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CIRC. 549

COATS—ECONOMIC SIGNIFICANCE OF REVISED AGE RELATIONS OF ROCKS, CORNUCOPIA MINING DISTRICT, NEV.—GEOLOGICAL SURVEY CIRCULAR 549

GEOLOGICAL SURVEY CIRCULAR 549

Economic Significance of Revised Age Relations of Rocks in the Cornucopia Mining District Elko County, Nevada

thickness varied greatly from place to place due to deposition of the rhyolite and rhyodacite units upon an irregular surface. Hence, it is not possible to give a precise estimate of the throw of the fault on the northeast boundary (A in fig. 2) of the ridge block that lies south of the mine shafts. However, if the tuff of the rhyolite and rhyodacite unit, exposed west of the road in the west half of sec. 18, corresponds to the tuff exposed in the hanging wall of this fault, then the buried upper surface of the mineralized andesite may be only a few scores of feet below the present ground surface, and concealed veins may offer attractive exploration targets.

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Economic Significance of Revised Age Relations of Rocks in the Cornucopia Mining District Elko County, Nevada

By R. R. Coats

GEOLOGICAL SURVEY CIRCULAR 549

Revision of geological interpretation and inferred possible unmined extensions of silver ore bodies

Washington 1967

United States Department of the Interior
STEWART L. UDALL, *Secretary*

Geological Survey
William T. Pecora, *Director*

Free on application to the U.S. Geological Survey, Washington, D.C. 20242

of rhyolitic and rhyodacitic rocks. The lower unit of these rocks, which in some places can be seen to rest on the andesite, is a biotitic rhyolite ignimbrite, the basal part of which is buff unwelded tuff that grades upward into a reddish-brown welded phase. Because of lack of exposures the maximum thickness in the area is not known. The minimum thickness is about 30 feet—measured in an exposure just west of the place where the road passes over the saddle which is near the center of sec. 18, T. 42 N., R. 51 E. The ignimbrite is overlain, possibly unconformably, by a dark, partly glassy, pigeonite rhyodacite containing much xenocrystic material. This rock forms the summit of Silver Peak and the surface of the long north-trending ridge immediately south of the mine shafts shown on the map.

The relations of the volcanics of Silver Peak to the mineralized andesite are critically important to the interpretation of the geology. Because of the prevalence of faulting and the ready disintegration of the tuffaceous lower portion of the ignimbrite, exposures showing the depositional contact are few. The most accessible exposure is in some artificial cuts about 0.4 mile east and 0.45 mile north of the southwest corner of sec. 18. As the map reveals, faulting is prevalent in the Cornucopia area. Some of these faults display characteristics indicating that at least some of the movement on them is premineral; others may also be in part premineral, but either cut the mineral deposits, or displace the contact of the volcanics of Silver Peak and the mineralized andesite.

An example of a fault that is probably in part, at least, premineral is marked "B" in figure 2. At the time of my visit, it was reported by one of the persons engaged in exploration that the Leopard vein, which has been extensively worked under the mine dumps shown on the map, has been traced northward to the point where it is cut off by a silicified fault-vein trending northwest (B in fig. 2). A branch of this fault may be exposed in the portal of an adit on the south side of the gully that bounds the mined block on the north. The fault at the portal has a strike about N. 10° W. and dips about 70° southwest. It also shows extensive silification. If, as the silicification along it suggests, this fault, or these faults, are premineral in age, the likelihood of finding a continuation of the Leopard ore body northeast of them is not great, although ore is known to occur in that area.

The volcanics of Silver Peak may be observed in fault contact with the mineralized andesite in a series of cuts about 0.4 mile east of the southwest corner of sec. 18. The buff, poorly consolidated, tuffaceous phase of the ignimbrite forms the hanging wall of a fault (A in fig. 2) that trends northwest and dips from 36° to 60° southwest. The fault trace is marked by a brick-red gouge that contains fragments of quartz vein material up to 4 inches in diameter. In the gully to the east of this point, several cuts expose massive buff rhyolite tuff. Obscure bedding in the tuff dips west about 45°. This steep westerly dip is thought to be caused by drag on a normal fault that must pass just east of the cuts and follows the course of the north-trending gully.

