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Preliminary report on the geology of the Sedalia mine area and its Proterozoic deposits of base-metal sulfides and gahnite, Chaffee County, Colorado

By

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ABSTRACT

The Sedalia mine, about 4 mi north-northwest of Salida, Chaffee County, Colorado, is developed in a Proterozoic zinc-copper sulfide deposit. Located in 1881, the mine produced about 90,000 tons of ore, largely from the oxidized upper part of the deposit, before closing in 1918 due to a decline in the price of copper. One of numerous Proterozoic sulfide deposits clustered in the Salida area, the Sedalia deposit is stratabound in a terrane of metasedimentary and metavolcanic rocks that trend northeast and dip steeply southeast. The Sedalia deposit occurs in a lithologic unit composed of interlayered garnet-cordierite-amphibole gneiss, garnetiferous quartz-mica schist, and other rocks that contain abundant cordierite and gahnite. This garnetiferous unit at the mine comprises the core of a major drag fold that apparently plunges northeastward at a shallow to moderate angle parallel to the plunge of lineations and the axes of minor folds. The orebody is inferred to be elongate and to plunge northeastward parallel to the fold axis. Galena from the Sedalia deposit yielded lead isotope data that indicate an age of 1,700-1,800 million years, the same age as the rocks that comprise much of the Proterozoic terrane in Colorado. The age data and the metamorphic textures of the sulfide-bearing rocks indicate that the sulfide deposits were metamorphosed with their host rocks during a major period of Proterozoic folding and regional metamorphism that reached its peak about 1,700 million years ago. The rocks in the Sedalia mine area were metamorphosed to the upper amphibolite facies (sillimanite zone of regional metamorphism).

Primary sulfides in the deposit consist most commonly of ore-grade amounts of chalcopyrite and sphalerite in a matrix of light-gray magnesian amphiboles. Gahnite is abundant in the ore. Silver-bearing galena, abundant in some of the ore, is distinctly less widespread than chalcopyrite and sphalerite. Magnetite is common in the ore, but pyrite and pyrrhotite form only a relatively small part of the matrix of the ore. The estimated metal content of the primary ore is: copper, 4 percent; zinc, at least 6 percent; lead, 0.5 percent; silver, 3/4 to 1 ounce per ton; gold, 0.01 to 0.03 ounce per ton. A significant amount of zinc in the ore is in the form of gahnite, the zinc spinel. Ore in the oxidized upper part of the deposit contains abundant chalcocite, chalcanthite, and goslarite, and a great variety of other secondary copper, zinc, and lead minerals.

The authors believe that the Sedalia deposit originated when exhalative hydrothermal fluids emanated from a vent in the sea floor, reacted with seawater, and deposited sulfides syngenetically with the progenitors of the garnetiferous unit that hosts the deposit. Rocks of probable volcanic affinity are in the mine area, the orebody is stratabound, and the deposit is one of a cluster of occurrences whose distribution is apparently lithologically controlled--all these factors suggest that the Sedalia deposit and other similar deposits in the Salida area belong to the family of volcanogenic sulfide deposits. An island arc setting rather than an oceanic spreading center is suggested by the fact that rocks of sedimentary origin are interlayered with rocks that probably are the products of bimodal volcanism.

The Sedalia deposit probably contains at least 1 million tons of ore, and exploration of the orebody at depth could result in greatly expanding this reserve estimate. The mine is considered to have an excellent potential for production of copper and zinc ores that contain subordinate amounts of lead, silver, and gold.

INTRODUCTION

A stratabound Proterozoic zinc-copper sulfide deposit is developed by the Sedalia mine, about 4 mi north-northwest of Salida, Chaffee County, Colorado (fig. 1). The mine workings were driven into a hill in the NW1/4 sec. 18, T. 50 N., R. 9 E., on the northeast side of the Arkansas River valley. The principal workings open from adits ranging in altitude from 7,680 ft to 8,140 ft (pl. 1). Extensive workings include at least 8,100 ft of drifts, crosscuts, stopes, and raises (Van Alstine, 1974, p. 13). Less than half of these workings remain safely accessible today.

The Sedalia mine was the largest producer of any of the mines in Proterozoic sulfide deposits in Colorado. The deposit was located in 1881 (Van Alstine, 1974, p. 13). According to J. V. Dodge (written commun., 1975) production from the mine ceased in December 1918, when the price of copper fell from 26¢ to 11¢ per pound. Since 1967 the property has been under lease to J. V. Dodge, a mining engineer, who has conducted a lengthy examination to determine ore reserves. A report by a mining engineer (C. H. Swanton, written commun., 1922), given to us by Dodge, indicates that from 1888 through 1918 the total production was about 90,000 tons having a gross value in those years of approximately $1,818,000, or an average per ton value of about $20. This production came principally from oxidized zinc and copper ores in the upper part of the deposit. The same report by Swanton indicated that the primary sulfide ore of the Sedalia deposit was too hard to be worked by hand-mining, the only method ever used in the mine. Therefore, very little sulfide ore was mined.

The Proterozoic sulfide deposit at the Sedalia mine is a significant and potentially minable source of ores valued chiefly for zinc and copper and to a lesser extent for lead, silver, and gold. The size of the deposit is at least 1 million tons and may be many times larger. This report, a preliminary summary of the results of field and laboratory studies, describes the general geology of the Sedalia mine area and the economic geology of the ores and their host rocks.

PREVIOUS WORK

Probably the first published geologic reference to the Sedalia deposit was by Whitman Cross (1895, p. 289) who described it as "a thick bed of actinolite schist richly impregnated with copper minerals." In 1907 Waldemar Lindgren made a more thorough study of the Sedalia deposit and described in considerable detail the mine developments at that time and the geology of the mine area and of the ore deposit (Lindgren, 1908, p. 161-166). In a study of oxidized zinc deposits in Colorado, A. V. Heyl described the geology and mineralogy of the copper-zinc-lead deposit at the Sedalia mine (Heyl, 1964, p. C31-C32, C42-C44, C83). Heyl (1964, p. C43-C44) included a detailed discussion concerning genesis of the oxidized ores of the upper portion of the deposit. Between 1961 and 1965, R. E. Van Alstine made field studies of the geology and mineral deposits of the Poncha Springs SE quadrangle, Chaffee County, Colorado. In his report Van Alstine (1974, p. 13-15) includes a detailed description of the Sedalia copper-zinc deposit. S. J. Boardman (1971) studied the Precambrian geology and mineral deposits of the Salida area for a Ph.D. thesis at the University of Michigan. Boardman's thesis includes production data and descriptions of the general geology and petrology of what he calls the "skarn deposit" at the Sedalia mine (1971, p. 58-59, 84-96) and a

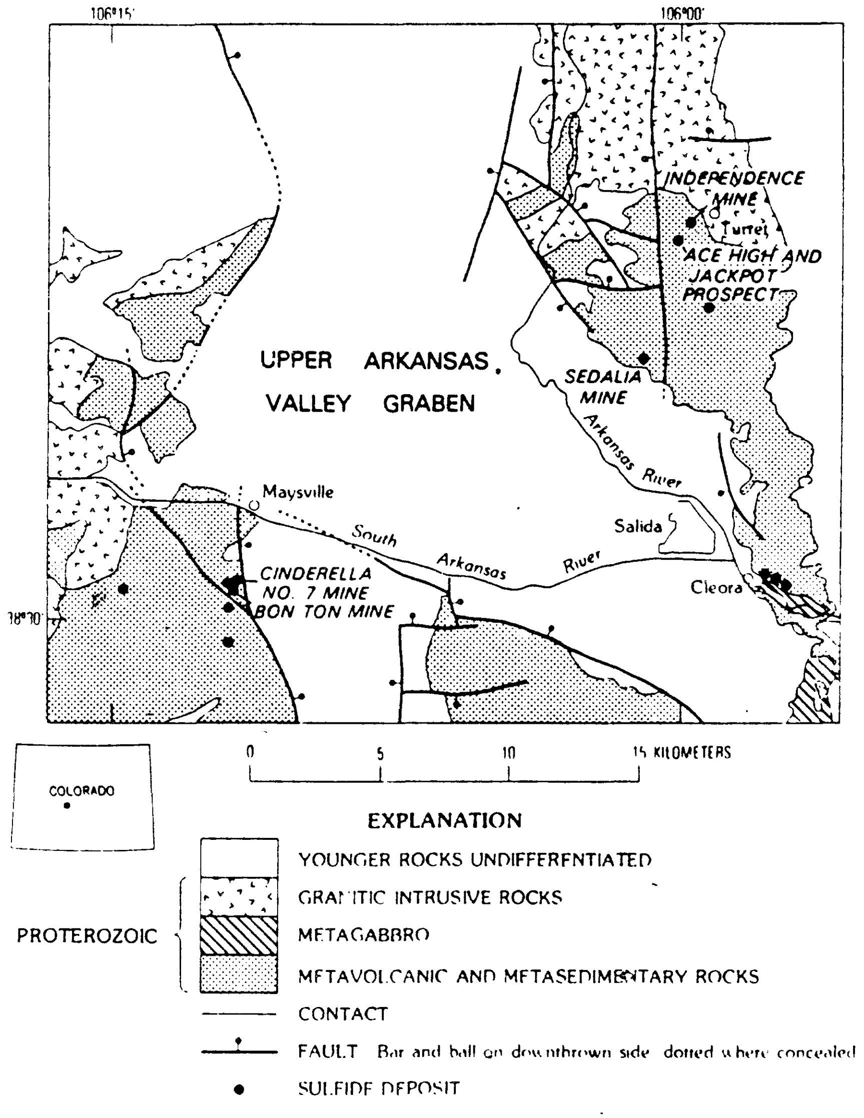

Figure 1.--Map showing location of the Sedalia mine and of other Proterozoic sulfide deposits in the Salida area, Colorado. Geology modified from Tweto and others (1976) and Scott and others (1975).

geologic map and sections of the mine (1971, pl. 3). In a publication titled "Precambrian tungsten and copper-zinc skarn deposits of south-central Colorado," E. W. Heinrich (1981, p. 93-99) described the Sedalia mine, utilizing both his own observations and data from Boardman (1971), Heyl (1964), Van Alstine (1974), and Lindgren (1908).

