically anomalous areas as a function of their contributing elements. An analysis using the GIS of the distribution of known skarns with respect to anomalous assemblages showed that the deposits and prospects were indeed concentrated within areas characterized by the assemblage iron-manganese-scandium-vanadium; 29 of 40 known skarn deposits and prospects are in such anomalous areas. Density, a measure of this concentration, was 2.4 compared with a density of 0.39 in the area characterized by all other assemblages. The composite anomaly map was analyzed in a similar manner. Using the results of these analyses, we excluded areas not characterized by the anomalous assemblage (they were given a value of zero) from consideration in preparing the composite-anomaly map, and we ranked intervals in the remaining anomalies on the basis of the calculated density. We also excluded from consideration anomalous areas of plutonic rocks on the grounds that skarns are not expected to be in plutons.

The resulting skarn submodel (map N) describes the quadrangle in terms of two levels of geochemical favorability; those having densities of 1.0–4.0 were assigned a score of 1 and those having densities greater than 4.0 were assigned a score of 2.

Subsurface plutons

Interpretation of geophysical data was used to locate subsurface plutons that are shown on map O. Exposed plutons are not shown on map O.

Remotely sensed limonite

Most skarn deposits in the quadrangle contain iron sulfides, and some contain magnetite and hematite. Thus, limonitic rocks derived mainly from weathering of these minerals are considered possible evidence for the presence of skarn deposits, although no distinction can be made between limonite derived from skarns and limonite derived from other deposit types or other sources of iron. The limonite anomalies and a zone 1 km in diameter around the anomalies are shown on map P.

ASSESSMENT SCHEME

The preceding kinds of data and relationships ("favorability criteria" of Pratt, Erickson, and others, 1984) were subjectively evaluated. The data for plutonic rocks were applied only to the area within 1 km outside exposed plutons. The host rock data were applied without regard to the proximity of known plutons. Geochemistry, geophysics, and remote sensing were applied to all areas except exposed plutons. This approach was used because of the uncertainty as to depth, and even existence, of plutons that do not crop out. The kind of host rock and kind of plutonic rock are believed to be by far the most significant criteria and hence were given the most weight. For manipulation in the GIS, each criterion was weighted subjectively and given a relative score as shown on figure 4. The scores were deliberately kept as low as possible in order to avoid giving the appearance that the data and the model are precise.

The scores for each of the data sets were summed by means of the GIS. Thus, the combined effect of the five criteria were determined for all parts of the quadrangle, and this effect is illustrated on map Q. The maximum possible score is 16, and each 200×200 m grid cell has a combined score of 0–16. Areas shown on map Q having the highest combined score were concluded to have the highest mineral resource potential for skarn deposits and, conversely, areas having the lowest score are least favorable. Map Q consists of a great many small areas, each having a total score that differs slightly or greatly from its neighbors. The distinction between areas having scores that differ by 1 or 2, such as between 14 and 15 or 16, for example, is probably not significant, in view of the reconnaissance nature of, and many uncertainties in, the data. Therefore, map Q was subjectively generalized into three groups of scores based, in part, on the distribution of known skarn deposits and prospects within areas described by the combined model score range 0-16: high (12–16), moderate (7–11), and low (1–6). Each group was inferred to have a certain mineral resource potential. Map T is the summary resource potential map for skarn deposits.

DISCUSSION

The most striking features of the skarn assessment map (map T) are the colored bands that surround the uncolored areas underlain by exposed plutons. These bands contain most of the high and moderate potential areas in the quadrangle, as determined by the procedure used here. Where plutons are in contact with map units that contain carbonate rocks, the potential is commonly high or moderate. Where plutons are in contact with unfavorable noncarbonate rocks, the potential in these host rocks is commonly low. Variations in the level of mineral potential, of course, also depend on the kind of plutonic rock and, to a lesser extent, on the other criteria. The exposed plutons are uncolored on the map (have a zero potential) because they are impossible as host rock for skarns, by definition. An exception to this general situation that cannot be treated with the present database is the possibility of inclusions or roof remnants of carbonate rocks within the plutons, which are rarely large enough to be shown at the scale of this study. Calvert Hill, one of the largest tungsten mines in Montana (on the basis of production), is in such an inclusion, showing clearly that the zero rating assigned to plutons cannot be taken as absolutely assured.

