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GEOLOGICAL SURVEY BULLETIN 1513

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By WILLIAM H. RAYMOND, PETER A. LEIGGI,
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Mineralogic relationships between sapphirine and sulfide-bearing Precambrian rocks

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By WILLIAM H. RAYMOND, PETER A. LEIGGI, and DOUGLAS M. SHERIDAN

ABSTRACT

Sapphirine, a rare magnesium-iron-aluminum silicate found only in widely scattered occurrences in the world in very high grade contact or regionally metamorphosed rocks, has been identified at three abandoned mines and prospects in the southern Wet Mountains, Colo. These occurrences of sapphirine, believed to be the first reported in the Rocky Mountains of western North America, are unlike most other occurrences reported elsewhere because the mineral is in the host rocks of Precambrian stratabound sulfide deposits. The sulfide deposits and their host rocks occur in very large xenoliths, as much as a square kilometer in surface area, within a small batholith of the San Isabel Granite of Boyer. Sapphirine, in grains as large as 3.8 mm (millimeters) and in amounts of as much as 25 percent of individual samples, occurs in fine- to medium-grained gneisses that are characterized at all three localities by magnesian amphiboles and green zincian spinel. At one locality the sapphirine-bearing gneisses extend along a strike length of at least 150 m. Coexisting with sapphirine in various assemblages are cordierite, orthorhombic and monoclinic amphiboles, phlogopitic biotite, zincian spinel, corundum, plagioclase (calcic andesine to labradorite), orthopyroxene, and the sulfide minerals, including sphalerite, chalcopyrite, and galena. Interlayered with the sapphirine-bearing gneisses are impure marble and calc-silicate gneiss containing forsterite, clinopyroxene, monoclinic amphibole, garnet, clinohumite, and sulfide minerals. Although the occurrences are in very large xenoliths, the intrusion of the San Isabel Granite about 1,400 m.y. ago is not believed to have played a causative role in the formation of sapphirine. Instead, presently available data indicate that the Precambrian sulfide deposits and their host rocks were regionally metamorphosed about 1,700 m.y. ago. Sapphirine is believed to have crystallized then with the coexisting silicates and zincian spinel under local pressure-temperature conditions of the amphibolite-granulite transitional facies.

INTRODUCTION

Sapphirine, a rare magnesium-iron-aluminum silicate, has been identified in the host rocks of Precambrian stratabound sulfide deposits at three localities approximately 4 km (kilometers) west of San Isabel in the southern Wet Mountains, Custer County, Colo. The index map of the San Isabel area (fig. 1) shows four abandoned mines and prospects that were examined as part of a study of Precambrian deposits of zinc, copper, and lead sulfides in Colorado. Sapphirine is abundant at the Amethyst prospect and occurs in lesser amounts at the unnamed prospect 150 m (meters) west-northwest of the Amethyst prospect and at the upper adit of the Marion mine, but none was found in samples collected at the Dewey prospect (fig. 1). These appear to be the first reported occurrences of sapphirine in the Rocky Mountains of western North America (Raymond and others, 1980). Sapphirine is rarely found in metamorphosed stratabound base-metal sulfide deposits. The only other known occurrences described in the literature are in gneisses containing stratabound deposits of chalcopyrite, sphalerite, and galena in central Australia (Stewart and Warren, 1977, p. 26).

Boyer (1962) published a report and a geologic map of the southern Wet Mountains in which he discussed the petrology and structure of the region. Boyer (1963) also published a brief description of the sulfide deposits at the Marion mine, the Amethyst prospect, and the Dewey prospect. Boyd (1934, p. 58–60) and Gabelman (1953, p. 193) also briefly described geologic features at the Marion mine. This mine is the largest of the old mining operations in the area and was opened in the early 1900's for the mining of sulfide ores of zinc, copper, and lead (Parmelee, 1910; Babbitt, 1911).

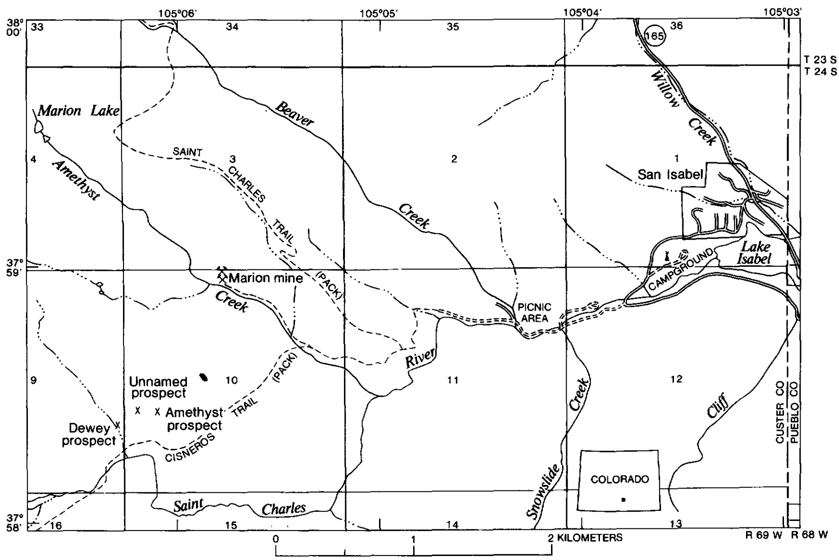

FIGURE 1.—Location map of the San Isabel area, Custer County, Colo.

Fieldwork for the present study consisted of reconnaissance examination and sampling of host rocks and deposits. Laboratory work included petrographic studies of standard and polished thin sections of rocks and ores and X-ray diffraction studies of mineral concentrates.