The areal geology of the region encompassing the Sedalia mine is shown on maps by Boardman (1971, pl. 1, 2; 1976, fig. 1), by Van Alstine (1974, pl. 1), by G. R. Scott and others (1975), and by Tweto and others (1976).

PRESENT STUDY

The present study is part of a larger investigation by the authors of Proterozoic sulfide deposits of Colorado. The purpose of the investigation is to evaluate these deposits as potentially minable resources of base and precious metals and to search for mineralogic, lithologic, stratigraphic, and structural characteristics that can be significant in exploring for undiscovered deposits and in suggesting guidance for development of known deposits. The investigation has included reconnaissance examinations of numerous deposits and sampling of the ores and host rocks. The Sedalia deposit is the most highly developed and has recorded the largest production of any of the known Proterozoic deposits. Therefore, the authors have made a more detailed study of the Sedalia mine and surrounding area.

During 3 weeks in 1975 and 1 week in 1976 the authors mapped the geology of the Sedalia mine area and completed underground mapping of the accessible portions of four levels of the mine. David Washington assisted with mine safety precautions and handling of numerous samples during the underground studies in 1975. Additional map data and samples were obtained both at the surface and underground during short visits during each of the years 1978 through 1982.

The areal geology was mapped on large-scale air photographs taken by our U.S. Geological Survey colleagues, R. B. Taylor and R. L. Parker. The geologic data were then transferred to a topographic base, scale 1:6,000, prepared by W. F. Gibbs of the National Mapping Division, U.S. Geological Survey. The resulting map appears in the present report as plate 1.

Underground workings were mapped on base maps, scale 1:360, provided by J. V. Dodge. Maps of this scale are too large to include in the present open-file report, but the data obtained from this underground mapping are incorporated in the descriptions included in this report.

Data concerning the study of the Sedalia deposit and other Proterozoic sulfide deposits in the vicinity of Salida, Colorado, are included also in two other reports (Sheridan and Raymond, 1977, p. 10-17; Sheridan and Raymond, in press). A brief report concerning the Sedalia deposit was published also in a guidebook for the 1978 field excursions of the International Association on the Genesis of Ore Deposits (Sheridan and Raymond, 1978, p. 146-150).

ACKNOWLEDGMENTS

The authors are grateful to Joseph V. Dodge for his permission to study and map the Sedalia deposit, claims for which he has leased since 1967. In 1975 Mr. Dodge provided a thorough and well-illustrated introduction to our studies by using numerous color photographs he had taken underground. On several occasions during the ensuing years he provided additional pertinent information. Mr. Dodge kindly supplied us with copies of base maps of the

underground workings and with copies of several unpublished reports involving investigations by geological and mining engineers. His patience is appreciated especially for granting permission to us to lead field trips to his claims for numerous visitors from the U.S. Geological Survey, foreign geological surveys, and American and foreign universities.

The authors are indebted to many members of the U.S. Geological Survey for various kinds of help during this study. Useful information pertinent to the areal and regional geology was provided by R. B. Taylor, Ogden Tweto, R. E. Van Alstine, and G. R. Scott. During and after field trips to the mine many welcome observations concerning the mineralogy and lithology of the ores and host rocks as well as structural and stratigraphic features were contributed by A. V. Heyl, R. B. Taylor, M. S. Allen, P. K. Sims, L. J. Cox, S. C. Creasey, and M. P. Foose. Analysts, whose careful work is greatly appreciated, are credited in the tables of this report. Microprobe data concerning gahnite and other minerals were supplied by G. A. Desborough and L. J. Cox.

While guiding field trips to the mine the authors benefited greatly from discussions with J. M. Franklin of the Geological Survey of Canada; D. T. Rickard, K. L. Karlsson, Waldo Vivallo, and Ake Johannson of the University of Stockholm, Sweden; and P. Joubert of the Precambrian Research Unit, University of Capetown, South Africa. Our underground mapping benefited from a preceding safety inspection by A. D. Stoutenger of the U.S. Mining Enforcement and Safety Administration.

GEOLOGIC SETTING

The geologic setting of the Salida area, Colorado, is shown on a simplified geologic map (fig. 1). Proterozoic rocks are exposed on both sides of the Upper Arkansas Valley graben. The Proterozoic terrane consists dominantly of metavolcanic and metasedimentary rocks and granitic intrusive rocks. Small bodies of Proterozoic metagabbro occur in the southeastern part of the area. Some Tertiary volcanic rocks occur within the Proterozoic terrane. Although not differentiated on this simplified map, rocks younger than Proterozoic comprise much of the area and are shown on more detailed maps by Van Alstine (1974, pl. 1) and by Scott and others (1975). These younger rocks consist of "semiconsolidated or loose alluvial, mudflow, and landslide deposits of late Tertiary and Quaternary ages, found chiefly in the downdropped Arkansas Valley" (Van Alstine, 1974, p. 3).

Van Alstine (1974, p. 11) reported that major structural features in this area include Precambrian folds and Tertiary faults. As a result of deformation during the Laramide orogeny of Late Cretaceous to early Tertiary age, thousands of feet of once-overlying Paleozoic and Mesozoic rocks were eroded from the area (Van Alstine, 1974, p. 11). Late Tertiary faults are related to the graben that formed as a northward extension of the Rio Grande trough (Van Alstine, 1974, p. 12).

The Proterozoic metavolcanic and metasedimentary terrane of the Salida area is of principal importance to the subject of this report because the terrane hosts the deposit at the Sedalia mine and other Proterozoic sulfide deposits (fig. 1).

It is significant to note that Proterozoic sulfide deposits occur not only in the Salida area but also in many other areas in Colorado (Sheridan and Raymond, 1977, fig. 1). All of these deposits occur in metamorphic terranes that are known to be Proterozoic, about 1,800 million years in age (Tweto, 1980, p. 37). The protoliths of these metamorphic rocks were sedimentary, volcanic, and subvolcanic intrusive rocks (Tweto, 1977, p. D3). 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) a major period of Precambrian regional metamorphism and folding reached its peak in Colorado about 1,700 m.y. ago. According to Hedge (1969) the available isotopic data indicate that no great amount of time elapsed between the original deposition and the time of metamorphism. Galena samples from Proterozoic sulfide deposits in Colorado, including the Sedalia mine, yielded lead isotope data indicating an age in the same 1,700-1,800 m.y. range (Bruce Doe, oral commun., 1979). The age data and the metamorphic textures of the ore-bearing rocks indicate that the sulfide deposits were metamorphosed simultaneously with their host rocks during the major period of Proterozoic folding and regional metamorphism. Late in this period plutonic rocks were intruded syntectonically in many areas and commonly are granodiorite and quartz monzonite of the Boulder Creek type (Tweto, 1977, p. D12).

The Proterozoic sedimentary and volcanic rocks in most of the Salida area were metamorphosed to the upper amphibolite facies (sillimanite zone of regional metamorphism). Pelitic schists and gneisses commonly contain sillimanite and andalusite, and host rocks of the sulfide deposits are commonly rich in magnesian amphiboles and cordierite. The origin of many of the rocks is difficult to determine because original textures and structures have been largely obliterated by intense deformation and regional metamorphism. However, studies by R. B. Taylor (oral commun., 1975) of Proterozoic rocks in a small area near Cleora, southeast of Salida, indicated that the rocks have been metamorphosed only to the lower amphibolite facies and that some original features are preserved. Among the metavolcanic rocks Taylor recognized in this area are a felsic unit containing phenocrysts and flattened pumice fragments, and breccia units that contain fragments of basaltic porphyry. North and northwest of the Cleora area the metamorphic grade changes from lower to upper amphibolite facies. Boardman (1976, p. 96) reported a gradual south-to-north transformation of welded tuff units into quartz-feldspar gneisses in this same general area.

