Skarn Alteration of the Commercial Limestone, Carr Fork Area, Bingham, Utah

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Abstract

Mineralogy and chemical composition of the altered Commercial limestone were investigated in surface rocks over a 1,500-meter interval outward from the monzonite stock which contains the Bingham porphyry copper deposit. Skarn alteration is divided into six mineralogical zones: (1) marble, (2) wollastonite, (3) cristobalite, (4) garnet-clay, (5) garnet-quartz, and (6) amphibole-epidote, in order approaching the intrusion. Outside the boundary of economic copper mineralization, alteration is dominantly controlled by faults, fractures, and sedimentary features. Within the copper orebody, coinciding with the area of most intense silication, relative proximity to the quartz monzonite porphyry is the most important factor in formation of mineralogical zones. These zones develop at the expense of adjacent outer zones, leaving evidence of overprinting at the periphery of each zone. Comparison of bulk chemical compositions in unaltered and altered limestone indicates that alteration was accompanied by overall addition of SiO_2, Al_2O_3, MgO, and MnO and depletion of CaO and CO_2; addition of TiO_2, BaO, Cu, Pb, and Zn in the marble and wollastonite zones; and addition of Cu, Mo, Zn, and Ag in the ore-grade zones.

Introduction

THE Commercial limestone in the Carr Fork area, one of several limestone exposures in the Bingham mine, is an excellent example of skarn alteration related to the porphyry copper deposit (Fig. 1). This unit extends laterally westward from its contact with the quartz monzonite porphyry phase of the Bingham stock, which is the center of hydrothermal alteration and mineral zoning. The limestone is 49 m thick and exposed in the open-pit mine and Carr Fork over a horizontal distance of 1,500 m with a 150-m change in elevation. The outermost outcrop near the termination of the unit on the Andy fault is recrystallized limestone, or marble, whereas the innermost outcrop near the porphyry contact is intensely silicated. The nearly continuous exposure of skarn allows detailed documentation of mineralogical changes as the intrusion is approached.

The major purpose of this investigation is to define mineralogical zoning. The zones are described in detail on the basis of field mapping and hand specimen and thin section observations supported by extensive X-ray diffraction analyses. Bulk chemical compositions of mineralogical zones were determined by emission spectrographic analyses of composite chip samples. Qualitative chemical gains and losses in the altered zones were established by comparison with atomic absorption analyses of unaltered Commercial limestone in Middle Canyon, 600 to 4,500 m from the Last Chance stock and over 1,500 m from the recrystallized limestone in Carr Fork. Throughout this discussion, the copper orebody refers to the

area of altered limestone which contains economic copper mineralization and whose boundary roughly coincides with the pit outline on Figure 2. The terms inner and outer refer to location in the limestone bed relative to the main portion of the quartz monzonite porphyry.

Previous studies

Limestone metamorphism at Bingham was first described by Boutwell (1905). Hunt (1924) described the relation between ore type and skarn alteration, noting that "ores are abundant in both highly
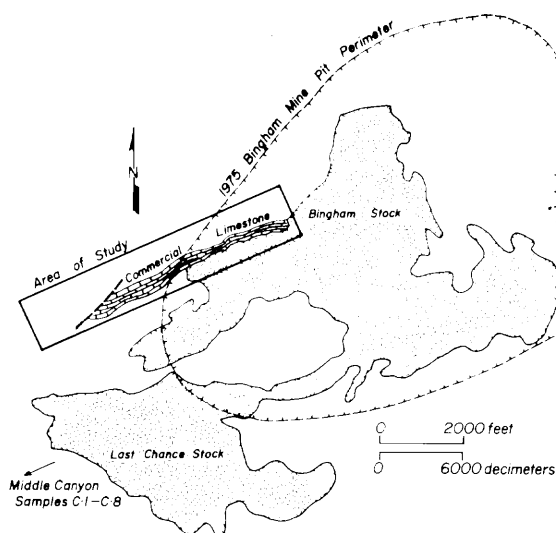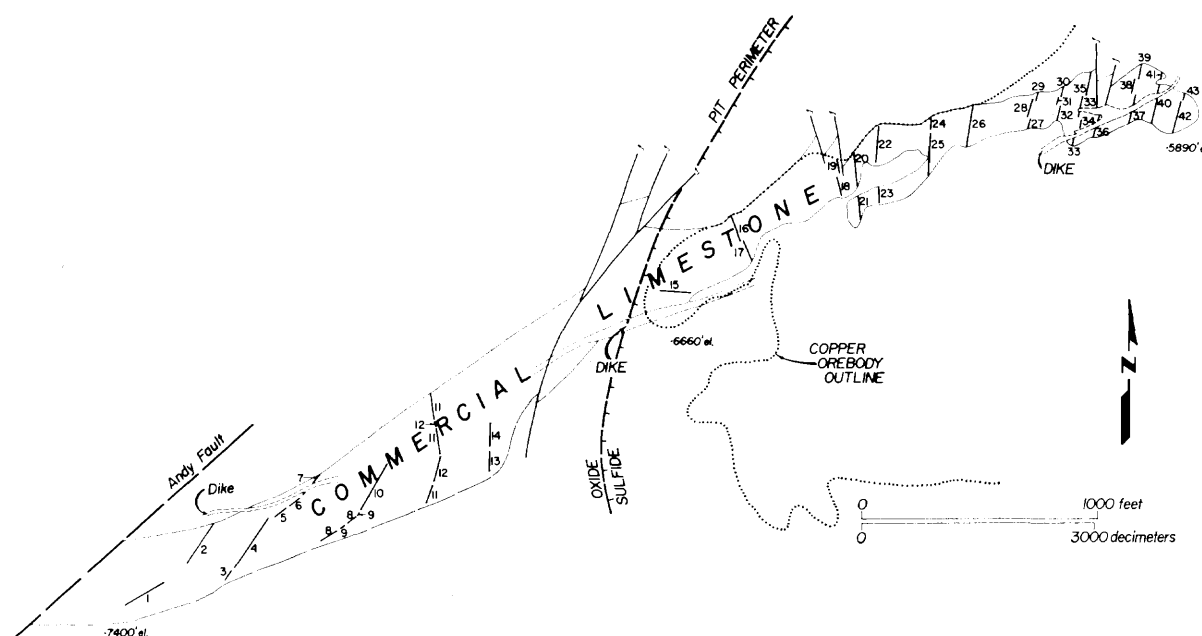

FIG. 1. Location map.

