Advances in Geology of the Porphyry Copper Deposits

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Geology of the Copper Flat Porphyry Copper Deposit

HILLSBORO, SIERRA COUNTY, NEW MEXICO

Peter G. Dunn

The Copper Flat porphyry copper deposit is in Sierra County in south-central New Mexico about 35 miles east-northeast of the Santa Rita deposit near Silver City and about 100 miles northwest of El Paso. It lies in Sections 26 and 35, T.15 S., R.7 W. in the Hillsboro, or Las Animas, mining district about 3½ miles north-northeast of the town of Hillsboro and about 15 miles west of the Rio Grande. The deposit is in a topographic low, Copper Flat, at the western foot of Animas Peak, which is a distinctive conical peak with an elevation of 6,170 ft. Copper Flat is approximately 700 ft. lower and is drained by Grayback Wash, an intermittent tributary to the Rio Grande.

Ore was first discovered in the Hillsboro district in April, 1877 (Jones, 1904), along one of the veins that extend southwest from the quartz monzonite stock in Copper Flat. Placer gold was discovered later in the same year. Production up to 1931 from the district was about $7 million using the prices at the time of production—nearly two-thirds of that amount from gold-silver-copper underground mines along the various veins (Harley, 1934). The deepest of these mines was about 500 ft., and most of the production occurred before 1893, although minor periods of activity continued until a few years prior to World War II (Lindgren et al., 1910).

The rest of the production from the district came from gold placers. Most of this gold was also produced early in the history of the area, but an additional 15,000 oz. of gold were produced between 1935 and 1942 (Segerstrom and Antweiler, 1975). The tailings from that operation were visible in the district, and a few small operators were still producing placer gold from gravels in the existing drainages in 1981.

Although about 200 tons of oxide copper ore were produced from the Sternberg mine in Copper Flat from 1911 to 1931 (Harley, 1934), no exploration of the Copper Flat stock for a potential porphyry copper deposit was made until 1952. Newmont Mining Company drilled 6 angle holes in Copper Flat in that year for a total of 3,369 ft. (Kuellmer, 1955), but the results were not encouraging. In 1958 and 1959 Bear Creek Mining Company drilled 20 holes in Copper Flat for a total of 9,346 ft. Their results indicated that a porphyry copper deposit, including a mineralized breccia pipe, existed in the Copper Flat stock but that no large supergene deposit was present.

Inspiration Consolidated Copper began work at Copper Flat in 1967, and by 1973 had drilled an additional 28 holes in the porphyry deposit for a total of 23,046 ft. They also did some deep drilling in the surrounding andesite, drilled two shallow water wells, and made a preliminary feasibility study and mine plan for a possible open-pit mine.

Quintana Minerals Corporation leased the property from Inspiration in 1974. Between August, 1974, and June, 1976, Quintana drilled 127 holes within the deposit for a total of 94,097 ft. This drilling was supplemented by 2,241 ft. of underground development (approximately 150 ft. below the surface) to provide bulk samples for pilot plant metallurgical testing and to provide a check on the reliability of ore reserve calculations made from vertical drill holes. Additional drilling was also done on potential mill sites, and an adequate water supply was established. The immediate area of the porphyry deposit was mapped at a scale of 1:2,400, and approximately 100 thin sections were examined.

A feasibility study on the Copper Flat deposit was completed in 1976, but the project was temporarily shelved at that time because of low copper prices. It was re-evaluated in 1979, and construction began in 1980. Starting in 1982, the concentrator was scheduled to produce both a copper concentrate with recoverable amounts of gold and silver and a molybdenum concentrate.

REGIONAL GEOLOGY OF THE HILLSBORO DISTRICT

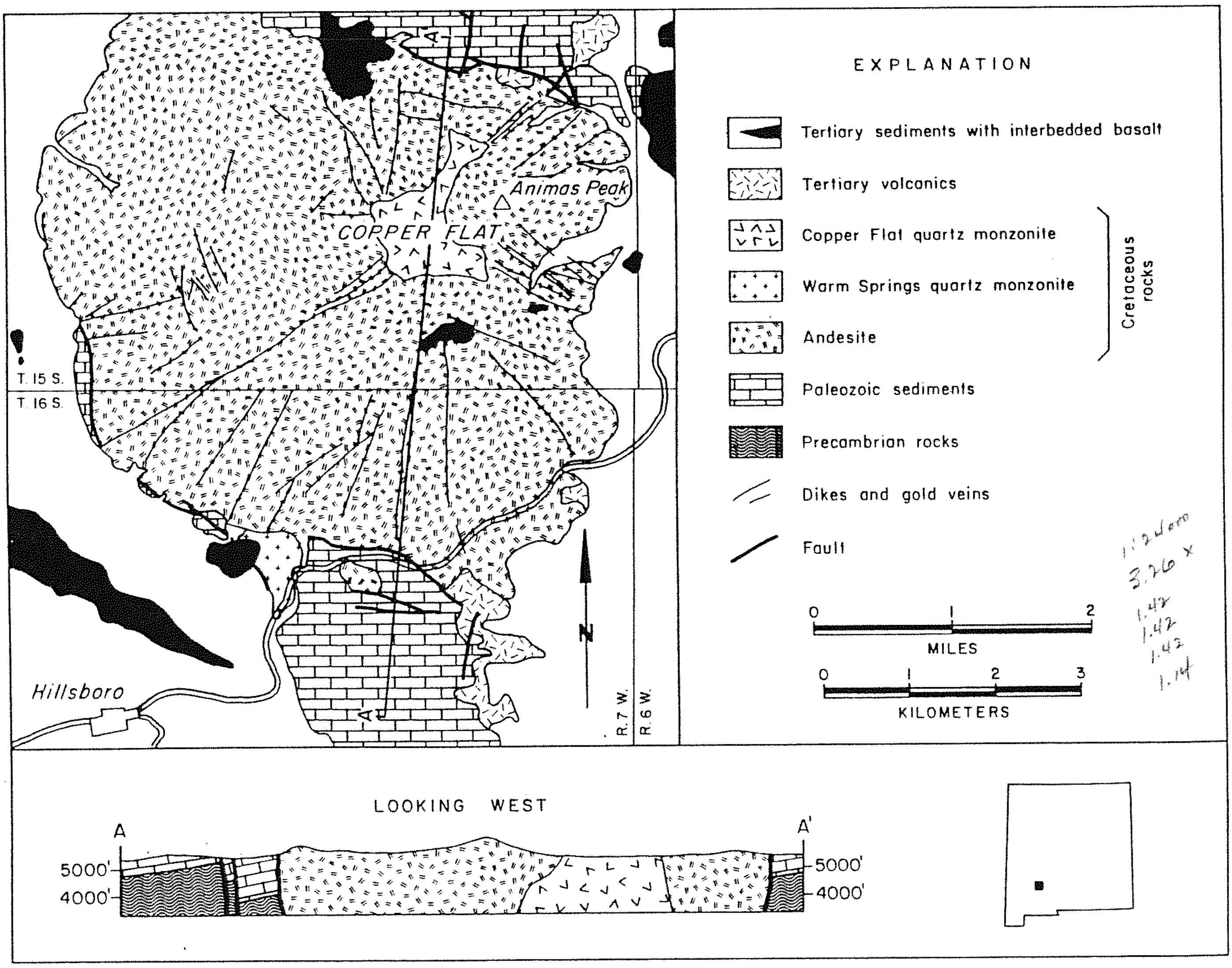
The Hillsboro mining district is in the Animas Hills, a low range formed by a horst at the western edge of the Rio Grande rift, and is separated from the Black Range by a graben in which the town of Hillsboro lies (Woodward et al., 1975). The faults that formed the Animas Hills horst are presumably related to the tectonic activity of the Rio Grande rift, which did not begin until early Miocene (Chapin and Seager, 1975), and were therefore not involved in the localization of the Cretaceous ore deposit.