In this report we describe the sapphirine in these occurrences, the assemblages in which it occurs, and the petrography of the sapphirine-bearing rocks.

ACKNOWLEDGMENTS

We are grateful to many U.S. Geological Survey colleagues for help during the preparation of this report. Fred Barker gave helpful advice during petrographic studies of the sapphirine-bearing rocks and acquainted us with pertinent references in the literature. George A. Desborough made a microprobe analysis of spinel from the Marion mine. Leslie J. Cox and Arthur J. Gude, 3d, provided information, obtained from studies using a scanning electron microscope, concerning the chemical compositions of spinel samples from the sapphirine localities. Richard B. Taylor and Ogden Tweto provided useful information concerning the areal geology of the Wet Mountains. Joseph T. Airey, formerly of the U.S. Geological Survey, provided welcome assistance during a brief backpacking trip to the sapphirine-bearing localities in September 1978. We are grateful to William N. Sharp for his help in improving the photographic illustrations.

GEOLOGIC SETTING

Precambrian sulfide deposits occur in many localities in Colorado (Sheridan and Raymond, 1977, fig. 1) in metamorphic rocks known to be more than 1,700 million years old (Tweto, 1977, p. D1). The progenitors of these metamorphic rocks were sedimentary, volcanic, and subvolcanic intrusive rocks. Available isotopic data (Hedge, 1969) indicate that no great amount of time elapsed between the original deposition of the rocks and the time of metamorphism. The major period of Precambrian folding and regional metamorphism in Colorado reached its peak about 1,700 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). Lead isotope studies on galena from Precambrian sulfide deposits in Colorado gave the same general 1,700-m.y. age (Bruce Doe, oral commun., 1979). The age data together with the metamorphic textures of the ore-bearing rocks indicate that the sulfide deposits were metamorphosed with their host rocks during regional metamorphism about 1,700 m.y. ago.

In the southern Wet Mountains the Precambrian metamorphic rocks were intruded by the San Isabel Granite batholith (Boyer, 1962, pl. 1, p. 1056) and associated smaller granite plutons. Tweto (1977, p. D8) included the San Isabel Granite in his group of granitic rocks of about 1,400-m.y. age on the basis of uranium-lead age determination.

Boyer (1963, p. 147) used the term "mineralized xenoliths" for the sulfide deposits at the Marion mine and the Amethyst and Dewey prospects; he described them as lens-shaped zones within the granite and noted that the sulfide mineralization is concentrated in calc-silicate rocks associated with paraschist and paragneiss. Although our field studies are of reconnaissance type, we accept Boyer's designation of these sulfide-bearing bodies of metamorphic rocks as xenoliths. Observations for this study indicate, however, that even the smallest of these is actually much larger than the term "xenolith" commonly denotes. Thus, the body of metamorphic rocks containing a stratabound sulfide deposit at the Marion mine is about 25 m thick and at least 60 m long, trends N. 50° E., and dips about 30° NW. Babbitt (1911, p. 548), based on study of underground workings at the Marion mine, reported that the ore body extends downdip from the surface for at least 225 ft (feet) (69 m). The total plunge length of the Marion xenolith, therefore, probably exceeds the longest dimension at the surface. Reconnaissance studies in the area to the southwest indicate that the Amethyst and Dewey prospects are not in relatively small xenoliths as depicted by Boyer (1963, pl. 2). Instead, our studies indicate that the entire area encompassing the Amethyst prospect, the unnamed prospect, and the Dewey prospect is composed of metamorphic rocks containing several stratabound sulfide deposits. Although not continuously exposed, this body of metamorphic rocks appears to be on the order of one square kilometer in size. Such a large body may indeed be a xenolith, but it also could be either a roof pendant or even a part of the basement projecting through the floor of the granite batholith.

Sapphirine was first identified in samples from the Amethyst prospect and subsequently identified in samples from the unnamed prospect and from the upper adit at the Marion mine. Metamorphic rocks at the Marion mine and the Amethyst prospect consist of an interlayered sequence of amphibole-rich gneisses, calc-silicate gneiss, and impure marble. At the unnamed prospect the amphibole-rich rocks also contain substantial amounts of orthopyroxene. Zincian spinel is abundant at all three localities. Sphalerite is the dominant sulfide at both the Marion mine and the Amethyst prospect. The ores at both of these workings also contain appreciable amounts of chalcopyrite and galena; pyrite and pyrrhotite were noted in the sulfide ores at the Marion mine. Sulfide minerals also are present at the unnamed prospect.

The Amethyst prospect consists of an inclined adit, now caved, and a small open pit. Sapphirine-bearing rocks were collected from the dump near the portal of the adit, from sparse outcrops to the west and east, and from abundant float that is distributed along the gentle hillside for about 100 m west and about 50 m east of the dump. Because the general strike of layering in the metamorphic rocks in this area is N. 50°–70° E., and the dip is moderately northwest, the strike length of the sapphirine-bearing rocks is probably at least 150 m.

The unnamed prospect consists of three closely spaced adits, all now caved. Grab samples of rock rich in zincian spinel were found to contain abundant orthopyroxene and minor sapphirine.

The Marion mine consists of a main adit, opening at the portal in San Isabel Granite, which is caved a short distance from the portal. Babbitt's description (1911, p. 548) noted that this crosscut tunnel was driven 225 ft (69 m) to the ore body, from which point an incline was sunk along the ore body for 100 feet (30 m); drifts were driven along the ore body for about 200 feet (61 m) at both the tunnel level and at the bottom of the incline. Sapphirine was not found on the main dump at the Marion mine, but it occurs in amphibole-rich gneiss in the back at the portal of a short upper adit, approximately 27 m above the main adit. A layer of impure marble about 2 m thick, containing clinopyroxene and scattered grains of galena, occurs about 1 m below the sapphirine-bearing rock.