FIG. 2. Sample locations in the altered Commercial limestone.

altered limestone and in limestone practically un-altered; but are most abundant in the metamorphosed area (p. 869)."

Several notable studies of limestone alteration at Bingham originated in connection with the lawsuit between Utah Consolidated Mining Company and Utah Apex Mining Company over apex rights to the so-called Commercial (Yampa) and Jordan (High-land Boy) limestone lodes (Peterson, 1924). Ex-tensive sampling and analyses of both limestone beds resulted in the studies published by Winchell (1924) and Lindgren (1924). Winchell concluded that "the lime-silicate rocks were produced by recrystal-lization of limestone . . . with no important change of volume (or of porosity), and the loss of carbon dioxide was balanced by the introduction of silica, with magnesia in some cases" (p. 899). This con-curs with the general conclusions of this investigation.
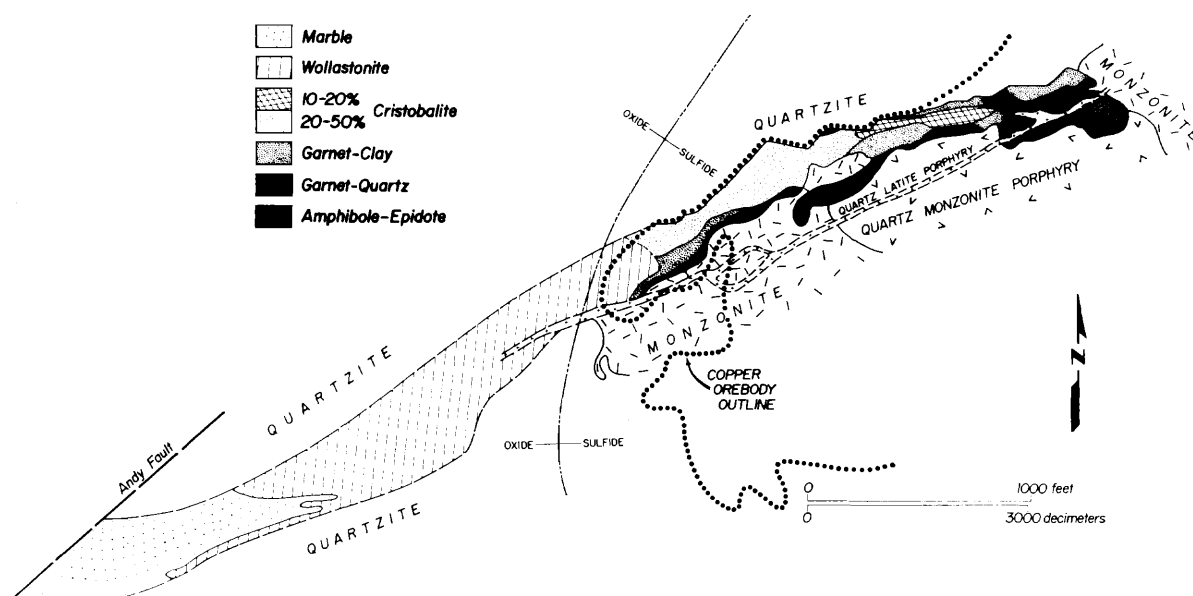

FIG. 3. Alteration zones in the Commercial limestone, revised from figure I-2 of Reid (1975) according to field mapping completed in the fall of 1976.

Table 1.   Mineralogy of Alteration Zones Listed in Approximate Order of Abundance

	Marble	Wollastonite	Cristobalite	Garnet-clay	Garnet-quartz	Amphibole-epidote
Major minerals	calcite quartz chert	calcite wollastonite quartz diopside	cristobalite garnet quartz montmorillonite	garnet quartz montmorillonite	garnet quartz pyroxene montmorillonite	garnet quartz amphibole epidote montmorillonite
Average insoluble residue content	56%	57%	94%	93%	92%	95%
Accessory minerals	diopside wollastonite garnet epidote dolomite orthoclase zircon talc idocrase mica?	cristobalite garnet epidote amphibole chlorite orthoclase zircon idocrase talc? mica?	diopside chlorite epidote amphibole talc specularite magnetite?	diopside amphibole epidote cristobalite chlorite biotite siderite? apatite? orthoclase? magnetite specularite	amphibole epidote chlorite mica apatite? orthoclase? magnetite specularite	diopside cristobalite chlorite mica biotite orthoclase talc siderite? apatite? magnetite specularite
Sulfides	pyrite chalcopyrite galena	pyrite chalcopyrite galena sphalerite?	pyrite chalcopyrite molybdenite bornite?	pyrite chalcopyrite molybdenite bornite?	pyrite chalcopyrite molybdenite bornite?	pyrite chalcopyrite molybdenite bornite?
Average total sulfide content	trace	trace	3.8%	5.2%	2.6%	6.3%
Copper content	60 ppm	170 ppm	0.6%	0.6%	0.7%	0.6%
Supergene minerals	limonite montmorillonite Cu sulfates calcite wad	limonite montmorillonite Cu sulfates calcite wad	limonite Cu sulfates gypsum montmorillonite?	limonite Cu sulfates gypsum montmorillonite? sericite	limonite Cu sulfates gypsum montmorillonite?	limonite Cu sulfates gypsum? montmorillonite?