The central part of the Animas Hills is underlain by a nearly circular block of andesite about 4 miles in diameter; it is shown on Figure 14.1, which has been simplified from the map of Hedlund (1975). The eastern edge of the andesite block coincides with the eastern edge of the horst, where the andesite is in fault contact with the Santa Fe group sediments. A hole drilled for water in the southwestern corner of T.15 S., R.6 W. immediately east of the highway was still in the sediments at a total depth of 2,000 ft.

MW-4

The rest of the periphery of the volcanic terrain is marked by nearly vertical faults along which the andesite has been down-dropped against Paleozoic sedimentary rocks. The vertical displacement along these faults is not known; deep drill holes in the andesite block were still in andesite at total depths of over 3,000 ft. Some isolated blocks of older rocks have been found in the andesite, and one drill hole has encountered Paleozoic sedimentary rocks underlying the andesite. The thickness of the andesite and the circular fault pattern suggest that the andesite, with related intrusive rocks and mineralization, represents a deeply eroded Cretaceous caldera.

The andesite has been intruded by the Copper Flat quartz monzonite in the center of the caldera, the Warm Springs quartz monzonite along the southern contact, and numerous latite dikes that radiate from the Copper Flat stock. The mineralization of the Hillsboro mining district is found in the Copper Flat stock and the associated dikes; the Warm Springs stock is fresh, with no related mineralization. The entire porphyry copper deposit is contained within the Copper Flat quartz monzonite stock.



1:24000
3.26 x
1.42
1.42
1.42
1.14

Figure 14.1. Regional geologic map of the Hillsboro district

The latite dikes cut both the andesite and the Copper Flat quartz monzonite, but do not cut the Warm Springs quartz monzonite. Most of the vein mineralization that has provided the production from the Hillsboro district occurs along the contacts of the latite dikes with the andesite (Harley, 1934). The productive veins range from 2 to 8 ft. wide and consist primarily of quartz with calcite, pyrite, chalcopyrite, and minor bornite; gold and silver production has come from the zone of oxidation, where enrichment took place (Reeves, 1963).

The Copper Flat quartz monzonite, the latite dikes, and probably the andesite are thought to be comagmatic. The mineralization of both the porphyry copper deposit and surrounding veins is also probably part of the same igneous sequence. The barren Warm Springs quartz monzonite appears to have been emplaced after the period of mineralization, but is still probably related to the other igneous rocks. Hedlund (1974) reported a K-Ar age date of 73.4 million years from biotite concentrate taken from Inspiration drill core. Secondary biotite is locally abundant from that portion of the Copper Flat stock, and the age date may indicate the age of mineralization.

Post-mineral rocks in the area include Tertiary siliceous pyroclastics (southeast of the andesite outcrop) and basalt flows. Rare dikes related to both of these post-mineral extrusive rocks cut the andesite and the Copper Flat stock. The basalt flows are interbedded with the Santa Fe group sediments in the Palomas Basin east of the Animas Hills and are therefore of Miocene or Pliocene age (Hawley et al., 1969). Both the pyroclastic rocks and the basalt are younger than the faults that bound the caldera. The gold placer deposits of the district occur in recent gravels that overlie the Santa Fe group sediments.

GEOLOGY OF COPPER FLAT

The geologic map of Copper Flat, Figure 14.2, has been simplified from Quintana mapping originally done at a scale of 1 in. to 200 ft. The mineable portion of the porphyry copper deposit is the shaded area of the map. It occurs entirely within the quartz monzonite and includes a central mineralized breccia pipe. Much of the deposit and almost all the breccia lie beneath 5 to 35 ft. of alluvial cover in Copper Flat; the outline of the breccia and the numerous faults shown in the covered area were determined from close-spaced drilling and underground development.

Lithology

The andesite is generally a fine-grained porphyritic rock with phenocrysts of plagioclase (originally andesine) and amphibole in a groundmass of plagioclase and potash feldspar with rare quartz. Agglomerates or flow breccias are locally present, but the andesite is generally massive and attitudes are difficult to determine. The andesite immediately south of the quartz monzonite is coarse-grained and may represent a shallow intrusive phase. Magnetite is commonly associated with the mafic phenocrysts, and accessory apatite is found in nearly every thin section.

An irregular mass of andesite breccia is shown along the northwestern contact of the quartz monzonite. It contains potash feldspar phenocrysts and andesitic rock fragments in a matrix of sericite with minor quartz; it is probably a pyroclastic unit. Similar tuff breccias have been encountered in drill holes and also occur in a few other outcrops in the map area that are too small to be mapped separately. Magnetite, chlorite, epidote, and accessory apatite are also present in the andesite breccia.

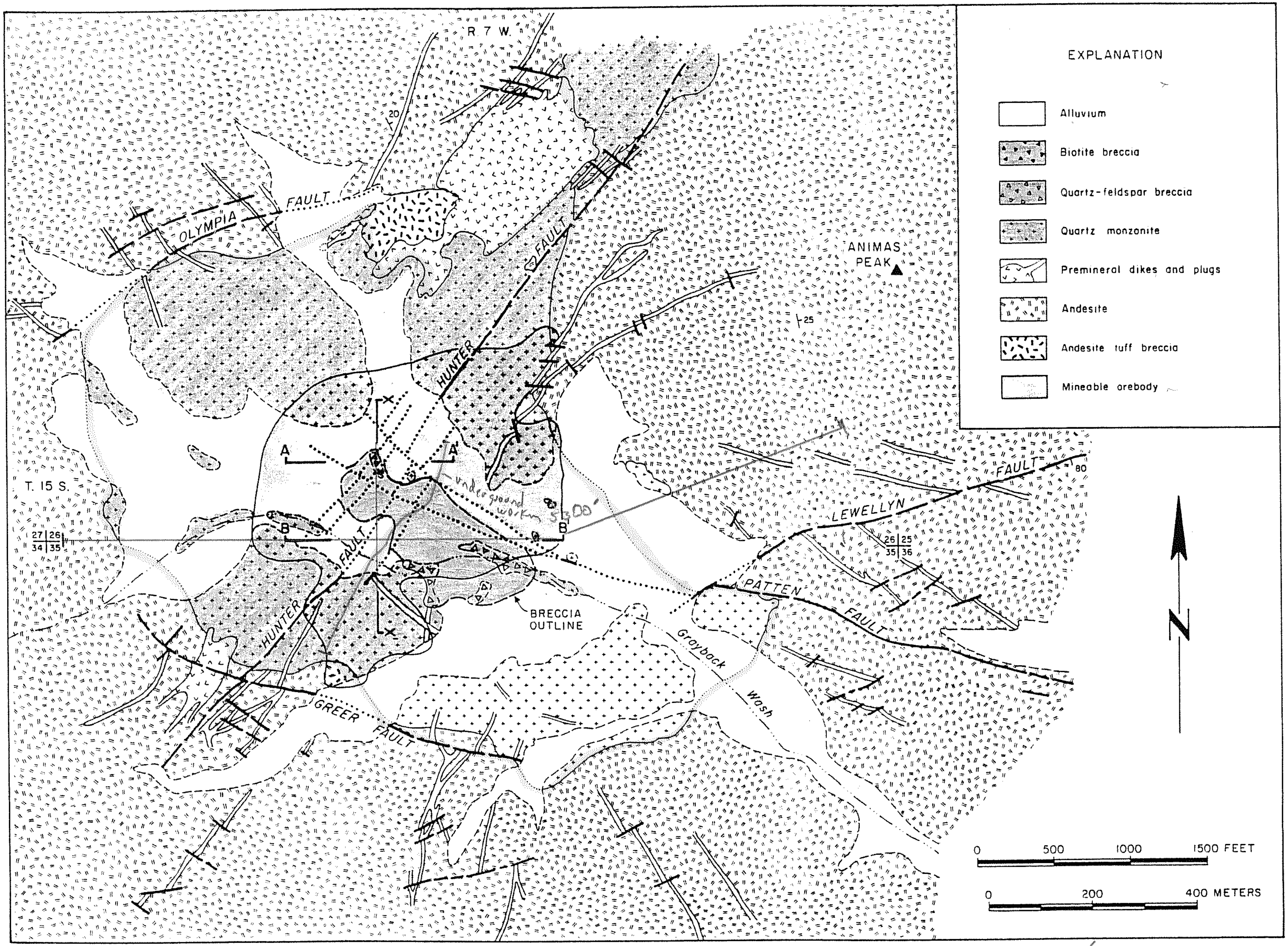
The Copper Flat quartz monzonite occupies the central portion of the map; the narrow neck shown in Figure 14.1 extends an additional 2,500 ft. to the northeast beyond the edge of the map in Figure 14.2. The stock contains a few mappable xenoliths or roof pendants of andesite, and a few isolated outcrops of quartz monzonite occur within the andesite. The andesite at the contact shows no obvious contact metamorphism, and the quartz monzonite rarely shows visible evidence of chilling at the contact.