The geologic evidence that suggests that the rhyolite and rhyodacite are postandesite is confirmed by the petrographic evidence. The buff tuffaceous lower part of the biotite rhyolite ignimbrite has a substantial content of clear unaltered sanidine phenocrysts, green euhedral biotite tablets, phenocrysts of quartz and plagioclase, and equant fragments of vesicular black glass. It is not likely that the biotite, sanidine, and glass would have survived unaltered while the adjacent andesite was being intensely propylitized and sericitized.

The lack of mineralization in the rhyolite and rhyodacite can thus be explained by the fact that they are younger than the andesite and the mineralization. The faults that separate the rhyolite and rhyodacite from the mineralized andesite in the mine area are postmineral; the entire ridge that lies southwest of the area of active mining is part of a block, downthrown with respect to the blocks lying to the north and east. As the available exposures suggest that the most important ore-bearing veins of the district are cut off by these postmineral normal faults, extensions of these veins may exist beneath the rhyolite and rhyodacite. Unfortunately, the thicknesses of the rhyolite and rhyodacite units are not well known both because an unknown amount of postdepositional erosion has occurred and because original

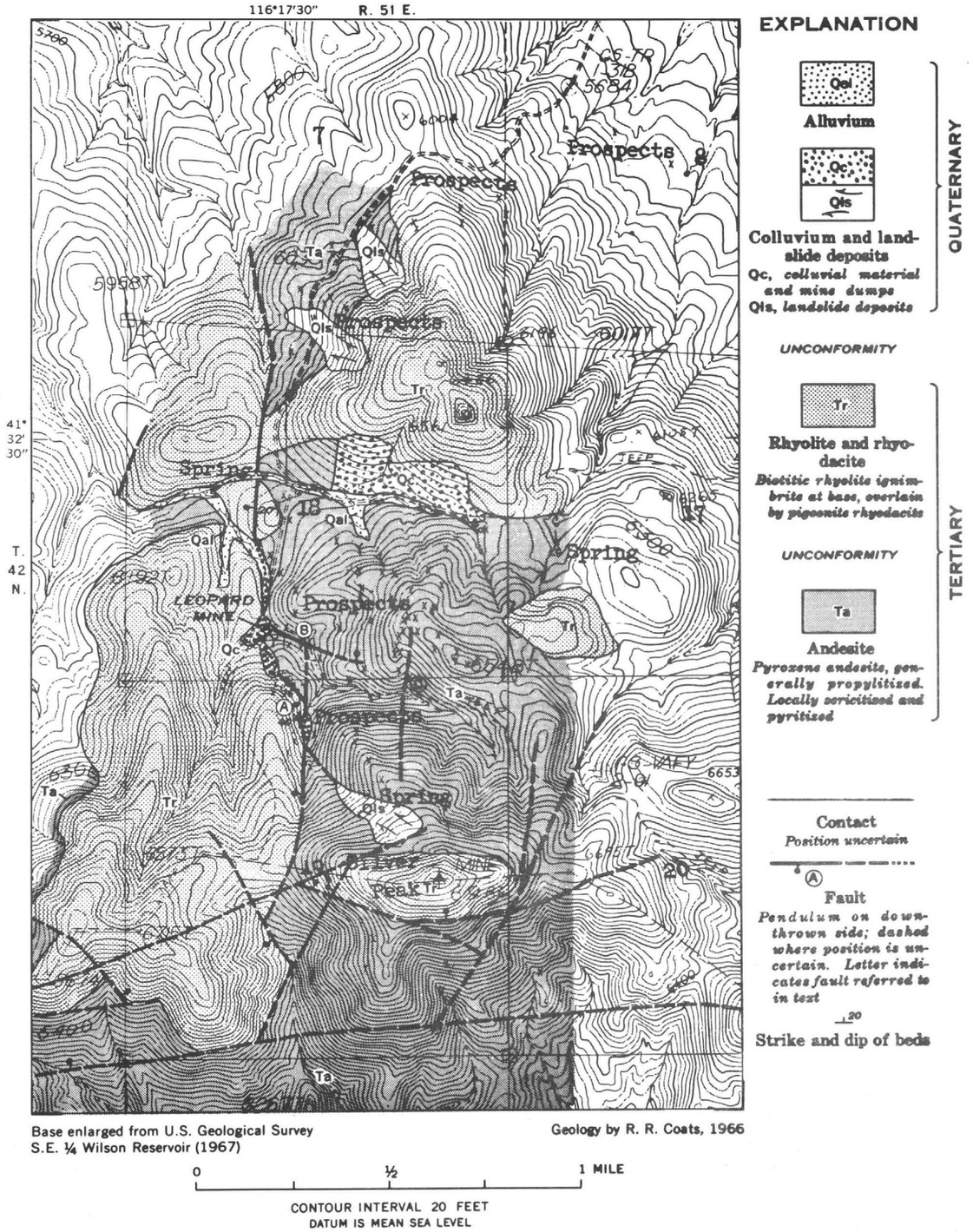

Figure 2.—Geologic sketch map of the Cornucopia mining district.

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ECONOMIC SIGNIFICANCE OF REVISED AGE RELATIONS OF ROCKS IN THE CORNUCOPIA MINING DISTRICT, ELKO COUNTY, NEVADA

By R. R. Coats

Abstract

Recent geologic work in the Cornucopia mining district, a small silver-gold mining district in northwestern Elko County, Nev., has resulted in significant revision of the geological interpretation. Rocks formerly thought to be premineralization in age, but unmineralized, are now known to be postmineral extrusives, resting unconformably on the altered andesite in which the ore bodies are found. Extensions of the known productive veins may be expected at shallow depth beneath the younger volcanic rocks, and are separated from the mined part of the veins by postmineral high-angle faults that have brought the younger volcanic rocks into fault contact with the mineralized andesite. Some veins are apparently terminated against premineral faults.