Lindgren calculated chemical gains and losses accompanying formation of "white (altered) limestone," equivalent to the wollastonite zone described here. His chemical data agree with analytical results of this study, although Lindgren's choice of grain density instead of bulk density to rationalize weight percent values (g/cc = wt % × grain density) fails to compensate for porosity changes.

Unusual zeolitic minerals formed by hydrothermal alteration of limestones at Bingham are described by Stephens and Bray (1973).

Atkinson (1975) described a similar alteration sequence in the Yampa and Highland Boy limestones in Carr Fork, encompassing the area of this study. Einaudi (1975) discussed the replacement of a wollastonite-diopside-quartz assemblage by garnet and actinolite during iron metasomatism of sedimentary rocks in Carr Fork.

Mineral Zoning

Skarn alteration is divided on the basis of field observations into six mineralogical zones (Fig. 3), listed in order approaching the intrusion: (1) marble, (2) wollastonite, (3) cristobalite, (4) garnet-clay, (5) garnet-quartz, and (6) amphibole-epidote. The transition between zones is identified by the appearance of diagnostic minerals but is not always accompanied by a change in the dominant mineralogy. The mineral phases in each zone do not necessarily represent an equilibrium assemblage.

Table 1 summarizes the mineral characteristics of the zones. Supergene minerals, which were excluded in defining zones, copper grade, and average sulfide and insoluble residue contents are also listed.

Unaltered Commercial limestone

The unaltered Commercial limestone is a black, fine-grained, thin- to medium-bedded limestone containing black nodular and banded chert. The pre-alteration composition of the limestone is difficult to establish with certainty because of extreme lateral and vertical variations involving sandy, argillaceous, and nearly pure carbonate facies. Insoluble residue ranges from 10 to 65 percent and consists of chert and angular to subrounded detrital quartz grains.

The matrix is composed of finely crystalline calcite and slightly coarser grained dolomite. MgO analyses indicate a maximum possible dolomite content of 4

percent. Detrital muscovite, orthoclase, and zircon make up less than 1 percent and are preserved in the altered limestone.

Marble zone

Marble extends from the unaltered limestone to within 750 m of the limestone-porphyry contact. It consists of dark gray recrystallized limestone slightly lighter in color than the unaltered rock. It retains sedimentary features including bedding, nodular or layered chert, fossil debris, and detrital quartz. This zone also includes areas which are banded with white marble, indistinguishable from darker marble in thin section. The white color indicates nearly complete removal of carbonaceous material.

Marble is composed of a recrystallized, 50-micron calcite matrix with irregular areas of interlocking, 20-micron quartz grains. It is unclear from thin section study whether silica has been introduced or recrystallized from detrital quartz and chert. Detrital quartz grains are present in the calcite matrix but appear to be less abundant than in the unaltered limestone. Dolomite, orthoclase (partially altered to sericite), and zircon occur in the calcite matrix but not in veins and are interpreted as sedimentary in origin.

Silicate alteration minerals include garnet, epidote, and pervasive subhedral, 20-micron grains of diopside (less than 1%) which also occur in calcite veins. Montmorillonite, largely fracture controlled, appears to be supergene in origin. Abundant cross-cutting veins include calcite, containing rare wollastonite, and chalcedony, which also forms selvages on calcite veins.

The marble zone is a broad feature extending 500 to at least 1,000 m from the copper orebody. This zone represents an area of strong recrystallization and bleaching. It is also the outermost site for pervasive formation of hypogene minerals including garnet, epidote, and sulfides. It has not been determined whether marble in Middle Canyon, 2,000 to 2,500 m from the orebody, is related to the marble zone in Carr Fork or is a contact metamorphic effect of the Last Chance stock. In Middle Canyon bleaching and recrystallization is fracture controlled, increasing in intensity near faults and locally forming discontinuous lenses. In the Carr Fork area, closer to the stock, limestone has been completely converted to marble, and recrystallization of silica in the calcite matrix becomes more pervasive approaching the intrusive.

Wollastonite zone

The wollastonite zone, spanning a 600-m interval between the marble zone and the orebody, is char-acterized by white fine-grained rock composed of wollastonite, calcite, quartz, and diopside. Wollastonite, which is most abundant in the inner and lower portion of the zone, is believed to have been largely reconverted to calcite and quartz. Present surface exposures of the wollastonite zone are mainly composed of recrystallized calcite and quartz with aggregates of wollastonite. Diopside grains are pervasive throughout the calcite and quartz matrix but are never abundant.

The contact with the marble zone is sharply defined by the appearance of black and white banding of marble and wollastonitic rock. Near the contact, spherical aggregates and lenses of wollastonite, rimming and replacing original chert, occur in marble. The outer portion of the wollastonite zone includes completely bleached marble containing wollastonite lenses.

Other skarn minerals become more abundant toward the intrusion. Clusters of fine- to medium-grained euhedral garnet and occasional epidote appear along fractures and infrequently in the matrix. Two distinct garnet compositions were identified by displacements of major X-ray diffraction peaks as approximately 100 mole percent and 20 mole percent andradite, assuming a binary grossularite-andradite solid solution series. Nodular and banded cristobalite occurs near the periphery of the cristobalite zone. Chlorite, orthoclase, talc, mica, zircon, and idocrase were tentatively identified by X-ray diffraction but not in thin section. Abundant calcite veins contain isolated grains of wollastonite and pyrite. Sulfide-quartz veins are uncommon. Montmorillonite, largely fractured controlled, is probably supergene in origin.

Thin, fingerlike extensions of the wollastonite zone continue outward along the footwall of the limestone. Orientation of these stringers is mainly controlled by bedding but also follows prealteration fracturing. Preferential development of wollastonite along the base of the limestone unit may reflect variations in original sedimentary composition or greater permeability along the lower limestone-quartzite contact.