Most of the quartz monzonite is porphyritic, with large orthoclase phenocrysts up to 5 cm long. It consists of about equal amounts of plagioclase (andesine) and orthoclase, although in places either feldspar may comprise more than 50 percent of the rock. Plagioclase usually occurs as smaller phenocrysts, less than 1 cm long; orthoclase comprises much of the groundmass. Quartz makes up 15 percent of the rock, and occurs as small phenocrysts and as part of the groundmass. Both hornblende and biotite occur as primary minerals. Magnetite is common, associated with the mafic minerals, and apatite is a ubiquitous accessory. Rare sphene crystals are present.

Several textural and compositional variants of the quartz monzonite have been observed, but have not been mapped separately. The rock is locally a nearly equigranular rock, and elsewhere is porphyritic but with only the small plagioclase phenocrysts. Quartz is absent in some parts of the stock. Some of the textural variations appear to be the result of later hydrothermal alteration. Although more detailed mapping may indicate that some of the variations represent separate intrusive phases, all the rock types of the stock are older than the later fine-grained dikes and older than the mineralization and alteration.

The latite dikes and plugs shown on the geologic map cut both the andesite and the quartz monzonite. Three different types of dikes can be distinguished in hand specimens, but they are not distinguished on this map. Many of the smaller dikes have also been omitted. Most of the dikes are fine-grained latite containing 5 to 10 percent euhedral plagioclase phenocrysts ranging up to 5 mm long in a groundmass of plagioclase, potash feldspar, and minor quartz. Apatite is again present. The other two types are similar; one contains 1 to 2 percent rounded quartz phenocrysts up to 2 mm, and the other contains no quartz but does contain abundant large orthoclase phenocrysts up to 25 mm long. Cross-cutting relationships indicate that the dikes with the quartz eyes are older than the latite, and that the dikes with the large phenocrysts are younger. The dikes are generally 5 to 30 ft. wide.

The two plugs on the map in Figure 14.2 consist of the fine-grained latite. The larger irregular plug to the north is not well exposed except for its contact with the quartz monzonite. Several small outcrops of both andesite and quartz monzonite occur within the plug, which may actually be a



B-B' = 1850'

Figure 14.2. Geologic map of the Copper Flat mineralized area

X-X' = 1550'

complex dike swarm. The smaller plug to the south is better exposed and is a single body of latite.

Postmineral rocks have been omitted from the geologic map. The only postmineral rocks in the area are a single feldspar porphyry dike that cuts the andesite northwest of the larger latite plug, and a few narrow basalt dikes that cut both the andesite and the quartz monzonite.

Structure

The structural elements in Copper Flat were established prior to the emplacement of the quartz monzonite stock and were controlling factors in the later igneous events and subsequent mineralization. The same structures were still active after the mineralization process; the alluvial covered area, Copper Flat, is due to more active erosion at the intersection of the numerous faults that have had post-mineral movement resulting in wide, strongly brecciated fault zones. Some of the post-mineral dikes have been emplaced within these fault zones.

Three principal structural directions are present in the area. The most prominent of these is northeast—a direction that includes the Hunter fault and the other parallel faults in Copper Flat. The other two structural directions are west-northwest, marked by the Patten and Greer faults, and east-northeast, marked by the Olympia and Lewellyn faults. All these structures are nearly vertical; the Hunter fault system dips 80° to the west, and both the other fault systems dip between 80° to the south and 90°.

The outline of the Copper Flat stock generally parallels one of these structural directions, although nowhere has the stock been emplaced by faulting. The southern contact nearly parallels the Greer fault, although the contact is cut by the fault, and the southeastern and northwestern contacts are roughly parallel to the Olympia and Lewellyn faults. The elongate neck of the stock is parallel to the Hunter fault system. It has not been possible to determine whether there was movement on the fault systems prior to the emplacement of the stock or whether these were simply well-defined fracture systems.

Most of the latite dikes strike in one or another of the three principal fracture directions; the majority, including those related to the most productive vein mines in the district, strike northeast. A narrow zone of fault gouge commonly occurs along the contact between a dike and the andesite, with the mineralization younger than the faulting (Harley, 1934). There is evidence at the extreme west of the map of fault movement during the period of emplacement of the dikes. A younger porphyritic dike was emplaced in a fault (possibly an extension of the Patten fault) that had previously offset an early latite dike.

Sulfide mineralization within the quartz monzonite has been controlled by the fractures following the same principal directions. The attitudes of 162 mineralized fractures in the quartz monzonite surrounding the breccia pipe have been plotted and contoured on an equal-area net and are shown on Figure 14.3. Three of the maxima shown on the diagram correspond very closely to the main structural directions as indicated by the faults and dikes. A fourth concentration indicates a set of fractures that strike N4°W. Although no faults with that orientation were noted in the surface mapping, some of the basalt dikes trend in that direction, and they are thought to have been emplaced along fault zones.