SAPPHIRINE

Sapphirine from the three occurrences in the southern Wet Mountains, Colo., is pale blue to blue in hand specimen and is as much as 25 percent by volume of individual rock samples. On weathered surfaces aggregates of sapphirine, commonly intergrown with zincian spinel and other minerals, stand out as resistant knots 1 to 7 mm in maximum dimension. In thin section, individual grains of sapphirine range in size from 0.02 to 3.8 mm, but most are in the range of 0.3–2.0 mm. Whereas most of the grains are anhedral, some are subhedral to euhedral, and tabular (fig. 2). The sapphirine is biaxial negative; the optic angle measured in one grain (table 1) is 61°±1°. Inclined dispersion $r<v$ is strong. The indices of refraction show a range of values (table 1): α=1.711–1.717; β=1.716–1.722; γ=1.718–1.724. The birefringence ($\gamma-\alpha$), calculated from refractive-index determinations, ranges from 0.005 to 0.007. The mineral is strongly pleochroic: α, colorless to pale yellowish or pale tan; β, blue; γ, deep blue to Prus-

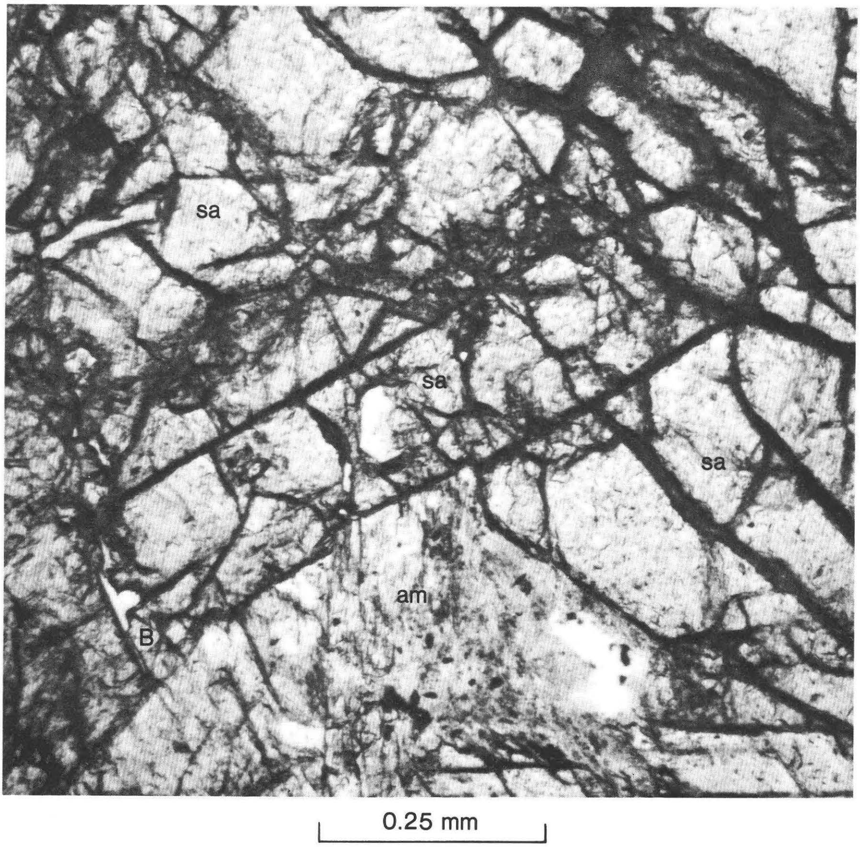

FIGURE 2.—Photomicrograph of a tabular grain of sapphirine (sa) associated with anhedral grains of sapphirine in a sample from the Amethyst prospect. Other minerals are biotite (B) and amphibole (am). Plane-polarized light.

sian blue. The absorption is $\alpha < \beta < \gamma$. Cleavage is very poorly developed; in one grain γ:[001] about 5°. Grains of sapphirine in thin section commonly show sector twinning (fig. 3) and simple twinning. Although less common, polysynthetic twinning is shown in some of the grains (fig. 4). In a manner similar to that commonly observed in altered olivine, some grains of sapphirine are crisscrossed in a braided or anastamosing pattern by thin stringers of an unidentified, very fine grained, white, talclike alteration product.

Merlino (1973) has reported that there are two types of sapphirine: (1) monoclinic (2M), a type that can be untwinned, simply twinned, or sector twinned; (2) triclinic (1Tc), a type that has been observed in polysynthetic twins. Preliminary work directed toward the determination of the unit cell of sapphirine from one sample from the

TABLE 1.—*Optical data for sapphirine from the southern Wet Mountains*

[Leaders (---), not determined]

Sample No.	Locality	Indices of refraction (±0.002)[1]			Birefringence	Optic angle (measured)
						(-)2V
S-51A-77, grain 1.	Amethyst prospect, dump.	[2]1.714	1.718	1.721	0.007	[3]61°±1°
S-51A-77, grain 2.	--do--	[2]1.716	1.719	1.721	.005	---
S-51Y-77	Outcrop east of Amethyst prospect.	[2]1.717	1.722	1.724	.007	---
S-30AX1-78	Portal of short adit about 27 m above main adit level, Marion mine.	[4]1.711	1.716	1.718	.007	---

[1]Optical data were obtained on single grains that were selected from crushed splits of each sample; the grains were studied petrographically by spindle-stage procedures described by Wilcox (1959).

