# Precambrian Deposits of Zinc-Copper-Lead Sulfides and Zinc Spinel (Gahnite) in Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 1550

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*By* DOUGLAS M. SHERIDAN *and* WILLIAM H. RAYMOND

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# PRECAMBRIAN DEPOSITS OF ZINC-COPPER-LEAD SULFIDES AND ZINC SPINEL (GAHNITE) IN COLORADO

By DOUGLAS M. SHERIDAN and WILLIAM H. RAYMOND

ABSTRACT

Precambrian sulfide deposits in the Southern Rocky Mountains in Colorado are being studied and reevaluated by the U.S. Geological Survey according to geologic concepts concerning ore-host rock associations, stratigraphic controls, and other factors. These concepts were developed elsewhere in recent years during successful research regarding economic massive sulfide deposits. Our work, initiated in 1974, has indicated that a new look at areas containing long-dormant mines and prospects may well lead to the discovery of economic Precambrian sulfide deposits. The zinc, copper, and lead contents of ores investigated to date, supplemented by silver and gold contents, indicate that many long-forgotten deposits may be minable today. The deposits occur in Precambrian rocks metamorphosed to the lower amphibolite facies in one major region and to the upper amphibolite facies in other regions. Field studies have provided ample evidence indicating that the search for commercial tonnages can be facilitated by using newer concepts of economic geology regarding ore-host rock associations as prospecting guides and by using structural considerations aimed toward learning how metamorphism and folding have modified the shapes and distribution of the ore bodies. Our field and laboratory data indicate that gahnite, a zinc spinel, can be used by geologists and prospectors as a guide to ore and can be considered by mining engineers as a potential major ore mineral, contributing significant amounts of zinc to the sulfide ores in many of the deposits. Our work to date indicates that the areas near Salida, Guffey, and Gunnison and several areas in the northern Park Range, the Front Range, and the Wet Mountains have particularly favorable ground for the occurrence of Precambrian sulfide deposits.

## INTRODUCTION

Precambrian sulfide deposits occur at numerous localities in the Southern Rocky Mountains in Colorado (fig. 1). Earlier studies of some of these deposits (Lindgren, 1908; Boyd, 1932, 1934; Lovering and Goddard, 1950), like similar earlier studies conducted elsewhere in the world, generally tended to evaluate the ores in terms of hydrothermal and magmatic concepts of origin, which were then conventional. During the last two decades, interest throughout the world has increased tremendously in massive sulfide deposits ranging in age from

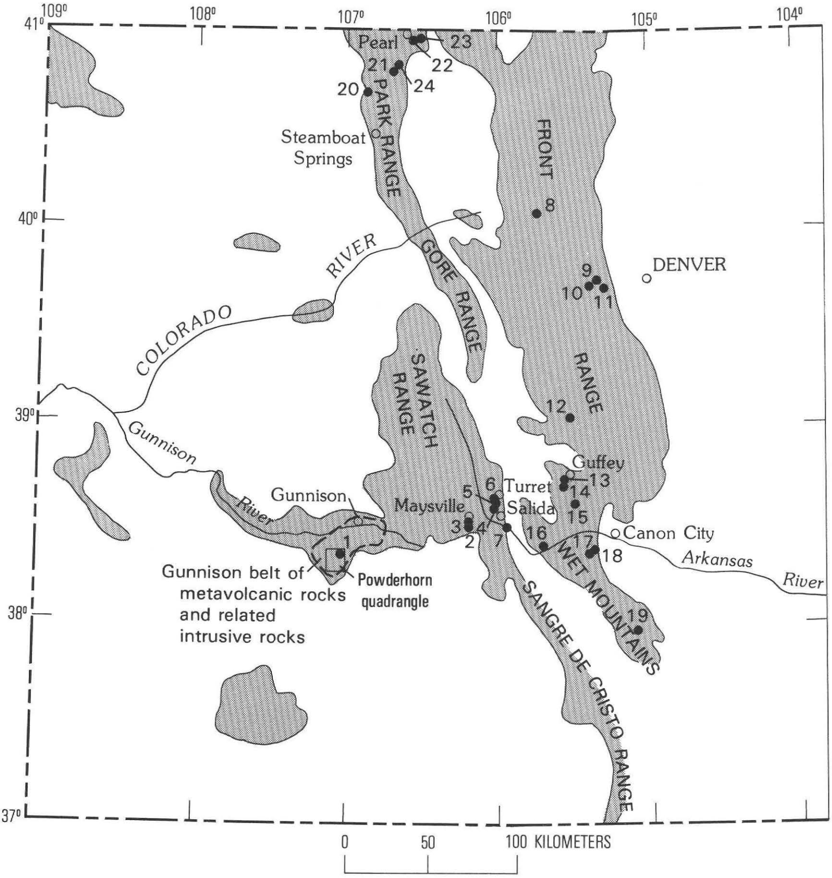



FIGURE 1.—Index map of western Colorado showing distribution of Precambrian rocks (shaded areas) and Precambrian sulfide deposits (numbered localities) mentioned in text: 1, Vulcan mine; 2, Bon Ton mine; 3, Cinderella No. 7 mine; 4, Sedalia mine; 5, Ace High and Jackpot prospect; 6, Independence mine; 7, mines and prospects near Cleora; 8, High Lonesome mine; 9, Hosa Lodge mine; 10, Creswell mine; 11, F. M. D. mine; 12, shafts at Wilkerson Pass; 13, Betty (Lone Chimney) mine; 14, Mill Gulch mine; 15, Isabel mine; 16, Cotopaxi mine; 17, Green Mountain mine; 18, mines and prospects in Grape Creek area; 19, Marion mine; 20, Greenville mines; 21, Slavonia mine (lower); 22, Wolverine mines; 23, Swede Group mines; 24, Slavonia mine (upper).

Precambrian to Tertiary. Much careful new work has been done concerning exhalative processes of ore formation and the relation of deposits to certain types of host-rock lithology (King and Thompson, 1953; Horikoshi, 1969; Anderson, 1969; Matsukuma and Horikoshi, 1970; Sangster, 1972; Stanton, 1972; Hutchinson, 1973). Many massive sulfide deposits in various parts of the world now are considered to be volcanogenic. Using the newer geologic concepts and newer, more refined guides to ore, mining companies have made many new discoveries, including, for example, the recent finding of two large Precambrian deposits: more than 7 million tons[1] of zinc-copper-lead ore at Izok Lake in the Northwest Territories, Canada (Money and Heslop, 1976, p. 24–25), and 60 million tons of zinc-copper ore at Crandon, Wis. (Eyde, 1977, p. 51).

Recognizing the importance of the newer concepts of economic geology and responding to increasing numbers of inquiries from the mining industry, the U.S. Geological Survey initiated a project in 1974 entitled "Precambrian sulfide deposits in Colorado." An earlier open-file report (Sheridan and Raymond, 1977) and the present report summarize the work that has been done and the results that have been obtained on this project through June 1977.

During the reconnaissance studies that were the basis for this interim report, sampling of the Precambrian sulfide ores and their host rocks was done at many old mines and prospects. Access to underground workings was not possible or was not considered safe at any of these old mines and prospects with the exception of the Sedalia mine near Salida, but even there access to unoxidized primary ore is extremely limited. Consequently, most of the sampling was conducted in the following manner from the materials available—usually those found on the dumps. Sampling of host rocks was done by searching for varieties presently available on dumps and in nearby outcrops and by selecting representative grab samples for petrographic studies to determine their lithology. Samples of sulfide-bearing materials, however, had to be collected with the realization that the miners and prospectors had already shipped the bulk of their ores long ago to whatever ore-buying and ore-testing facilities were available. At each mine and prospect, therefore, a diligent search was made to find and collect representative samples of sulfide-bearing materials that had been overlooked and discarded in the dumps. Such materials commonly represent only the minimal base- and precious-metal contents of the ores present in these deposits. Our sampling was done by collecting large composite samples of these sulfide-bearing materials. At some of the mines and prospects only one large composite sample was obtained. At others where a possible zoning of ores was recognized, large composite samples of each of the varieties were obtained. Splits of each of these samples were then made, with one part reserved for mineralogic and petrographic studies and the other part for analyses. In this interim report, the analytical data concerning the samples are tabulated as ranges and averages of the base- and precious-metal contents for various mining areas.

[1]Figures cited from published sources are in the units originally reported.

