Alteration and Mineralization in the Ruth Porphyry Copper Deposit near Ely, Nevada

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Abstract

The Ruth-Ruth Extension porphyry copper deposit in the Robinson mining district, east central Nevada, represents the eastern extremity of a once-continuous, large sulfide system that has been fragmented by normal faulting in early mid-Tertiary time. Mineralization and alteration are confined to a miogeoclinal sedimentary sequence ranging in age from Devonian to Permian and to Early Cretaceous quartz monzonite porphyry apophyses of a larger pluton that underlies the district.

Prior to intrusion the sedimentary rocks were folded into a northwest-trending, locally overturned anticline. Bedding plane thrusting greatly reduced the thickness of the flat-dipping upper limb of the anticline, and at least six tectonic units separated by flat faults can be distinguished. Ore-grade hypogene copper mineralization only occurs within the steeply dipping lower limb of the anticline.

Alteration and mineralization are spatially and temporally related to the emplacement of an early quartz monzonite porphyry pluton. In the mine area this intrusion is cylindrical and plunges 25° west with smaller offshoots penetrating the overlying sedimentary rocks. At the lower west end of the cylinder this early quartz monzonite porphyry was intruded by, and graded into, a weakly altered and weakly mineralized late quartz monzonite porphyry. A granodiorite porphyry sill exposed in the southwest wall of the Ruth pit postdates mineralization.

Intrusion of the early quartz monzonite porphyry resulted in the formation of biotite-andalusite hornfels in the Mississippian Chainman Shale and massive garnet skarn in Pennsylvania Ely Limestone. In contrast to the sulfide-rich garnet-pyroxene skarns elsewhere in the district, the predominant skarn type at Ruth is a massive garnet skarn low in sulfides. Following crystallization of this early porphyry phase a major fracturing event shattered the porphyry and surrounding hornfels but left the massive garnet skarn unaffected. At this time an extensive zone of biotite-orthoclase alteration formed in early porphyry and in the directly surrounding hornfels, which subsequently was largely obliterated by pervasive quartz-sericite alteration. Limestone within the zone of quartz-sericite alteration was replaced by an assemblage of quartz, chalcedony, and pyrite, locally termed silica-pyrite rock which at higher elevations gives way to pyritic marble. Chainman hornfels adjacent to Ely skarn contains epidote, actinolite, diopside, garnet, calcite, pyrite, chalcopyrite, and magnetite along fractures. At the Ely-Chainman contact there is a magnetite-rich zone which also contains pyrite, pyrrhotite, and chalcopyrite.

Early quartz monzonite porphyry outside the quartz-sericite zone of alteration has been argillized. An inner zone with predominantly kaolinite and an outer zone—the clay-calcite zone with montmorillonite, kaolinite, and calcite—have been distinguished. Limestone within the kaolinite zone was converted to a pyritic marble, whereas in the clay-calcite zone it was only recrystallized. The marble halo extends for 460 m south of the Ruth deposit and contains minor amounts of wollastonite and tremolite in addition to calcite and chert. Within the marble halo minor structurally controlled lead-zinc-silver mineralization occurs. Early quartz monzonite porphyry apophyses and Permian Rib Hill Sandstone above the top of the porphyry cylinder contain quartz, kaolinite, alunite, zunyite, pyrite, and minor sericite, minerals characteristic of advanced argillic alteration.

Early quartz monzonite porphyry in the core of the hydrothermal system shows biotite-orthoclase alteration and contains chalcopyrite mineralization. An increase in quartz vein density at the upper margin of the cylinder resulted in formation of a zone of pervasive silicification at the interface of the quartz-sericite and biotite-orthoclase alteration zones. This high silica zone contains high-grade chalcopyrite mineralization. Ore-grade hypogene copper mineralization (>0.4%) is largely restricted to the early quartz monzonite porphyry in the Ruth and Ruth Extension deposits and forms a 25° west-dipping tabular ore zone. Following the crystallization of the late quartz monzonite porphyry, the early quartz monzonite porphyry...
RUTH COPPER DEPOSIT, NEVADA

Introduction

The Ruth porphyry copper deposit, located in the Robinson mining district west of Ely in White Pine County, Nevada, is one of a number of deposits that occur in a west-trending zone of alteration and mineralization 13 km long and 300 to 460 m wide (Fig. 1). The district geology and mineralization have been documented by Bauer et al. (1960, 1964, 1966). James (1972, 1976) studied the Veteran and Tripp deposits at the west end of the district, and Fournier (1967a and b) and James (1972, 1976) described the large Liberty deposit. Bauer et al. (1960, 1966) and Wilson (1978) discuss the geologic setting of the Ruth deposit.

Spencer (1917) recorded the discovery and early history of the Ruth deposit. Between 1915 and 1961, 19.1 million tons of ore averaging 1.66 percent copper were mined in an underground block caving operation (Bauer et al., 1966). The small High Grade deposit in the Ruth area was mined by square set stoping. Stripping of overburden for open-pit mining operations started in 1968 and by late 1975, 31.5 million tons of 0.72 percent copper ore had been mined in the Ruth open-pit mine. Since June, 1980 the mine has been inactive. The orebody plunges west and the down-faulted part is called the Ruth Extension orebody (Fig. 4).

This paper summarizes the results of field and laboratory work conducted between July 1974 and January 1976 at the Nevada Mines Division of the Kennebott Corporation. The aim of the investigation was to determine the character and extent of the Ruth sulfide system and its relation to adjacent deposits. A geologic map of the Ruth open pit and surroundings on a scale of 1:600 was constructed using tape and compass and photogrammetric methods. All drill holes within the Ruth and Ruth Extension areas, consisting of 70,122 m of rotary cuttings and diamond drill core, were relogged. Rock samples from pit exposures and drill core were studied in 222 thin and 40 polished sections and by means of X-ray diffraction. X-ray diffraction patterns of heavy liquid separates were used to determine the total sulfide content and the pyrite/chalcopyrite ratio in rock samples. Routine X-ray diffraction determinations were made of vein material and mineral separates. Whole-rock X-ray diffraction was performed on 90 samples and clay slides were made of 17 sedimentary rock samples. The alteration assemblages of 40 igneous plagioclase samples were also determined by means of X-ray diffraction.