[2]Refractive indices were determined by focal masking techniques described by Cherkasov (1955a, b; 1957).

[3]The grain of sapphirine was mounted so that the optic plane was normal to the spindle axis; measurement of 2V was then made directly by rotation of the spindle from one melatope to the other.

[4]Refractive indices were determined by the Becke line method; an interference filter was used that passes a wavelength near the D-line of the spectrum.

Amethyst prospect indicates that it is the monoclinic type. Polysynthetically twinned grains of sapphirine in some of the thin sections suggest that triclinic sapphirine also may be present.

MINERAL ASSEMBLAGES AND PETROGRAPHY

Sapphirine-bearing, fine- to medium-grained gneisses at all three localities in the San Isabel area are characterized by light-colored amphiboles and green zincian spinel. Other minerals typically associated with sapphirine in these rocks are pale brown biotite, cordierite,

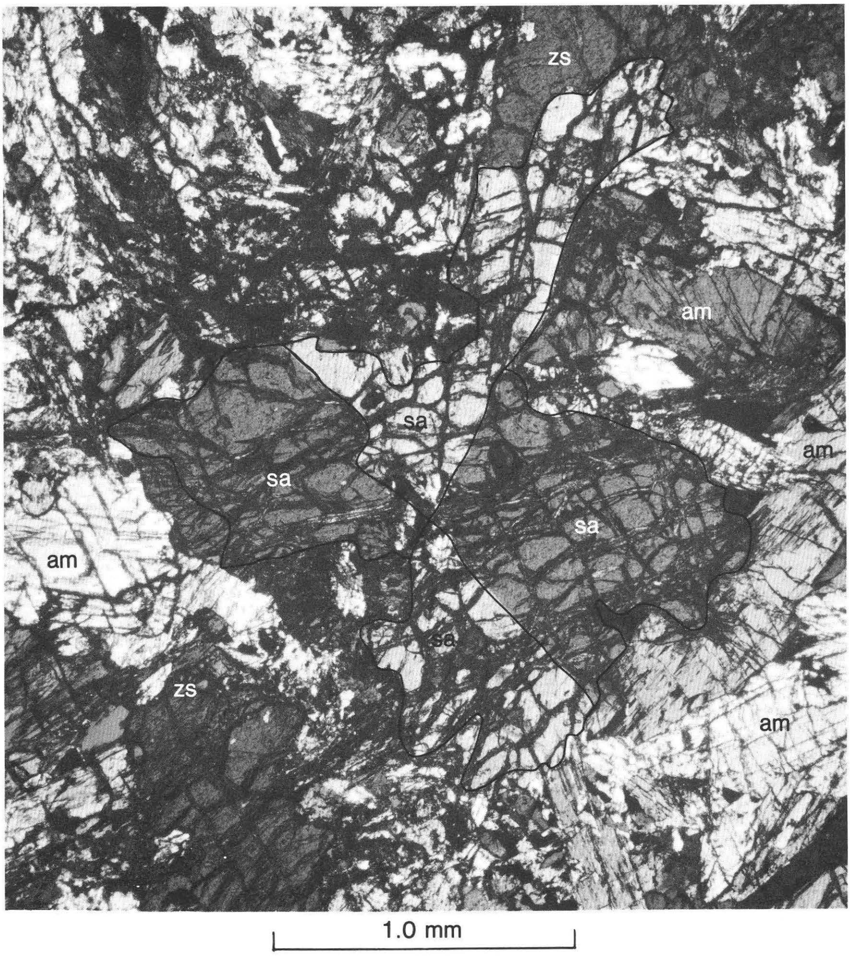

FIGURE 3.—Photomicrograph showing sector twinning in sapphirine (sa) in a sample from the Amethyst prospect; each of four sectors is labeled with the letter symbol (sa). Other minerals are amphibole (am) and zincian spinel (zs). Crossed polars.

FIGURE 4.—Photomicrograph showing polysynthetic twinning in the right half of a simple twin of sapphirine (sa) in a sample from the Amethyst prospect. Other minerals are amphibole (am), biotite (B), sphalerite (sl), and zincian spinel (zs). Crossed polars.

plagioclase, and sulfide minerals; a less common associate is corundum. Orthopyroxene is present in the rocks at the unnamed prospect. Quartz has not been found in any of the sapphirine-bearing gneisses but is fairly common in some of the associated sapphirine-free rocks. Sapphirine has not been found in the impure marble and calc-silicate gneiss at the Marion mine and the Amethyst prospect, although zincian spinel occurs in these rocks as well as in the sapphirine-bearing rocks.

Sapphirine-bearing assemblages of minerals observed in thin sections of rocks from the three localities are listed as follows:

AMETHYST PROSPECT

Sapphirine-amphibole-cordierite-zincian spinel
Sapphirine-amphibole-cordierite±plagioclase±biotite±sulfides
Sapphirine-amphibole-plagioclase-zincian spinel±biotite
Sapphirine-amphibole-zincian spinel±cordierite±biotite±sulfides
Sapphirine-amphibole-zincian spinel±biotite±corundum
Sapphirine-cordierite-plagioclase-zincian spinel
Sapphirine-cordierite-zincian spinel-biotite
Sapphirine-zincian spinel-biotite±corundum±sulfides

UNNAMED PROSPECT

Sapphirine-amphibole-orthopyroxene±sulfides
Sapphirine-orthopyroxene-zincian spinel-biotite±sulfides
Sapphirine-amphibole-cordierite±sulfides
Sapphirine-amphibole-zincian spinel±sulfides

UPPER ADIT, MARION MINE

Sapphirine-amphibole±zincian spinel±biotite

Each of the assemblages includes minerals that are in mutual contact. With microprobe analyses and more detailed petrographic studies at a later time, an evaluation of equilibrium conditions can be made.