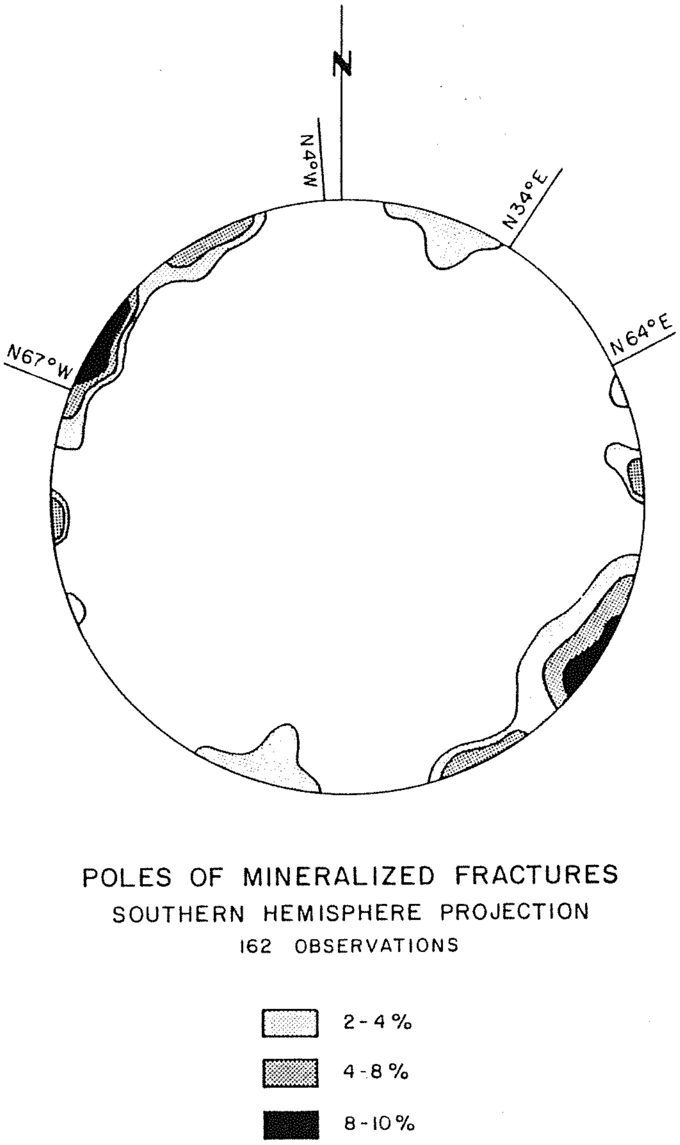


Figure 14.3. Orientation of mineralized fractures in quartz monzonite

The three principal structural directions have been marked by post-dike movement, and both the Hunter fault and the Patten fault systems have had definite post-mineral movement. They are both marked by smeared-out sulfides, and both offset the breccia pipe and the zones within it. Both in drill core and in the underground workings the fault surfaces are marked by nearly horizontal slickensides. This apparent strike-slip movement is usually compatible with the displacement of the dikes mapped on the surface. The Greer fault, however, shows both right-lateral and left-lateral displacement of different offset features; such evidence indicates that there has been some vertical displacement.

Limited information on the fault zones (from drill hole intersections and from the underground workings) suggests that the material within the fault zones is different in the differently oriented faults. The material in the northeast fault zones contains a high proportion of wet gouge, often with no recognizable rock fragments. Where the Hunter fault zone has been encountered underground, material in it has had the same consistency as wet concrete and has actually flowed. The material in the east-northeast fault zones, however, contains only highly broken rock and little obvious gouge. The fault zones in both systems range in width from less than a foot to nearly 25 ft. along the Patten fault east of Copper Flat. The width of the fault zones varies along strike. Despite the intense brecciation within the fault zones, the total displacement along the faults does not appear to exceed a few tens of feet.

Breccia Pipe

The central high-grade portion of the deposit is contained in a mineralized breccia pipe that is almost completely covered by the alluvium in Copper Flat. The shape of the body (beneath the alluvium) is shown on the geologic map in Figure 14.2. The eastern portion of the breccia is outside the outline of mineable ore; the rest of the breccia, however, has a higher grade than the surrounding quartz monzonite. The result of this mineralization is that the breccia will produce nearly one-half of the copper from the mineable deposit although it comprises only about one-third of the total ore that will be mined.

The breccia pipe is a zone within the quartz monzonite that has been cut by numerous, randomly oriented, irregular veins that are thicker and coarser-grained than the narrow fracture-controlled veinlets in the surrounding stock. Part of the northwestern section of the pipe contains angular, rotated fragments cemented by the same hydrothermal matrix. The extent of breccia with rotated fragments can be determined only roughly, because most of the data have come from drill core samples. The entire breccia pipe in Copper Flat, therefore, corresponds to both Zone 2 (crackle breccia) and Zone 3 (breccia pipes) in Copper Basin, Arizona, as described by Johnston and Lowell (1961).

The pipe is 1,300 ft. long and approximately 600 ft. wide at the surface with the long axis perpendicular to the predominant northeast fracture direction. The breccia is exposed in only a few places. It has a vertical extent of over 1,000 ft., with veins of coarse pegmatitic material occurring almost 1,700 ft. deep in one drill hole. Close-spaced drill holes, approximately 100 ft. apart within the center of the deposit, show that the breccia pipe occurs as a single, continuous body. Only two drill holes outside the breccia encountered short intervals of stockwork veining similar to that in the main breccia pipe.

The shape of the main body is shown in detail on the geologic map of Copper Flat at the 5,300 ft. level (the elevation of the underground workings) in Figure 14.4. This map
and two vertical cross sections (Fig. 14.5*a*, *c*) also show
approximate extent of the zone containing rotated fragme
cross section *B-B*' (Fig. 14.5*b*) is south of that zone.
though the breccia does reach the surface beneath the
luvium, much of the body is covered by overlying qu
monzonite. This upper contact with the quartz monzonit
relatively sharp, and is shown on the cross sections to h
a gentle south dip, suggesting that the top of the pipe
barely been uncovered by erosion.

The pipe has a steep plunge to the southwest, which
be the result of post-mineral rotation. A few attitudes ta
in the andesite show 20° dips to the east; if these do repre
later movement, the breccia would have originally been v
cal. Drill holes at the eastern edge of the pipe drill back
quartz monzonite with a relatively sharp contact. If rota
has taken place, these holes actually drill out the side of
breccia pipe. Drill holes along the western edge drill f
breccia into quartz monzonite but with a long gradati
contact; this probably represents the true bottom of the

Most of the fragments in the breccia consist of mine
ized quartz monzonite. Fragments of mineralized latite
locally abundant; these are usually found where dikes
posed in the quartz monzonite can be projected into
brecciated zone. Andesite fragments in the breccia pipe o
only as mixed fragments partially in contact with intru
quartz monzonite; these fragments are clustered within s
intervals in only a few drill holes. These observations indi
that the andesite fragments represent only the brecciatio
original andesite xenoliths in the quartz monzonite. No o
rock types have been recognized as fragments in the bre

The matrix of the breccia consists primarily of var
proportions of quartz, biotite (phlogopite), potash felds
pyrite and chalcopyrite. Magnetite, molybdenite, fluo
and calcite are locally common, and apatite is again a
mon accessory mineral. No tourmaline has been found i
breccia matrix or in the surrounding veins. Minerals in
matrix are commonly quite large, with biotite books up
cm across, and much of the quartz-feldspar matrix h
pegmatitic texture. Either biotite or potash feldspar
formed along the edge of the breccia fragments, and
quartz and sulfide minerals have generally formed in
center of the matrix. Large biotite crystals have gene
grown nearly perpendicular to the matrix-fragment con
which in these instances is very sharp. Magnetite is com
in the matrix and is the principal matrix mineral in one
hole near the center of the body. The primary magn
however, has been destroyed in the quartz monzonite in
diately surrounding the breccia pipe and in the fragm
Some open cavities lined with euhedral crystals, gene
quartz and sulfides, have been found but are not com
Fluorite, calcite, and apatite also occur in open cavities.
tite also forms as euhedral crystals up to 10 mm across i
center of large sulfide or magnetite crystals. It appears
concentrated near the center of the breccia pipe assoc
with magnetite.

Although the matrix is in sharp contact with the
ments in many instances, other fragments are quite diffu
a result of the formation of a broad alteration envelo