The significance of gahnite, the zinc spinel, as a prospector's guide to base-metal sulfide deposits in Colorado is described both in this report and in the earlier open-file report (Sheridan and Raymond, 1977). Although we had arrived at this conclusion independently through our own field and laboratory studies, we have learned subsequently that this same concept had been recognized much earlier in Australia. Paul G. Spry (written commun., 1982) informed us that gahnite has been used by mining companies for many years as an exploration guide for deposits of Broken Hill-type mineralization in the Willyama Complex in New South Wales. In his letter, Spry kindly referred us to three reports from Australian sources that are especially pertinent. Reports by Dewar (1968), Forwood (1968), and Stevens (1974) contain information indicating the usefulness of gahnite as an indicator of base-metal sulfide deposits of the Broken Hill type.

We gratefully acknowledge the advice and help given at various stages of this project by J. M. Franklin of the Geological Survey of Canada, by P. G. Spry of the University of Toronto, Canada, by J. E. Bever of Miami University, Ohio, and by our U.S. Geological Survey colleagues: R. B. Taylor, A. V. Heyl, Ogden Tweto, J. C. Olson, D. C. Hedlund, G. A. Desborough, W. J. Hasler, P. K. Sims, B. R. Doe, and G. L. Snyder.

## HISTORY

Many of the old mines and prospects in Precambrian sulfide deposits in Colorado date back to the last two decades of the nineteenth century. Most of them did not progress much beyond the prospecting and initial development stages, probably because of their low content of precious metals. The Precambrian sulfide ores generally contain less than 10 g (grams) of gold per metric ton (0.3 oz (ounce) per ton) and less than 70 g of silver per metric ton (2 oz per ton). Such contents of the precious metals were not sufficient at that time to support mining that was directed toward gold and silver, and other mines that opened during this early period were better sources of copper and zinc ores. The Sedalia mine near Salida has been the largest producer of ore from Precambrian sulfide deposits in Colorado. Heyl (1964, p. C83) estimated that nearly 100,000 tons of copper-zinc ore was produced from the Sedalia mine. According to J. V. Dodge (written commun., 1975), the Sedalia mine produced ores until the end of 1918 when copper ore prices dropped. The production from the Sedalia mine was principally from the oxidized zone of the deposit. A mining engineer's report (C. H. Swanton, written commun., 1922), given to us by J. V. Dodge, indicated that the sulfide ore was too hard to be worked by hand-mining, the only method ever used on the property, and that, consequently, little of the sulfide ore had been mined. Other mines, such as the Betty (Lone Chimney) mine in the Guffey area, managed to keep operating intermittently into the 1950's (Buford Dell, oral commun., 1975). According to G. L. Snyder (oral commun., 1977), production of ore at the Greenville mine in the Park Range occurred as recently as the World War II era. In general, however, activity at mines and prospects in Precambrian sulfide deposits has been long dormant in most areas in Colorado. The search for minable Precambrian sulfide deposits has become quite active in recent years in numerous areas in Colorado, New Mexico, and southern Wyoming. Currently, many of the known deposits are being reexamined closely by the U.S. Geological Survey, other governmental agencies, and mining companies. Some of the initial stimulus for this renewed interest most likely was given by Giles' suggestion (1974) that a significant part of the Precambrian terrane in northern New Mexico and southern Colorado may be a "previously unrecognized volcanogenic massive sulfide metallogenic province."

## GEOLOGIC SETTING AND GENERAL CHARACTER OF THE ORES

Precambrian sulfide deposits occur at many localities in Colorado (fig. 1) in metamorphic terranes that are known to be about 1,800 million years (m.y.) in age (Tweto, 1980, p. 37), that is, Proterozoic X. The progenitors of the metamorphic rocks were sedimentary, volcanic, and subvolcanic intrusive rocks (Tweto, 1977, p. D3). A major period of Precambrian folding and regional metamorphism reached its peak in the period 1,700–1,775 m.y. ago, according to radiometric age determinations (Hedge and others, 1967; Hedge and others, 1968; Hansen and Peterman, 1968; Silver and Barker, 1968; Stern and others, 1971). Hedge (1969) has suggested that the available isotopic data indicate that no great amount of time elapsed between the original deposition of the rocks and the time of metamorphism. Lead isotope studies on galena samples from Precambrian sulfide deposits in Colorado indicate an age falling in the same 1,700–1,800 m.y. bracket (Bruce Doe, oral commun., 1979). Syntectonic intrusive igneous rocks ranging in age from 1,650 to 1,730 m.y. are present in many areas and commonly are granodiorite and quartz monzonite of the Boulder Creek type (Tweto, 1977, p. D12).

Precambrian sulfide deposits occur in rocks metamorphosed principally to the lower amphibolite facies in the Gunnison area and in rocks metamorphosed to the upper amphibolite facies (sillimanite zone of regional metamorphism) in most other areas in Colorado. Whereas garnet is present in the lower grade terranes, sillimanite, cordierite, garnet, and, locally, andalusite are characteristic of the higher grade terranes.

The Precambrian sulfide deposits contain sphalerite, chalcopyrite, and galena as the principal ore minerals, but silver and gold also are present consistently in noteworthy amounts. Gahnite is present in many of the deposits, ranging in abundance from accessory amounts to ore quantities. Locally, molybdenum, tungsten, titanium, and nickel are present. Some of the ores consist of base-metal sulfides in a matrix composed predominantly of pyrite and (or) pyrrhotite; this type of ore is "massive sulfide," as defined by Sangster (1972, p. 11). More commonly, the ore specimens noted on dumps are of the disseminated type, characterized by probable minable-grade concentrations of base-metal sulfides complexly intergrown with a matrix of silicate minerals. The textural features observed in the ores indicate that the sulfide minerals and the silicates and other minerals of the matrix recrystallized together at the time of regional metamorphism.

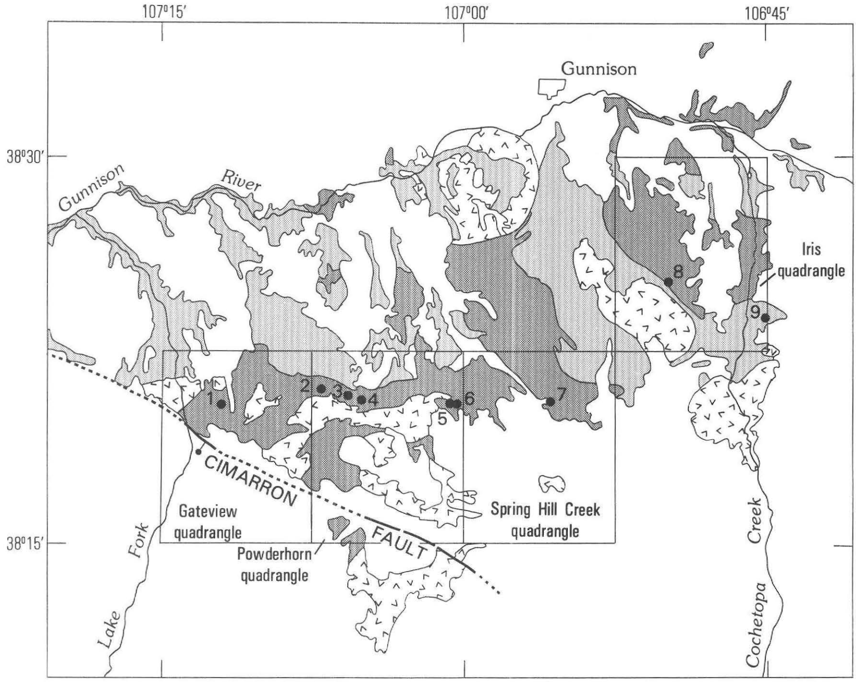
## DEPOSITS IN ROCKS METAMORPHOSED TO LOWER AMPHIBOLITE FACIES

The Gunnison area is one of few areas in Colorado where Precambrian metamorphism has not been severe enough to obliterate original textures and structures, which can be recognized in many of the outcrops. According to J. C. Olson and D. C. Hedlund (oral commun., 1977), most of the Precambrian rocks in this area are in the lower amphibolite facies, although the metamorphic grade in the western part is locally higher where rocks contain staurolite, kyanite, or andalusite; they noted that the rocks in the easternmost part of the area are in the greenschist facies.

### DEPOSITS IN THE GUNNISON AREA

The Gunnison area contains a belt of Precambrian greenstone, long known as "the Gunnison gold belt" (Lakes, 1896). This belt of metavolcanic rocks (the Proterozoic X Dubois Greenstone), together with related intrusive rocks, trends northeasterly (fig. 2) for about 50 km (kilometers) and is as much as 10 km wide. J. C. Olson and D. C. Hedlund recognized that gold deposits in the area "are spatially and probably genetically related to a belt of Precambrian metavolcanic rocks" (U.S. Geological Survey, 1970, p. A3).