ROCKS OF THE SEDALIA MINE AREA

The bedrock of the Sedalia mine area (pl. 1) consists of metamorphosed sedimentary and volcanic rocks, metamorphosed intrusive igneous rocks, and pegmatite, all of Proterozoic age. Overlying the faulted bedrock at the mountain front are Quaternary deposits of colluvium, fan alluvium, and eolian sand. Deposits of eolian sand also occur elsewhere in the area.

PROTEROZOIC ROCKS

The layered succession of Proterozoic metamorphosed sedimentary and volcanic rocks strikes northeast and dips steeply southeast (pl. 1). From west to east major lithologic units are: (1) a thick unit of feldspathic gneiss, only part of which is included in the mapped area; (2) a unit composed of garnet-cordierite-amphibole gneiss, garnetiferous quartz-mica schist, and other interlayered rocks; (3) quartz-mica schist, portions of which are feldspathic; (4) feldspathic gneiss; and (5) amphibolite which contains a thin mapped layer of porphyroblastic schist and, farther east, unmapped layers of feldspathic gneiss. The ore zone at the mine occurs in rocks of the garnetiferous unit (unit 2 above).

The layered succession was intruded by igneous rocks, also of Proterozoic age, which also have been metamorphosed. These include bodies of pistachio-colored amphibolite, bodies of metagabbro, and dikes and sills of metabasalt. Granitic pegmatites, the youngest Proterozoic rocks in the area, are numerous.

METAMORPHOSED SEDIMENTARY AND VOLCANIC ROCKS

FELDSPATHIC GNEISS

Two major units of feldspathic gneiss are shown on the geologic map (pl. 1); one is along the northwestern side of the mapped area and the other is farther east. Although they are lithologically similar, the two units are believed to be stratigraphically distinct and not folded repetitions of the same unit. Both are commonly fine grained and contain abundant feldspar. The gneissic layering of these units can be recognized at a scale of a foot to several tens of feet. The gneissic structure is not as prominent as it is in some of the other types of gneisses in the area.

The northwestern unit of feldspathic gneiss extends beyond the limits of the mapped area. Reconnaissance traverses to the northwest indicated that this unit is very much thicker than the other unit of feldspathic gneiss. Petrographic studies of several thin sections indicate that the gneiss is composed of abundant microcline, quartz, and plagioclase with lesser amounts of muscovite and biotite. Much of the rock is almost white; the other feldspathic gneiss unit is mostly tan to gray. West of a north-trending left-lateral fault the feldspathic gneiss is in contact with the garnetiferous unit, except where the gneiss is intruded by pistachio-colored amphibolite (pl. 1). A generally thin, unmapped layer that consists of quartz-mica schist together with varying amounts of dark-colored hornblende gneiss or amphibolite occurs along the contact. East of the fault, the quartz-mica schist thickens and becomes a mappable unit that separates the feldspathic gneiss from the garnetiferous unit (pl. 1).

The other unit of feldspathic gneiss trends northeastward between a major unit of quartz-mica schist and a thick unit of amphibolite. East of the mine workings this unit of feldspathic gneiss forms steep, bold outcrops and is cut by several light-colored pegmatite dikes. Study of several thin sections indicates that the gneiss is generally fine grained and contains abundant microcline, quartz, and plagioclase and less abundant biotite and muscovite. Some layers in the unit are more micaceous and grade in appearance to feldspathic schist. Lenses of calc-silicate gneiss occur within this feldspathic gneiss unit and become more numerous as the unit is traced along strike to the northeast.

Although original textural and structural features have been almost completely obliterated from the feldspathic gneiss units by the regional metamorphism, a few weathered outcrops show small grains that resemble relict phenocrysts and other features that resemble flattened pumice. This evidence together with the present mineralogic composition of the gneiss suggests that the progenitor may have been flows or tuffs having the composition of rhyodacite. Some of the gneiss, however, may represent transported material deposited as sediments, because features resembling crossbedding were noted in an outcrop east of the mine workings.

GAHNITE-BEARING QUARTZ-MICA SCHIST

A lens of gahnite-bearing quartz-mica schist occurs along the northern contact of the garnetiferous map unit in the northern part of the mapped area (pl. 1). The outcrop width is as much as 135 ft and the strike length is about 800 ft. To the north, a larger lens of quartz-mica schist separates the gahnite-bearing schist and the garnetiferous map unit in this area from the feldspathic gneiss unit farther north.

The gahnite-bearing schist is fine grained, light to medium gray, and is composed principally of quartz, biotite, and muscovite. Green grains of gahnite occur in equant to elongate aggregates ranging from less than 0.1 in. to 0.5 in. in length. The aggregates of gahnite are distributed irregularly through the schist and are readily recognized in weathered outcrops where they protrude from the weathered surface as resistant clots. Small grains of garnet, commonly about 0.1 in. in diameter, occur locally with the gahnite.

Gahnite from this schist was analyzed by microprobe methods by G. A. Desborough (written commun., 1977). From these analytical results, L. J. Cox calculated the composition of this spinel in terms of the following spinels (in moles refigured to 100 percent) as follows: gahnite ($ZnAl_2O_4$), 65.1; hercynite ($FeAl_2O_4$), 25.8; and ordinary spinel ($MgAl_2O_4$), 9.1 (L. J. Cox, written commun., 1981). Garnet from this schist, as determined by Cox from microprobe analyses, is almandine with a fairly large spessartine component (about 35 mole percent).

As noted below in a discussion of the various gahnite-bearing rocks, a sample of gahnite-bearing schist from this lens contains 1.25 percent zinc.

GARNET-CORDIERITE-AMPHIBOLE GNEISS, GARNETIFEROUS QUARTZ-MICA SCHIST, AND OTHER INTERLAYERED ROCKS

The map unit that is most important in terms of the economic geology of the Sedalia mine area consists of garnet-cordierite-amphibole gneiss, garnetiferous quartz-mica schist, and other interlayered rocks, some of which are garnetiferous. As shown on plate 1 a belt of these rocks trends northeastward throughout the length of the mapped area. Rocks of this same unit are the host for the ore zone at the Sedalia mine and are separated from the longer belt by rocks of the quartz-mica schist unit. In the mine area most of the rocks in this map unit contain variable amounts of base-metal sulfides. As discussed below under the heading of structural geology, we believe that the garnetiferous unit at the mine is the core of a major dragfold.

A major rock type that characterizes this map unit is garnet-cordierite-amphibole gneiss. This gneiss occurs as layers and lenses, is reddish gray to reddish black, and commonly is medium to coarse grained. The amphibole in this rock is commonly an orthoamphibole, with the optical and chemical characteristics of anthophyllite. As observed in thin sections, the cordierite is generally very poikiloblastic, and in some samples the garnet is also poikiloblastic. The gneiss contains lesser amounts of quartz, chlorite, magnetite, and zircon. Garnet from this gneiss was analyzed by microprobe methods by G. A. Desborough (written commun., 1977). From these data, L. J. Cox (written commun., 1981) calculated the composition of the garnet to be almandine (78 mole percent), pyrope (10 mole percent), and smaller amounts of spessartine and grossularite.

Garnetiferous quartz-mica schist is another major rock type and is especially common in the long belt of this unit. Variable amounts of reddish brown garnet occur as porphyroblastic grains, commonly 1/4 to 1/2 in., in a grayish fine-grained matrix composed principally of biotite, muscovite, and quartz.

In both the long belt of this map unit and in the unit at the mine, the garnetiferous schist grades to several varieties of garnetiferous gneiss that contain less mica. These rocks are light to dark gray and are generally fine to medium grained. A common variety is sillimanitic, garnetiferous, quartz-biotite gneiss in which the sillimanite is in fibrolitic aggregates. Some samples of the sillimanitic variety also contain appreciable amounts of andalusite. This andalusite is not porphyroblastic in habit and its presence was detected only after examination of thin sections. However, in sillimanitic, garnetiferous, quartz-biotite gneiss near the gahnite-bearing schist in the northern part of the area, andalusite occurs as elongate aggregates that are recognizable megascopically by their pink color. Another variety of garnetiferous, biotite-quartz gneiss, sampled 17 ft underground from the portal of the 600-Level of the mine, contains fibrolitic sillimanite, andalusite, and scattered small grains of staurolite.

Porphyroblastic, biotite-quartz gneiss or schist with little or no garnet also occurs in this map unit. In some varieties of this rock mica-sheathed ovoidal-shaped porphyroblasts, 1/4 to 1 1/2 in. in diameter, are composed of andalusite. In some samples the andalusite porphyroblasts are light-colored lath-shaped grains, 1/4 to 1 in. in length, but in a rock of similar megascopic appearance, the lath-shaped grains are composed of sillimanite. In porphyroblastic gneiss along the northwestern and southeastern contacts of the garnetiferous unit at the mine, ovoidal-shaped knots, generally 1/2 in. in size, are composed of cordierite rather than andalusite.