For an area to be rated moderate (a score of 7–11), at least two of the five criteria must be present, and for an area to be rated high (a score of 12–16), at least three criteria must be present. Where the most favorable pluton and host rock are in contact, the rating score is at least 10, and that area therefore has at least moderate potential.

Some parts of the quadrangle more than 1 km from pluton contacts at the surface have low or moderate potential for skarn deposits, but never a high rating because of the absence of exposed plutons. Such low and moderate ratings result chiefly from the presence of favorable host rock at the surface and also various combinations of the other criteria except exposed plutons. In such places, a rating as great as moderate would seem to be valid only if a pluton can be postulated in the rather shallow subsurface. The geophysical data do not give a measure or estimate of depth to the postulated pluton, however, and further work would definitely be necessary to establish a likely site for a buried deposit.

One weakness in the procedure is that, because of the scale of the data and the grid-cell size chosen, favorable host rocks were lumped with unfavorable host rocks into map units of sufficient size for treatment. Such lumping has the affect of having only the noncarbonate rock as the only part of the unit that is present at certain places, and these places cannot be determined from available data. Only field examination or reference to large-scale maps, where they are available, can determine whether the favorable Mississippian strata (when considering tungsten deposits, for example) are actually present at any particular place that Permian to Mississippian sedimentary rocks (unit PMs) is shown on the generalized geologic map.

Skarn mines and prospects, particularly the most productive mines, are located mostly within or adjacent to areas of high or moderate potential (map T). The high scores along the east margin of the Pioneer batholith and

Favorability criteria	Favorability scores				Maximum possible score
	5	3	2	1	
Plutonic rock type	Hornblende-biotite granodiorite (Kghb[1])	Biotite granodiorite, diorite, and granite (Kbgg)		All other except Yqmp, which is scored 0	5
Host rocks	Upper Paleozoic sedimentary rocks (PMs)	Lower Paleozoic sedimentary rocks (DЄs)	Mesozoic sedimentary rocks (KTRs)	Precambrian carbonate rocks (Yh, Yc, Ac)	5
Subsurface plutons inferred from geophysical anomalies		Area of anomaly			3
Stream-sediment geochemical anomalies			Moderately anomalous	Weakly anomalous	2
Limonitic alteration				Area of anomaly and 1 km around anomaly	1

[1] Symbols refer to geologic map units; see map T.

Total maximum score 16

Figure 4. Diagram summarizing favorability criteria and scores for skarn deposits, Dillon 1°×2° quadrangle, Idaho and Montana.

at other localities known to contain skarn occurrences, for example, indicate that for the Dillon quadrangle the model used here is reasonably precise and complete. Some of the mine and prospect symbols appear on map T just within plutons as a result of generalizing of an irregular contact or because the raster format may tend to shift the location slightly from its actual location.

Except where mineral exploration has demonstrated otherwise, all areas shown on map T as having high potential and several shown as having moderate potential would seem to be worthy of investigation for skarn deposits. The most significant of these are the contact zones between the major batholiths (Pioneer and Boulder) and Paleozoic carbonate rocks. The most productive known tungsten skarns are along the east side of the Pioneer batholith, especially adjacent to Uphill Creek Granodiorite, and additional targets may be present along this and other segments of the same pluton margin. Detailed studies of stratigraphy and structure will be required to locate potential targets in Mississippian limestone at the contact. Places where younger strata are at the surface and the more favorable Mississippian strata can be inferred at depth might be investigated. Several tungsten prospects in the Baldy Mountain mining district suggest that that area could have substantial potential although no significant deposits have been discovered to date. Other areas that seem to deserve serious consideration are in the north-central part of the quadrangle adjacent to the Mount Fleecer stock, Granulated Mountain stock, and Hungry Hill stock and in some areas along contacts of various plutons of the Boulder batholith. The major skarn deposits associated with the Boulder batholith are the gold-bearing skarns in the Silver Star district, which are adjacent to the granodiorite of Rader Creek.

Some areas shown on map T as having potential as great as moderate are probably rated higher than most knowledgeable geologists would rate them subjectively using the same data. The Ruby Range, for example, has areas shown as having moderate potential (score of 7 on map Q) in very favorable host rock, but no Phanerozoic pluton is known in the range nor is any likely to be present, and in its absence, skarn deposits are most unlikely to occur. Similar favorable host rock (score of 7 on map Q) is in the Snowcrest Range at the southeast corner of the quadrangle, where no pluton is present near them in the Dillon quadrangle or known in immediately adjacent quadrangles.

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