General Geology

For a general introduction to the geology of the Robinson mining district, the reader is referred to Bauer et al. (1960, 1964, 1966) who discuss its geologic setting and structural history. The U. S. Geological Survey has published geologic maps covering the district (Brokaw, 1967; Brokaw and Barosh, 1968; Brokaw and Heidrick, 1966; Brokaw et al., 1973). Table 1 shows a stratigraphic section of rocks exposed in the area.

Alteration and mineralization affected Early Cretaceous igneous rocks and a miogeoclinal section ranging from Devonian Guilmette Limestone to Permian Arcturus Formation. Detailed district studies by J. E. Welsh and R. A. Breitrick under the guidance of H. L. Bauer (former mines geologist at the Nevada Mines Division) revealed that an episode of folding and thrusting predated the emplacement of hypabyssal stocks and the associated porphyry copper mineralization in the Robinson mining district (J. E. Welsh, pers. commun., 1974). The formation of the north- to northwest-trending, locally overturned Radar Ridge-Rib Hill anticline was accompanied by bedding plane thrusting which resulted in a sharply reduced thickness of the horizontal to gently dipping eastern limb. According to Welsh (pers. commun., 1974), at least six zones of thrusting were localized by zones of incompetence in the stratigraphic section. Welsh recognized the presence of at least five thrust plates within the eastern limb, here designated thrust...
plates I through V starting with the structurally highest unit. The lower (western) limb of the anticline—plate VI—consists of steeply dipping Pennsylvanian and older sedimentary rocks.

Spencer (1917) recognized two igneous episodes in the district. An Early Cretaceous event dated by the K-Ar method at 115 to 103 m.y. (McDowell and Kulp, 1967) is genetically closely related to the alteration and mineralization in the district (Bauer et al., 1960, 1964, 1966; James, 1976). An Eocene-Oligocene igneous event was dated by McDowell and Kulp (1967) at 41 to 87 m.y. These younger rocks form sills, dikes, and plugs ranging from flow-banded rhyolite to biotite quartz latite porphyry. Rhyolite breccias containing altered and mineralized fragments of sedimentary rocks and porphyry are exposed in the Tripp pit (Bauer et al., 1966), the Liberty and Ruth pits, and in an area south of the Kimbley pit.

**Geology of the Ruth Deposit**

The structural complexity of the Ruth mine area reflects the structural style of the Robinson mining district. The geologic map and cross sections are shown in Figures 2, 3, 10, and 14A. Plate VI, the lowest tectonic unit exposed in the Ruth pit (Fig. 3), consists of northwest-striking, steeply southwest-dipping Mississippian Chainman Shale and Pennsylvanian Ely Limestone that represent the lower (i.e., southwestern) limb of the Radar Ridge-Rib Hill anticline. Hypogene copper mineralization in the district is restricted to rocks within plate VI.

Overlying plate VI and separated from it by the 30° west-dipping High Grade fault is a thin slice of plate V (Figs. 3 and 14A) consisting of the upper Chainman section and possibly the basal part of the Ely Limestone. Elsewhere the High Grade fault and its equivalent in the Ruth Extension—the Saxton thrust—separate steeply dipping sedimentary rocks of plate VI from gently dipping Ely Limestone or younger rocks of plates IV, III, or II + III (Fig. 3).

A klippe of Permian Kaibab Limestone (J.E. Welsh, pers. commun., 1974) along the west side of the Ruth pit represents the structurally highest unit found in the district. These flat-lying structural units, I through V, comprise the eastern overthrust structural units, I through V, comprise the eastern overthrust structural units. Plate VI, the lower (western) limb of the anticline—plate VI—consists of steeply dipping Pennsylvanian and older sedimentary rocks.

This large pluton underlies much of the district and is capped by several apophyses that form irregular stocks and sills of quartz monzonite porphyry and granodiorite porphyry. In the Ruth mine area the quartz monzonite magma followed the steeply dipping Chainman Shale-Ely Limestone contact and the main magma body crystallized as a 25° west-dipping cylindrical mass of quartz monzonite porphyry some 1,370 m long and 335 m in diameter (Figs. 10 and 14A). To the east of the Ruth Extension deposit, the igneous body breaks up into several small offshoots. Smaller magma volumes broke through the overlying flat-dipping Ely Limestone and crystallized as irregular small stocks and numerous sills. Two texturally distinct quartz monzonite porphyry phases can be recognized: an early quartz monzonite porphyry which shows intense alteration and mineralization, and a late quartz monzonite porphyry which is only weakly altered and weakly mineralized. The early quartz monzonite porphyry recognized in the Ruth pit appears to be the equivalent of Fournier's (1967a) early-stage northeastern porphyry in the Liberty pit, whereas the late quartz monzonite porphyry may correspond to his late-stage northeastern porphyry. Alteration and mineralization closely followed the intrusion of early quartz monzonite porphyry.