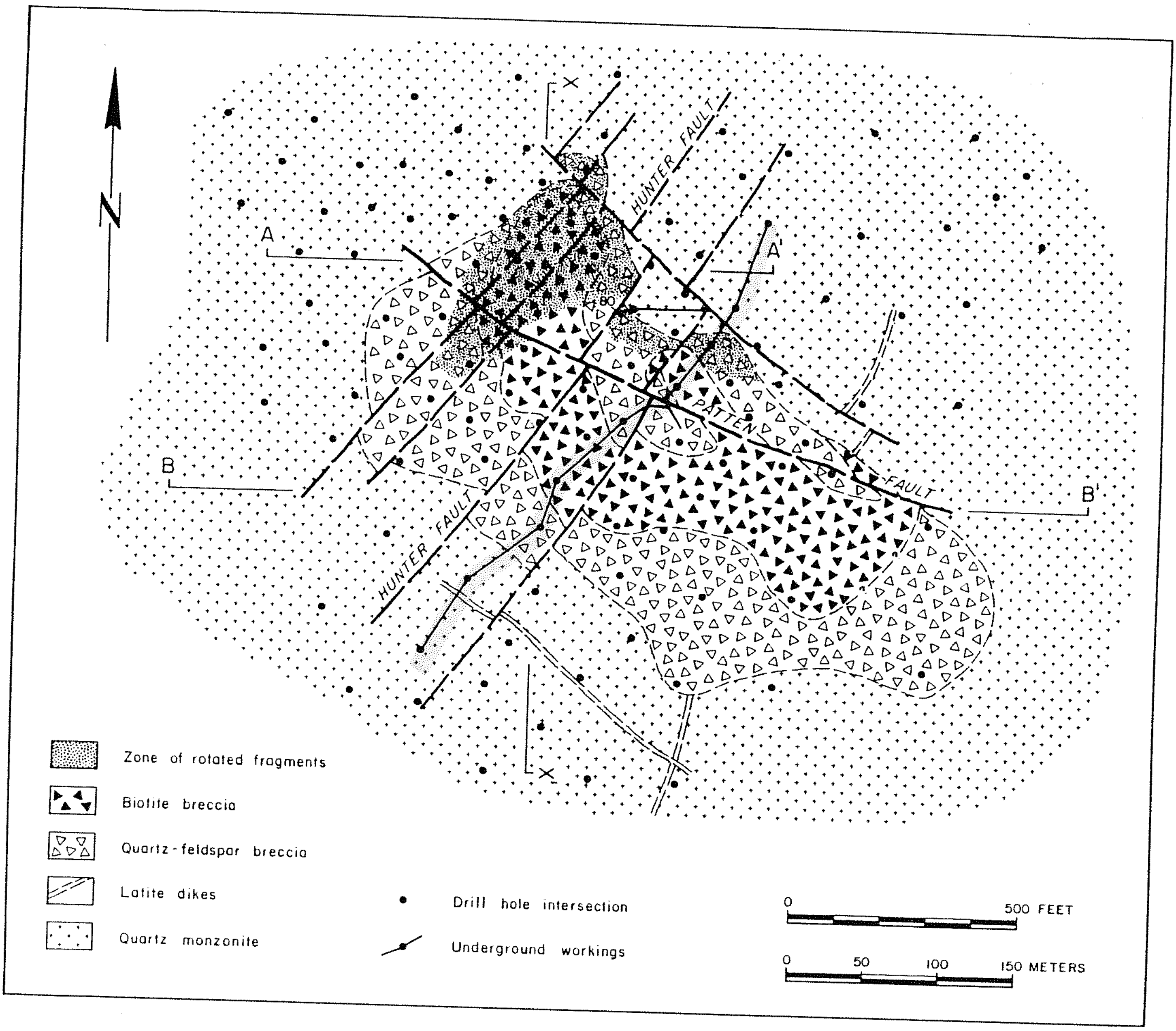


Figure 14.4. Geologic map of Copper Flat at the 5,300-ft. level

very fine grained secondary biotite surrounding the matrix. Other fragments are deeply embayed, and appear to have been corroded by the hydrothermal fluid that formed the matrix.

The proportions of the major hydrothermal minerals vary in different parts of the breccia, and the pipe has been divided—on the basis of the principal gangue minerals in the matrix—into biotite breccia and quartz-feldspar breccia. These sub-divisions do not correspond to the division be-ween breccia with or without rotated fragments. The distri-ution of biotite breccia is important because it almost always orms high-grade chalcopyrite ore. The grade in the quartz-eldspar breccia is considerably more variable; in general the halcopyrite content varies with the quartz content. The ma-ix in the eastern waste portion of the breccia consists primarily of pegmatitic potash feldspar with subordinate amounts of quartz and pyrite and only rare chalcopyrite.

This elliptical body of breccia that forms the center of the Copper Flat porphyry deposit is very similar to the high-grade core of the Ajo orebody that Gilluly (1946) ascribed to pegmatitic replacement. Much of the high-grade core has been mined out at Ajo, but some large boulders are still present in the pit. These contain definite rotated angular fragments of quartz monzonite in a matrix of very coarse grained chlorite, quartz, and chalcopyrite.

MINERALIZATION AND ALTERATION

The mineralization and alteration at Copper Flat are similar to most of the porphyry copper deposits in the South-

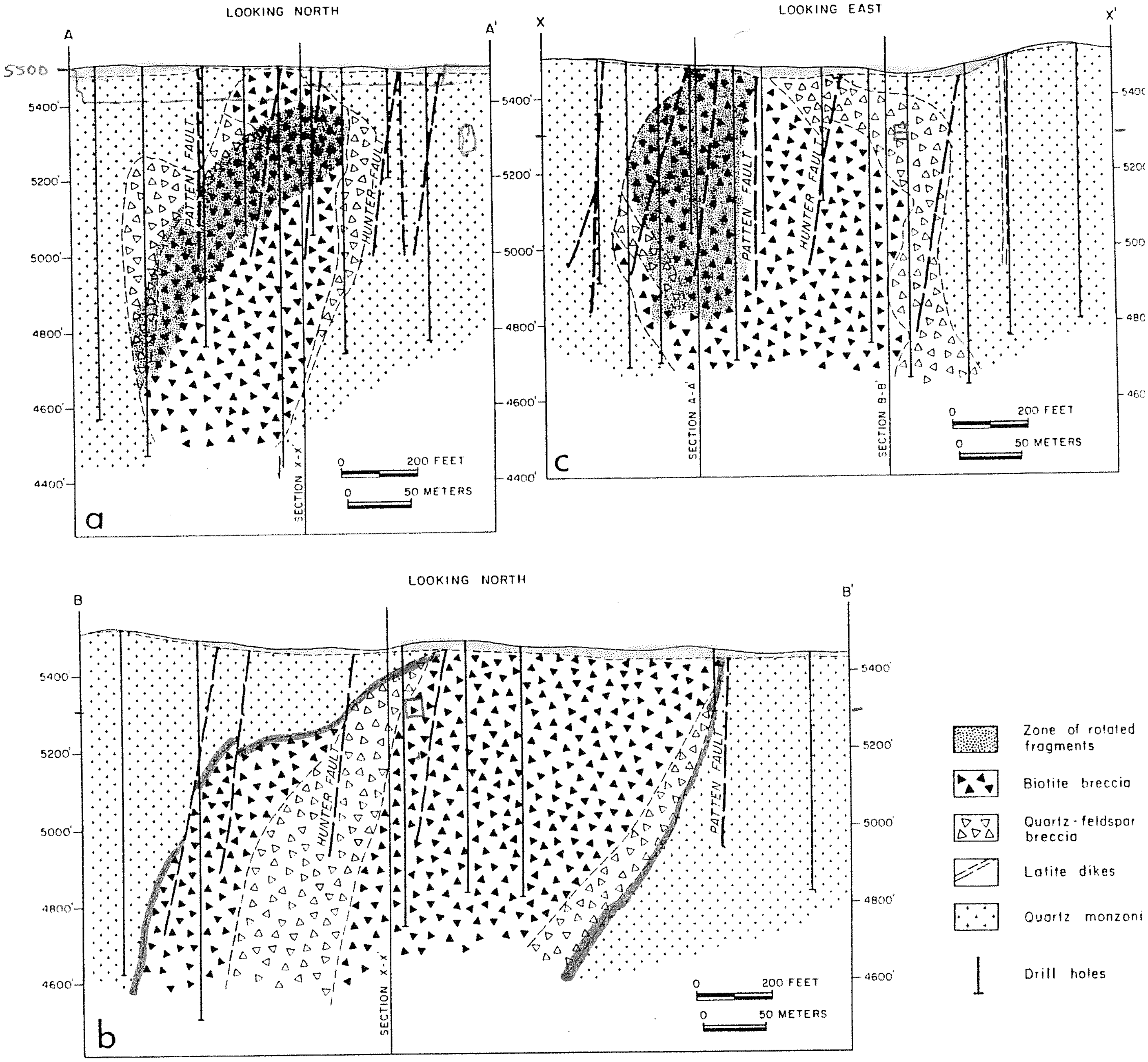


Figure 14.5. Geologic cross sections at Copper Flat: *a,* cross section *A-A'*; *b,* cross section *B-B'*; *c,* cross section *X-X'*.

west, differing in that much of the economic mineralization occurs in the breccia pipe and that few supergene effects are present.