We consider this belt of metavolcanic rocks to be especially favorable for discovery of minable Precambrian sulfide deposits, because the geologic environment is similar to that in productive areas in some parts of Canada and the United States. In addition to mafic metavolcanic rocks, the belt contains large volumes of felsic metavolcanics and numerous thin layers of quartzite that are believed to have originated as seafloor chert beds. Most of the presently known Precambri-




Geology simplified from
Tweto and others (1976)
Montrose 1° x 2° quadrangle

0 10 20 KILOMETERS

**EXPLANATION**

PHANEROZOIC ROCKS UNDIFFERENTIATED

PRECAMBRIAN
- GRANITIC INTRUSIVE ROCKS
- METASEDIMENTARY ROCKS
- DUBOIS GREENSTONE—METAVOLCANIC ROCKS

CONTACT

FAULT—Dotted where concealed, bar and ball on downthrown side

•3 SULFIDE DEPOSIT

NAMES OF MINES
1 White Iron
2 Headlight
3 Anaconda
4 Ironcap
5 Good Hope
6 Vulcan
7 Midland
8 Denver City
9 Yukon

FIGURE 2.—Distribution of Precambrian sulfide deposits in the Gunnison area, Colorado.

an sulfide deposits occur within the belt of metavolcanic rocks (fig. 2), but one deposit occurs in metasedimentary terrane. Geologic maps that provide coverage of the entire greenstone belt have been published in recent years by the U.S. Geological Survey on 7½-minute topographic quadrangle bases (Olson, 1974, 1976a,b; Olson and Hedlund, 1973; Olson and Steven, 1976a,b; Olson and others, 1975; Hedlund, 1974; Hedlund and Olson, 1973, 1974, 1975).

We examined and sampled dumps and outcrops at numerous mines and prospects in the greenstone belt—mostly in the Powderhorn quadrangle (Hedlund and Olson, 1975), including the Vulcan mine (Lakes, 1896), and to a lesser extent elsewhere in the belt. The Precambrian sulfide deposits are elongate parallel to gradational and interfingering contacts between mafic and felsic metavolcanic rocks. Groups of deposits appear to be strung out parallel to contacts. Some groups of deposits are adjacent to thin beds of magnetite-bearing quartzite. Sulfides commonly occur in laminae or elongate aggregates parallel to layering and foliation. Some specimens of ores are crudely banded. The ores are characterized by abundant pyrite accompanied by variable amounts of sphalerite and chalcopyrite. The sulfides generally are fine grained (<1 mm—millimeter) but locally are medium grained (1–5 mm). Locally, as at the Headlight mine in the Powderhorn quadrangle, the zinc spinel, gahnite, also is present in the ore; the terrane in the vicinity of the Headlight mine has been metamorphosed to a somewhat higher grade than the lower amphibolite facies.

The base-metal and precious-metal contents of samples of ore from five mines in the Powderhorn quadrangle are summarized in table 1. Zinc is the principal base metal, followed in abundance by copper and a minor amount of lead.

At the time of our reconnaissance studies in 1975, exploration for Precambrian massive sulfide deposits was being conducted in the Powderhorn quadrangle by two mining companies. In 1976, one company also conducted some exploration in a small area near Cochetopa Canyon in the eastern part of the greenstone belt. We understand that these exploratory efforts revealed deposits of minable grade but, in light of only scattered drilling, of insufficient size to mount a major mining effort.

## ECONOMIC POTENTIAL

Despite the fact that limited drilling has revealed no minable deposits thus far, we believe that the Gunnison belt of metavolcanic rocks has good potential for the discovery of large economic Precambrian sulfide deposits. The geologic evidence is compelling that the deposits are volcanogenic. The large size of this belt of metavolcanic rocks, the generally favorable geologic setting in the belt, the existence of ores previously mined economically, and the fact that clusters of old mines and prospects are present in many parts of the belt suggest that additional search may lead to the discovery of large con-

TABLE 1.—*Analyses of Precambrian ores from the Powderhorn quadrangle, Colorado*

[Data for copper, zinc, lead, and silver from semiquantitative spectrographic analyses by N. M. Conklin, U.S. Geological Survey; data for gold from analyses by fire assay and atomic absorption methods by J. G. Crock, A. W. Haubert, and Joseph Haffty, U.S. Geological Survey]

| | 5 samples from dumps of 5 mines | |
|---|---|---|
| | Range | Average |
| Copper (percent) | 0.07-7.0 | 2.3 |
| Zinc (percent) | .1->10 | >6 |
| Lead (percent) | 0-.3 | .13 |
| Silver (grams/metric ton) | 3-70 | 30 |
| Silver (troy ounces/short ton) | .09-2.06 | .94 |
| Gold (grams/metric ton) | .13-2.11 | .71 |
| Gold (troy ounces/short ton) | .004-.061 | .021 |

cealed deposits or to the discovery that some known deposits may extend down-plunge a considerable distance from their surface showings.

Search can be continued in various parts of the greenstone belt, both in areas where deposits are clustered and in areas extending laterally from such clusters. Commonly used Canadian guides to ore (lithologic and stratigraphic) can be used to search for favorable areas for exploration along contacts between felsic and mafic metavolcanics and along the thin layers of metachert. A search for so-called "mill-rock" (pyroclastic breccias), as advocated by Sangster (1972, p. 3) for Canadian terranes, may prove useful in prospecting for areas in which massive sulfide deposits are likely to occur. In addition to advocating use of these lithologic and stratigraphic guides to ore, we also urge strongly that special attention be paid to folds and lineations. Folds are present in this region, and they probably formed at the time of regional metamorphism. The deformation may well have modified considerably the original (presumably tabular) shapes of Precambrian sulfide deposits. The possibility should be recognized that deposits may be rod-shaped rather than discoidal or tabular, and a search for fold-axes and other b-lineations defining the dominant plunge direction is pertinent. Although plunge directions may not form a consistent regional pattern, the directions found in local areas could well be highly significant in determining the extent, shape, and size of ore bodies.

## DEPOSITS IN ROCKS METAMORPHOSED TO UPPER AMPHIBOLITE FACIES

With the exception of a small area of rocks belonging to the lower amphibolite facies southeast of Salida, the Precambrian rocks in all other areas examined have been metamorphosed to the upper amphibolite facies (the sillimanite zone of regional metamorphism) and locally even higher. In or close to all the areas examined, sillimanite is present in layers of pelitic gneiss or schist, and cordierite is common in the host rocks of the deposits. Original textures and structures have been modified so greatly by intense regional metamorphism and deformation that the original nature of many rocks is difficult to determine. Despite these difficulties, the combination of adequate prior study with mapping in many of these areas is sufficient to establish that the Precambrian metamorphic complex consists of interlayered metasedimentary and metavolcanic rocks. In some areas the rocks have been modified by retrograde processes, but the changes have been only moderate.

In the areas studied, amphibolites and feldspar-rich gneisses are abundant and are interlayered with varying amounts of sillimanitic gneiss or schist, calc-silicate gneiss, and, locally, impure marble. Many of the amphibolitic rocks are interpreted as having been derived from mafic volcanic rocks, and many of the feldspar-rich gneisses are interpreted as having been derived from felsic volcanic rocks. The sillimanitic schists and gneisses, the calc-silicate gneisses, and the impure marbles probably were originally shales and limestones.

R. B. Taylor (oral commun., 1975) acquainted us in the field with a small area southeast of Salida. The rocks there are lower in metamorphic grade, having been metamorphosed only as high as the lower amphibolite facies. They resemble some of the rocks in the Gunnison greenstone belt. They include breccia units with basaltic porphyry fragments and a felsic unit containing phenocrysts and flattened pumice fragments; present also are fine-grained quartzitic layers. North and northwest from this area, however, the metamorphic grade changes to that of the upper amphibolite facies, and most of the original textural and structural features have been obliterated. In describing this same general area, Boardman (1976, p. 96) reported a gradual south-to-north transformation of welded tuff units into quartz-feldspar gneisses.

Precambrian sulfide deposits occur in rocks of the upper amphibolite facies in most of the Salida area and in the Front Range, Wet Mountains, and Park Range (fig. 1). Locally in parts of the Wet Mountains, the metamorphic grade reached the amphibolite-granulite transitional facies (Raymond and others, 1980, p. 19–20). The principal ore minerals are sphalerite, chalcopyrite, and lesser amounts of silver-bearing galena. Gahnite, the zinc spinel, occurs in most of these sulfide deposits; and, in some, it is so abundant that it merits consideration as an ore mineral.