In addition to the rocks described above, several other varieties of grayish to tan, fine- to medium-grained gneiss occur as interlayers in the mine area. One common variety is cordierite-quartz-biotite gneiss, some of which contains appreciable amounts of orthoamphibole. Cordierite-quartz-biotite gneiss at the portal of the No. 2 adit (300-Level) and along the southeastern contact of the map unit in the mine area contains variable amounts of dark-green gahnite. The biotite in these cordierite-rich rocks is commonly pale brown and is probably the magnesian variety, phlogopite. Other minerals, commonly present in small amounts, are rutile, muscovite, chlorite, and zircon. Another variety is garnetiferous, cordierite-quartz-biotite gneiss that contains plagioclase and small greenish grains of gahnite. Still another variety is sillimanitic, biotite-quartz gneiss that contains minor staurolite.

The Sedalia mine has long been famous for large crystals of garnet which occur as dodecahedrons as much as 6 in. or more in diameter in garnet-chlorite schist south of a pegmatite near the portal of the No. 2 adit. Other large crystals occur in several places in the underground workings, both in similar garnet-chlorite schist and in garnet-amphibole gneiss. Large crystals of garnet occur also in garnetiferous gneiss in the vicinity of the large, complexly shaped pegmatite in the northern part of the area.

The garnetiferous quartz-mica schist and the garnetiferous gneisses characterized by sillimanite and (or) andalusite probably originated as pelitic sediments, some of which contained appreciable amounts of alumina. The progenitors of the garnet-cordierite-amphibole gneiss and the cordierite-quartz-biotite gneiss cannot be inferred with the same degree of certainty.

Such rocks are rather common in various places throughout the world but, because they contain uncommonly large amounts of magnesium, their origin has been the subject of much argument for many years. Some authors favor petrogenesis that involves modification by magnesium metasomatism. After considerable research concerning high-grade cordierite gneisses in the Front Range, Colorado, Gable and Sims (1969, p. 57-59) concluded that most, if not all, of these cordierite rocks are of sedimentary origin. The gneisses characterized by cordierite in the Sedalia mine area are lithologically similar to some of the rocks described by Gable and Sims (1969) and to some of the cordierite-bearing gneisses mapped by Sheridan and Marsh (1976) in the Front Range. A sedimentary origin seems probable for these cordierite gneisses in the Sedalia mine area. Their high magnesium content may be due to adsorption of magnesium from circulating seawater during and immediately after deposition.

QUARTZ-MICA SCHIST

Quartz-mica schist forms a major unit that extends northeastward through the central part of the mapped area (pl. 1). In the southern part of the area the schist occurs on each side of the garnetiferous unit that hosts the ore zone. Northeast from that area the schist from each side of the mine coalesces to form a single unit that separates the southeastern feldspathic gneiss from the garnetiferous unit. Another unit of quartz-mica schist occurs in the northern part of the area where it separates the northwestern feldspathic gneiss from the garnetiferous unit.

The schist is light gray to dark gray. Most of it is fine grained, but some is very fine grained and phyllitic. Some layers on both sides of the mined area and in several places farther northeast are porphyroblastic. In addition to the layers expressed by the presence or absence of porphyroblasts, other layers reflect differences in mineralogic composition. Although the schistosity is most commonly parallel to the layering, in a few outcrops the schistosity cuts the layering at high angles.

A large part of the schist unit is composed principally of quartz, biotite, and muscovite, and some is composed principally of biotite, quartz, and plagioclase. Other feldspathic varieties of the schist contain abundant microcline and plagioclase and smaller amounts of the micas. The feldspathic schist is similar in appearance to some of the layers in the feldspathic gneiss. Locally, weathered outcrops of the feldspathic varieties of schist, like some of the feldspathic gneiss, contain textural features that resemble flattened pumice and small light-colored grains that resemble relict phenocrysts.

Porphyroblastic layers in the schist contain mica-sheathed ovoidal porphyroblasts that range in diameter from 0.1 in. to 1.5 in. The porphyroblasts are composed of andalusite, which is very poikiloblastic, containing abundant tiny inclusions of the other minerals of the schist.

Except for the possible relict phenocrysts and flattened pumice found in only a few exposures of feldspathic schist, no other original textural and structural features were recognized. Feldspathic schists that contain noteworthy amounts of microcline and plagioclase may have originally been volcanic flows or tuffs, as is inferred for the possible progenitors of much of the feldspathic gneiss. Quartz- and mica-rich varieties of schist may have been pelitic sediments. The andalusite-bearing porphyroblastic schist layers very likely were derived from alumina-rich shales.

AMPHIBOLITE

A major unit of amphibolitic rocks forms the southeastern margin of the mapped area (pl. 1). In the area near the mountain front the unit contains a layer of porphyroblastic schist (see next section). The eastern portion of the unit contains abundant, unmapped interlayers of feldspathic gneiss.

Dark-gray to black, fine- to medium-grained rocks of this unit range in character from common amphibolite, composed of subequal amounts of hornblende and plagioclase, to hornblende-plagioclase gneisses that contain variable amounts of biotite, quartz, and other minerals. One sample of biotitic, hornblende gneiss contains noteworthy amounts of microcline. Some layers of the unit weather to a spotted appearance; the spots, 0.1 to 0.5 in. in size, are grains and aggregates of hornblende scattered in a finer grained matrix.

Although no pillow structures or other original features were recognized, the mineralogic composition of the amphibolitic rocks and their concordant relations with other rocks suggest that the progenitors were basaltic flows. The more gneissic varieties that contain hornblende, plagioclase, biotite, quartz, and other minerals may represent sedimentary deposits derived in part from such flows.

A thin (4 ft thick) layer of fine-grained, greenish-black amphibolite occurs within the southeastern unit of feldspathic gneiss in the mine area near the contact with quartz-mica schist. This unmapped, concordant layer lenses out at the ridge-top area and is characterized by light-colored rounded spots 1/16 to 1/4 in. in diameter. It is probably a metabasalt flow and its spotted texture may reflect relict amygdule fillings.

PORPHYROBLASTIC SCHIST

A layer of porphyroblastic schist in the amphibolite unit near the mountain front (pl. 1) extends northeastward to a left-lateral fault. This layer of schist may also be present northeast of the fault, but additional detailed mapping would be needed to confirm its presence in that area.

The porphyroblastic schist is light gray and is characterized by mica-sheathed, ovoidal to blocky, porphyroblastic clots, 0.25 in. to 1.5 in. in diameter, set in a fine-grained, schistose matrix. The porphyroblasts are composed of poikiloblastic andalusite, and they contain numerous tiny grains of the other minerals of the schist. The matrix consists principally of biotite, quartz, muscovite, and variable amounts of plagioclase. Tiny grains of magnetite are common, and some of the schist contains sparse tiny grains of garnet.

Although no original textural features were observed, the concordant relations with the amphibolite unit and the mineralogic composition suggest that the porphyroblastic schist is a pelitic rock, possibly derived from an alumina-rich shale.

Other porphyroblastic schists within the garnetiferous map unit and the quartz-mica schist unit were described above.

METAMORPHOSED INTRUSIVE ROCKS

PISTACHIO-COLORED AMPHIBOLITE

Bodies of pistachio-colored (yellowish-green) amphibolite occur in the southwestern part of the mapped area (pl. 1). An intrusive origin for this amphibolite is indicated by discordant contacts of the bodies, in some places, with rocks of the feldspathic gneiss unit and the garnetiferous map unit.

The amphibolite is fine grained, poorly to moderately well foliated, and composed principally of clinoamphibole. Other minerals observed in thin section are chlorite, quartz, and abundant magnetite. A suite of samples taken from various localities within the pistachio-colored amphibolite was analyzed spectrographically by J. C. Hamilton (written commun., 1977). His data show that the rock commonly contains (in parts per million): chromium, 2,000; nickel, 700; and cobalt, 20 to 70.

The intrusive relationships, mineralogic composition, and metal contents suggest that the progenitor of this amphibolite was an ultramafic igneous rock.

METAGABBRO

Bodies of metagabbro are common in the mapped area (pl. 1). Most of these occur within the garnetiferous map unit. An elongate body of metagabbro was intruded along part of the contact between the quartz-mica schist unit and the southeastern unit of feldspathic gneiss. Although the metagabbro in these various bodies appears massive in contrast to the layered or gneissic character of the intruded metamorphic rocks, it is commonly moderately well foliated.

On the weathered surfaces of outcrops the metagabbro has a spotted appearance caused by light-colored, highly altered, blocky grains of calcic plagioclase, as much as 1/2 in. in diameter, in a dark-gray to black matrix. Where the blocky grains of plagioclase are abundant, the rock is medium to coarse grained, but where the plagioclase grains are not as abundant, the rock is fine to medium grained. The matrix is rich in hornblende and contains finer grained plagioclase and accessory sphene and magnetite. Van Alstine (1974, p. 5) noted that ophitic texture is locally preserved in the metagabbro and that remnants of diopsidic pyroxene occur in some grains of hornblende; he also noted small quantities of the minerals biotite, quartz, apatite, epidote group minerals, and chlorite.