**Table 1. Stratigraphic Section of the Robinson Mining District, White Pine County, Nevada (from Bauer et al., 1966)**

<table>
<thead>
<tr>
<th>System</th>
<th>Formation</th>
<th>Thickness (meters)</th>
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</thead>
<tbody>
<tr>
<td>Quaternary</td>
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<tr>
<td>Tertiary</td>
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<td>Permian</td>
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<td></td>
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<td></td>
<td>Arcturus Formation</td>
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<td></td>
<td>Lower Member</td>
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</tr>
<tr>
<td></td>
<td>Rib Hill Sandstone</td>
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<tr>
<td></td>
<td>Riepe Springs Limestone</td>
<td>75</td>
</tr>
<tr>
<td>Pennsylvanian</td>
<td>Ely Limestone</td>
<td>700</td>
</tr>
<tr>
<td>Mississippian</td>
<td>Chainman Shale</td>
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<tr>
<td></td>
<td>Joana Limestone</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>Pilot Shale</td>
<td>110</td>
</tr>
<tr>
<td>Devonian</td>
<td>Guilmette Limestone</td>
<td>760</td>
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</tbody>
</table>
FIG. 2. Geology of the Ruth open-pit copper mine. Pit topography, October 1974. Note that cross section B-B' extends east of the area covered in this map. Geological features in the caved area are taken from geologic maps of underground workings compiled by J. S. Vanderpool and reconstructed with the aid of drill-hole information that predates the mining activity.
Following the hydrothermal event, a sill of hornblende granodiorite porphyry intruded intensely altered Ely Limestone and early quartz monzonite porphyry along the southwest side of the Ruth pit (Fig. 2). Deep drilling revealed the presence of porphyritic quartz monzonite stocks below the Eureka fault (Fig. 14A) and in the subsurface north of the Ruth pit (Fig. 10). This rock is characterized by the presence of K-feldspar phenocrysts up to one inch in length and by a small volume of interstitial quartz and K-feldspar. Based on relationships established elsewhere in the district, consolidation of this rock type probably followed the formation of the sulfide system (Westra, 1979).

Early to mid-Tertiary faulting caused the fragmentation of the large Ely porphyry copper system along moderately east-dipping, north-striking normal faults (Brokaw et al., 1969; Kreis, 1973; James, 1976; Westra, 1979). In the Ruth area, major faulting occurred along the Eureka and Queen faults (Figs. 2 and 14A). The Eureka fault is exposed in the east wall of the Liberty pit (Fournier, 1967a), dips 30° east, and has a dip-slip movement of approximately 1,160 m. As a result, mineralized porphyry now present in the Deep Ruth deposit became detached from the East Liberty orebody (Figs. 4 and 5). Subsequent movement along the Queen fault resulted in a 490-m dip-slip displacement of the Ruth Extension deposit (Fig. 4). Minor late adjustments along thrust faults (e.g., the High Grade and Jupiter faults) and along zones of contrasting competence (e.g., the Bernie fault zone) occurred during normal movement along the Eureka and Queen faults. Latest normal movement took place along north 60° to 70° east-striking faults showing steep north and south dips. These structures appear to have localized the large rhyolite breccia mass exposed along the north wall of the Ruth pit (Fig. 2). Rhyolite, quartz latite, and obsidian dikes have also locally intruded the Eureka and Queen faults. Exposed in the western part of the Ruth open pit is a megabreccia composed of boulders of pyritic marble embedded in rhyolite pumice breccia.

**Alteration**

The distribution of alteration assemblages and mineralization in the Ruth mine area is shown in Figures 6 through 15 and summarized in Figure 16. Alteration zoning is centered on the cylindrical early quartz monzonite porphyry stock and the axis of the zoning pattern dips 25° west. Hydrothermal alteration has affected the stock and sedimentary rocks ranging from the Devonian Guilmette Limestone to the Permian Lower Arcturus Formation. Due to the extreme structural thinning, the thickness of the section involved in the Ruth area was less than 600 m, considerably less than the normal section which is approximately 3,050 m thick.

The alteration assemblages documented in the Ruth deposits are similar to those described for the “average” porphyry copper deposit in the southwestern United States (Lowell and Guilbert, 1970). The alteration distribution pattern shows a well-developed vertical zonation. James (1976) established the spatial and temporal relation between alteration facies in igneous rocks and adjacent sedimentary rocks in the Liberty, Tripp, and Veteran deposits. Apart from some minor differences, this study indicates that the Ruth area is similar to these deposits. The intrusion of early quartz monzonite porphyry produced a contact metamorphic aureole in the Chainman Shale and contact metasomatic garnet skarn in the Ely Limestone, which predate the mineralization. Following crystallization of the early porphyry, a major fracturing event was responsible for the formation of a zone of stockwork fractures in the porphyry and the surrounding hornfels. Garnet skarn in the Ruth area was little affected by this fracturing event. The main hydrothermal stage followed and resulted in the formation of an extensive zone of biotite-orthoclase alteration which was subsequently largely obliterated by superposition of quartz-sericite alteration. The periphery of the deposit is characterized by argillic and rare propylitic assemblages. Alteration and mineralization characteristics of the deposit will be discussed from the core of the system to its periphery.
Biotite-orthoclase alteration in igneous rocks

Biotite-orthoclase alteration of quartz monzonite porphyry in the Ruth and Ruth Extension areas largely coincides with the cylindrical porphyry pluton (Figs. 6, 11, and 14B). Remnants of hydrothermal biotite present in the quartz-sericite zone indicate that the original zone of biotite-orthoclase alteration was much more extensive than its present size would suggest. This potassic alteration developed early in the hydrothermal sequence and was in part obscured by later quartz-sericite and hypogene argillic alteration. Early quartz monzonite porphyry in the lower part of the porphyry cylinder is least influenced by later hydrothermal events and contains abundant hydrothermal biotite and K-feldspar. The biotite forms aggregates pseudomorphic after hornblende phenocrysts and occurs as disseminations in the groundmass. Lenses, 2 to 4 inches across, of coarse-grained pegmatitic biotite also are common. Hydrothermal K-feldspar veinlets cut plagioclase and K-feldspar phenocrysts; K-feldspar of presumably hydrothermal origin is very abundant in the aplitic groundmass of early quartz monzonite porphyry. Biotite and K-feldspar are common constituents in quartz-pyrite-chalcopyrite and in quartz-magnetite veinlets. Chalcopyrite also occurs in discontinuous veinlets and disseminations in hydrothermal biotite aggregates. The total sulfide content ranges from 2 to 3 weight percent with a pyrite/chalcopyrite ratio of 1 or less. Hydrothermal magnetite is common (Fig. 7) and increases with depth. A stage of very intense later hypogene argillization resulted in complete replacement of plagioclase by montmorillonite and kaolinite in the biotite-orthoclase zone.