The general term "amphibole" is used in the list of mineral assemblages because more than one species are present in some of the rocks. All are very pale gray to colorless in thin section. Orthorhombic amphibole appears to be the most common type present. Optical data and X-ray studies indicate that some is anthophyllite and that some probably is another species in the anthophyllite-gedrite series. In addition to orthorhombic amphibole, some of the rocks also contain one or more monoclinic amphiboles, some of which are well twinned.

In a sapphirine-free amphibole-cordierite-orthopyroxene gneiss from the unnamed prospect, the orthopyroxene is distinctly pleochroic (pink to pale greenish gray), is biaxial negative, and has a large 2V. These aspects plus X-ray data indicate that the pyroxene is hypersthene. In the sapphirine-bearing gneiss from this locality (fig. 5) the pleochroism of the orthopyroxene is much less distinct, although it also is biaxial negative and has a large 2V. X-ray data indicate that the peaks are shifted toward enstatite, so we have used the general term "orthopyroxene" in the mineral assemblages.

Most of the biotite in these assemblages as viewed in thin section is very pale brown, and some is almost colorless. It is probably phlogopitic biotite, but, as with the amphiboles and pyroxenes, more precise terminology will require microprobe data.

Spinel that contains significant but variable amounts of zinc is characteristic of the three sapphirine localities. Its color in hand specimens ranges from pale bluish green in the vicinity of the upper adit of the Marion mine to green almost everywhere else. In some of

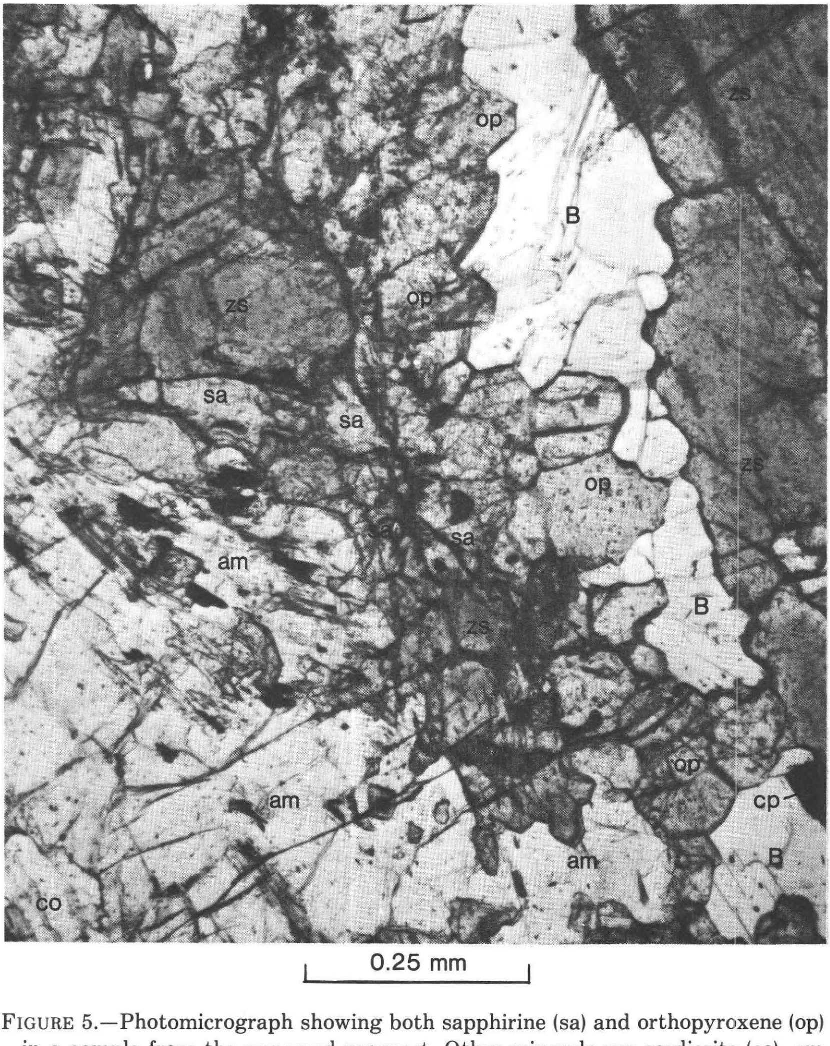

FIGURE 5.—Photomicrograph showing both sapphirine (sa) and orthopyroxene (op) in a sample from the unnamed prospect. Other minerals are cordierite (co), amphibole (am), biotite (B), zincian spinel (zs), and chalcopyrite (cp). Plane-polarized light.

FIGURE 6.—Photomicrograph showing the common assemblage sapphirine (sa)-amphibole (am)-cordierite (co)-zincian spinel (zs) in a sample from the Amethyst prospect. Other minerals are an intergrowth (sl-cp) of sphalerite and chalcopyrite. Plane-polarized light.

the rocks at the unnamed prospect it is very dark green to nearly black. Microprobe data (G. A. Desborough, written commun., 1977) for spinel from calc-silicate gneiss at the Marion mine are: 12.0

weight percent magnesium, 10.0 weight percent zinc, and 2.0 weight percent iron. Green spinel from the Amethyst prospect was found to have a refractive index of 1.741±0.002, a value intermediate in the spinel-gahnite series (Winchell and Winchell, 1951, p. 83). Qualitative studies using a scanning electron microscope indicate that the relative amounts of magnesium, zinc, and iron vary considerably in spinels from the three sapphirine localities. Although no zinc was detected in one sample, in the other samples the amounts of zinc, estimated from peak intensities, range from low or moderate to dominant, suggesting probable compositions ranging from zincian spinel to gahnite. For these reasons the general term "zincian spinel" has been used in this report; we recognize, however, that the composition probably ranges considerably.