METABASALT

Metabasalt occurs as dikes and sills which are generally only 2 to 7 ft thick but may be as much as 25 ft thick locally in the mine area. Metabasalt is fairly common in underground exposures on the 600-Level of the mine. The metabasalt is probably the youngest of the Proterozoic rocks that were affected by regional metamorphism. It is older than the Proterozoic pegmatite because an unmetamorphosed pegmatite dike near the portal of the Number 2 adit cuts a metabasalt dike.

The metabasalt is black and is very fine grained to fine grained. Preliminary examination of a few thin sections indicates that the principal components are hornblende and calcic plagioclase with accessory sphene and opaque minerals. One sample from the mine area contains small (0.3 in.) euhedral crystals of garnet that probably represents recrystallization of contaminants from the host rock during the intrusion of the basaltic dike.

Some metabasalt on the 600-Level of the mine occurs as segmented, angular blocks 5 ft in exposed diameter and separated by metamorphic rocks of the host unit at the mine. Such segmentation of the basaltic dikes may have occurred late in the period of regional metamorphism and folding because there is no clear-cut evidence that it was caused by faults of the type recognized elsewhere in surface and underground exposures.

PEGMATITE

Pegmatite of granitic composition is the youngest Proterozoic rock in the Sedalia mine area. Bodies of pegmatite show crosscutting relations with all of the metamorphosed sedimentary and volcanic rocks and also with all of the metamorphosed intrusive rocks (pl. 1). Many of the pegmatite bodies are long, thin, steeply dipping dikes, which follow the general northeast trend of the metamorphic rocks but commonly transect the contacts between those units. Other bodies are lenslike or irregular in shape, and some of the bodies have complexly branching shapes.

The pegmatites are composed mainly of quartz, microcline, plagioclase, muscovite, and biotite. Van Alstine (1974, p. 5) noted that some of the pegmatites in this region contain beryl, columbite-tantalite, magnetite, hematite, fluorite, and garnet.

The large, complexly branching pegmatite shown cutting the garnetiferous unit, quartz-mica schist unit, and metagabbro in the northern part of the area (pl. 1) is known as the Bonus Extension pegmatite. The following data concerning this pegmatite are from a description by Van Alstine (1974, p. 17). Workings consist mainly of an opencut quarry over 150 ft in length. The pegmatite explored by these workings is zoned and consists chiefly of an intermediate zone, composed of microcline, albite, quartz, muscovite, biotite, and garnet, and a core of quartz and feldspar. Beryl and columbite-tantalite occur erratically in both zones. The pegmatite produced a small quantity of feldspar, mica, beryl, and columbite-tantalite in the 1950's and 1960's.

UNCONSOLIDATED DEPOSITS OF QUATERNARY AGE

ALLUVIUM

Alluvium occurs in the southernmost part of the map area where it forms deposits of silt, sand, cobbles, and boulders along the stream course to the east of the Sedalia mine. Much smaller alluvial deposits, not shown on the map, occur locally along minor dry stream beds in the area.

COLLUVIUM AND FAN ALLUVIUM, UNDIVIDED

Alluvial fans from several streams tributary to the Arkansas River coalesce south of the Sedalia mine area to form a large compound fan, called Sand Park on maps by Van Alstine (1974, pl. 1) and by Scott and others (1975).

On plate 1 the fan alluvium is shown together with colluvium as an undivided unit along the base of the mountain front. The colluvium is a heterogeneous deposit of coarse, angular, boulder-sized fragments of Proterozoic rocks and fine-grained material. It grades downslope to the sandy deposits of the alluvial fans.

EOLIAN SAND

Deposits of tan to yellowish-gray eolian sand mantle the fan alluvium and colluvium along the base of the mountain front (pl. 1). Remnants of other deposits of windblown sand occur farther northeast along a major stream and its tributaries. According to Van Alstine (1974, p. 16) eolian sand along the Arkansas and South Arkansas valleys is locally more than 25 ft thick.

STRUCTURAL GEOLOGY

The principal structural features in the region encompassing the Sedalia mine area are folds of Precambrian age and faults of Tertiary age (Van Alstine, 1974, p. 11). It is possible that some of the faults may be of Precambrian ancestry.

FOLDS

The northeastward-trending trace of a major Precambrian antiform is shown by Van Alstine (1974, pl. 1) 1.2 mi northwest of the Sedalia mine. The metamorphic rocks comprising the layered succession in the Sedalia mine area are in the eastern limb of this antiform. As shown on the map (pl. 1), this layered succession trends northeast and dips steeply southeast.

The lens-shaped garnetiferous unit (pl. 1) that hosts the ore zone at the mine is here inferred to comprise the core of a major dragfold in the eastern limb of the antiform. Prior to regional metamorphism and folding, the progenitors of rocks now comprising the long belt of the garnetiferous unit were probably continuous with the progenitors of the garnetiferous unit at the mine. A major northeastward-plunging dragfold was formed during regional metamorphism and resulted in the present distribution of rock units with the quartz-mica schist unit wrapped around a core composed of the garnetiferous unit at the mine. Later faulting related to the formation of the Upper Arkansas Valley graben then dropped the synclinal keel of the adjacent portion of the dragfold into the graben to the south.

Several lines of lithologic and structural evidence support this hypothesis. Highly significant is the fact that rocks of identical lithology characterize both the long belt of the garnetiferous unit and the garnetiferous unit at the mine. Moreover, porphyroblastic schist occurs at several places along the southeastern contact of the long belt of the garnetiferous unit and along both the northwestern and southeastern contacts of the garnetiferous unit at the mine. Most of the minor folds and lineations observed in the area plunge at low to moderate angles to the northeast and east. In describing folds in the area north of Salida, Van Alstine (1974, p. 11) also noted that small dragfolds plunge gently northeast. The northeastward plunge of these observed minor structural features is compatible with our hypothesis regarding a major northeast-plunging dragfold.

During underground mapping on the 600-Level two minor folds were noted in rocks near the northwestern contact of the garnetiferous unit. One of these folds is tightly anticlinal in shape, is 6 ft in amplitude and about 4 ft in wavelength, and plunges 5° N. 80° E. The other fold is open and synclinal in shape and has wavelength of 5 ft and amplitude of about 2 1/2 ft. The synclinal fold appears to have been warped by a later stage of cross-folding because it is doubly plunging.

Minor folding was also noted during areal mapping of the northwestern and southeastern contacts of the garnetiferous unit in the mine area (pl. 1). These folds are asymmetric and are characterized by long limbs that strike northeasterly, parallel to the regional strike, and dip steeply southeasterly, and by short limbs that strike northwesterly and dip northeasterly at shallow to moderate angles. On the long limbs the foliation (schistosity) is parallel to the lithologic layering, but on the short limbs the foliation is sharply discordant to the lithologic layering. Structural projections, that utilized the attitudes of these long and short limbs, were made to determine the plunge of these minor folds. These calculations indicate that the axes of these minor folds plunge 25° to 50° N. 77°-90° E.

In the schist unit just east of the mine workings structural measurements were made on calc-silicate lenses that are ellipsoidal in cross-section but elongate (cigar-shaped) in down-plunge direction. The down-plunge orientation of these elongate lenses is considered to be a b-lineation parallel to the axes of minor folding in that area. The average of readings taken on the long axes of these features indicates a plunge of 27° N. 60° E.

FAULTS AND FRACTURE ZONES

A major structural feature in this region is the Upper Arkansas Valley graben (Scott and others, 1975) which is downdropped between the uplifted blocks comprising the Sawatch Range on the west and the Mosquito Range on the east (Van Alstine, 1974, fig. 1 and p. 11). The Sedalia mine area is in the eastern uplifted block which extends northward to include the Mosquito Range. Although the boundaries of this graben actually consist of a complex system of subparallel faults, the total effect has been to drop the Proterozoic bedrock several thousand feet downward in the graben (R. B. Taylor, oral commun., 1983).

Two northwest-trending curving faults, shown in the southernmost part of the mapped area (pl. 1), are part of the graben system. The southernmost of these is entirely concealed by Quaternary deposits, but its presence is inferred from the apparent offset indicated by several small exposures of the Proterozoic units. The more northerly of these two faults has small offsets of the contacts between Proterozoic units along most of its extent and passes southeastward into a fracture zone.

In the area just north of the two faults described above, the layered succession at the mine area is cut by two west-northwest-trending right-lateral faults. The longer of these passes eastward into a fracture zone that merges with another fracture zone. Farther northeast the layered succession is cut by a prominent north-trending left-lateral fault. Still farther northeast, in the area southeast of the large complex pegmatite, the Proterozoic units are cut by two north-northwest-trending fracture zones.

A fracture zone significant to the oxidation of the ore in the upper levels of the Sedalia mine trends northeast in the northeastern part of the garnetiferous unit that hosts the ore zone. This fracture zone caused strong shattering of the rocks and ores in its vicinity. As a result, most of the sulfide ore in the upper 300 ft of the ore zone has been strongly oxidized.