Toward the upper margin of the porphyry cylinder (Figs. 11 and 14B), quartz veins become more abundant and the total sulfide content increases to between 6 and 10 weight percent. The pyrite/chalcopyrite ratio remains 1 or less. Feldspar phenocrysts are sericitized, and the groundmass is partly replaced by granular quartz aggregates. This systematic increase in quartz culminates in the formation of a high silica zone within the upper one-third of the cylinder directly below the High Grade fault in the Ruth area and in the footwall of the Saxton thrust in the Ruth Extension orebody. This high silica zone consists of granular quartz with lesser amounts of coarse-grained sericite and abundant chalcopyrite and pyrite in interstices and in veinlets. The hypogene copper grade commonly exceeds 1.5 percent and may be as high as 2 percent. In the Ruth Extension deposit this high silica zone extends to the east beyond strong chalcopyrite mineralization. Relicts of pale red hydrothermal biotite aggregates within the high silica zone indicate that the stage of pervasive silicification and chalcopyrite mineralization followed an earlier bio-
tite-orthoclase alteration stage. The intense copper mineralization in the high silica zone seems to be localized near or at the interface between the biotite-orthoclase zone and the overlying quartz-sericite zone. The copper content decreases abruptly at the top of the high silica zone and in many places this decrease coincides with the High Grade fault zones.

Biotite-orthoclase alteration also affected the late quartz monzonite porphyry found in the lower west end of the porphyry cylinder. In this rock type, alteration and stockwork fractures and veins are only weakly developed. The sulfide content is estimated at 1 to 2 weight percent and pyrite predominates. Magnetite occurs in veins and disseminations. Magnetic K-feldspar remains unaltered and in places encases plagioclase phenocrysts. Plagioclase is variably replaced by montmorillonite, but the original compositional zoning remains visible. Remnants of magmatic sphene, partly replaced by leucoxene, are common. Hydrothermal biotite aggregates completely replace hornblende phenocrysts. In the deep western part of the pluton, hornblende is only partly replaced by hydrothermal biotite, the amount of disseminated and vein-controlled magnetite increases, and the amount of sulfides sharply decreases. Epidote is a common mineral in this area.

Biotite-orthoclase alteration in shale

Within the Ruth porphyry copper deposit, mineral associations found in the Chainman Shale record an early phase of thermal metamorphism and one or more later hydrothermal alteration stages (Figs. 8, 9, 12, and 15). Three hydrothermal alteration assemblages are recognized in the Chainman Shale: (1) biotite-orthoclase, (2) quartz-sericite-pyrite, and (3) calc-silicate-bearing hornfels. The alteration mineralogy is a function of the distance from the early quartz monzonite porphyry stock. The intrusion of the early porphyry was associated with the formation of a zone of biotite-andalusite hornfels as much as 245 m wide. The fine-grained disseminated biotite in this rock is at least in part of contact metamorphic origin. The inner part of the biotite hornfels zone was subsequently hydrothermally altered during the biotite-orthoclase stage, whereas the outer part of the biotite hornfels zone was largely obliterated by later quartz-sericite alteration.

The biotite-orthoclase altered hornfels zone is 90 to 150 m wide adjacent to early quartz monzonite porphyry showing biotite-orthoclase alteration. This hornfels zone is cut by an intense stockwork of quartz, quartz-biotite, and quartz-K-feldspar veins with or without pyrite, chalcopyrite, and molybdenite. These veins comprise 5 to 10 percent of the rock volume. Contradicting crosscutting relationships between these vein types do not permit determination of a parasitic sequence, but these veins are clearly older than pyrite veins with sericite envelopes and late clay-sericite veins. Local zones of pervasive silicification (Figs. 8 and 15) may contain abundant chalcopyrite...
and minor molybdenite, but as a rule, biotite hornfels contains marginal ore. In the Ruth Extension these zones of silica flooding are magnetite rich. The contact of hornfels with early porphyry is locally a fault zone or a zone of assimilation characterized by the formation of K-feldspar and plagioclase metacrysts in hornfels. In places a contact breccia developed. Moderately to intensely silicified hybrid porphyry-shale mixtures contain abundant biotite, magnetite, pyrite, and several percent chalcopyrite.

**Skarn in limestone**

The Ely Limestone in the Ruth and Ruth Extension area has been extensively converted to skarn, but locally skarns have also formed in the Mississippian Joana Limestone, in thin calcareous beds within the Chainman Shale, and in a chert-rich calcareous zone at the base of the Rib Hill Sandstone (Figs. 9, 12, and 15). The Joana Limestone in contact with a porphyritic quartz monzonite stock in the subsurface north of the Ruth open-pit mine consists of a biotite-chlorite-garnet-magnetite skarn with pods of massive pyrite, pyrrhotite, and minor chalcopyrite. Calcite is a minor constituent. Scarce black limestone beds found in the Chainman Shale in the biotite-orthoclase zone have been altered to a hydrous skarn assemblage dominated by epidote, pyrite, and magnetite with lesser amounts of actinolite, calcite, and chalcopyrite.