INTRODUCTION

The Cornucopia district is a silver-gold mining district in northwestern Elko County, Nev., (fig. 1). According to Granger, Bell, Simmons, and Lee (1957, p. 41) it has had a production of about $1¼ million in gold and silver, nine-tenths before 1883. The silver-gold ratio by weight for the latest production was about 68:1; earlier records are not adequate to permit an estimate of the ratio.

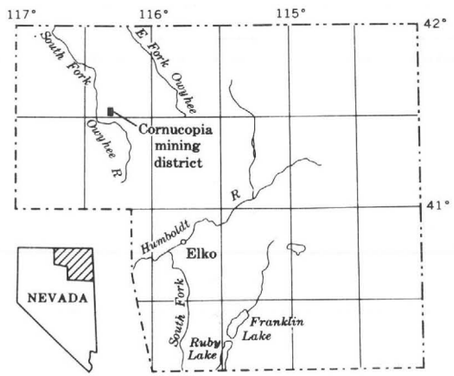

Figure 1.—Index map of Elko County, Nev., showing location of the Cornucopia mining district.

GEOLOGY

The only available geological information is a brief report by Emmons (1910, p. 63–65), who visited the district in 1908 after mining had ceased and when most of the workings were inaccessible. Emmons recognized that the ore deposits are in altered andesite and that the hills "in the main, are capped with rhyolite and obsidian." He described the rhyolite as having a "glassy, microlitic groundmass and phenocrysts of quartz, oligoclase, pyroxene, magnetite and a little hornblende." Some phases of the rhyolite were said to be vesicular and some pumiceous. Emmons noted that the accessible ore deposits are restricted to the andesite, but thought the andesite intruded the rhyolite.

The mines are no more accessible now than they were in 1908. In the course of a brief examination of the surface in 1966, I made the sketch map presented herewith (fig. 2). Fortunately, recent surficial prospecting disclosed critically important information on the rock relations.

The oldest exposed rock is the andesite in which the ore deposits occur. The fresher rocks examined in thin sections are pyroxene andesites. Most of the clinopyroxene is fresh augite; some patches of chlorite and nontronite appear to be pseudomorphs after orthopyroxene. More highly altered rocks are bleached and partly replaced by calcite, pyrite, and sericite. Some of these bleached rocks have nests of secondary quartz that simulate quartz phenocrysts in hand specimen.