ECONOMIC GEOLOGY

Proterozoic sulfide deposits are numerous in the vicinity of Salida and their distribution is shown on a simplified geologic map of this region (fig. 1). In addition to the Sedalia mine this cluster of deposits includes the Bon Ton mine (Crawford, 1913, p. 280), the Cinderella #7, and several other deposits in the area south of Maysville, a small community 10 mi west of Salida; the Ace High and Jackpot prospect (Van Alstine, 1969, p. 43-44), now called the Azurite claim, the Independence mine (Lindgren, 1908, p. 166), and several other deposits in the vicinity of Turret, an abandoned mining town 6 1/2 mi north of Salida. The principal ore minerals in these deposits are sphalerite and chalcopyrite; some contain lesser amounts of silver-bearing galena. Gahnite, the zinc spinel, is common in most of the sulfide deposits and in some it is so abundant that it may be considered a potential ore of zinc. Near Cleora, 1.5 mi southeast of Salida, are Precambrian quartz veins containing copper and tungsten (Tweto, 1960, p. 1420-1422).

The base metals, zinc and copper, are the principal mineral commodities sought in the Sedalia mine area although the deposit also contains lesser amounts of lead, silver, and gold. As reported in the description of pegmatites, some exploration and production has been conducted in this general area on pegmatite mineral commodities such as feldspar and beryl. No activity was noted in mining of pegmatite minerals during our field studies. Therefore, the following discussion of economic geology is devoted entirely to the Precambrian deposits of base-metal sulfides and gahnite at the Sedalia mine.

SHAPE AND SIZE OF THE ORE DEPOSIT

Definitive data regarding the exact shape and size of the orebody at the Sedalia mine are not available at the present time because significant portions of the mine workings are no longer safely accessible. Also, only a small amount of drilling, mainly for developmental purposes, has been done at the mine. As a result, the down-plunge shape and extent of the orebody have not been determined. The information presently available is summarized below and inferences are made concerning the down-plunge character of the orebody by utilizing information in reports about other deposits that occur in similar strongly metamorphosed and folded terranes.

Because of the limited access noted above, the size and shape of the orebody within the limits of the mine workings is incompletely known. However, the zone in which the orebody occurs is stratabound and is within the unit of garnetiferous gneiss and other interlayered rocks. The southeasterly dipping footwall and hanging wall of the ore zone are composed of quartz-mica schist. Examination of old mining reports and maps made available by J. V. Dodge (written commun., 1975) together with assessment of our own field data obtained both at the surface and underground indicates that the ore zone is at least 1,000 ft long, 165 ft wide, and 650 ft deep within the limits of the mine workings. In the lowermost portions of the workings the orebody is closer to the southeastern (hanging wall) side of the ore zone than it is in higher levels.

From the surface down to about the 300-Level most of the ore is oxidized. Chalcopyrite and sphalerite were altered to secondary copper and zinc minerals which are concentrated along numerous fractures over much of the width of the ore zone. Oxidation of the primary ore minerals occurred readily in the upper portion of the deposit because the rocks there had been strongly shattered within and near a northeasterly trending fracture zone.

From the 300-Level down to the winze driven below the 600-Level the ore is mainly of the primary sulfide type. It is apparent from our mapping underground and from the mining reports provided by J. V. Dodge that the primary ore is distributed along the entire strike length of the ore zone developed by the mine workings on the 300-Level and on several levels below. Exposures accessible when the mine was still active indicated that the width of the orebody in various stopes and crosscuts ranged from 40 ft to 100 ft. Lindgren (1908, p. 164) noted that the orebody is about 50 ft wide in workings driven 40 ft above the 600-Level. The orebody mentioned by Lindgren is apparently located southeast of the middle of the ore zone and probably is continuous down-dip with ore exposed in the winze and adjacent area on and below the 600-Level. At the winze and in the adjacent drift, ore is exposed over a width of about 8 ft, but the total width could not be determined at that level.

The primary orebody may continue down-plunge to the northeastward for an undetermined but potentially significant distance. As reported in the discussion of structural geology, the garnetiferous unit which hosts the ore is inferred to occupy the core of a major dragfold. Evidence obtained from minor folds and lineations indicates that this fold probably plunges northeastward at a shallow or moderate angle. Because the sulfide ore was metamorphosed and folded together with the enclosing host rocks, it is very probable that the orebody has been deformed to an elongate body that plunges northeastward parallel to the northeastward-plunging minor folds and lineations.

Sangster and Scott (1976, p. 189-190) summarized the changes in form of Precambrian massive sulfide orebodies that can occur during metamorphism, noting that the orebodies at Chisel Lake, Manitoba (also described by Martin, 1966) and at Balmat, New York (also described by Lea and Dill, 1968) have been changed from a presumably oval form to a linear- or rod-shaped form during medium- to high-grade metamorphism. Coats and others, (1970, p. 970) described the copper-zinc deposits of Stall Lake Mines Ltd. in the Snow Lake area of Manitoba as "lenses of massive sulfide whose plunge lengths are commonly many times greater than their widths or thicknesses." The exploration which revealed the down-plunge character of these deposits was based on the plunge direction indicated by mineral lineation in outcrops (Coats and others, 1970, p. 971). Although such orebodies illustrate considerable modification in shape during folding and metamorphism, even more complex forms of orebodies, including pinching and swelling (possibly related to boudinage), are reported by Sangster and Scott (1976, p. 190). According to Money and Heslop (1976, p. 26-27) some thickening and thinning of Canadian orebodies associated with cordierite- and gahnite-bearing rocks may have been partly an original feature and (or) possibly related to boudinage during deformation.

The information summarized above concerning modifications in form during metamorphism and folding suggests that the orebody at the Sedalia mine probably is also elongate in the down-plunge direction although perhaps oval to crescentic in cross-section. The orebody may pinch and swell and show various complexities in shape along its plunge length. If boudinage has occurred, there may be more than one orebody but all probably plunge northeastward parallel to the fold axes.

We believe that the Sedalia deposit contains at least 1 million tons of ore and that exploration of the orebody at depth could result in greatly expanding this estimate of reserves. Maps and reports provided by J. V. Dodge (written commun., 1975) indicate that approximately 900,000 tons of ore remain as pillars and undeveloped portions of the deposit above a level 60 ft above the 600-Level. Because ore is also known from Lindgren's studies (Lindgren, 1908, p. 164) in workings 40 ft above the 600-Level and because the orebody is also partly exposed in the winze and adjoining drift on the 600-Level, we believe that reserves of at least 1 million tons are present in the deposit. Because the deposit may continue down-plunge to the northeast for a considerable distance, we believe that total reserves may be substantially larger than 1 million tons.

MINERALOGY AND TEXTURE OF THE PRIMARY ORF

The primary ore in the deposit consists most commonly of the base-metal sulfides, chalcopyrite and sphalerite, in a matrix composed predominantly of light-gray magnesian amphiboles. The ore also commonly contains noteworthy amounts of the zinc spinel, gahnite. Magnetite is also a common constituent in much of the primary ore. Some of the ore contains appreciable amounts of silver-bearing galena, but the distribution of galena in the deposit is distinctly less widespread than that of chalcopyrite and sphalerite. Although pyrite and pyrrhotite are also present in some of the ore, they form only a relatively small part of the matrix of the ore. Scheelite has also been reported at the Sedalia mine (Tweto, 1960, p. 1420-1421).

The base-metal sulfides and gahnite and magnetite commonly are medium grained, but they are fine grained in parts of the ore zone. Locally some of the sphalerite and chalcopyrite is coarse grained. The silicate matrix, dominated by light-gray magnesian amphiboles, is usually fine to medium grained, but locally is coarse grained. The base-metal sulfide minerals and gahnite occur both as disseminated grains and aggregates and in crude laminations that are parallel to the lithologic layering. Textural parallelism between ore minerals and silicate minerals is characteristic of the ores. As observed in thin and polished sections, the base-metal sulfide minerals and gahnite commonly show complex metamorphic intergrowths with one another and with silicate minerals of the matrix. Locally some of the sulfide minerals appear to have been mobilized to form discordant irregular stringers.

Some specimens of ore obtained from the dumps and from the winze and adjacent drift on the 600-Level are truly massive sulfide ore, in that sphalerite and (or) chalcopyrite forms over 50 percent of the ore. In other specimens the three minerals--sphalerite, chalcopyrite, and gahnite--comprise over 50 percent of the ore. Lindgren (1908, p. 164) described a portion of the orebody that was freshly exposed at the time of his visit as follows: "The bulk of the ore is massive, and contains both zinc blende and chalcopyrite, with about 10 percent of magnetite and some pyrite; as broken it is said to contain about 20 percent of zinc."