The Ely Limestone in contact with early quartz monzonite porphyry showing biotite-orthoclase alteration is extensively replaced by massive garnet with minor pyroxene. Hydrous calc-silicates are largely restricted to crosscutting structures. The skarns are low in sulfide content and quartz veins are generally absent. No fracture-controlled clay-sulfide alteration stage has been recognized. In contrast to skarns in the Liberty, Tripp, and Veteran deposits (James, 1976), skarns in the Ruth and Ruth Extension areas do not
contain significant tonnages of ore-grade material. The width of skarn ranges from 150 to 210 m. Skarn-marble contacts are sharp, but locally the two are separated by a 3- to 4.5-m-wide zone of pyritic marble. James (1972) mapped a 6- to 12-m-wide wollastonite-quartz band separating marble and skarn along the upper south side of the Ruth open-pit mine. Mining has removed this horizon and at the levels exposed in 1974, garnet skarn and marble were in direct contact.

In the Ruth pit the predominantly massive garnet skarn contains only traces of chalcopyrite even where in contact with potassically altered early quartz monzonite porphyry with ore-grade copper mineralization. Along strike to the east-southeast, away from the intrusive contact (Fig. 9), massive garnet gives way to alternating zones of garnet, pyroxene, and garnet-pyroxene. The skarn zone in Ely Formation cuts across potassic and phyllic alteration zones in the Chainman Shale in the Ruth pit. A sulfide-bearing
zone occurs along the steeply dipping Ely-Chainman contact at the base of the skarn zone and varies from 15 to 20 m wide in the Ruth pit, to 90 m in the subsurface southwest of the Ruth pit, and to 80 m in the Ruth Extension. The zone contains abundant magnetite with 1.5- to 3-m thick lenses rich in pyrite and marcasite replacing pyrrhotite. Chalcopyrite forms rims around coarse-grained pyrite masses and occurs in chalcopyrite-siderite aggregates. The massive magnetite layer is cut by later pyrite veinlets. Erratic high copper values are present in the sulfide shoots, but the bulk of the skarn contains from 0.5 to 1.0 percent disseminated chalcopyrite.

Thin section study indicates the presence of an early garnet-pyroxene assemblage which is partly replaced by epidote and actinolite in areas of sulfide introduction. The formation of hydrous calc-silicates and sulfides appears structurally controlled and may have been facilitated by an increase in permeability due to minor strike-slip movement along the Bernie fault zone during mineralization.

The distribution and shape of the skarn bodies in the Ruth-Ruth Extension area reflect the position of the early quartz monzonite porphyry intrusion with respect to the Ely-Chainman contact zone. The long axis of the porphyry cylinder is approximately parallel to this contact zone and only in the southwest side of the Ruth pit does the porphyry contact cut
it (Figs. 2 and 10). The elongated tabular shape and decreasing thickness of the skarn horizon along strike away from the porphyry contact suggest that fluids migrated chiefly along bedding planes. The major fracturing event that shattered the early quartz monzonite porphyry was not effective in fracturing the garnet skarn because of its lateral position, and as a result, no clay-sulfide alteration developed. Consequently little ore-grade skarn material was formed in the Ruth-Ruth Extension area. In contrast, the large ore-grade skarn bodies in the Liberty pit formed adjacent to, and directly above, quartz monzonite porphyries that intersected steeply dipping bedding planes at a high angle, thus providing easy access for mineralizing hydrothermal fluids. In addition, the skarn envelope above the intrusive in the Liberty pit was pervasively shattered during a period of stockwork fracturing in the porphyry, greatly increasing its permeability and allowing easy access for mineralizing hydrothermal fluids.

**Calc-silicate hornfels in shale**

A 90- to 120-m-wide zone of Chainman Shale in contact with Ely Limestone along the south side of the early quartz monzonite porphyry cylinder in the Ruth and Ruth Extension deposits was converted to a green, intensely fractured hornfels characterized by the presence of fracture-controlled calc-silicates (Figs. 8 and 12). In the subsurface a similar zone occurs along the Chainman-Joana contact. Veins in the calc-
silicate hornfels contain variable amounts of epidote, actinolite, pyroxene, garnet, quartz, calcite, pyrite, magnetite, and chalcopyrite. Zeolite veins with chabazite, heulandite, and laumontite cut across sulfide-bearing veins and in turn are cut by calcite veins. Toward the porphyry contact the amount of calc-silicate increases steadily until, ultimately, poikilitic garnet and epidote completely replace the original hornfels. The change from calc-silicate hornfels to biotite hornfels or quartz-sericite-altered hornfels is abrupt (Fig. 8).

Within the High Grade fault zone in the Ruth pit
and in the Saxton thrust zone in the Ruth Extension, an epidote skarn rich in montmorillonite, calcite, and pyrite occurs, which alternates with Chainman hornfels showing quartz-sericite alteration. This skarn contains minor amounts of chlorite, siderite, sphene, and apatite and, in places, garnet and magnetite are also present. The lack of calcium in unaltered Chainman Shale (J. E. Welsh, pers. commun.) suggests that significant amounts of calcium were introduced by hydrothermal fluids migrating through these fault zones. Alternatively the skarns may represent the calcareous lower Ely-upper Chainman transition beds described by Fournier (1958) from the Liberty pit and by Heidrick (1965) from the Ward Mountain district.

Quartz-sericite alteration in igneous rocks

Pervasive quartz-sericite alteration of early quartz monzonite porphyry is widespread in the hanging wall of the High Grade fault and along the eastern extremity of the porphyry cylinder in the Ruth Extension deposit. The quartz-sericite zone forms a pyritic halo over the top of the deposit, which in places extends in excess of 300 m above the 0.4 percent copper ore zone (Figs. 11 and 14B). With increasing distance away from the primary ore zone, quartz-sericite alteration gives way to argillic assemblages. At depth the quartz-sericite zone grades into the biotite-orthoclase zone. The widespread occurrence of relict hydrothermal biotite in the quartz-sericite zone shows that biotite-orthoclase alteration originally had a much wider distribution. It also demonstrates that in large areas of the hydrothermal system, biotite-orthoclase alteration preceded quartz-sericite alteration.