The andesite and the mineral deposits that it contains are overlain unconformably by a series

hydrothermal solutions. The source of these solutions is, however, not so evident. It is commonly assumed that vein-forming solutions are given off as final consolidation products of granitic magmas and that the position and configuration of the magma chamber is of much genetic significance.[25] At Cornucopia no such control is manifest and there is no direct evidence of magmatic origin. Some small veinlets have been formed apparently as a product of recrystallization, and it is possible that some of the larger veins derived part of their quartz by this process of metamorphic differentiation. Although the gold quartz veins are distinctly later than the metamorphic and plutonic rocks, they probably belong to the final phase of metamorphism that was characterized by decreasing temperature; hence they may be considered as having been formed by retrogressive metamorphism. During this episode, despite the decrease in temperature, shearing still continued, affording the opportunity for the upward rise of the hydrothermal solutions, which were probably alkaline, as indicated by the sericitization of the wall rocks. These solutions also caused a considerable amount of carbonatization. Development of sericite and calcite in adjacent walls and included fragments gives evidence of these occurrences.

This type of alteration is found in numerous joint cracks, which commonly have the same structural attitude as the gold quartz veins; i.e., similar strike and dip. It is especially prominent near some of the larger veins, where it produces a veritable banded effect. The bands of alteration range from a fraction of an inch to more than an inch in width parallel to the central joint plane. Where they traverse granodiorite there is reduction in grain size and a marked pinkish coloration. In the darker colored, fine-grained hornfels the alteration border is much lighter in color, commonly exhibiting a silvery appearance due to sericite. These effects are accentuated along the contacts of the larger veins and in fragments of the wall rock within the veins, but since anastomosing veinlets from the main veins traverse and even intersect the altered zones without affecting them, it is evident that this alteration preceded the quartz-forming stage.

In the field these bands of altered rock might be mistaken for injected dikes but microscopic examination of appropriate thin sections reveals a gradual replacement of the original minerals by the alteration products, which are chiefly aggregates of sericite, carbonate and quartz where the walls are granodiorite, and sericite, chlorite and carbonate where the walls are hornfels. In the altered granodiorite it is not uncommon to find one side of a feldspar crystal completely altered and the other side quite fresh. The aggregate of alteration minerals merges from one crystal to another so that only the faintest outlines of the original feldspars are discernible. The original quartz is attacked and partly replaced by quartz that has either been introduced with the hydrothermal solutions or, in part at least,

AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS

Technical Publication No. 1035

(Class I, Mining Geology, No. 85)

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Geology of the Gold Quartz Veins of Cornucopia

By G. E. Goodspeed,* Member A.I.M.E.

(New York Meeting, February, 1939)

The Cornucopia gold quartz veins form a parallel vein system traversing metamorphic and granodioritic rocks. Field and petrographic evidence suggests that metasomatism has played an important role both in the emplacement of the granodiorite and in the formation of the veins. Structurally the veins appear to be related to the major tectonic features of the Wallowa Mountains and to be narrow shear zones rather than filled fissures. Petrographic studies indicate a complex history of formation starting from initial alteration along fractures or joints followed by recurrent fracturing and a quartz-forming stage, and closing with continued shearing and microbrecciation, which permitted the upward percolation of the later ore-forming solutions. The precipitation of ore minerals from these solutions formed ore shoots. Postmineral effects include the injection of Tertiary basaltic dikes, a slight amount of cross faulting, and some movement along the planes of the veins as well as oxidation.

Introduction

Cornucopia is in the southeastern part of the rugged Wallowa Mountains of northeastern Oregon. It was founded over 50 years ago following the discovery of its system of gold quartz veins. The major veins are roughly parallel and dip into the western side of Pine Valley, which drains the southern slope of the range. Previous operations had cut the upper portion of four major veins with two tunnels over 1000 ft. apart, when the present operating company drove a third tunnel, called the Coulter, at the level of the valley over 1000 ft. lower to intersect the most easterly major vein at over 6200 ft. from the portal.