## DEPOSITS IN THE VICINITY OF SALIDA

Numerous Precambrian sulfide deposits are clustered in the vicinity of Salida (fig. 3), including the Sedalia mine, northwest of Salida; the Independence mine (Lindgren, 1908, p. 166) and the Ace High and

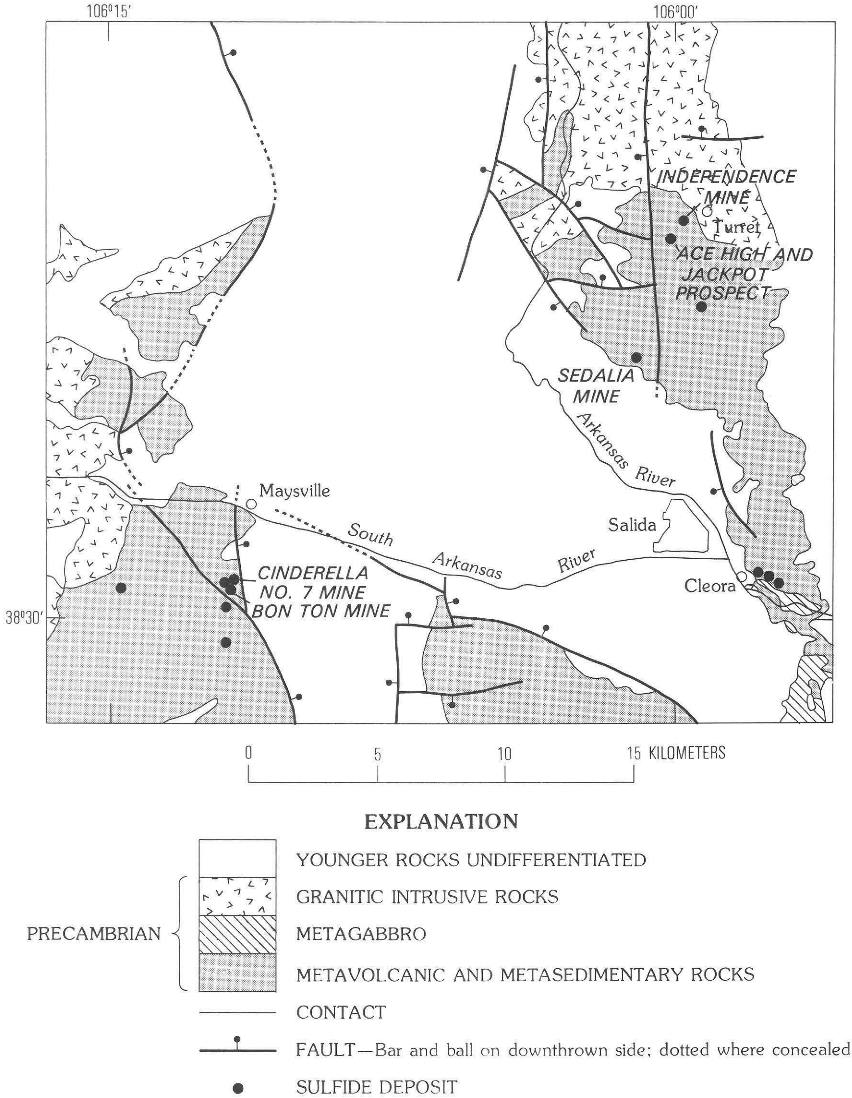



FIGURE 3.—Distribution of Precambrian sulfide deposits in the Salida area, Colorado. Geology modified from Tweto and others (1976) and Scott and others (1975).

Jackpot prospect (Van Alstine, 1969, p. 43–44) in the vicinity of Turret, an abandoned mining town north of Salida; and the Bon Ton mine (Crawford, 1913, p. 280), Cinderella No. 7, and several other deposits in the area south of Maysville, a small community west of Salida. In addition, Precambrian quartz veins containing copper and tungsten are present near Cleora, 3 km southeast of Salida (Tweto, 1960, p. 1420–1422). The general geology of the region is shown on a map of the Salida area (Boardman, 1976, fig. 1) and on maps of the Poncha Springs quadrangle (Scott and others, 1975; Van Alstine, 1969, 1974).

In 1975 and 1976, all the main mines and numerous other prospects were visited, and samples of ores and host rocks were collected. The area surrounding the Sedalia mine was mapped on large-scale aerial photographs, and the geology of accessible parts of the mine was mapped.

The layered succession of metamorphic rocks in the Sedalia mine area (fig. 4) trends northeast and dips steeply southeast. Major lithologic units mapped in the area are amphibolite, feldspathic gneiss, mica schist, and garnet-cordierite-amphibole gneiss and garnetiferous schist. These units were intruded by small bodies of metagabbro and pegmatite. The Precambrian sulfide deposit at the mine is associated with and is alined along medium- to coarse-grained garnet-cordierite-amphibole gneiss. Present locally in the ore zone is a carbonate-bearing calc-silicate rock. Sphalerite, chalcopyrite, and lesser amounts of silver-bearing galena are the major primary ore minerals in the deposit. Although pyrite, pyrrhotite, and magnetite are present also, the iron sulfides do not form a dominating matrix. Instead, the base-metal sulfides commonly are contained in ore-grade amounts in a rock rich in pale-gray magnesian amphiboles. Common also in this same type of rock are green grains and aggregates of gahnite, the zinc spinel (fig. 5). The sulfide minerals occur both as disseminated grains and aggregates and as crude laminations parallel to the lithologic layering. Evidence for textural parallelism between ore minerals and silicate minerals is abundant, although locally some of the sulfide minerals appear to have been mobilized to form discordant irregular stringers. The ore minerals, iron sulfides, gahnite, and magnetite are commonly medium grained, although locally some fine-grained and coarse-grained textures are present also. Scheelite has been reported at the Sedalia mine (Tweto, 1960, p. 1420–1421). The uppermost 100 m (meters) of the ore body is partly oxidized and contains various secondary zinc and copper minerals, which supplied most of an estimated 100,000 tons of ore previously mined. Much tonnage of such supergene ore still remains and includes chalcocite, hydrozincite, malachite, smithsonite, hemimorphite, willemite, aurichalcite, rosasite(?), chalcanthite, cerussite, goslarite, anglesite, linarite, and cuprite (Heyl, 1964, p. C31; written commun., 1981).

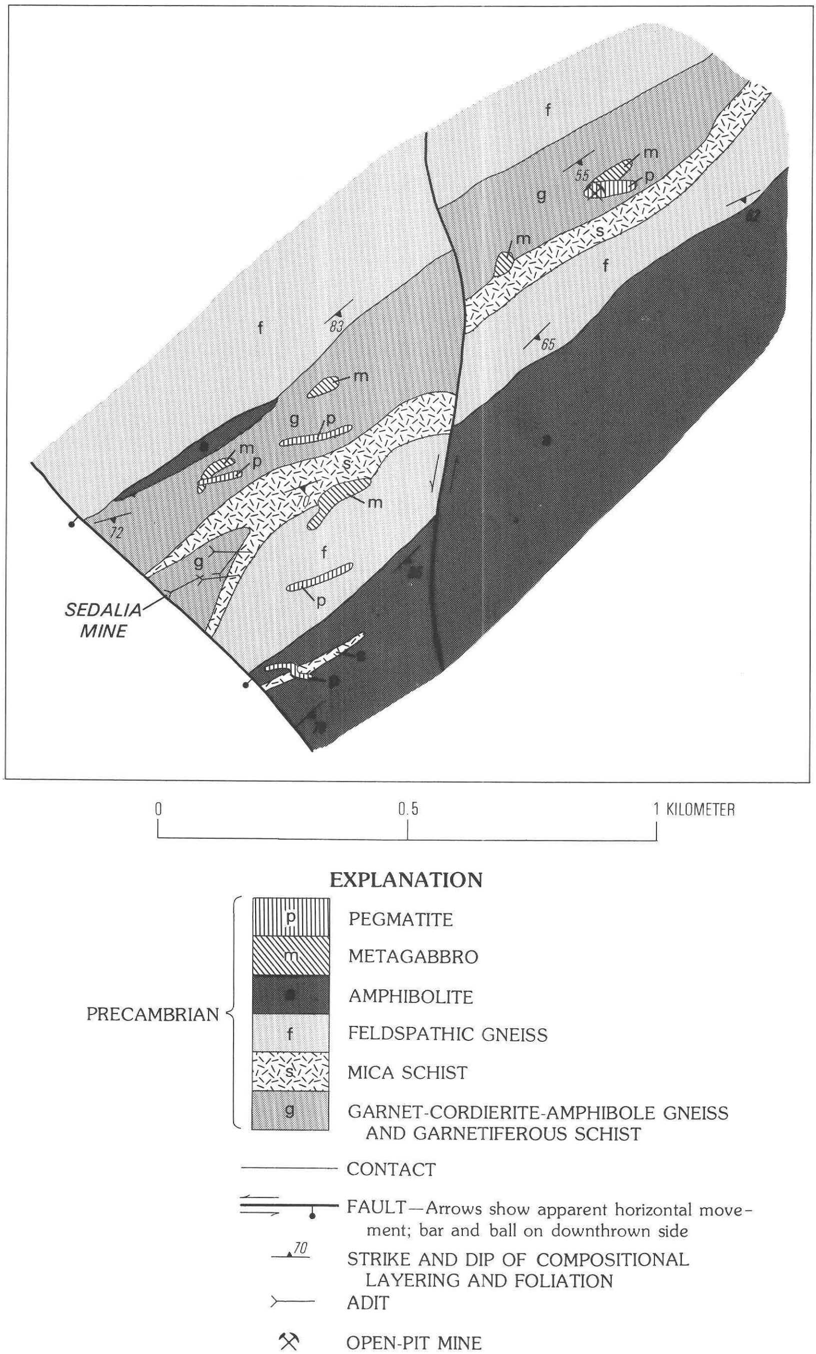



FIGURE 4.—Geologic map of the Sedalia mine area, Colorado. Geology by D. M. Sheridan and W. H. Raymond, 1976.