Primary Mineralization

The Copper Flat porphyry deposit is almost entirely a hypogene sulfide deposit with nearly all the copper occurring as chalcopyrite. Pyrite is the other main sulfide mineral; subordinate amounts of molybdenite, galena, and sphalerite are present. Rare bornite has been recognized but, surprisingly, most of it occurs outside the orebody. A few small tetrahedrite crystals have been found in drill core samples. The total sulfide content is generally low compared to mo of the porphyry copper deposits in the Southwest; it rang from approximately 1 percent (by volume) in the easte portion of the breccia pipe and the surrounding quartz mo zonite to 5 percent in the quartz monzonite surrounding tl mineable orebody to the south and west. Sulfide content highly variable within the breccia, with small areas contai ing as much as 20 percent sulfides. Sulfide mineralization restricted almost entirely to the quartz monzonite, with abrupt drop in the sulfide content at the andesite contac Minor pyrite mineralization extends into the andesite alo the pre-mineral dikes.

Mineralization within the quartz monzonite consists of pyrite, which occurs as disseminations or along discontinuous, fracture-controlled veinlets, and chalcopyrite, which occurs principally as disseminations associated with the original mafic minerals. Pyrite is more abundant than chalcopyrite in the quartz monzonite except in two separate areas: (1) a narrow zone immediately surrounding and overlying the western end of the breccia pipe containing abundant chalcopyrite in quartz-sulfide veinlets, and (2) the outcrops southeast of the breccia and south of Grayback Wash, where disseminated chalcopyrite is present with no associated pyrite. The first area contains the highest-grade quartz monzonite ore. Changes in the copper grade in the quartz monzonite, due to changes in the total sulfide content and in the ratio of pyrite to chalcopyrite, are gradational both laterally and vertically.

Molybdenite is not abundant in the quartz monzonite. Where it is present, it occurs either in quartz veins or as thin coatings on fractures. Minor sphalerite and galena are present in both carbonate and quartz veinlets in the stock.

Sulfide mineralization in the pre-mineral dikes is similar to that in the surrounding quartz monzonite. Both pyrite and chalcopyrite generally occur as disseminations. In some areas the copper grade in the dikes is lower than that in the adjacent stock, but in most places there is no marked change in grade between the two rock types.

Mineralization within the breccia pipe is characterized by large, irregular masses of pyrite and chalcopyrite as part of the breccia matrix, and is associated with large crystals of quartz, biotite, and potash feldspar. Some of the larger sulfide masses encountered in the underground workings have measured up to 2 ft. across. Molybdenite occurs in the matrix as coarse crystals up to 2 in. across. Minor amounts of pyrite and molybdenite, with rare sphalerite and galena, occur in narrow quartz and carbonate veinlets that cut both the fragments and the breccia matrix.

Chalcopyrite is most abundant within the biotite breccia, which is almost invariably ore-grade material. The chalcopyrite occurs both as large, irregular masses and as fine disseminations within the large biotite books. A definite horizontal mineral zoning occurs within the quartz-feldspar breccia. In general the highest copper content is at the western end of the breccia and is associated with abundant quartz and only subordinate amounts of potash feldspar. The highest molybdenum content occurs in this area. Pyrite and potash feldspar both become increasingly abundant to the east at the expense of chalcopyrite, molybdenite, and quartz, and even pyrite becomes scarce at the extreme eastern edge of the breccia.

The breccia outside the mineable orebody shown on the map in Figure 14.2 has a matrix comprised almost entirely of pegmatitic potash feldspar and a copper grade of less than 0.1 percent. This matrix mineralization has been superimposed on the existing disseminated mineralization within the fragments of quartz monzonite. The form of the resulting mineralization within the breccia pipe has caused abrupt changes in the copper content over very short distances. Copper assays of adjacent intervals in the same drill hole sample within the breccia may differ by more than 1 percent copper.

Supergene Mineralization

Very little oxidation and supergene enrichment have occurred at Copper Flat, presumably because erosion has been able to keep pace with the rate of oxidation, which, in turn, may have been slower than elsewhere in the Southwest due to the low total sulfide content. Fresh pyrite and chalcopyrite can be found in outcrops along Grayback Wash within the orebody.

A small chalcocite zone occurs in the quartz monzonite adjacent to and overlying the breccia pipe. It also extends to the northeast for about 200 ft. along the N35°E fracture direction. Chalcocite has been found as deep as 200 ft. in some drill holes, but in most places it occurs only within a few tens of feet of the surface. The chalcocite occurs as film on chalcopyrite and rarely comprises any significant amount of the copper within the zone of enrichment. Almost no chalcocite has been recognized within the breccia pipe.

No sizeable tonnage of oxidized copper mineralization is present, although some oxidized copper minerals are present overlying the area of chalcocite enrichment. The base of oxidation is abrupt and is nowhere deeper than 50 ft., in most places it is less than 30 ft., even within fault zones. Malachite and chrysocolla are the main oxidized minerals; small aggregates of euhedral malachite and azurite are found in the post-mineral basalt dikes within the zone of oxidation.

The copper and molybdenum assays in some of the drill hole samples that intersected visible chalcocite mineralization show a remarkable correlation between high-grade enriched copper and high-grade molybdenum within the same assay intervals. The assay results of samples from the top of one of these drill holes are shown graphically on Figure 14.6. These data give at least empirical support for molybdenum enrichment.

The form of the molybdenum in these higher-grade samples is not known. No visible ferrimolybdite or other oxide minerals have been identified, and visible molybdenite is almost completely absent in these samples. Quartz veins are also rare or absent. Below the zone of enrichment at Copper Flat, molybdenite is easily recognized with a hand lens in samples containing as little as 0.010 percent molybdenum, and samples with a high molybdenum grade—comparable to those in the zone of enrichment—usually contain obvious coarse-grained molybdenite in quartz veins.

Several other drill holes also encountered minor chalcocite enrichment, but with no apparent enrichment in the molybdenum. The difference between these core samples and those that do show molybdenum enrichment is in the original total sulfide content and the ratio of pyrite:chalcopyrite. Molybdenum enrichment occurs in areas of low total sulfides (1 to 2 volume %) and approximately equal amounts of pyrite and chalcopyrite; samples that have chalcocite but no molybdenum enrichment are in areas where total sulfides are 3 to 5 volume percent and where pyrite is several times more abundant than chalcopyrite.