Silicate minerals in the wollastonite zone were probably formed by additions of hydrothermal silica associated with the porphyry phase of the Bingham stock. Winchell (1924, p. 890) notes that "original quartz is not used (at least in all cases) in the formation of lime silicates, for in some thin sections the calcite matrix has been converted into lime-silicate minerals with no encroachment on the rounded outlines of the detrital quartz grains." Similar observations were made in this investigation, and chemical data, although inconclusive, also suggest silica addition. It is possible that some sedimentary quartz may have served as a source of silica.

Cristobalite zone

The cristobalite zone contains discontinuous lenses or spherical nodules up to 20 cm in diameter of translucent material composed of opal largely converted to cristobalite. This zone, defined by the first occurrence of the nodules, is located within the copper orebody mainly along the limestone-quartzite contact. The narrow, inward portion of the zone contains 10 to 20 percent cristobalite and forms a thin band through the center of the garnet-clay zone. The majority of this zone contains 20 to 50 percent cristobalite (Fig. 3).

Cristobalite nodules usually have concentric layers ranging in color from white to tan or brown and from blue green to dark green. The green variety predominates near the intrusion. In thin section the translucent opaline material is isotropic with up to 60 percent microcrystalline grains. Small white spheres in the cristobalite are isotropic opal with microcrystalline quartz centers. The opal contains isolated subhedral diopside grains, chlorite, and disseminated sulfides. Aside from the presence of opal, this zone is essentially indistinguishable from the garnet-clay zone. Diopside, partially replaced by garnet, appears to be slightly more abundant in this zone than in the garnet-clay zone. Talc and amphibole were identified by X-ray methods. Garnet-quartz-sulfide veins and microcrystalline quartz veins cut the cristobalite nodules. Abundant quartz veins and sulfide-quartz veins crosscut the garnet veins. Later calcite veins contain isolated diopside grains or microcrystalline quartz.

Minor cristobalite also occurs as nodules in the wollastonite zone, forming more massive areas near the contact between the wollastonite and cristobalite zones. The actual contact is not presently exposed. Nodules and lenses of cristobalite occur erratically in the garnet-clay and amphibole-epidote zones but were not found in the garnet-quartz zone.

Petrographic and textural evidence strongly suggests that the cristobalite zone represents the remnant of a much more extensive zone which was largely replaced by the garnet-clay zone. Garnet-sulfide veins cut the cristobalite and are clearly connected to areas of massive garnet, suggesting that cristobalite formation preceded garnet and sulfides. Such veining is particularly intense near the contact between cristobalite and garnet-clay zones. Cristobalite adjacent to garnet-sulfide veins is commonly bleached, and more intense bleaching is observed where garnet-sulfide veins are closely spaced. X-ray patterns of several bleached envelopes show peaks similar to unbleached cristobalite. The occurrence of garnet-rich spherical aggregates also suggests direct replacement of cristobalite nodules by garnet. The narrow inner

portion of the cristobalite zone appears to have been almost entirely replaced by garnet.

The conclusion that opal remained stable in the same thermal environment as garnet is difficult to reconcile with estimated temperatures of opal formation. One interpretation which conforms to current chemical data is that opal preferentially replaced marble and/or wollastonite remnants in a zone containing garnet veins and spherical aggregates. Opal, chalcedony, and quartz are common silica phases which are deposited in large quantities when low temperature, silica-rich fluids encounter limestone. Such an explanation, however, contradicts field evidence that garnet veins crosscut and bleached the surrounding opal.

The significant features of this zone are conversion of opal to cristobalite and veining and replacement of opal/cristobalite by garnet and quartz. Diopside, possibly formed during recrystallization of the original limestone, is found throughout this zone. Amphibole is apparently related to the subsequent formation of the adjacent amphibole-epidote zone.

Garnet-clay zone

The garnet-clay zone, located between the cristobalite and amphibole-epidote zones, is a white, tan- and red-brown medium-grained rock. Major minerals are garnet, clay, and quartz which range in relative abundance, although clay is usually the smallest component. Garnet typically forms small pockets or aggregates within more quartz rich material, and on a microscopic scale garnet layers interfinger with quartz layers. Garnet composition is believed to be an intermediate member of the grossularite-andradite solid solution series.[1] Equigranular euhedral garnet and quartz form 0.05- to 0.10-mm grains, although quartz is locally coarser. Microcrystalline quartz interstitial to the garnet and clay matrix probably formed later than the coarser grained quartz in this zone. Light brown montmorillonite, ranging from 15 to 60 percent, appears to be largely an alteration product of garnet and pyroxene and may be either supergene or hypogene in origin. Pervasive occurrence of clay at depths below obvious supergene alteration suggests a hypogene origin for some, if not all, clay found in the four inner skarn zones.

Trace amounts of diopside occur as single subhedral grains in garnet aggregates. Large chlorite grains surround garnet and sulfides. Epidote and amphibole occur as random grains in sulfide veins. Biotite, siderite, apatite, and orthoclase were tentatively identified by X-ray diffraction in a few sam-

[1] J. D. Stephens (pers. commun., Kennecott Research Center), infrared analysis of 12 5-kg composite samples from prominent skarn outcrops in the open pit.

ples. Interstitial calcite forms less than 5 percent of the rock and has nonuniform distribution.

Veins containing sulfides intermixed with clay, amphibole, epidote, and magnetite cut the garnet-quartz-clay rock. Sulfide-quartz veins ($\pm$ magnetite) are also present. Quartz, calcite, and sulfides form veinlets.

Garnet, quartz, and clay are present throughout the limestone within the copper orebody. The garnet-clay zone closely resembles the cristobalite zone except for the absence of cristobalite nodules. Both zones contain partially replaced pyroxene grains as well as amphibole and epidote associated with more intense alteration. The contact between the wollastonite and garnet-clay zones is gradational. Clusters of euhedral garnet occur along fractures in both the marble and wollastonite zones, and garnet veins are found near the wollastonite and garnet-clay zone contact.