Petrographic studies of the ore indicate that the amphiboles comprising much of the matrix are of at least two kinds. One variety is colorless to pale grayish in thin section and has parallel extinction. Microprobe data for this orthoamphibole obtained by L. J. Cox (wrtten commun., 1981) suggest that it probably is ferroanthophyllite. Another variety of amphibole as viewed in thin section is colorless to pleochroic in shades of pale blue, shows inclined extinction, and commonly shows twinning, some of which is polysynthetic. This clinoamphibole may be cummingtonite. Some samples of the ore contain either one or the other of these two varieties of amphibole, and in some samples both varieties appear to be present. The amphiboles are prismatic in habit and are complexly intergrown with the sulfides and gahnite. In a specimen of ore from the winze driven from the 600-Level the matrix is composed of clinoamphibole, chlorite, and sparse biotite. A chalcopyrite-rich specimen from the same locality has biotite as the principal mineral in the matrix. Much of the ore contains magnetite, commonly as subhedral to euhedral grains, and some specimens also contain sparse small grains of pyrite and pyrrhotite. Some samples of ore show a gradation in mineralogic character to one or more of the lithologic varieties that comprise the garnetiferous unit. Thus, garnet and (or) cordierite are found in some samples together with the amphiboles that are characteristic of the ore. Intermingled with some of the ore is a fine-grained, dark-gray to black, quartz-rich rock that contains disseminated sulfides and small blades of pale-gray amphibole. In some of the rock interlayered with the ore the amphibole is a dark-green bladed variety that is probably actinolite. Such rock commonly shows alteration to a very fine grained talc-like mineral.

OXIDIZED ORE

Much of the ore deposit above the 300-Level consists of oxidized ore. The 90,000 tons of recorded production from the mine was principally this type of ore. A considerable tonnage of such oxidized ore remains in the deposit.

The complex mineralogy of the oxidized ore is due to the formation of a large variety of secondary minerals. Heyl (1964, p. C31) made the following observation: "The upper hundred feet has been leached to a gossan consisting mostly of limonite, quartz (jasperoid variety), malachite and a little yellow earthy sulfate of lead and copper." The yellow earthy mineral is unnamed but is reported by Lindgren (1908, p. 164) to have the formula $PbSO_4 \cdot CuSO_4 \cdot CuO$. Other secondary minerals reported by Heyl (1964, p. C31, C43; written commun., 1981) as constituents of the oxidized ore below the gossan include chalcocite, hydrozincite, malachite, smithsonite, hemimorphite, willemite, aurichalcite, rosasite, chalcanthite, cerussite, goslarite, anglesite, linarite, cuprite, tenorite, and an unidentified bright blue fibrous mineral. During our studies we noted that the species which are particularly abundant include the sulfide, chalcocite, and the sulfates, chalcanthite and goslarite. R. R. Cobban (written commun., 1981) of the Colorado School of Mines examined some samples of secondary minerals collected by us from the mine and confirmed the identification of rosasite. Other minerals that Cobban identified, that are not listed above, include chrysocolla, brochantite, and antlerite. Eckel (1961, p. 275) noted that J. W. Adams reported the presence of apple-green chrysoprase, a variety of quartz, on the dump.

BASE- AND PRECIOUS-METAL CONTENTS OF THE ORES

During the present study ten samples of ores were taken from the Sedalia mine in order to obtain data concerning the base- and precious-metal contents of the ores. Five of the samples were obtained from mine dumps and five others were obtained from the underground workings. Three samples are of oxidized to partly oxidized material, and the other seven are representative of the primary sulfide ores. Each of the samples was taken by breaking and collecting numerous pieces of ore to obtain a large sample--usually 10 lbs or more for each sample. In the underground workings the samples were taken over as large an area as possible, from the orebody as exposed in the sills of stopes and in the wall of a drift. Separate samples from several dumps were taken in a similar manner by collecting numerous pieces of ore for each. Splits of each of the samples were then made, with one portion reserved for mineralogic and petrographic studies and the other portion for analyses.

Data regarding the base- and precious-metal contents of the ten samples are reported in table 1. Amounts of base metals (copper, zinc, and lead) are reported in percent and amounts of precious metals (silver and gold) are reported in ounces per ton.

Copper and zinc are the most important base metals in the ore. The copper content ranges from 0.15 percent in a sample of sphalerite-rich ore to over 10 percent in a partially oxidized sample of chalcopyrite-rich ore. The

Table 1.--Analyses of ores from the Sedalia mine

[Data for copper, zinc, and lead (in percent) and for silver (in ounces/ton) converted from semiquantitative spectrographic analyses (in parts per million) by J. C. Hamilton, N. M. Conklin, and M. W. Solt, U.S. Geological Survey; data for gold (in ounces/ton) converted from analyses by fire assay and atomic absorption methods (in parts per million) by J. G. Crock, A. W. Haubert, and Joseph Haffty, U.S. Geological Survey]

Sample number	Sampled locality	Description	Copper (percent)	Zinc (percent)	Lead (percent)	Silver (ounces/ton)	Gold (ounces/ton)
S-14-75	Dump-------------	Sphalerite-rich ore---	0.15	>10	0.1	0.58	0.003
S-14M-75	Dump-------------	Ore rich in copper pitch.	2.0	2.0	0.02	0.06	
S-64-75	Dump-------------	Galena-bearing ore----	5.0	1.0	5.0	2.04	0.012
S-119-75	Dump-------------	Sulfide ore-----------	1.5	1.5	0.002	0.29	0.005
S-120-75	Dump-------------	Oxidized ore----------	5.0	0.3	0.3	0.88	0.012[1/]
S-84-75	600-Level, drift near winze.	Sulfide ore-----------	3.0	>10	0.007	0.58	0.004
S-97-75	Jackpot Level, sill of stope.	Sulfide ore-----------	7.0	10.0	0.003	0.88	0.009
S-98-75	300-Level--------	Chalcopyrite-rich ore, partly oxidized.	>10	1.5	0.03	2.04	0.019
S-101-75	300-Level--------	Sulfide ore-----------	3.0	7.0	0.007	0.29	0.004
S-102-75	300-Level--------	Sulfide ore-----------	2.0	0.7	0.003	0.09	0.002
Average			>4.0	>5.8	0.5	0.77	0.007

[1/] Au was extracted on these two samples by HBr/Br_2 procedure rather than preconcentration by fire assay.

average copper content of all ten samples is greater than 4 percent. The zinc content ranges from 0.3 percent in one sample of oxidized ore to over 10 percent in two samples of primary ore. The average zinc content of all ten samples is greater than 5.8 percent. The lead content ranges from insignificant amounts in some samples to as much as 5 percent in one sample of galena-bearing ore. The average lead content of all ten samples is 0.5 percent.

The silver content of the ten samples ranges from 0.06 to 2.04 ounces per ton (oz/ton) and averages 0.77 oz/ton. The gold content of the ten samples ranges from less than 0.003 to 0.019 oz/ton and averages 0.007 oz/ton. Sample number S-57A-76, not listed in table 1, contains the highest amount of gold of any of the samples analyzed during the present study. J. G. Crock (written commun., 1983) reported that the sample contains 2.2 ppm gold, which is equivalent to 0.064 oz/ton. The sample, obtained from the dump, is a gahnite-bearing rock rich in light-colored amphiboles.

The following information on the grade of ores from the Sedalia mine was made available to us by J. V. Dodge (written commun., 1975). Dodge's records indicate that the average base and precious metal contents of ore shipments (largely oxidized ore) for the years 1915 through 1918 ranged as follows: copper, 3.39 to 4.85 percent; zinc, 17.35 to 22.93 percent; silver, 0.87 to 1.73 oz/ton; gold, 0.03 oz/ton. A new crosscut and winze, driven on the 600-Level in 1918, intersected primary ore. Dodge's records indicate that four chip samples taken in the winze in 1929 ranged in length from 26 to 51 in. and contained: copper, 2.7 to 8.5 percent; zinc, 4.8 to 22.2 percent; silver, 0 3 to 1.5 oz/ton; gold, 0.01 to 0.04 oz/ton. A long chip sample taken in 1969 in the winze and adjoining area contained: copper, 3.53 percent; zinc, 8.1 percent; silver, 0.5 oz/ton; gold, 0.02 oz/ton.

The average base- and precious-metal contents in the samples in table 1 are of the same general order of magnitude as the contents reported from the earlier investigations. However, the actual average gold content is probably somewhat higher than the average reported in table 1. A conservative estimate of the base and precious metal contents of the primary sulfide ore, which constitutes the most important reserves of the deposit, based both on our data and the data from earlier records, is as follows: copper, about 4 percent; zinc, at least 6 percent; lead, 0.5 percent; silver, 3/4 to 1 oz/ton; gold, 0.01 to 0.03 oz/ton.

Although the base and precious metals described above are the principal metals in the Sedalia mine, the ores also contain other metallic constituents as indicated by spectrographic analyses of the samples in table 1. Iron, partly in the form of magnetite, generally constitutes 10 percent or more of the ore. Cadmium is present in the sphalerite-bearing ores and is notably lacking in gahnite-bearing ore that contains no sphalerite. The cadmium content commonly ranges from 50 to 700 ppm; one sample contains as much as 1,500 ppm. The cobalt content ranges from 0 to as much as 500 ppm. Chromium ranges from 0 to 50 ppm. As much as 70 ppm of bismuth occurs in galena-bearing ore, but in other samples in which galena was not recognized megascopically, the bismuth content ranges from 0 to 30 ppm. Tin ranges from 0 to 50 ppm and nickel from 0 to 70 ppm. Molybdenum ranges from 0 to 50 ppm. Tungsten is generally absent in the samples reported in table 1, but constitutes as much as 300 ppm of one sample.