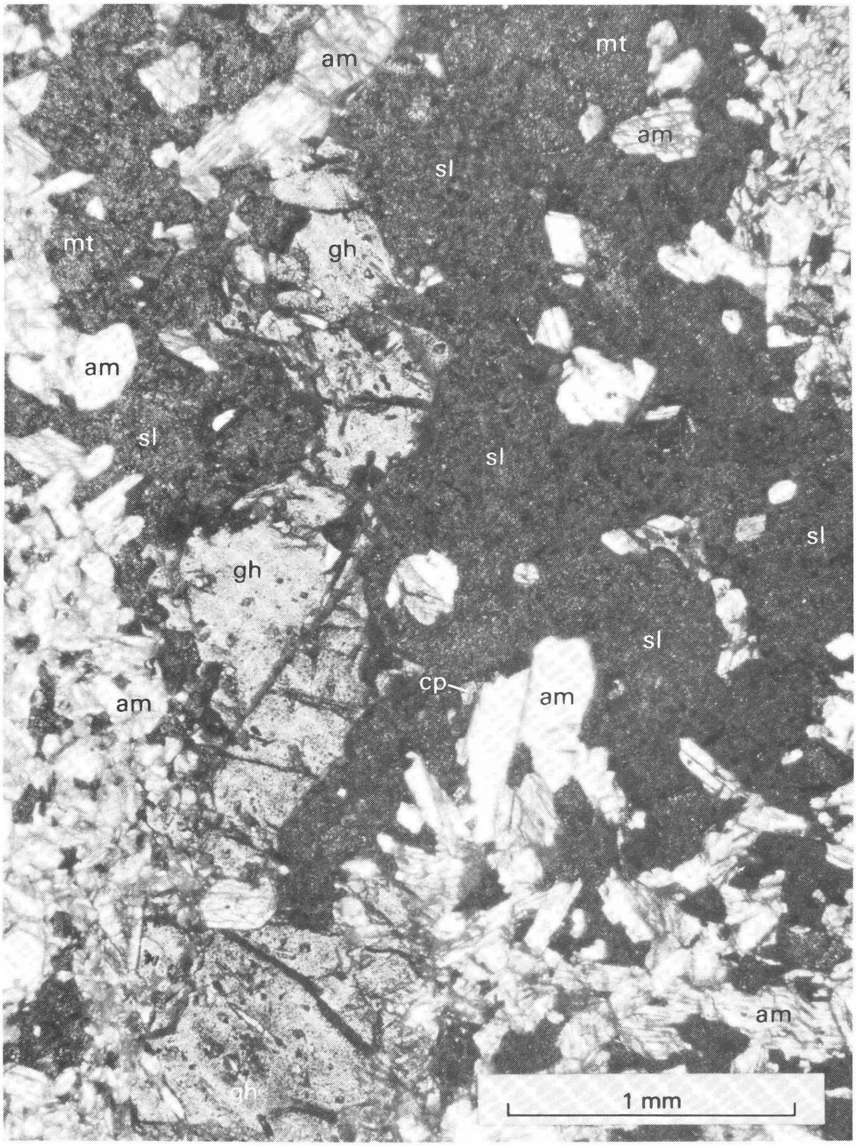



FIGURE 5.—Photomicrograph of gahnite-bearing ore from the Sedalia mine, Colorado. Gahnite (gh) is intergrown with sphalerite (sl) in a matrix of light-colored amphibole (am). Other minerals are magnetite (mt) and chalcopyrite (cp). Plane-polarized light.

At the other mines and prospects in the vicinity of Salida, the ore minerals are associated with rocks similar to those forming the layered succession at the Sedalia mine. Garnetiferous biotite-quartz gneiss, various kinds of amphibole-rich rocks, and cordierite-biotite-amphibole gneiss are commonly the main host rocks. In the area south of Maysville, a layer of banded magnetite-quartz iron-formation forms part of the layered succession near the sulfide deposits. Sphalerite and chalcopyrite are the principal sulfide minerals present in deposits throughout the Salida region. In the Maysville area, galena was observed at one mine and scheelite at another mine. In the Turret area, molybdenite was noted at one mine and noteworthy amounts of rutile were observed at another mine. Textural features and grain size of the ores are similar to those at the Sedalia mine.

The clustering of numerous deposits in the Salida region and the association of ore minerals with magnesium-rich amphiboles and garnetiferous gneiss suggest a common mode of origin. Although the shapes of the ore bodies are not known in detail, they clearly are alined approximately parallel to the lithologic layering. A logical assumption, therefore, is that the ore bodies were originally stratiform deposits that have been recrystallized and deformed during high-grade regional metamorphism to their present mineralogy and distribution. In the light of recent studies in Canada and elsewhere, the combination of evidence in the Salida area suggests that the deposits originally may have been products of some sort of exhalative process, although high-grade metamorphism makes it difficult to prove that they are volcanogenic.

The base-metal and precious-metal contents of ore samples from the vicinity of Salida are summarized in table 2. The summary indicates that the ores contain appreciable amounts of zinc and copper and that silver averages between 20 and 30 g/metric ton (between 0.5 and 1 oz/ton).

## GAHNITE AND ITS SIGNIFICANCE

During field studies in the vicinity of Salida, we found that gahnite, the zinc spinel, occurs at all the mines and at most of the prospects in Precambrian sulfide deposits. Although Lindgren (1908, p. 165) had noted the presence of spinel at the Sedalia mine and Crawford (1913, p. 205) had reported the presence of gahnite at the Bon Ton mine in the area south of Maysville, the zinc spinel apparently has been considered merely as a mineralogic curiosity during the ensuing years. Instead of finding it as a rare accessory, we found that gahnite is characteristic of the ores and is present in noteworthy amounts at some of the deposits. At the Bon Ton mine, for example, gahnite-biotite-quartz gneiss (figs. 6 and 7) and gahnite-bearing garnet-biotite-quartz gneiss (fig. 8) are abundant. Moreover, we also found gahnite to be megascopically identifiable in lithologic units adjacent to and along strike from some of the known sulfide deposits.

Because gahnite occurs in such abundance in several of the deposits,

TABLE 2.—*Analyses of Precambrian ores from the vicinity of Salida, Colo.*

[Data for copper, zinc, lead, and silver from semiquantitative spectrographic analyses by J. C. Hamilton, N. M. Conklin, and M. W. Solt, U.S. Geological Survey; data for gold from analyses by fire assay and atomic absorption methods by J. G. Crock, A. W. Haubert, and Joseph Haffty, U.S. Geological Survey]

| | Sedalia mine (5 samples from dumps and 5 samples from underground workings) | | Turret area (4 samples from 2 mine dumps) | | Maysville area (5 samples from dumps of 3 mines and 1 prospect) | |
|---|---|---|---|---|---|---|
| | Range | Average | Range | Average | Range | Average |
| Copper (percent) | 0.15->10 | >3.8 | 0.05-3.0 | 0.8 | 0.07-3.0 | 1.3 |
| Zinc (percent) | .3->10 | >5.2 | 1.0-5.0 | 3.5 | 1.5->10 | >6.9 |
| Lead (percent) | .001-5.0 | .5 | 0-.002 | Trace | .002-.1 | .03 |
| Silver (grams/metric ton) | 3-70 | 30 | 0-70 | 20 | 7-70 | 30 |
| Silver (troy ounces/short ton) | .10-2.06 | .79 | 0-2.06 | .65 | 0-2.06 | .91 |
| Gold (grams/metric ton) | .08-.64 | [1].24 | .07-2.00 | [2]1.04 | .12-.68 | [3].40 |
| Gold (troy ounces/short ton) | .002-.019 | [1].007 | .002-.058 | [2].030 | .004-.020 | [3].012 |

[1]Average of 8 analyses.
[2]Average of 2 analyses.
[3]Average of 2 analyses.