Garnet-quartz zone

The garnet-quartz zone, located at the innermost limestone-porphyry contact, forms an extremely hard blocky outcrop of red-brown garnet and quartz with irregular areas of massive pyroxene. Garnet and quartz occur as interlocking 0.2-mm grains, with garnet predominating, and often form alternating layers several inches wide. Interstitial clay replacing garnet and pyroxene as well as trace amounts of chlorite are less abundant than in the garnet-clay zone.

The irregular areas of massive pyroxene consist of interlocking 1-mm grains of light green diopside (65%), partially altered to clay, and small clusters of garnet and quartz which contain isolated pyroxene grains. Dense black microcrystalline material containing pyroxene and clay, possibly nontronite, is also present. Sulfide-quartz with amphibole, epidote, and locally magnetite usually have montmorillonite envelopes, and are particularly abundant near the porphyry contact.

The garnet-quartz zone differs from the garnet-clay zone primarily in having less abundant clay, greater pyroxene content, and a more pronounced occurrence of amphibole and epidote in veins. Pyroxene in this zone may be genetically related to the pyroxene disseminations throughout the other alteration zones. If so, the garnet-quartz zone might be considered a subzone of the garnet-clay zone in which pyroxene replacement and clay alteration are less intense.

Amphibole-epidote zone

The amphibole-epidote zone, developed along the limestone-porphyry contact, is marked by the presence of amphibole and/or epidote in veins or clots throughout the zone. The rock has a medium-grained, garnet-quartz-clay matrix similar to the garnet-clay zone with light to dark green streaks and blotches. Amphibole color changes suggest a compositional trend from tremolite to actinolite eastward toward the main portion of the porphyry stock. Epidote is pervasive (up to 40%) in the upper, outer portion of the zone, whereas vein amphibole makes up to 25 percent of the lower, inner portion of the zone. Garnet, quartz, and to a lesser extent interstitial clay compose the remainder of the rock. Garnet and amphibole are partially altered to clay. Orthoclase, talc, biotite, mica, siderite, and apatite were identified by X-ray diffraction only.

Sulfides, quartz, and clay locally with magnetite and amphibole form veins. Garnet-quartz veins may contain epidote. Calcite is present up to 15 percent in veins and interstitially to garnet and quartz.

This zone is characterized by the presence of hydrous hypogene minerals, notably amphibole and epidote. The zone extends outward in a thin band along the intrusive contact and for a shorter distance along the upper limestone-quartzite contact.

Sulfide distribution

Fracture-controlled pyrite is the dominant sulfide mineralization in the marble and wollastonite zones, which lie outside the copper orebody. In the marble zone, pyrite is disseminated in trace amounts generally near premineral faults. Significant amounts of disseminated chalcopyrite, pyrite, and, rarely, galena appear in the inner, lower portion of the wollastonite zone. In these zones, roughly coinciding with the zone of oxidation, supergene chalcocite coats pyrite.

Within the orebody, pyrite and chalcopyrite predominate. The pyrite: chalcopyrite ratio varies considerably but generally decreases inward. Sulfides are mainly fracture controlled, although disseminations occur throughout the garnet, quartz, and clay rock which constitutes the majority of ore-grade skarn. Molybdenite is limited to veins and increases in abundance toward the stock. Supergene chalcocite occurs on pyrite near the edge of the open pit. Bornite was tentatively identified coating chalcopyrite. Pyrite and chalcopyrite disseminations in the limestone apparently favor sites of unaltered pyroxene grains in massive garnet and in the opaline matrix of cristobalite nodules. Sulfides form inclusions within amphibole and chlorite grains, often elongated parallel to actinolite cleavage. Vein sulfides are associated with quartz or amphibole and epidote veins with montmorillonite selvages.

Magnetite and, less commonly, specular hematite form small pockets in sulfide veins and along fractures. Overall magnetite abundance within ore-

grade skarn is visually estimated to be less than 1 percent.

Endoskarn

The equigranular monzonite along the Commercial limestone contact contains patches of actinolite syenite, a hybrid rock or endoskarn. The endoskarn bodies range in size from 1 to nearly 15 m in diameter. Actinolite syenite, described in detail by Stringham (1953, p. 959–960), has a granitoid texture and is predominantly composed of orthoclase and varying amounts of actinolite, epidote, and pyroxene. Quartz and biotite are locally present; plagioclase is rare.

Contacts between limestone and both the quartz monzonite porphyry and the latite dikes are sharp without endoskarn development.

Discussion

Outside the copper orebody, skarn alteration is dominantly controlled by fracturing and faulting, variation in original composition, sedimentary features such as chert nodules and bedding, and the nature of the upper and lower limestone contacts. The importance of these controls decreases toward the igneous contact.

Within the copper orebody, coinciding with the area of most intense alteration, silicate formation is dominantly related to the proximity of the porphyry contact. Alteration zones lie parallel to the intrusive contact, extending farther outward along the intrusive than along the limestone-quartzite contact. Hydrous minerals decrease in abundance away from the porphyry.

Diagnostic minerals of a particular zone appear in outer zones as fracture-controlled or disseminated grains, clusters of grains along fractures, continuous veins, and discontinuous lenses and spherical nodules.

Formation of skarn minerals appears to have begun at many foci, as illustrated by spherical wollastonite aggregates rimmed and connected by bleached marble surrounded by dark gray marble. Marble, bleached marble, and wollastonite apparently formed in that sequence with alteration starting around nuclei connected by fractures. Chert served as loci for both wollastonite and cristobalite nucleation. The characteristic occurrence of alteration minerals such as garnet and epidote in small isolated aggregates also suggests a nucleation process.