General Geology of District

The oldest rocks in the vicinity are metamorphosed sediments and volcanics. These, for the most part, are presumably Mesozoic in age, although some black argillites outcropping along East Pine Creek are considered to be Permian.[1,2] These rocks have been deformed and metamorphosed in general to hornfels at the close of the Jurassic. The series was then invaded by a granodiorite batholith, the origin of which is

Manuscript received at the office of the Institute Dec. 1, 1938.

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[1] References are at the end of the paper.

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Mining Technology, March, 1939. Printed in U. S. A.

attributed by the writer essentially to metasomatic replacement rather than to the intrusion of a liquid silicate melt. The associated major veins have developed from hydrothermal action on planes of recurrent fracture. This region was then subjected to a general uplift and subsequent erosion. In some of the deeper canyons, such as that of the Snake River, the old surface is visible beneath the Columbia River basalt, and shows the development of a mature topography with a relief of about

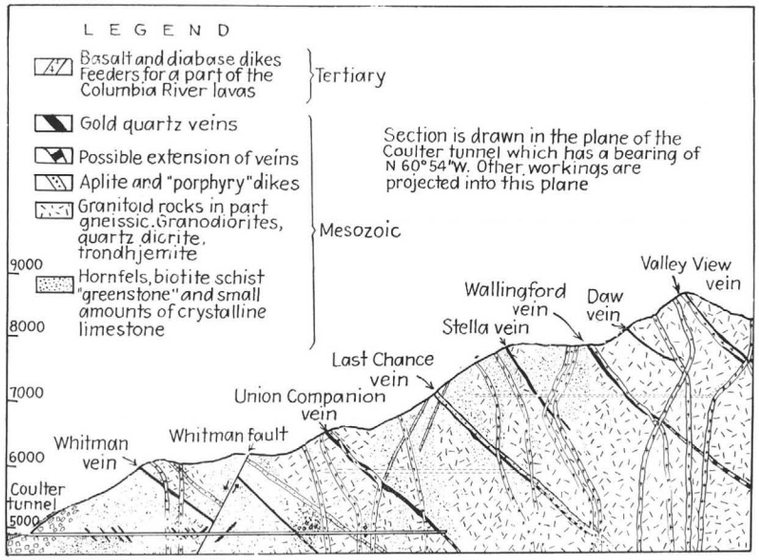

FIG. 1.—GENERALIZED GEOLOGIC CROSS SECTION, CORNUCOPIA, OREGON.

3000 ft. The Wallowa Mountains are locally capped by basaltic lavas, and their present elevation is definitely due to faulting.

CHARACTERISTICS OF THE METAMORPHIC SERIES

Although many facies of metamorphic rocks occur within a few miles of Cornucopia, hornfels, schistose hornfels, and biotite schists predominate locally. (Figs. 2 and 3.) Highly siliceous hornfels may contain small quartz porphyroblasts, while the more basic hornfels (locally called greenstone) are characterized by variable but conspicuous amounts of epidote, chlorite diopside and garnet.[3] Quartz-garnet-diopside veinlets are common in certain parts of the hornfels.[4] In texture most of the hornfels are very fine grained, but where extensive feldspathization has taken place, they approach the texture of a granulite (Fig. 4). Some of the transitional facies have the appearance of a porphyritic igneous rock, but the microscope clearly shows that the plagioclase crystals are porphyroblasts and not phenocrysts.[5] Most of the hornfels are

become imbricated. These features were interpreted by some early observers as the ending of the veins. Some of the offsets are joined by short connecting veins. Such a condition was recently found on the north 2000 drifts of the Union Companion vein (Fig. 7). These connecting veins are in the nature of large gash veins and as such they represent filled fissures and apparently have not been subjected to extensive shearing.

From a structural standpoint all of the major and minor veins of Cornucopia appear to be in reality narrow shear zones. Slickensides, gouge and fractures both in the veins and in the contiguous wall rocks, as well as definite petrographic evidence of microbrecciation, prove that movement in the veins continued during the time of their formation, and contributed to the irregularity of the lenses.[24] Grooves in slickenside surfaces indicate that a distinct change in direction of movement took place during vein formation. The earlier slipping appears to be in the direction of the dip; some of the later grooves have a rake to the south.