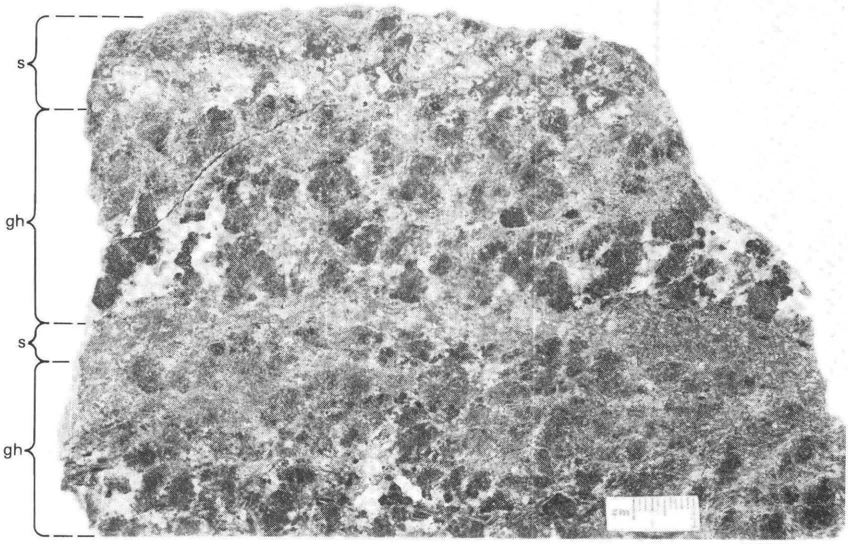



FIGURE 6.—Photograph of polished slab of gahnite-biotite-quartz gneiss from the Bon Ton mine, Colorado, showing layers of gahnite-rich rock (gh) alternating with thinner sulfide-bearing layers (s). Many of the larger grains of gahnite, 3–10 mm in size, are clearly visible as prominent dark grains in the photograph, but many smaller grains of gahnite are interspersed among the biotite and quartz of the matrix. Sulfide minerals in the thinner layers are sphalerite, chalcopyrite, and minor pyrite and galena.

we collected samples to determine analytically how much zinc such rocks contain. Although gahnite occurs in varying proportions with the base-metal sulfides, the samples chosen for this study are gahnite-bearing rocks containing only minor amounts of sulfides; this was done in order to ascertain the amounts of zinc contributed principally by gahnite. Analyses of gahnite-bearing rocks from several mines and prospects are reported in table 3.

In light of these analytical results and the large quantities of gahnite-bearing material observed on some of the dumps, gahnite must be considered a potentially significant ore mineral in these deposits. Note, in this regard, that franklinite (another zinc-bearing spinel), willemite, tephroite, and gahnite—all highly refractory multiple oxides and silicates—are components of ores that have been mined and smelted successfully for many years from the deposits at Franklin and Sterling Hill, N. J. Therefore, modified beneficiation processes and metallurgical methods may make possible the utilization of both the gahnite and the sulfide components of the ores of the Salida region.

Shown also in table 3 are the results of analytical work on two samples obtained from outcrops of gahnite-bearing rocks. Analysis 10, giving 5 percent zinc, is a gahnite-bearing cordierite-biotite gneiss

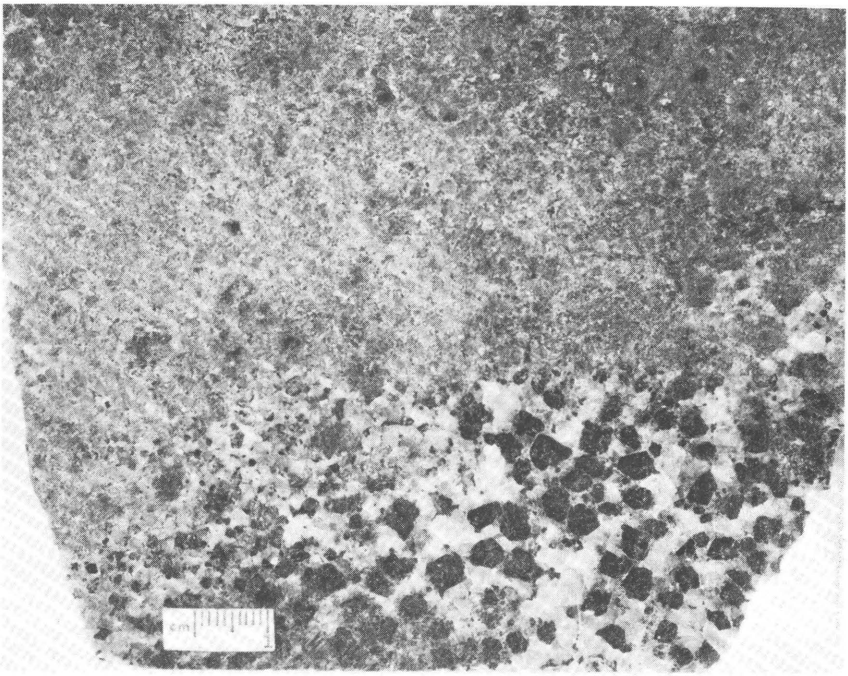


FIGURE 7.—Photograph of polished slab of gahnite-rich rock from the Bon Ton mine, Colorado. A layer of gahnite-quartz rock in the lower part of the photograph contains subhedral to euhedral grains of gahnite as much as 6 mm across. The finer-grained layer comprising the upper part of the photograph contains equally abundant but finer grains of gahnite interspersed in a matrix of biotite and quartz containing abundant chalcopyrite.

that crops out along the southeast side of the ore zone at the Sedalia mine. Analysis 11, giving 1.25 percent zinc, is a gahnite-bearing quartz-mica schist that occurs along the northern margin of the layer of garnet-cordierite-amphibole gneiss and garnetiferous schist in an area 2 km northeast of the Sedalia mine (fig. 4). Although not delineated separately on figure 4, the gahnite-bearing schist crops out intermittently for 240 m along strike and is as much as 40 m thick. In addition to its occurrence in outcrops in the Sedalia mine area, gahnite also can be traced along the trend of layering in the cluster of deposits south of Maysville. The presence of gahnite in outcrops where sulfides are sparse or even absent may be a significant and useful clue in searching for concealed Precambrian sulfide deposits.

## ECONOMIC POTENTIAL

Field and laboratory studies to date suggest that the Salida region has good potential for workable deposits. The clustering in this region of numerous deposits containing materials of probable economic grade