Each zone has apparently developed at the expense of the adjacent outer zone. Zone fronts may have been advancing simultaneously during skarn formation, leaving evidence of overprinting at the periphery of each zone: (1) marble develops within unaltered limestone, (2) further bleaching occurs in marble, (3) wollastonite and diopside form within bleached marble, (4) garnet forms at the expense of wollastonite and diopside, (5) garnet forms at the expense of opal and cristobalite, (6) amphibole and epidote form within garnet-clay and garnet-quartz material. Pervasive development of amphibole and epidote in several zones suggests that the hydrous phase of alteration followed nonhydrous alteration. Retrograde clay alteration of pyroxene and garnet is probably a late hydrous phase of undetermined age but appears to be contemporaneous or later than amphibole and epidote.

The majority of sulfides were introduced during the hydrous stage of alteration, although sulfide-quartz veining probably continued after the formation of hydrous calc-silicate minerals. Sulfide abundance in the limestone depends more on proximity to the limestone-porphyry contact than on mineralogical zoning.

Calcite veining probably represents redeposition of calcium carbonate which was mobilized during hydrothermal alteration.

Chemical Composition of Mineralogical Zones

Valid comparison of chemical data requires that weight percent values obtained from laboratory analyses be converted to g/100 cc, or the product of weight percent and bulk specific gravity, in order to compensate for changes in grain density and porosity (Table 2). This method rests on the assumption, previously employed at Bingham, that the total volume of the limestone bed remained constant throughout metamorphic and metasomatic events. Winchell (1924) in his study of skarn alteration of Commerical and Jordan limestones cites field evidence that the thickness of limestone beds is constant in the Bingham mine area. He also states that "there is evidence in thin section that an abundant calcite cement can be converted into lime-silicate minerals without change of volume" (p. 889). Lindgren (1924) used a constant volume assumption on the basis of Winchell's findings. Variations of bed thickness in the mine area and elsewhere in the district are attributed to facies changes rather than to changes in volume accompanying alteration.

Alteration apparently increases grain density as much as 30 percent and porosity up to 400 percent (Table 2), although some increases in porosity are caused by weathering of strongly clay altered skarn. Bulk density remains fairly constant because porosity is inversely related to grain density in these altered rocks. Average porosity is 3 percent in unaltered Commercial limestone and slightly higher in the marble zone (7.4%) and wollastonite zone (5.6%). These results generally agree with Winchell's (1924) porosity determinations on 23 selected limestone samples. Porosities of the inner four zones deter-

TABLE 2.   Bulk and Grain Densities and
Calculated Porosities

Alteration zone	Sample	Bulk density g/cc	Grain density g/cc	Porosity %
Unaltered limestone	C1	2.67	2.72	1.8
	C2	2.65	2.70	1.9
	C3	2.58	2.71	4.8
	C4	2.62	2.69	2.6
	C5	2.69	2.71	0.7
	C6	2.55	2.72	6.3
	C7	2.67	2.69	0.7
	C8	2.61	2.72	4.0
	average	2.63	2.71	2.9
Marble	1	2.63	2.78	5.4
	2	2.50	2.74	8.8
	4	2.58	2.91	11.3
	9	2.68	2.79	3.9
	average	2.60	2.81	7.4
Wollastonite	3	2.65	2.73	2.9
	5	2.70	2.82	4.3
	6	2.65	2.78	4.7
	7	2.77	2.85	2.8
	8	2.89	2.96	2.4
	10	2.47	2.70	8.5
	11	2.61	2.84	8.1
	12	2.40	2.57	6.6
	13	2.55	2.81	9.3
	14	2.64	2.81	6.1
	average	2.63	2.79	5.6
Cristobalite	16	3.15	3.63	13.2
	17	2.99	3.30	9.4
	18	2.22	2.56	13.3
	19	1.88	2.55	26.3
	20	2.77	2.95	6.1
	22	2.51	2.65	5.3
	24	2.60	2.99	13.0
	28	2.92	3.39	13.9
	average	2.63	3.00	12.6
Garnet-clay	25	2.86	3.10	7.7
	26	2.89	3.32	13.0
	29	3.14	3.62	13.3
	32	2.82	3.55	20.6
	35	2.48	2.86	13.3
	39	3.11	3.38	8.0
	average	2.88	3.31	12.7
Garnet-quartz	40	2.97	3.18	6.6
	41	2.55	3.08	17.2
	42	3.17	3.32	4.5
	43	2.65	3.08	14.0
	average	2.83	3.17	10.6
Amphibole-epidote	15	2.71	3.20	15.3
	21	2.90	3.15	7.9
	23	—	—	—
	27	2.70	2.60	—
	30	2.11	2.84	25.7
	31	2.38	2.70	11.9
	33	—	—	—
	34	2.35	3.14	25.2
	36	2.26	2.97	23.9
	37	—	—	—
	38	2.61	3.05	14.4
	average	2.50	2.96	17.8

Analyses performed by Kennecott Exploration, Inc., Salt Lake City, Utah.

mined in this study are substantially higher than porosity of unaltered limestone: 13 percent in the cristobalite and garnet-clay zones, 11 percent in the garnet-quartz zone, and 18 percent in the amphibole-epidote zone.   However, Winchell reports an average porosity of 3.3 percent in "completely silicated" rock collected underground at greater distance from the porphyry contact.