Cordierite is a prominent constituent of some of the sapphirine-bearing gneisses. It occurs in the common assemblage sapphirine-amphibole-cordierite-zincian spinel (fig. 6). In some of the sapphirine-bearing gneisses, plagioclase, ranging from calcic andesine to labradorite, occurs to the exclusion of cordierite, whereas in other samples both cordierite and plagioclase are present. In some thin sections the rocks show thin plagioclase-rich layers separated from cordierite-rich layers by layers rich in amphibole and biotite. Some of the cordierite is well twinned.

Corundum occurs in some of the sapphirine-bearing gneisses at the Amethyst prospect and in a sapphirine-free sillimanitic cordierite-amphibole-plagioclase gneiss at the Marion mine. Corundum was not observed, however, in samples of orthopyroxene-bearing gneiss from the unnamed prospect.

Modes of five representative samples of sapphirine-bearing gneisses were determined by the point-count method (1,000 points each) and are reported in table 2. Modes 1 and 2, representing samples from the Amethyst prospect, contain nearly equal amounts of amphibole but variable amounts of cordierite, sapphirine, zincian spinel, and biotite. In mode 3, also from the Amethyst prospect, plagioclase is abundant, cordierite is absent, and the amphibole content is much lower than in the other two samples from the Amethyst prospect. A small amount of corundum occurs in this plagioclase-rich gneiss. Mode 4 characterizes the orthopyroxene-rich gneiss at the unnamed prospect. Mode 5, a sample from the upper adit of the Marion mine, illustrates a rock in which the principal minerals are amphibole and sapphirine. Sulfide minerals, commonly sphalerite and chalcopyrite, are present in each of the samples described in table 2. Other accessory minerals observed are: zircon, causing pleochroic halos in biotite and cordierite; tiny acicular crystals that probably are

TABLE 2.—*Modes of sapphirine-bearing gneisses, southern Wet Mountains, Colorado*

[Values in volume percent. Tr, trace; .... indicates mineral not present]

Mode	1	2	3	4	5
Amphibole	55.5	51.1	10.7	23.7	70.2
Cordierite	23.8	11.7	----	15.1	----
Sapphirine	14.8	9.8	9.8	.7	18.5
Zincian spinel	3.5	10.8	13.7	15.7	6.6
Biotite	1.9	15.7	17.9	7.9	3.3
Orthopyroxene	----	----	----	35.8	----
Plagioclase[1]	----	----	44.3	----	----
Corundum	----	----	2.9	----	----
Sillimanite(?)	----	----	----	.4	----
Prismatic mineral[2]	----	----	.5	----	----
Sulfide minerals and their oxidation products	.5	.9	.2	.7	1.4
Rutile(?)	Tr.	----	Tr.	----	----
Carbonate mineral	----	----	tr.	----	----
Zircon	tr.	Tr.	tr.	Tr.	Tr.
Total	100.0	100.0	100.0	100.0	100.0

[1]Partly sericitized.

[2]Unidentified pale-brownish prismatic mineral: commonly 0.08-0.16 mm long and 0.02-0.03 mm thick; length-slow; parallel extinction; low birefringence and high refringence.

Mode	Sample No.	Locality and rock type
1--	S-25F1-78	Amethyst prospect: zincian spinel-bearing amphibole-cordierite-sapphirine gneiss.
2--	S-25J2-78	Amethyst prospect: sapphirine-bearing amphibole-biotite-cordierite-zincian spinel gneiss.
3--	S-25K2-78	Amethyst prospect: sapphirine- and corundum-bearing plagioclase-biotite-zincian spinel-amphibole gneiss.
4--	S-26C1-78	Unnamed prospect: sapphirine-bearing biotitic orthopyroxene-amphibole-zincian spinel-cordierite gneiss.
5--	S-30A1-78	Upper adit, Marion mine: zincian spinel-bearing amphibole-sapphirine gneiss.

sillimanite; tiny yellowish grains that are probably rutile; a carbonate mineral; and an unidentified pale-brownish prismatic mineral.

Textural relations observed in the sapphirine-bearing gneisses are closely similar to the metamorphic textures observed in many of the host rocks of Precambrian sulfide deposits elsewhere in Colorado. In all of these rocks, including those from the San Isabel area, silicate minerals, sulfide minerals, and zincian spinel are complexly intergrown; in many of the rocks elongate grains and aggregates of the various minerals are alined along the gneissic and compositional layering. Although sapphirine was observed rimming zincian spinel in some thin sections, this is by no means the dominating textural relationship shown by these two minerals. Instead, sapphirine and zincian spinel occur just as commonly as independent individual grains; aggregates of each of these minerals are commonly alined along the gneissic layering. In some of the rocks sapphirine and zincian spinel are intergrown (fig. 7). Examples of sapphirine poikiloblastically intergrown in zincian spinel appear to be as com-

FIGURE 7.—Photomicrograph showing an intergrowth of sapphirine (sa) and zincian spinel (zs) in a sample from the Amethyst prospect. Other minerals are biotite (B) and amphibole (am). Plane-polarized light.

mon as the reverse relation. Orthopyroxene occurs in elongate grains and aggregates alined parallel to the layering shown by the associated cordierite, amphibole, biotite, and zincian spinel (see, for example, fig. 5).