Based on the mineral associations present in the quartz-sericite zone, three subfacies can be distinguished: (1) quartz-sericite-pyrite-rutile, (2) quartz-sericite-pyrite-rutile-andalusite, and (3) quartz-seri-
FIG. 12. Cross section A-A' looking east showing the distribution of alteration assemblages in sedimentary rocks in the Ruth mine area. For legend, see Figure 15.

cite-pyrite-magmatic K-feldspar-biotite-calcite-rutile ± chalcopyrite. Mineral assemblage (1) is by far the most common. Alteration is generally pervasive and quartz-sericite-altered early quartz monzonite porphyry consists of a matrix of quartz and sericite with pseudomorphs of sericite after all phenocrysts. Sericite after biotite contains abundant rutile needles. The quartz-sericite zone is characterized by a closely spaced network of quartz, quartz-pyrite, and pyrite veins. The total sulfide content commonly exceeds 10 weight percent and the pyrite/chalcopyrite ratio is 25 or more (Fig. 7). Consequently, the hypogene copper content of the quartz-sericite zone rarely exceeds 0.1 percent.

Three rock samples of quartz-sericite-altered early porphyry contain hydrothermal andalusite which forms radial aggregates replacing plagioclase phenocrysts. The andalusite is intergrown with and partly replaced by sericite. The biotite-bearing subzone is located within 60 m of the 0.4 percent copper contour and apparently represents a disequilibrium assemblage. Within this zone plagioclase is completely replaced by aggregates of sericite and calcite, whereas magmatic K-feldspar relics are commonly rimmed by sericite. Relicts of biotite—both of magmatic and hydrothermal origin—are rimmed by sericite and contain numerous rutile inclusions.

Quartz-sericite alteration in shale

Chainman hornfels in the Ruth and Ruth Extension areas shows extensive quartz-sericite alteration characterized by the mineral association quartz-sericite-pyrite-rutile ± kaolinite. Relicts of metamorphic andalusite mantled by sericite occur in the quartz-sericite zone within 245 m of the early quartz monzonite porphyry contact (Fig. 8). Quartz-sericite-altered hornfels is intensely fractured, and the rock is cut by quartz, pyrite-quartz, quartz-molybdenite, and pyrite-sericite veins. These veins show conflicting age relationships, but all are cut by halloysite and later calcite veins. An area in and directly below the porphyry intrusion in the Ruth pit is characterized by an abundance of subhorizontal pyrite ± quartz ± calcite veins with sericite selvages up to 3 cm wide.
These veins have been superimposed on potassically altered biotite hornfels and early quartz monzonite porphyry (Fig. 6). A zone transitional between quartz-sericite and biotite hornfels contains several percent biotite and minor K-feldspar in addition to the mineral association listed above. Biotite is partly sericitized or replaced by chlorite and rutile.

The inner part of the quartz-sericite halo in the Chainman Shale contains molybdenum values as high as 750 ppm in a subore-grade zone east of and below the Ruth Extension copper ore zone. A pronounced molybdenum anomaly (>200 ppm) occurs in a similar position below the eastern part of the porphyry cylinder in the Ruth open-pit mine. Within the ore zone, however, the molybdenum content decreases to between 50 and 150 ppm. The position of the molybdenum anomaly in the Ruth deposits and its association with quartz-sericite alteration differs markedly from its central position and association with potassic alteration in many porphyry copper deposits (e.g., Bingham; John, 1975).

**Advanced argillic alteration in early quartz monzonite porphyry and Rib Hill Sandstone**

Along the east side of the Ruth open-pit mine, intensely fractured and altered Rib Hill Sandstone in the hanging wall of the Queen fault is intruded by irregular masses of early quartz monzonite porphyry (Fig. 2). In addition to quartz, both rock types contain abundant kaolinite and variable amounts of alunite, natroalunite, halloysite, zunyite, and traces of sericite. Feldspars are completely destroyed. Coarse, bladed alunite and zunyite of hypogene origin are intimately intergrown with pyrite below the base of oxidation. The presence of supergene chalcocite in the area suggests that part of the kaolinite is supergene in origin. This mineral assemblage is typical of advanced argillic alteration (Meyer and Hemley, 1967). The limited distribution of advanced argillic assemblages may have resulted from (1) the lack of Ely Limestone in this area which allowed the hydrothermal fluids to attain a very low pH, and (2) the topographically high location of this area within the original Ely sulfide prior to normal faulting (Westra, 1979).

**Silica-pyrite rock in limestone**

Along the southwest side of the Ruth pit, the Ely Limestone is completely replaced by quartz, chalcedony, and pyrite (Figs. 7, 9, and 12). James (1976) found a similar alteration assemblage in the Tripp-Veteran pit and called it silica-pyrite rock. In addition to quartz and pyrite, marcasite, fluorite, sphalerite,
Fig. 14. A. Cross section B-B' looking north showing the geology in the Ruth-Ruth Extension area. Note that the cross section extends east of the surface geologic map shown in Figure 2. Roman numerals indicate tectonic units as described in the text. For legend, see Figure 10. B. Cross section B-B' looking north showing the distribution of alteration types in igneous rocks in the Ruth-Ruth Extension area. For legend, see Figure 11.
and kaolinite are common constituents, whereas magnetite and siderite are less common. The pyrite content in silica-pyrite rock can be very high and, in places, massive fine-grained pyrite with minor gray quartz are the only minerals present. The area with an extremely high pyrite content appears restricted to a highly fractured zone exposed along the southwest wall of the Ruth pit. The silica-pyrite rock in the Ruth pit occurs above the hypogene copper ore and alternates with numerous dikes, sills, and irregular masses of early quartz monzonite porphyry showing quartz-sericite alteration. In places remnants of earlier formed skarn adjacent to porphyry intrusions were only partly replaced by later quartz and pyrite. The hypogene copper content of silica-pyrite rock is low, but in a zone of high fracture density at the intersection of the High Grade and Bernie fault zones, enrichment produced the small High Grade orebody in the hanging wall of the High Grade fault.