The bulk chemical composition of each mineralogical zone is shown in Figure 4.   The range and mean value for total oxide and trace metal contents are plotted in g/100 cc for each zone.   Average chemical compositions, weighted to allow for different outcrop length in sampling, are presented by weight percent in Table 3.
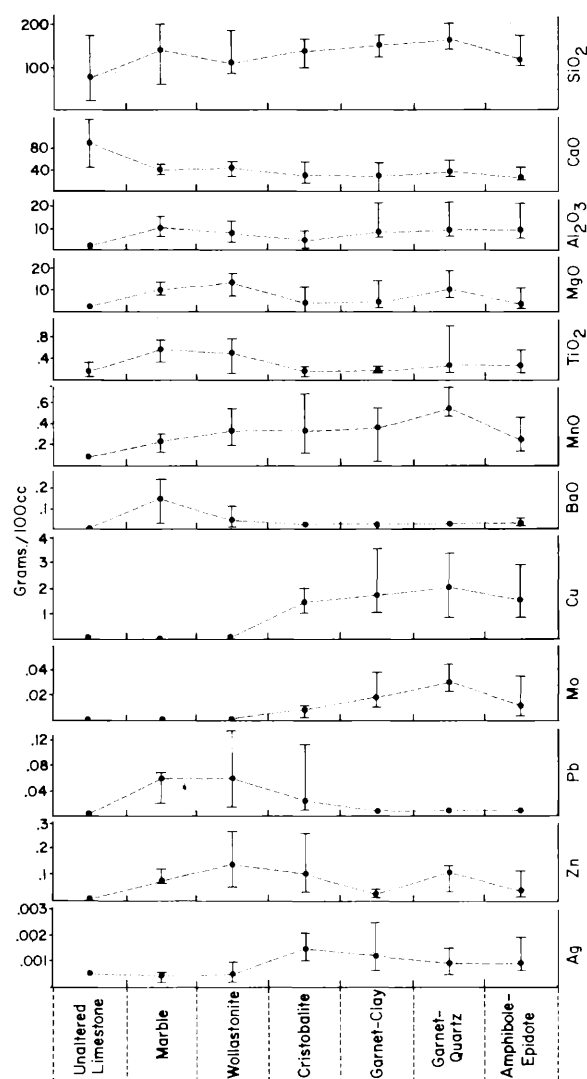

FIG. 4.   Major and minor elements and trace metals in the Commercial limestone.   Vertical bars represent range of values; dots show average value.

TABLE 3. Average Partial Chemical Compositions of Unaltered and Altered Commercial Limestone

	Unaltered limestone	Marble	Wollastonite	Cristobalite	Garnet-clay	Garnet-quartz	Amphibole-epidote
				Weight percent			
SiO_2	31	54	45	52	55	56	67
TiO_2	0.08	0.20	0.17	0.06	0.07	0.11	0.10
Al_2O_3	0.9	4	3	2	3	3	4
CaO	35	>16	>16	12	11	13	10
MgO	0.9	4	5	2	2	4	1
MnO	0.05	0.09	0.12	0.12	0.12	0.18	0.10
BaO	0.006	0.06	0.02	0.008	0.007	0.006	0.009
				Parts per million			
Cu	5	60	170	0.6%	0.6%	0.7%	0.6%
Mo	<1	2	4	30	70	100	50
Pb	7	220	230	70	20	20	20
Zn	60	290	550	380	120	240	160
Ag	<1	1	1	6	4	3	4
V	37	47	46	50	45	37	48
Bi	—	2	7	18	4	2	3

Present but not analyzed for: CO_2, H_2O^+, S, FeO, and Fe_2O_3.
$Na_2O < 0.05\%$, $K_2O < 2.0\%$, As < 200 ppm, Sb < 200 ppm.
Analyses performed by Kennecott Exploration, Inc., Salt Lake City, Utah.

Sampling methods

Chemical composition of unaltered Commercial limestone is represented by eight samples from Middle Canyon between 600 and 4,500 m southwest of the Last Chance stock (Fig. 1). Outcrops of limestone in this area appear relatively fresh except for minor alteration features: calcite veining, sericite, manganese dendrites on fracture and bedding planes, occasional goethite and hematite, and infrequent pyrite casts. Each analyzed sample consisted of a 2.5-kg chip composite across the width of the unit. Because traverses contained only 60 to 70 percent outcrop, some samples were unavoidably biased in favor of more resistant sandy or cherty layers.

Forty-three composite chip samples were taken from altered Commercial limestone over a 1,500-m surface interval between the contact with the Bingham stock in the open pit and the Andy fault (Fig. 2). Along a particular level the outcrop was divided into intervals of similar mineralogy, which were individually sampled for chemical analysis. A major gap in sampling of nearly 150 m occurs at the edge of the open pit, between samples 14 and 15, due to the severe weathering of the two lowermost outcrops in Carr Fork. Several levels in the open pit were also excluded because mineralogical variations did not warrant sampling each level.

Analytical procedures

Eight whole rock samples of unaltered Commercial limestone were analyzed by atomic absorption spectroscopy with average analytical precision of 3 percent relative standard deviation. Forty-three samples of altered limestone were analyzed by semi-quantitative optical emission spectrography. Total sulfide abundance was determined gravimetrically, and magnetite content was determined with a Frantz magnetic separator. Heavy mineral separations using liquids with 2.8 and 3.3 g/cc specific gravity and subsequent X-ray analyses were performed on all samples. Bulk and grain specific gravities were determined on representative hand specimens from each sample.

Major and minor element distribution

The important chemical break with respect to major and minor element distribution in the altered limestone coincides with the edge of the copper orebody, or the open-pit outline (Fig. 4). The marble and wollastonite zones contain relatively high CaO, MgO, TiO_2, and BaO and low MnO, and are chemically distinct from the four zones within the orebody. The cristobalite and garnet-clay zones have similar bulk compositions. The garnet-quartz zone is uniformly high in SiO_2, MgO, and MnO, although abundant Al_2O_3 and TiO_2 in this zone may reflect inclusion of igneous rock in two samples. The amphibole-epidote zone is relatively low in SiO_2, CaO, MgO, and MnO. Na_2O and K_2O are below detection limits in all but two samples in the marble zone and are omitted from Figure 4. The alteration zones can be distinguished to only a limited extent by bulk chemical analysis, because zone boundaries do not represent radical changes in bulk mineralogy.