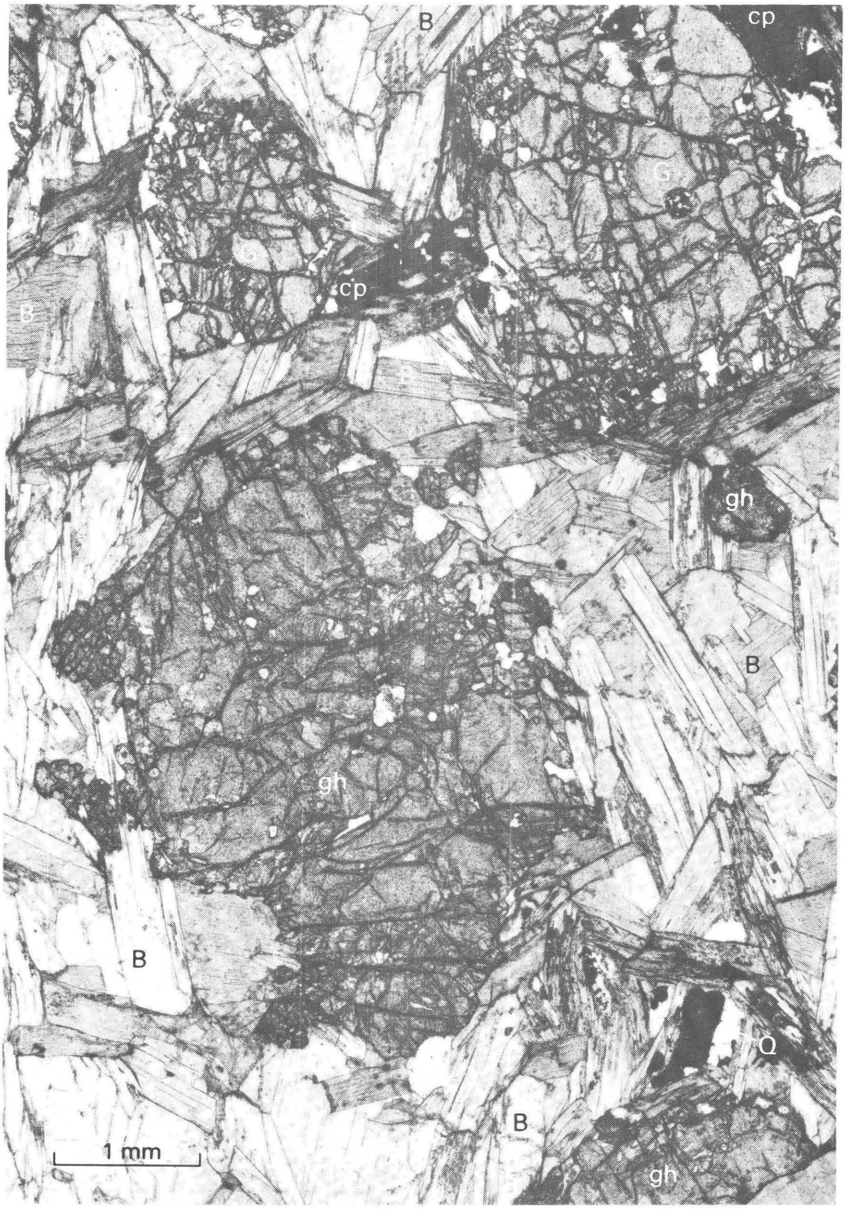



FIGURE 8.—Photomicrograph of gahnite-bearing garnet-biotite-quartz gneiss from the Bon Ton mine, Colorado. Gahnite (gh) and garnet (G) are in large subhedral to euhedral grains set in a matrix of biotite (B) and quartz (Q). Other mineral shown is chalcopyrite (cp). Plane-polarized light.

(table 2), the significant quantities of gahnite (table 3), and the association of the ores with garnetiferous and magnesium-rich rocks suggest both a common mode of origin for all these deposits and the favorabil-

TABLE 3.—*Zinc content of gahnite-bearing rocks from the vicinity of Salida, Colo.*

[C, chemical analyses for zinc (in percent) determined by $NA_2O_2$ fusion-atomic absorption method by J. G. Crock, U.S. Geolgoical Survey; S, analyses for zinc (in percent) converted from semiquantitative spectrographic analyses (in parts per million) by J. C. Hamilton and M. W. Solt, U.S. Geological Survey]

| Analysis Number | Locality | Lithology | Zinc (percent) | Type of analysis |
|---|---|---|---|---|
| 1. | Sedalia mine, dump-------------- | Gahnite-amphibole rock----------------- | 7.0 | C |
| 2. | Sedalia mine, Dewey level------- | -----do-------------------------------- | 7.7 | C |
| 3. | Mine A, dump (Turret area)------ | Gahnite-bearing amphibole-mica rock---- | 3.5 | C |
| 4. | Mine A, dump (Turret area)------ | -----do-------------------------------- | 4.2 | C |
| 5. | Mine B, dump (Turret area)------ | Gahnite-biotite-amphibole rock--------- | 7.3 | C |
| 6. | Mine C, dump (Maysville area)--- | Gahnite-bearing garnetiferous gneiss--- | 7.8 | C |
| 7. | Mine C, dump (Maysville area)--- | Gahnite-rich gneiss-------------------- | 12.5 | C |
| 8. | Prospect, dump (Maysville area)- | Gahnite-quartz gneiss------------------ | 10 | S |
| 9. | Mine D, dump (Maysville area)--- | Gahnite-quartz-mica gneiss------------- | 10 | S |
| 10. | Outcrop, east side of Sedalia mine. | Gahnite-bearing cordierite-biotite gneiss. | 5 | S |
| 11. | Outcrop 2 km northeast of Sedalia mine. | Gahnite-bearing quartz-mica schist----- | 1.25 | C |

ity of this region for additional search. Exploration might lead to the discovery of large concealed deposits along the trend of favorable lithologic units and to the discovery that some of the known deposits have a large down-plunge dimension.

Exploration for Precambrian sulfide deposits in this region can utilize the lithologic affinities noted in this report, together with the occurrence of gahnite as an ore-guide. Because the grade of metamorphism is high and because evidence for folding was noted by us in our studies and by Van Alstine (1974, p. 11, plate 1) and Boardman (1976, fig. 1), an important possibility to consider is that the shapes of Precambrian sulfide deposits, whatever their original shapes, have been modified considerably by folding and metamorphism. Sangster and Scott (1976, p. 189–190) have summarized changes in form that can occur during metamorphism, noting that the ore bodies at Balmat, N. Y. (also described by Lea and Dill, 1968), and at Chisel Lake, Manitoba (also described by Martin, 1966), have been changed from a presumably oval form to a linear- or rod-shaped form during medium- to high-grade metamorphism. Even more complex forms of ore bodies, including pinching and swelling (possibly related to boudinage), are reported by Sangster and Scott (1976, p. 190). Money and Heslop (1976, p. 26–27) noted that some thickening and thinning of Canadian ore bodies associated with cordierite- and gahnite-bearing rocks may have been partly an original feature and (or) possibly related to boudinage during deformation. Most massive and disseminated sulfide bodies seen by A. V. Heyl, J. L. Jolly, and C. N. Bozion in the Appalachians in 1966–1968 are elongated along the lineations as boudins (A. V. Heyl, oral commun., 1981). Due consideration must be given therefore to the probability that ore bodies may have been modified considerably in form and distribution by folding and high-grade regional metamorphism. Local evidence of plunge directions could be of great value in planning exploration programs, although complexly folded, thinned, thickened, and even dislocated ore bodies are all possible in terrane that has been so highly metamorphosed. Due allowance for the potential economic value of gahnite as an ore mineral should be made in any evaluation of the Precambrian sulfide deposits in the Salida region.

## DEPOSITS IN OTHER AREAS IN COLORADO

During the field seasons of 1975 and 1976, we visited and sampled ores and host rocks at numerous Precambrian sulfide deposits in widely scattered areas in the Front Range, Wet Mountains, and Park Range. Mines visited in the Front Range (fig. 1) include the High Lonesome mine (Lovering and Goddard, 1950, p. 71); the Creswell mine (Eckel, 1961, p. 22) and F. M. D. and Hosa Lodge mines (Lovering and Goddard, 1950, p. 67, 70), all in the east-central Front Range; mine shafts at Wilkerson Pass; the Betty (Lone Chimney) and Mill Gulch mines (Lovering and Goddard, 1950, p. 69) and others in the Guffey area; the Isabel mine (Lovering and Goddard, 1950, p. 68); and the Cotopaxi mine (Lindgren, 1908, p. 166–167; Salotti, 1965, p. 1179–1212). Mines visited in the Wet Mountains (fig. 1) include the Green Mountain mine, numerous mines and prospects in the Grape Creek area, and the Marion mine (Salotti, 1965, p. 1179). Preliminary studies made late in the 1976 field season in the Park Range (fig. 1) included brief visits to the Greenville mines, the Slavonia mine (lower), and several mines near the old mining community of Pearl, including the Wolverine mines and the Swede Group mines. In addition to these reconnaissance studies, a more detailed study was made of the Betty mine area southwest of Guffey; this study was aided by field visits with James E. Bever, who also kindly provided geologic maps (Bever, 1954).

Host rocks in these widely scattered localities are more diverse in lithology than those in the Salida area and range in character from garnetiferous gneisses and amphibole-rich rocks to calc-silicate gneisses and impure marbles. Deposits such as the F. M. D. mine in the east-central Front Range and some of the prospects in the Grape Creek area in the Wet Mountains have garnetiferous biotitic gneiss and dark amphibolites as the hosts of the sulfide minerals. At the other extreme, the deposit at the Creswell mine in the east-central Front Range is associated with a calc-silicate gneiss gradational locally to impure marble. Other deposits, such as the Betty mine in the Guffey area, have several interlayered host rocks, including cordierite-sillimanite-quartz gneiss and amphibole-rich rocks of various types; calc-silicate rocks are also present in the mine area. At the Marion mine in the Wet Mountains, the host rocks are interlayered amphibole-rich gneiss, calc-silicate gneiss, and impure marble. Sapphirine, a rare magnesium-iron-aluminum silicate, has been identified (Raymond and others, 1980) in the host rocks of Precambrian sulfide deposits at three mines and prospects in the Marion mine area.