The supergene alteration of a highly pyritic marble resulted in the formation of massive kaolinite and locally gibbsite (J.E. Welsh, pers. commun., 1975) and the replacement of pyrite by abundant chalcocite and digenite.

Drill-hole data from an area west of the Ruth pit indicate that, with increasing depth, silica-pyrite rock grades into a partly silicified pyritic marble with epidote, garnet, and small quantities of chalcopyrite and magnetite. Laterally away from the highly pyritic zones, silica-pyrite rock consists predominantly of quartz with abundant pyrite but without calcite. With increasing distance from the ore zone, silica-pyrite rock gradually changes to a pyrite-rich marble cut by a network of quartz veins. This pyritic marble still contains abundant pyrite and common sphalerite. Variable amounts of clays, nontronite, talc, epidote, tremolite, and garnet are also present. Early quartz monzonite porphyry exposures in the area of pyritic
marble development contain alteration assemblages characteristic of the quartz-sericite and argillic alteration zones.

Drill holes below the Ruth deposit intersected a zone of silica-pyrite rock with significant chalcopyrite in the Joana Limestone some 122 m below the base of the 0.4 percent copper contour (Fig. 15). The upper part of the Joana is completely replaced by pyrite, marcasite, and quartz, with some chalcopyrite. This silica-pyrite rock is in sharp contact with barren marble. To the east, as the distance between the base of the ore zone and the Joana Limestone increases, only the upper 1 m of the formation is replaced by silica and pyrite.

**Argillic alteration in igneous rocks**

Scattered early quartz monzonite porphyry dikes intersected in drill holes in the peripheral upper parts of the Ruth and Ruth Extension hydrothermal system define a clay-calcite zone of alteration characterized by the complete replacement of plagioclase and mafic minerals by calcite, montmorillonite, and minor kaolinite. Epidote is present in trace amounts and small quantities of pyrite occur as disseminations in altered plagioclase phenocrysts. Magmatic K-feldspar in the aplite groundmass and in phenocrysts remains unaffected but is cut by numerous calcite veins. Quartz and quartz-sulfide veins are exceedingly scarce within the clay-calcite zone.

Closer to the center of the hydrothermal system but still 120 to 305 m above the 0.4 percent hypogene copper contour, a kaolinite-rich zone is exposed along the western and eastern slopes of the Ruth pit. In this zone plagioclase and mafic phenocrysts in early quartz monzonite porphyry are completely replaced by kaolinite with trace amounts of sericite. Magmatic K-feldspar crystals are preserved. Calcite is absent. The pyrite content in the kaolinite zone ranges from 6.6 to 7.4 weight percent; nevertheless, pyrite occurs predominantly as disseminations in altered plagioclase and mafic sites.

**Argillic alteration in Rib Hill Sandstone**

Unaltered Rib Hill Sandstone consists of well-sorted quartz grains and minor amounts of detrital K-feldspar and plagioclase, clay, or calcite. In zones of argillic alteration, Rib Hill Sandstone is made up of quartz, calcite, and abundant kaolinite and several weight percent pyrite. Some pyrite-calcite and quartz-pyrite veins are present. Small amounts of galena and sphalerite are also common. With an increasing degree of alteration, quartz replaces the calcite cement. Within the zone of oxidation these sandstones commonly form hematite surface breccias which are cut by structurally controlled zones of jasperoid and massive siderite.

**Fringe alteration in igneous rocks**

As a result of the paucity of rocks of appropriate chemical composition around the Ruth deposit, propylitic alteration assemblages are scarce. A kaolinitized early quartz monzonite porphyry sill in the Deep Ruth shaft some 670 m north of the ore zone contains epidote after hornblende and plagioclase. The porphyritic quartz monzonite stock in the subsurface north of the Ruth deposit contains small amounts of epidote, chlorite, and calcite and is cut by zeolite veins. However, the age relation between this stock and the formation of the hydrothermal system is not clear.

**Fringe alteration in limestone**

Ely Limestone along the south side of the Ruth pit was recrystallized to a gray and white marble. The marble line is located within 60 m of the 0.4 percent copper contour. The outer limit of macroscopically recognizable alteration effects is placed 305 to 460 m south of the intrusive center. Within the marble zone chert nodules may be surrounded by white reaction rims composed in places of montmorillonite and elsewhere of wollastonite. The marble contains scattered tremolite needles, irregular patches of vesuvianite, and rare green garnet veins. Ubiquitous calcite veins and veins containing stilbite and apophyllite cut the marble. South of the Ruth Extension the marble zone contains highly goethitic jasperoids that are highly anomalous in base metals and that represent oxidized fissure veins. Fist-sized masses of fluorite, and less commonly of sphalerite and siderite, are locally found in Ely marble and in marble formed in the Arcturus Formation.

**Mineralization**

**Hypogene copper distribution**

Primary mineralization in the Ruth deposit consisting of chalcopyrite, minor molybdenite, and traces of bornite is centered on the cylindrical porphyry stock (Figs. 4 and 13) and reaches its highest grade in a zone of pervasive silicification at the top of the pluton. Economic mineralization terminates abruptly against the High Grade fault and the Saxton thrust. Below the ore zone the decrease in copper grade is gradual. Hypogene copper mineralization extends up to 30 m into altered wallrock, but copper grades rapidly decrease away from the contact.