This field relationship is in agreement with chemical data on the behavior of molybdenum under oxidizing conditions (Titley and Anthony, 1961; Hansuld, 1966). In an acid

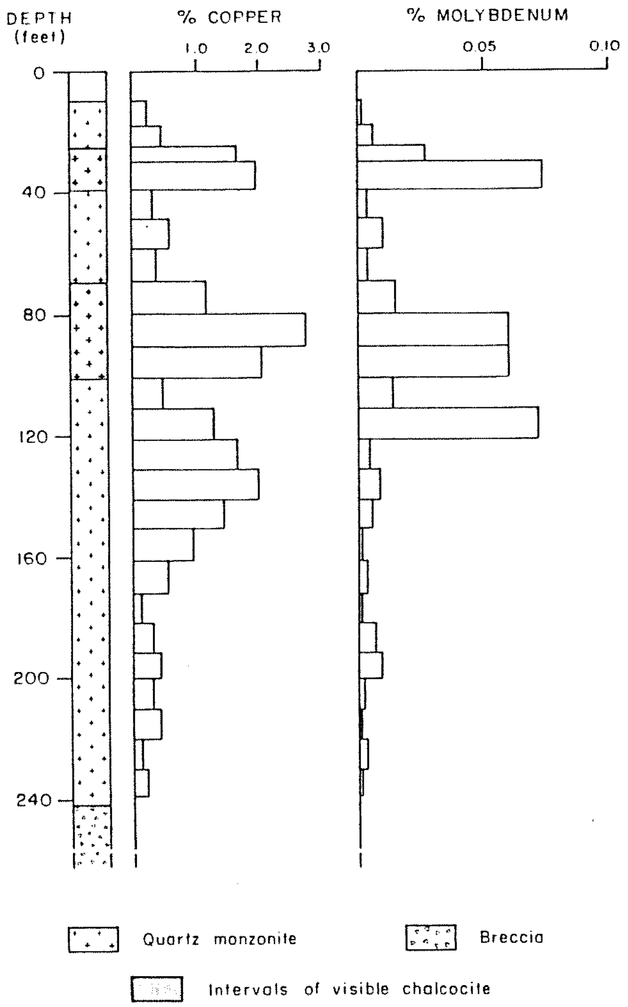


Figure 14.6. Drill hole assays for copper and molybdenum

environment (high pyrite) oxidized molybdenum is fixed; it would remain in the oxidized zone and eventually would be removed by erosion. A more alkaline environment (pH of 6 or greater) causes molybdenum to be mobile and allows it to travel downward into the zone of enrichment. This more alkaline environment, however, is one in which copper is less mobile, so the range of pH under which both copper and molybdenum could form supergene mineralization is quite small.

Alteration

The Copper Flat deposit does not show the symmetrical zoning of alteration types that is considered typical of porphyry copper deposits in the Southwest, although the same alteration minerals are present. A central zone of potassic alteration extends from the breccia pipe almost to the southeastern contact of the quartz monzonite stock and includes the area of chalcopyrite mineralization with no associated pyrite.

The strong potassic alteration within and immediately surrounding the breccia pipe is the most prominent alteration feature of the deposit. Secondary biotite and potash feldspar occur in the breccia matrix as large crystals and also replace the rock fragments. The biotite that forms as replacement occurs as finely shredded aggregates; euhedral primary biotite books in the quartz monzonite are apparently stable, although they have locally been partially altered to chlorite. The secondary potash feldspar occurs as narrow veinlets or alteration envelopes along quartz veins and as almost complete replacement of the original rock, with only vague outlines remaining to indicate the original texture. Quartz occurs as veinlets and in the breccia matrix; it apparently formed together with biotite and potash feldspar during the period of potassic alteration. Chlorite is locally associated with secondary biotite but may have formed later at the expense of biotite. Anhydrite is absent, although rare gypsum occurs as thin coatings on fractures.

Sericite alteration has affected almost the entire quartz monzonite stock and the related dikes; it has also affected the fragments in the breccia. Sericite has replaced the plagioclase and also occurs in the groundmass of the rocks; both sericite and chlorite have replaced original mafic minerals. Quartz and carbonate veins and minor kaolinite are associated with the sericite alteration. Rare zeolites have also been tentatively identified.

Sericite alteration is strongly developed in one near-surface zone south and west from the breccia pipe. Both the quartz monzonite and the dikes in this area have been completely altered to sericite and quartz to the extent that the original texture has been obliterated and it is difficult to distinguish the stock from the dikes on the surface. This intense alteration, however, extends only a few tens of feet from the surface and is clearly a supergene effect that was controlled by the original high pyrite:chalcopyrite ratio in this area. The zone of supergene alteration extends for about 500 ft. south of Grayback Wash and to within about 500 ft. of the western margin of the stock.

Two separate periods of hypogene sericite alteration occurred at Copper Flat—one prior to the formation of the breccia and the potassic alteration, and a later one that postdates the potassic alteration. The sericite in the stock and in the fragments in the breccia surrounding it has been replaced by both secondary biotite and secondary potash feldspar. Areas of pervasive secondary feldspar and the breccia matrix have been subsequently cut by quartz veinlets with only minor sulfides but with well-developed sericite envelopes. The two periods of sericite alteration are associated with a different assemblage of sulfide minerals—pyrite with minor chalcopyrite in the early period, and pyrite, galena, and sphalerite in the later period.

Propylitic alteration is common in the andesite and the andesite breccia, but it is rarely developed in the quartz monzonite or in the latite dikes. Dikes containing weak quartz-sericite alteration with minor pyrite have been observed cutting unmineralized andesite, which shows only chlorite and epidote alteration.

Paragenesis

The sequence of mineralizing events that formed the Copper Flat deposit is depicted schematically on Figure 14.7. Three stages of hypogene mineralization have been recorded, although it is likely that these were not three separate periods but rather a continuous change during time. The three stages