Sapphirine-free rocks from the Marion mine and the Amethyst prospect commonly range from impure marble to calc-silicate gneiss. These rocks are commonly fine to medium grained, although locally some are coarse grained. Silicate minerals present in these rocks include forsterite (commonly altered partly or almost entirely to serpentine), clinopyroxene, garnet, monoclinic amphibole, and clinohumite. Brucite also was identified in one of these rocks. Quartz is fairly common in some of the calc-silicate gneisses and also occurs at the unnamed prospect in an amphibole-cordierite-plagioclase gneiss. A mineral of the humite group occurs in an amphibole-rich gneiss containing abundant dark-green grains of zincian spinel at the unnamed prospect.

DISCUSSION OF METAMORPHIC HISTORY

The rarity of sapphirine and its unexpected discovery in the southern Wet Mountains merit an appraisal of data pertinent to the geologic history and conditions that caused its development. An assessment of presently available data suggests that sapphirine and orthopyroxene probably formed in these rocks during the regional metamorphism that prevailed in much of Colorado about 1,700 m.y. ago. Although the intrusion of the San Isabel Granite about 1,400 m.y. ago may have played a causative role in the formation of sapphirine and orthopyroxene, the present data suggest that such an origin relating to thermal metamorphism during this later event is not likely.

Except for the presence of sapphirine and orthopyroxene, the mineralogy of the host rocks of Precambrian sulfide deposits in the San Isabel area is notably similar to the mineralogy of host rocks at many other localities in Colorado. Many Precambrian stratabound sulfide deposits and their host rocks have been metamorphosed to the upper amphibolite facies (sillimanite zone of regional metamorphism) elsewhere in the Wet Mountains, the Salida area, the Front Range, and the northern Park Range (Sheridan and Raymond, 1977, p. 9–10). In these widespread localities gahnite and(or) zincian spinel, cordierite, orthorhombic amphibole, and phlogopitic biotite very commonly characterize the host rocks of the sulfide deposits. Corundum is present in at least one of these other localities. In the impure marbles and calc-silicate gneisses commonly interlayered with these magnesium-rich amphibole and cordierite gneisses, the mineralogy also is duplicated by the common presence of clinopyroxene, gahnite and(or) zincian spinel, forsterite, minerals of the humite group, monoclinic amphibole, garnet, and sulfide minerals. The only differences we noted are that sillimanite, quartz, and garnet, which are abundant in some of the host rocks elsewhere in Colorado, are not that abundant in the host rocks sampled in the San Isabel area.

In addition to the mineralogic similarities noted above, the metamorphic textures observed in thin sections of rocks from localities in the San Isabel area are closely similar to those observed in thin sections of rocks from the other localities in Colorado. These textural features are described in some detail in the preceding description of mineral assemblages and petrography. Important in this regard is the fact that both sapphirine and orthopyroxene, the only minerals not observed in the widespread other localities, appear to fit into the same pattern of metamorphic textures. Both are commonly in elongate aggregates alined along the gneissic compositional layering. Although sapphirine occurs as a rim on zincian spinel in some of the rocks, as noted in the descriptions, such relations are not a dominating textural feature. Occurrence as independent individual grains and aggregates appears to be just as common, and, where the two minerals are intergrown, poikiloblastic inclusions of sapphirine in zincian spinel are as common as zincian spinel in sapphirine. The rimming relation to the spinel, therefore, does not appear to be as prevalent in the rocks of the San Isabel area as it is in some other sapphirine localities. Thus, Sørenson (1955, p. 26) found that sapphirine in West Greenland occurs most commonly around centers of spinel and(or) corundum, and Nixon and others (1973, p. 421–422) found that sapphirine in granulites in Uganda occurs as rims on aggregates of ilmenite, green spinel, and corundum.

The close similarities in mineralogy and texture noted above are the principal reasons for the suggestion that sapphirine and orthopyroxene formed in these rocks during the regional metamorphism about 1,700 m.y. ago. That event clearly was responsible for the principal features of mineralogy and texture of host rocks of the majority of Precambrian sulfide deposits elsewhere in Colorado. Consequently, this same metamorphism probably caused the mineralogy and textures of the host rocks of the Precambrian sulfide deposits in the San Isabel area, although the grade of metamorphism was probably somewhat higher there. If the presence of sapphirine and orthopyroxene was caused by thermal metamorphism by the San Isabel Granite about 1,400 m.y. ago, these minerals should have prominent textural features that would indicate their occurrence as a late overprint on previously existing minerals and textures. It seems reasonable to assume also that lead-lead ages for galena occurring in the ore at the Marion mine would have been adjusted to something younger than 1,700 m.y. if the temperature had reached a sapphirine-forming level at the time of intrusion of the San Isabel Granite. Except for the rimming of zincian spinel by sapphirine, a feature that can be as readily explained as a stage in progressive regional metamorphism, there is no clear-cut evidence presently available that would date sapphirine and orthopyroxene as relatively late contact metamorphic minerals in these occurrences. On the contrary, the available data suggest that they formed essentially at the same time as the associated metamorphic minerals in a regional metamorphic environment.