Chemical trends between alteration zones exist for certain major and minor elements. SiO_2 content progressively increases toward the stock, with a slight decrease in the amphibole-epidote zone. Un-

expectedly, SiO_2 values are not higher in the cristobalite zone despite the presence of massive silica, nor does SiO_2 content reflect variations in cristobalite abundance. This suggests that silicate mineralogy mainly represents reconstitution rather than a major redistribution of silica. CaO content is slightly lower in the inner garnet-bearing zones than in the marble and wollastonite zones. The decrease in CaO is much less abrupt than the decrease in $CaCO_3$ established by insoluble residue studies, indicating that in the inner zones CO_2 has been depleted and CaO occurs mainly in calc-silicate minerals. The range of Al_2O_3 values is greatest in the ore-grade zones, although average Al_2O_3 content is fairly constant throughout the altered limestone. MgO values correlate with diopside abundance: high in the wollastonite and garnet-quartz zones and low in the amphibole-epidote zone where pyroxene has been largely replaced by garnet. MnO values generally increase inward, with a distinct decrease in the amphibole-epidote zone. Strong additions of TiO_2 and BaO have occurred in the altered limestone outside the orebody.

Although analytical data were not obtained for sulfur or total iron content, mineral distribution indicates that sulfur in the form of sulfide minerals was added throughout the skarn with increasing abundance toward the porphyry intrusion. Strong iron addition, in the form of pyrite, magnetite, actinolite, andradite, and possibly nontronite, occurred primarily within the copper orebody.

Trace metal distribution

Significant zoning of Cu, Mo, Pb, Zn, and Ag occurs in the altered limestone (Fig. 4). Cu, Mo, and Ag are high but extremely variable within the orebody, although Cu and Mo are distinctly less abundant in the cristobalite zone than in the inner alteration zones. The strong correlation between Cu and Ag values from individual samples indicates that Ag is associated with Cu sulfides. Pb and Zn form halos in less altered limestone, roughly coinciding with the Pb-Zn halo which surrounds the copper orebody. The Pb high is located in the marble and wollastonite zones, whereas the Zn high lies slightly inward in the wollastonite and cristobalite zones. A minor Bi halo (up to 40 ppm) exists at the edge of the copper orebody. No marked zoning occurs in V (30 to 75 ppm) or As and Sb (both less than 200 ppm).

Weathering and oxidation have affected to some extent trace metal distribution in the marble and wollastonite zones outside the open pit. The abrupt increase in some trace metals between the wollastonite and cristobalite zones also coincides with the transition from oxidized to unoxidized rocks. However,

TABLE 4. Unaltered Commercial and Jordan Limestones, Bingham Mining District, Utah

Element	Anomaly threshold (ppm)	Range (ppm)
Cu	9	1–13,000
Mo	6	1– 210
Pb	12	1– 525
Zn	23	20– 1,100
Ag	2	1– 9
MnO	290	28– 2,300
BaO	48	50– 1,000
V	56	12– 75

101 samples, S. W. Caddey, Kennecott Exploration, Inc., Salt Lake City, Utah.

oxidation is minor in the sample area in Carr Fork, based on the following observations: presence of pyrite and chalcopyrite, infrequent pyrite casts, restriction of limonite to fractures, and minor amounts of supergene minerals such as copper sulfates, manganese dendrites, and gypsum. Depletion of trace metals by weathering and oxidation does not appear to be extensive enough to invalidate the analytical results.

Comparison of unaltered and altered Commercial limestone

The compositions of the six skarn alteration zones in the Carr Fork area can be qualitatively compared to unaltered Commercial limestone from Middle Canyon 3 km from the copper orebody (Table 3). Quantitative calculation of chemical changes could not be completed because compositional variations within the Commercial limestone make it impossible to determine the prealteration composition of individual samples.

The six alteration zones, including marble, show an overall addition of SiO_2, Al_2O_3, MgO, MnO, S, and total Fe and depletion of CaO and CO_2. Silica addition in the marble zone is ambiguous because two samples represent the sandy upper portion of the Commercial bed. TiO_2 BaO, Cu, Pb, and Zn are added to the marble and wollastonite zones, and Cu, Mo, Zn, and Ag to the orebody zones. Changes in Na_2O and K_2O were not calculated because of lack of analytical precision. Background populations (Table 4) were calculated from analyses of both Commercial and Jordan limestones. Qualitative gains and losses established by this study generally agree with Lindgren's (1924) conclusions in his study of the wollastonite zone in the Commercial (Yampa) limestone. Lindgren also noted the addition Na_2O in altered rock.

Summary and Conclusions

The Commercial limestone in the Carr Fork area displays progressive changes in mineralogy approach-

ing the quartz monzonite porphyry phase of the Bingham stock. Altered limestone is divided into six mineralogical zones: (1) marble, (2) wollastonite, (3) cristobalite, (4) garnet-clay, (5) garnet-quartz, and (6) amphibole-epidote, in order approaching the porphyry intrusion.

The marble zone consists of light gray recrystallized limestone and extends for a considerable distance to fresh rock. The wollastonite zone, in which wollastonite, quartz, and diopside occur in the recrystallized calcite matrix, extends 600 m from the edge of the copper orebody. Skarn mineralogy is relatively constant within the orebody, and garnet, quartz, and clay form the bulk of the rock in all four inner zones. Mineralogical zones are distinguished by the presence of diagnostic minerals: the cristobalite zone by spherical nodules or discontinuous bands of cristobalite, the garnet-quartz zone by increased quartz content and massive pyroxene, and the amphibole-epidote zone by the presence of those minerals in a garnet and clay mixture. The cristobalite zone apparently represents an area of incomplete replacement by garnet. The garnet-quartz zone represents a local alteration feature in which the garnet, quartz, and clay matrix contains remnants of earlier formed pyroxene. Amphibole and epidote probably belong to a later hydrous phase following anhydrous alteration.

The six alteration zones can be grouped into three relatively distinct chemical zones: (1) the marble and wollastonite zones, mainly reconstituted isochemically from the original limestone, (2) the cristobalite, garnet-clay, and garnet-quartz zones which are dominantly composed of garnet and silica, and (3) the amphibole-epidote zone which includes late-stage hydrous mineralization.

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