The copper grade diminishes from west to east in the inclined porphyry cylinder and the pyrite content increases markedly relative to chalcopyrite in the Ruth Extension deposit. East of the Ruth Extension copper mineralization decreases gradually, but to the west ore-grade mineralization of the Deep Ruth deposit is cut off by the Eureka fault (Fig. 4). Prior to
normal faulting, mineralization in the Ruth deposit was continuous with the east end of the Liberty deposit (Brokaw et al., 1969). The reconstructed Ruth-Ruth Extension segment of the Ely sulfide system (Westra, 1979) originally contained approximately 200 million tons of >0.4 percent copper. Following normal movement along the Queen fault, a small portion of this rock volume was eroded, but most of the copper contained in the eroded rock was leached and redeposited in a high-grade chalcocite blanket.

**Supergene copper mineralization**

Supergene chalcocite ore provided most of the underground production in the Ruth area. The main chalcocite blanket was located directly above the zone of higher grade primary mineralization in the footwall of the High Grade fault (Fig. 4). The original blanket measured approximately 300 by 300 m in plan and had an average thickness of about 75 m. Copper grades commonly exceeded 2 percent. Enrichment in the hanging wall of the High Grade fault is erratic. A small, but very high grade chalcocite-digenite orebody, the High Grade orebody, and the small Minnesota High orebody were located in the hanging wall of the High Grade fault.

The chalcocite distribution and the copper grades attained in the blanket depended on the primary copper grades of mineralization, its total sulfide content, and the reactivity and permeability of the wall rock. The highest supergene copper grades are found below oxidized, highly siliceous porphyry exposures that originally contained high primary copper grades. Chalcocite enrichment is erratic and low in tenor below oxidized porphyry in the quartz-sericite zone. Oxidized Chainman hornfels with a low to moderate original copper content is relatively impermeable and does not cover significant chalcocite enrichment blankets.

Mid-Tertiary postore rhyolite breccias exposed in the north wall of the Ruth pit contain fragments of chalcocite-enriched quartz-sericite-altered early porphyry. The breccia also contains quartz-sericite-altered porphyry fragments that do not show enrichment. Thus the breccia must have intruded into previously enriched material, which implies that enrichment at Ely started in early Tertiary time. Oxidation and enrichment continued after intrusion of the rhyolite and a thin irregular chalcocite blanket formed at the base of the present water table in the Rib Hill Sandstone overlying the Ruth Extension deposit.

The average thickness of leached capping over chalcocite ore was 135 m. The caprock was completely leached of its copper content and in many places is also devoid of limonites. Where present, jarosite and goethite are the dominant limonite minerals. Sedimentary inclusions within leached porphyry in the cap form highly goethitic and hematitic jasperoids. Continued erosion and oxidation and a concomitant downward movement of the base of oxidation resulted in a continuous upgrading and downward migration of the chalcocite blanket. Slight late movements along the Queen fault placed a thin chalcocite blanket within the zone of oxidation and a thin mixed oxide-chalcocite body, the Ingersoll orebody, was formed.

**Conclusions**

The Ruth and Ruth Extension porphyry copper deposits are fragments of a large, once continuous sulfide system in the Robinson mining district that also included the Liberty, Emma, Tripp, and Veteran deposits (Brokaw et al., 1969; Kreis, 1973; James, 1972, 1976; Westra, 1979). The alteration and mineralization in the Ruth-Ruth Extension area is centered on a 25° west-dipping composite cylindrical quartz monzonite porphyry intrusion which represents the eastern extremity of a porphyry apophysis at the top of a large equigranular quartz monzonite to granodiorite stock (Fig. 5).

The hypogene copper ore zone forms a 25° west-dipping tabular body in the upper part of the porphyry cylinder. The alteration assemblages and their relationship to mineralization conform to the average porphyry copper deposit of the southwestern United States (Lowell and Guilbert, 1970), but the inclined
axis of the hydrothermal system resulted in a pronounced vertical zonation. At first glance, the asymmetric alteration and mineralization distribution might suggest that the system as presently known represents only one-half of a tilted cylindrical copper ore shell (cf. Kalamazoo; Lowell, 1968). However, no evidence for major tilting following mineralization has been documented to support this configuration. Alteration and metal gradients show the system to be complete and the tilt of the system to be original.

The hydrothermal system developed through multiple mineralization-alteration stages. Westra (1979) discussed the relationship between magma crystallization and the formation of the porphyry copper deposit at Ely. In the Ruth area, intrusion of the quartz monzonite magma resulted in the formation of a zone of contact-metamorphic biotite-andalusite hornfels in shale and massive garnet in limestone, which predate the main stage of alteration and mineralization. Crystallization of early quartz monzonite porphyry was accompanied by explosive water release and the formation of a zone of stockwork fractures. Formation of the zone of stockwork fractures was closely followed by widespread biotite-orthoclase alteration (Fig. 16), presumably in the presence of predominantly magmatic hydrothermal fluids (Sheppard et al., 1971). Meteoric hydrothermal fluids probably predominated during the formation of the quartz-sericite-pyrite zone (Sheppard et al., 1971) which partly overlaps the earlier biotite-orthoclase zone. High-grade hypogene copper mineralization occurs within a zone of intense silicification at the interface between the quartz-sericite and biotite-orthoclase alteration zones. Metal distribution patterns and pyrite/chalcopyrite ratio trends suggest that the hydrothermal fluids entered the hot, strongly fractured porphyry mass at the lower west side and migrated toward the top of the cylinder.

Following the main stage of copper mineralization, the late quartz monzonite porphyry crystallized, and subsequently, meteoric waters encroached upon the potassic core of the hydrothermal system causing pervasive argillization of biotite-orthoclase-altered early quartz monzonite porphyry. The late quartz monzonite porphyry, probably due to its low permeability, was only weakly affected. Fragmentation by normal faulting of the Ely porphyry copper system in mid-Tertiary time was followed by uplift, oxidation, erosion, and enrichment. The resulting mature chalcocite blanket provided the incentive to develop the Ruth ore deposit in 1915.

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