GAHNITE-BEARING ROCKS AND ORES

During field studies in the Salida area and in numerous other areas in the Precambrian terrane of Colorado, the authors found that the zinc spinel, gahnite, occurs in many of the Precambrian sulfide deposits (Sheridan and Raymond, 1977, p. 14-16, 20; in press). Although the presence of gahnite at some of the deposits had been noted previously by earlier investigators, it had apparently been considered a mineralogic curiosity. We found that gahnite is characteristic of many of the ores and that substantial amounts of zinc in some of these deposits is in the form of gahnite.

As noted in the preceding descriptions of rocks and ores of the Sedalia mine, gahnite is not only abundant in much of the base-metal sulfide ore but also is characteristic of other parts of the host rocks. For example, gahnite is abundant in otherwise unmineralized cordierite-rich gneiss that occurs along both the northwestern and southeastern sides of the ore zone. The spinel also is a constituent of the lens of gahnite-bearing quartz-mica schist in the northeastern part of the mapped area. L. J. Cox (written commun., 1981) reported that microprobe studies of gahnite from the Sedalia mine and adjacent area by G. A. Desborough and herself indicated that the zinc content of the gahnite is between 23.5 and 24.7 weight percent regardless of whether the host is a rock rich in light-colored amphiboles, cordierite-rich gneiss, or quartz-mica schist.

Samples of gahnite-bearing rocks were collected in order to determine their zinc content analytically. The results for four samples are reported in table 2. In samples from outcrops, the zinc content ranges from 1.25 percent in the gahnite-bearing schist 1 1/4 mi northeast of the Sedalia mine to 5.0 percent in the cordierite-rich gneiss on the east side of the mine. The other two samples, one from the Dewey Level and one from the dump, were chosen for this particular study because they contain very little or no sphalerite. Both of these samples are rocks rich in light-colored amphiboles and, except for the lack of abundant sulfides, they are identical in lithology to the matrix of much of the sulfide ore. In fact, these two samples are representative of rocks commonly associated with and gradational to the base-metal sulfide ore. The results reported in table 2 show that their zinc content ranges from 7 to nearly 8 percent.

We believe that gahnite should be considered a potentially significant ore mineral of zinc in the Sedalia deposit because it is abundant in the ore and because the analytical data indicate that it contributes substantial amounts of zinc to the ore. Pertinent in this regard is the fact that gahnite, franklinite (another zinc-bearing spinel), willemite, and tephroite--all highly refractory multiple oxides and silicates--are components of ores that for many years have been mined and smelted successfully from the zinc deposits at Franklin and Sterling Hill, New Jersey. Modern technological advances in beneficiation processes and metallurgical methods could make it possible to utilize both the base-metal sulfides and the gahnite in the ores of the Sedalia mine.

ECONOMIC POTENTIAL

We believe that the Sedalia mine has an excellent potential for the production of copper and zinc ores with subordinate amounts of lead, silver, and gold. The ore probably averages about 4 percent copper and at least 6 percent zinc. Reserves of at least a million tons of oxidized and primary

Table 2.--Zinc content of gahnite-bearing rocks from the Sedalia mine area

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

Sample number	Sampled locality	Lithology	Zinc (percent)	Type of (analysis)
S-79-75	Outcrop, east side of Sedalia mine.	Gahnite-bearing cordierite-quartz-biotite gneiss.	5.0	S
S-92-75	Dewey Level--------	Gahnite-bearing rock rich in light-colored amphibole.	7.66	C
S-57A-76	Dump---------------	Gahnite-bearing rock rich in light-colored amphibole.	7.01	C
S-8-76	Outcrop, 1 1/4 mi northeast of the Sedalia mine.	Gahnite-bearing quartz-mica schist.	1.25	C

ores exist in the known portions of the deposit. The total reserves may be much greater because the orebody probably continues down-plunge to the northeast for an undetermined but potentially significant distance.

Exploration by diamond drilling seems to offer the best means of determining the down-plunge extent and shape of the orebody. Our preliminary studies suggest that the orebody probably plunges northeast at a shallow to moderate angle parallel to the plunge of lineations and the axes of minor folds. Collection of additional data on the bearing and plunge of structural features should be done prior to any exploration in order to define the probable position and configuration of the orebody at depth. As has been pointed out by Sangster and Scott (1976, p. 189) one of the most common results of metamorphism of sulfide deposits is the development of linear or rod-shaped orebodies aligned parallel to structural features such as fold axes and mineral lineations. Especially pertinent in this regard are the comments made by Coats and others (1970, p. 971-972, 975-976), because structural information concerning lineations led to the discovery and outlining of the No. 2 ore zone of the copper-zinc deposits of Stall Lake Mines Ltd. in the Snow Lake area, Manitoba. They reported that an arithmetic average of 100 measurements of lineation in outcrops provided a mean bearing and angle of plunge that successfully guided the drilling program. Structural data should be measured in surface outcrops and in underground exposures at the Sedalia mine. Stereographic plotting of such data on an equal-area net is probably the best method for arriving at figures that could be useful as a mean bearing and angle of plunge. Due consideration should also be given for the possibility that the detailed shape of the body may vary down-plunge, with some portions being thicker or more complex in shape than others.

In an evaluation of the Sedalia ore deposit consideration should be given for the potential economic value of gahnite as an ore mineral. The occurrence of gahnite in the lens of schist in the northeastern part of the area may also be significant because it might indicate that a base-metal sulfide deposit is present down-dip or down-plunge from that locality. As described previously (Sheridan and Raymond, 1977, p. 16, 20), the presence of gahnite in rocks adjacent to or along strike from base-metal sulfide deposits at several localities in Colorado suggests that gahnite can be used as a prospector's guide to ore, even where sulfide minerals are not seen in outcrops.

ORIGIN

We believe that the origin of the Sedalia base-metal sufide deposit involved syngenetic deposition of the sulfides on the sea floor together with the progenitors of the unit of garnet-cordierite-amphibole gneiss and other interlayered rocks that hosts the deposit. Hydrothermal fluids containing the metallic constituents of the present deposit presumably rose through a fracture system and were vented at some place in the sea floor. By interaction with the seawater, these exhalative fluids then deposited the copper, zinc, and lead as sulfides. Such a vent may have been close by because the present matrix of much of the ore is rich in magnesian amphiboles, the protolith for which can best be ascribed to chloritic material (Mg-chlorite) formed as a hydrothermal alteration of materials being deposited with the sulfides. Although the rocks of the garnetiferous unit are probably sedimentary in origin, other rocks in the stratigraphic section are very likely volcanic in origin. Some of these probably were deposited subaqueously also. Much of the amphibolite that occurs in the southeastern part of the mine area probably originated as basaltic flows, whereas much of the feldspathic gneiss probably originated as flows or tuffs having the composition of rhyodacite. The volcanism, therefore, was probably bimodal in character.

Although high-grade regional metamorphism has destroyed or made obscure many of the original features of the deposit, the origin hypothesized above seems to fit the geological evidence available at the Sedalia deposit. Because the primary ore is apparently stratabound in the garnetiferous unit, its protolith probably was a stratiform body deposited on the sea floor. After subsequent burial and during high-grade regional metamorphism and folding, the sulfides and other constituents of the enclosing host recrystallized to their present mineralogy and were deformed to their present distribution. Evidence for simultaneous metamorphism of the sulfides and their host materials is seen in the complex metamorphic intergrowths and in the preponderance of textural parallelism of sulfide minerals and minerals of the host rock over discordant relations of these minerals. The age data concerning galena and the host rocks also support the conclusion that the sulfides were metamorphosed simultaneously with their host rocks. The gahnite that is abundant in the sulfide ore may have formed there by desulfurization of some of the sphalerite. We are not certain, however, that desulfurization is a necessary requirement for the formation of the gahnite, because some of the gahnite-bearing rocks contain no evidence of pre-existing sulfides. The gahnite in such rocks more likely formed as a metamorphic product from an original argillaceous or chloritic material that contained adsorbed zinc.

Numerous other base-metal sulfide deposits occur in the Salida area (Sheridan and Raymond, 1977, p. 10-23; in press). All appear to be aligned approximately parallel to the lithologic layering and most of them are similar to the Sedalia deposit in the association of ore minerals with garnetiferous gneisses and (or) magnesium-rich amphiboles. Most of these deposits also contain noteworthy amounts of gahnite. We believe that the features of these deposits and the Sedalia deposit, their stratabound character, their occurrence as a cluster in the Salida area (fig. 1), and the presence of abundant metavolcanic rocks are significantly similar to the geologic setting and features displayed by numerous sulfide deposits considered to be volcanogenic in Canada and other parts of the world (Sangster, 1972; Hutchinson, 1973; Sangster and Scott, 1976; Franklin and others, 1981). We conclude, therefore, that the Sedalia deposit and the other similar deposits in the Salida area belong to the family of volcanogenic sulfide deposits. The fact that rocks of sedimentary origin are interlayered with rocks that probably are the products of bimodal volcanism suggests that the setting for these deposits was an island arc rather than an oceanic spreading center.

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