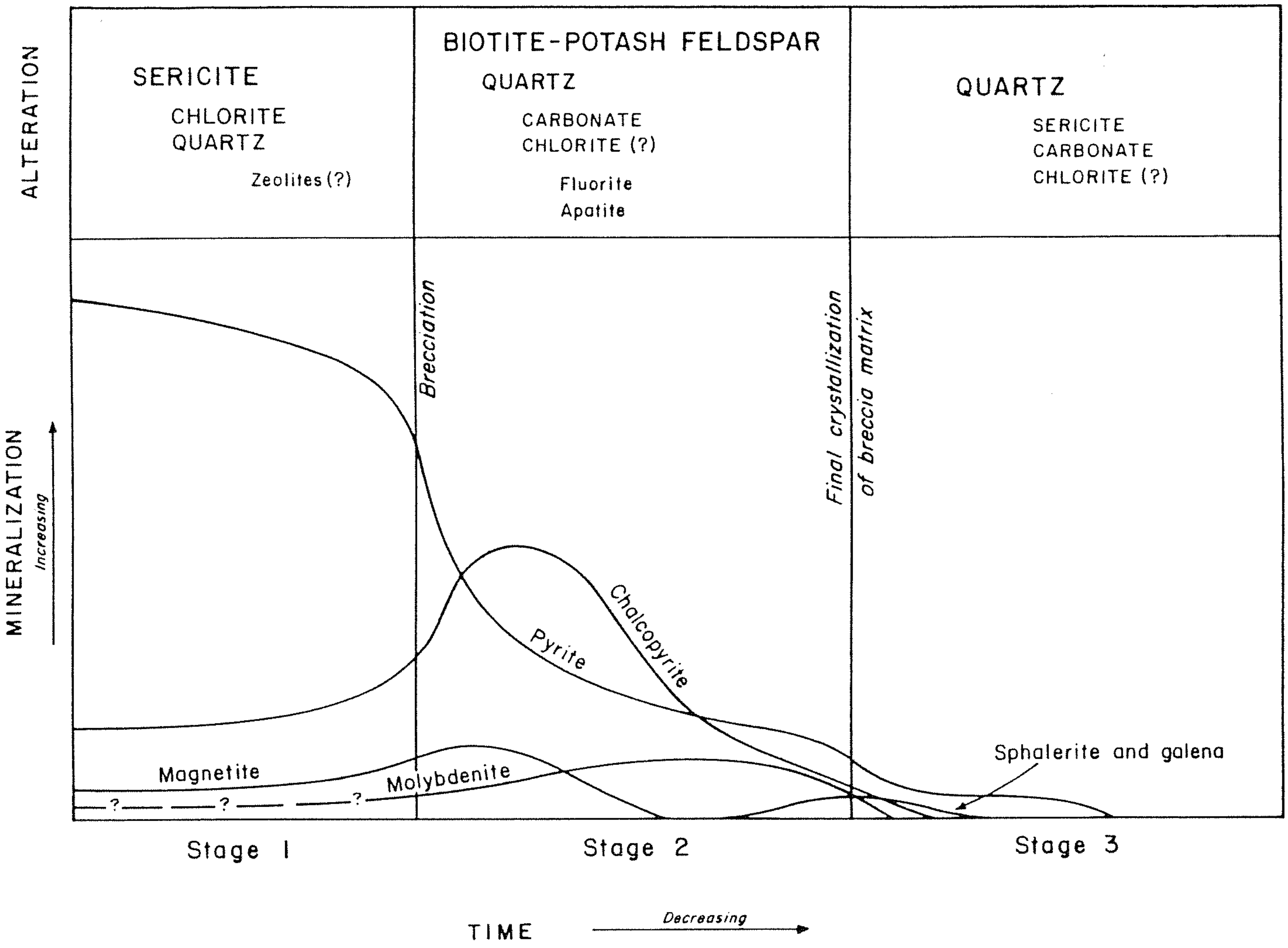


Figure 14.7. Schematic paragenetic sequence for the Copper Flat deposit

are associated with different sulfide and alteration assemblages. No absolute figures are available for the temperature, pressure, or time for the mineralization.

The first stage of mineralization—the introduction of pyrite with subordinate amounts of chalcopyrite—affected nearly the entire stock. This stage occurred after the formation of the latite dikes but prior to the formation of the breccia pipe. The chalcopyrite generally formed as disseminations and the pyrite as coatings along fractures and as discrete veins. No definite first stage molybdenite can be identified. Magnetite formed during this stage as replacements of original mafic minerals. This mineralization was associated with the first stage of sericite and chlorite alteration with subordinate quartz and minor carbonates. It probably formed no ore-grade material.

The second stage began with the formation of the breccia and continued through the crystallization of the breccia matrix. Pyrite and chalcopyrite were both deposited with subordinate amounts of molybdenite and magnetite and trace amounts of sphalerite and galena. This stage affected the breccia pipe and the surrounding and overlying quartz monzonite. Most of the mineralization formed as open space filling between the fragments and as veins in the stock, although some second stage mineralization formed as replacement—particularly of the fragments within the breccia. Higher-grade veins of quartz, chalcopyrite, and molybdenite have been emplaced along the N35°E fracture system for several hundred feet away from the breccia and are thought to have formed during the second stage of mineralization. The gold-silver-copper veins surrounding the Copper Flat quartz monzonite stock are also thought to be related to the second stage. Second stage mineralization was associated with the strong potassic alteration minerals that were forming gangue minerals in the breccia matrix. There is no clear evidence of the age relationship between the biotite breccia and the quartz-feldspar breccia, although the pegmatitic potash feldspar matrix at the extreme eastern edge of the breccia pipe is thought to have been the last material to crystallize.

The first-stage mineralization may have been only peripheral disseminated mineralization that formed contemporaneously with the breccia mineralization. Careful examination of the fragments in the breccia, however, has led to the conclusion that two stages were involved. A few fragments contain narrow quartz-pyrite veinlets or narrow chlorite veinlets that are restricted to the fragment; such veining indicates pre-breccia mineralization. Many of the fragments show only disseminated pyrite and minor chalcopyrite mineralization with sericite alteration, but they are cemented by a matrix of chalcopyrite, magnetite, and molybdenite, with secondary biotite and potash feldspar. This difference between the mineralization in the fragments and that in the matrix suggests that the mineralizing periods were separated in time.

The third stage of mineralization is clearly separate from the second stage: it occurs as narrow quartz, pyrite, and chalcopyrite veinlets that cut both the fragments and the matrix of the breccia. Molybdenite in quartz veins and sphalerite and galena in carbonate veins are also related to third-stage mineralization. These veins have alteration envelopes of late sericite. Third-stage mineralization contributes a very minor amount of sulfide minerals to the Copper Flat deposit compared to the first two stages.

ORIGIN OF THE BRECCIA PIPE

Any hypothesis concerning the origin of the breccia pipe that forms the high-grade center of the Copper Flat porphyry copper deposit must account for the following observations:

1. The matrix cementing the breccia fragments consists entirely of hydrothermal minerals—the same minerals which formed the second stage veins that cut the surrounding stock. No rock flour nor any igneous rock material occurs as part of the matrix.
2. The quartz monzonite and latite fragments within the breccia were mineralized prior to the formation of the breccia.
3. Only a small proportion of the breccia pipe contains definite rotated fragments. The most intense brecciation occurs near the top of the breccia body along the northern and western margin. The zone containing rotated fragments plunges to the west and shows a gradual decrease in the amount of separation and rotation with depth.
4. The bottom of the breccia pipe is marked by a gradual decrease in the number of stockwork veins within the quartz monzonite.
5. The amount of displacement between rotated fragments appears to be very slight. Much of the movement between fragments was no more than a few inches—the width of the intervening matrix. First stage veins can often be traced from one fragment to an adjacent one, even though these veins have been cut by the breccia matrix.
6. Latite fragments within the pipe are concentrated along the projection of the dikes that intrude the stock, and andesite fragments are found together (apparently the brecciation of andesite xenoliths).
7. The long axis of the breccia pipe is perpendicular to the principal fracture direction (northeast) in the stock—parallel to the least-stress direction.

The lack of any rock flour or gouge in the matrix indicates that brecciation was not the result of tectonic movement. The apparent lack of appreciable movement between the fragments and the gradational contact between true breccia and the zone of stockwork veining preclude any explosive mechanism for the brecciation. The process of mineralization-stoping (Locke, 1926) would result in appreciable downward movement and mixing of the fragments; it is therefore precluded at Copper Flat by the same observations.

The mechanism for the formation of the Copper Flat mineralized breccia pipe that appears most compatible with the above observations is that of autobrecciation caused by retrograde boiling when the pressure of the mineralizing fluid exceeded the confining pressure (Phillips, 1973). Expansion and brecciation caused by retrograde boiling within consolidated rock form breccia with the following characteristics that are observed at Copper Flat:

1. The breccia consists of zones of rotated fragments with no appreciable displacement. The zones of true breccia are enclosed within a body of stockwork or crackle breccia where no movement of the rock has occurred.
2. The most intense brecciation occurs near the top of the body, where the difference between the vapor pressure of the hydrothermal fluid and the confining pressure was greatest. The amount of brecciation decreases with depth due to increased confining pressure.
3. Horizontal expansion is greatest parallel to the least-stress direction resulting in an elongate body oriented in the same direction.
4. Retrograde boiling and subsequent expansion and fracturing initially had to occur beneath a cover of unfractured rock; when the fracturing reached the surface, the vapor pressure was released and brecciation ceased.

Unbrecciated quartz monzonite still overlies much of the breccia at Copper Flat, and the dip of the upper contact suggests that the breccia has only been unroofed by later erosion. Small, high-grade breccia bodies within the quartz diorite at El Teniente (Camus, 1975) and elsewhere in Chile (Kents, 1964) are very similar to the Copper Flat breccia pipe. These are still covered by unfractured rock and are thought to have formed through autobrecciation. Camus suggests that those at El Teniente formed at a depth of about 2,000 m; the depth of formation of the Copper Flat breccia pipe may be of the same magnitude.

The open spaces in the breccia at Copper Flat provided by the expansion were filled by hydrothermal minerals forming the matrix of the breccia and the irregular veins in the surrounding crackle breccia. Some part of the second stage mineralization occurred as replacement, which modified the original breccia texture.

The geology of Copper Flat indicates that the hypogene mineralization, including the formation of the breccia pipe, was the result of the final crystallization of the igneous melt that formed the quartz monzonite stock and related dikes. The mineralization was the culminating event of an igneous sequence that probably began with the extrusion of the andesite that forms the caldera.

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