If the interpretation given above is correct, the following question remains to be answered: Why did sapphirine and orthopyroxene form in the host rocks of these particular Precambrian sulfide deposits? The question is pertinent because elsewhere in Colorado the highest metamorphic grade recognized in host rocks of Precambrian sulfide deposits is the upper amphibolite facies. Yet sapphirine and orthopyroxene are minerals that commonly connote very high grade metamorphic conditions at or in pressure-temperature conditions of the granulite facies. In the remainder of this discussion we attempt to answer this question in relation to the voluminous literature regarding regional metamorphism.

In describing the granulite facies, Turner (1968, p. 330) noted that sapphirine is "a rare but seemingly characteristic phase in silica-deficient assemblages, rich in both Mg and Al." And Seifert (1974, p. 201) noted that sapphirine is a mineral requiring high temperatures and that high pressures will favor its appearance. Despite these connotations, the research over the years has not really restricted sapphirine to the granulite facies. Thus, Ramberg (1948, p. 21–22) concluded from work on sapphirine-bearing rocks from West Greenland that the physical stability field of sapphirine is a narrow pressure-temperature field between the granulite facies and the amphibolite facies. And Sørenson (1955, p. 26), who also worked on rocks from West Greenland, concluded that sapphirine is found in associations "typical for the low granulite- or the high amphibolite facies." Following more recent work on the occurrences in West Greenland, Herd and others (1969, p. 2, 41) found that sapphirine is stable within a wide range of pressure and temperature conditions (from amphibolite facies to hornblende-granulite facies) but within a limited range of chemical environments.

Orthopyroxene commonly is mentioned as being characteristic of the granulite facies. Turner (1968, p. 328–329) listed orthopyroxene, more particularly hypersthene, in several assemblages characteristic of the metamorphic rocks and related charnockitic rocks belonging to the granulite facies. Although orthopyroxene occurs locally in the area described in our present report, it is not a common mineral in Colorado's Precambrian metamorphic rocks. R. B. Taylor (oral commun., 1979) pointed out that in regional mapping of the metamorphic rocks surrounding the San Isabel Granite batholith he recognized only those assemblages characteristic of the upper amphibolite facies. However, about 30 km northwest of the San Isabel area, Brock and Singewald (1968) have mapped charnockitic gneisses characterized by hypersthene in the Mount Tyndall quadrangle.

In arbitrarily drawing a line that divides the amphibolite facies, in a strict sense, from the granulite facies, Turner (1968, p. 320) accepted Buddington's following definition (1963, p. 1163–1168) of the critical assemblage characterizing the granulite facies: plagioclase-clinopyroxene-hypersthene-hornblende. Turner also recognized the fact that in many regions it is possible to trace in the field a gradational transition from the amphibolite facies toward or into the granulite facies, and, for that reason, Turner listed in his classification the "Amphibolite-granulite transitional facies" (1968, p. 320–328). The mineral assemblages of sapphirine-bearing rocks and associated granulitic rocks from Sonapahar, Assam, India, were studied by Lal and others who concluded (1978, p. 177) that the mineral parageneses suggest "metamorphism within amphibole-granulite transition facies of Turner (1968)."

When the mineral assemblages observed in the sapphirine-bearing localities of the San Isabel area are assessed in relation to the foregoing references from the literature, we conclude that the regional metamorphism probably was within the amphibolite-granulite transitional facies of Turner (1968, p. 320–328) rather than the granulite facies. Although both orthopyroxene and clinopyroxene have been identified in rocks from these localities, we have not observed these two minerals in mutual contact as in Buddington's critical assemblage cited by Turner (1968, p. 320) for the granulite facies. Moreover, the abundance of phlogopitic biotite in many of the rocks suggests that the metamorphic conditions were not sufficiently intense to produce the ideal anhydrous assemblages of the granulite facies.

The occurrences of sapphirine in Colorado are closely similar in some respects to certain occurrences in Australia and India. In the southern part of the Arunta Block in central Australia, Stewart and Warren (1977, p. 26) reported that among the rock types associated with stratabound deposits of chalcopyrite, sphalerite, and galena are gneisses containing abundant magnesium and aluminum, and characterized by anthophyllite, cummingtonite-gedrite, magnesium-aluminum spinel, enstatite, and sapphirine. In assemblages described by Lal and others (1978, p. 171) at Sonapahar, Assam, India, sapphirine coexists with cordierite, orthorhombic amphibole, corundum, phlogopite, and spinel. Interestingly, Lal and others (1978, p. 171) noted that pyrrhotite and pyrite occur in some of the associated rocks, but they do not mention any sphalerite, chalcopyrite, or galena. And Lal and others (1978, p. 172) also reported that a few samples of spinel contain as much as 7 mole percent of gahnite, although most of their analyses range between ordinary magnesian spinel and hercynite.

Until the more detailed studies currently in progress are completed, a tentative conclusion is made that the pressure-temperature conditions in the San Isabel area during the regional metamorphism about 1,700 m.y. ago locally exceeded conditions of the upper amphibolite facies but were not as intense as those set for the granulite facies proper. Thus, under such conditions, sapphirine formed where the host rocks of the Precambrian sulfide deposits provided the proper silica-poor, magnesia-rich chemical environment favorable for this uncommon mineral. Locally in the same area and more abundantly elsewhere in the Wet Mountains, as in the Mount Tyndall quadrangle, orthopyroxene formed in response to these same elevated conditions of pressure and temperature.

Although sapphirine may be a rare mineral, experience in the San Isabel area suggests that it can easily be overlooked even where it is relatively abundant. Apparently the mineral was not recognized by previous workers in that area because no reports of its occurrence were published. It could easily have been missed during this study had not samples been taken of rocks having a somewhat unusual bluish color as well as of rocks that contain a more noticeable zincian spinel.

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