The ores noted on dumps at these various localities range from typical massive sulfide, containing greater than 50 percent sulfide minerals (Sangster, 1972, p. 11), to disseminated types containing ore-grade concentrations of base-metal sulfides in a matrix of silicate minerals. Some specimens from the F. M. D. mine and mines in the Grape Creek area consist of base-metal sulfides in a matrix composed almost entirely of pyrite or pyrrhotite. Some ore specimens at the Betty mine and the Marion mine contain more than 50 percent copper sulfide or combined copper and zinc sulfide. Ores of the disseminated type are more common, however. In these the ore minerals are commonly alined along the layering and foliation. In the impure marbles and calc-silicate rocks, the sulfides are disseminated more randomly, with galena, sphalerite, and chalcopyrite occurring in irregularly scattered clots and aggregates. The ore minerals in most of these deposits are medium to coarse grained. Grains or aggregates of galena and sphalerite as large as 5 cm occur in skarn-like calc-silicate rocks.

The deposits in the Front Range, Wet Mountains, and Park Range are varied and all may not be of the same origin. Although some may be of an exhalative seafloor origin, some, particularly the disseminated deposits associated with calc-silicate rocks and impure marbles, possibly may have been syngenetic or epigenetic stratiform ore deposits in sedimentary rocks before metamorphism.

The base-metal and precious-metal contents of ore samples from the Front Range and the Wet Mountains are summarized in table 4. As in the Salida region, zinc is again the chief base metal. Lead is somewhat more abundant than in the Salida region. The ores average more than 40 g of silver per metric ton (more than 1.2 oz of silver per ton).

## DISTRIBUTION AND SIGNIFICANCE OF GAHNITE

The zinc spinel, gahnite, is present in varying amounts in numerous localities in the Wet Mountains, Front Range, and Park Range. Table 5 presents several analyses of gahnite-bearing rocks from this broad region. Analyses 1 through 3 from the Betty mine and another mine in the Guffey area of the Front Range indicate that gahnite could make a noteworthy contribution to the total zinc content of sulfide ores from this area. Analysis 4 from Mine F in the Wet Mountains suggests that gahnite might be useful as a prospecting guide in that area. Analysis 5 from Mine G in the Wet Mountains is of a gahnite-rich amphibole rock (fig. 9) that could contribute significant amounts of zinc to the ore. Analysis 6 is of a gahnite-bearing gneiss that crops out north of the Cotopaxi mine. Megascopically identifiable gahnite in these outcrops, confirmed by this analysis, suggest again that gahnite can be used as a prospector's guide to ore, even where sulfide minerals or their oxidation products are not seen in the outcrops. Our preliminary work in the Park Range indicates that gahnite also may be significant in that region. Gahnite is present in samples we obtained from the Greenville mines and is present also in certain layers of Precambrian metamorphic rocks in the Pearl area.

Analysis 7 in table 5 represents a gahnite-bearing layer of sillimanite-quartz gneiss that occurs 0.25 km north of the Creswell mine in the east-central Front Range. The Creswell mine is shown (but

TABLE 4.—*Analyses of Precambrian ores from other areas in Colorado*

[Data for copper, zinc, lead, and silver from semiquantitative spectrographic analyses by J. C. Hamilton, N. M. Conklin, and M. W. Solt, U.S. Geological Survey; data for gold from analyses by fire assay and atomic absorption methods by J. G. Crock, A. W. Haubert, and Joseph Haffty, U.S. Geological Survey]

| | Front Range (9 samples from dumps of 6 mines) | | Wet Mountains (12 samples from dumps of 4 mines) | |
|---|---|---|---|---|
| | Range | Average | Range | Average |
| Copper (percent) | 0.3-5.0 | 1.8 | 0.15-7.0 | 2.1 |
| Zinc (percent) | .2->10 | >4.7 | .10->10 | >4.4 |
| Lead (percent) | .002-1.5 | .3 | .001-10 | 1.1 |
| Silver (grams/metric ton) | 3-150 | 70 | 1.5-300 | 45 |
| Silver (troy ounces/short ton) | .09-4.41 | 1.97 | .04-8.82 | 1.26 |
| Gold (grams/metric ton) | .05-3.58 | [1].98 | <.05-9.24 | [2]1.6 |
| Gold (troy ounces/short ton) | .001-.105 | [1].029 | .001-.272 | [2].048 |

[1]Average of 6 analyses.
[2]Average of 9 analyses.

TABLE 5.—*Zinc content of gahnite-bearing rocks from other areas in Colorado*

[C, chemical analyses for zinc (in percent) determined by $Na_2O_2$ fusion-atomic absorption method by J. G. Crock, U.S. Geological Survey; S, analyses for zinc (in percent) converted from semiquantitative spectrographic analyses (in parts per million) by J. C. Hamilton and M. W. Solt, U.S. Geological Survey]

| Analysis Number | Locality | Lithology | Zinc (percent) | Type of analysis |
|---|---|---|---|---|
| 1. | Betty mine, dump (Front Range)--- | Gahnite-amphibole rock------------------ | 8.0 | C |
| 2. | Betty mine, dump (Front Range)--- | Gahnite-amphibole-cordierite rock------- | 19.1 | C |
| 3. | Mine E, dump (Front Range)------- | Oxidized copper ore containing gahnite-- | 10 | S |
| 4. | Mine F, dump (Wet Mountains)----- | Gahnite-bearing impure marble----------- | 1.25 | C |
| 5. | Mine G, dump (Wet Mountains)----- | Gahnite-amphibole rock------------------ | 7 | S |
| 6. | Outcrop, 90 m north of Cotopaxi mine (Front Range). | Gahnite-bearing quartz-sillimanite-mica gneiss. | 1.08 | C |
| 7. | Outcrop, 0.25 km north of Creswell mine (Front Range). | Gahnite-bearing sillimanite-quartz gneiss. | 3.9 | C |


FIGURE 9.—Photomicrograph of gahnite-amphibole rock from Mine G in the Wet Mountains, Colo. Gahnite (gh) and light-colored amphibole (am) form a foliated intergrowth in this specimen. Other mineral shown is chalcopyrite (cp). Plane-polarized light.

not by name) by symbols for mine shafts (recently bulldozed and backfilled) on the geologic map of the Evergreen 7½-minute quadrangle (Sheridan and others, 1972) in the SW¼ sec. 17, T. 4 S., R. 71 W. The gahnite-bearing layer crops out near the fault shown on this map north of the mine shafts within a map unit (map symbol hcs) of interlayered hornblende gneiss, calc-silicate gneiss, and amphibolite. As shown on a geologic map of the adjacent Squaw Pass quadrangle (Sheridan and Marsh, 1976), similar layers of light-colored gneiss containing small but variable amounts of gahnite and rutile (map symbol Xrg) extend for long distances subparallel to the main rutile-bearing layers of light-colored Precambrian gneiss reported in previous studies (Sheridan and others, 1968; Marsh and Sheridan, 1976). Gahnite also occurs with galena, sphalerite, chalcopyrite, calcite, and calc-silicate minerals in the sulfide-bearing zone at the Creswell mine.

## ECONOMIC POTENTIAL

Our field and laboratory studies to date in the Front Range, Wet Mountains, and Park Range suggest that certain areas are especially promising. The Betty mine area near Guffey in the Front Range (fig. 1) is considered one of the better areas in which to search for extensions of known deposits as well as to search for concealed deposits. Clustering of deposits in this area, ample evidence of ores of economic grade, and presence of anomalous amounts of zinc in lithologic units along strike from known sulfide deposits are evidence favoring the economic potential. Local clusters of deposits of minable grade in the Grape Creek area and in the vicinity of the Green Mountain mine in the Wet Mountains (fig. 1) also may be considered favorable for further economic consideration. Mines such as the Cotopaxi and Marion sometimes have been considered less favorably because they occur in xenoliths of metamorphic rocks engulfed in Precambrian granitic plutons. Our observations, however, suggest that the size of these xenoliths is so great that they could contain major ore bodies. Our studies in the Park Range (fig. 1) are barely started, but preliminary indications are that minable deposits also may occur in this region.

Exploration in these areas in Colorado can utilize the various lithologic affinities noted in this report, together with the presence of gahnite as an indicator mineral in many areas. As we emphasized in the discussion of the economic potential of the Salida region, due allowance must be made for the possible deformation of ore bodies; they may range from rod-shaped to complexly thinned, thickened, folded, and even dislocated, because of the intensity of metamorphism and folding in these areas. Such structural considerations are mandatory in terrane like this that has been subject not only to high-grade regional metamorphism but also to several episodes of folding (Moench and others, 1962; Sheridan and others, 1967, p. 57–70; Taylor, 1976). Attention to the significance of gahnite, both as a prospecting tool and as a potential ore mineral, is urged for this entire region.

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