Some of the Cornucopia veins are situated near the southeastern border of an irregular granodioritic mass and some are in nearly the central part of the granodiorite. This granitic mass is about four miles in a northwest-southeast direction and three miles in a northeast-southwest direction. The strike of the veins is parallel to anticlinal and synclinal axes in the older rocks of this part of the Wallowa Mountains. In the vicinity of Cornucopia there are a multitude of shear planes in the hornfels and schist as well as in the granodiorite, and the veins are parallel to these planes.

Some of the Cornucopia veins have parallel branch veins, which do not seem to have been sheared as much as the main vein. The veins of the Red Jacket mine that belong to the Union Companion system might be cited as an example of this branching. These branch veins were probably formed nearer the existing surface than the other veins. Under such conditions it might be expected that lessened rock pressure would favor the opening of parallel fractures and fissures in addition to the main zones of shearing.

The salient features of the field relations of the Cornucopia veins are shown in the generalized geologic cross section (Fig. 1). This section is constructed on the plane containing the Coulter tunnel with the Clark adit and the Lawrence tunnel projected into this plane. As shown in the section, an inclined raise was driven from the Clark-adit level to the upper levels of the Last Chance mine. A winze has also been driven for 100 ft. or more below the Coulter-tunnel level on the Union Companion vein. Both the Union and Last Chance veins have been drifted on for several thousand feet on various levels.

FORMATION AND METALLIZATION OF THE QUARTZ VEINS

All evidence, both field and petrographic, points definitely to the assumption that the Cornucopia gold quartz veins have been formed by

percolation of the surface waters. Some of the joints become veritable water courses, as do also portions of some of the quartz veins.

General Field Relations of Cornucopia Veins

The Cornucopia veins appear to be structurally related to the major tectonic features belonging to the late Mesozoic orogeny. Of these the westerly dipping shear planes have exercised the principal structural control, although some of the smaller veins follow the subsidiary eastward-dipping complementary fissures. At Cornucopia the important veins, beginning with the most eastern one, are: Whitman, Union Companion-Red Jacket, Last Chance, Wallingford and Valley View. These veins are 1500 to 2500 ft. apart, and have in general a strike of N. 40° E., and a dip

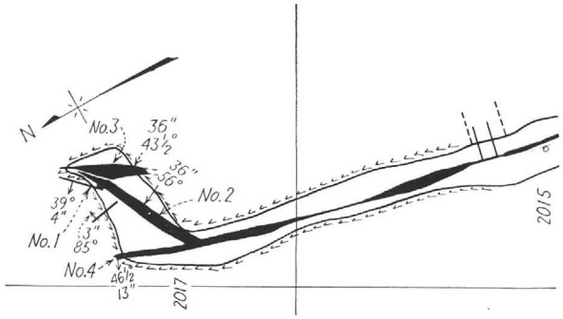

Fig. 7.—Offset in Union Companion vein 2000 drift north.
Specimens 1, 3 and 4 exhibit microbrecciation while No. 2 does not. The connecting vein with an easterly strike (No. 2) probably represents a filled fissure while the main veins are of the cataclastic shear type.

of 40° W. All the veins are irregularly lenticular, in some places very narrow, practically a gouge seam, and at others several feet wide. To date the greatest thickness has been encountered on the Union Companion, where several places show widths of from 8 to 10 ft. Some of the lenses in the Cornucopia veins are long and tabular, while others are more abrupt. Structurally these veins appear to be similar to the larger veins, but on a smaller scale.

Some of the Cornucopia veins, as now exposed by erosion and by mine workings, are entirely within the granitic rock, some are within the hornfels and schists, and others traverse remnant masses of these rocks in the granitic rock. Most of the upper workings of the Last Chance vein are in hornfels and schist; granodiorite is the prevailing wall rock in the lower workings. In many places this vein consists of two veins, one on the hanging and one on the footwall of a 30-ft. aplite dike.

The veins that have been developed along the strike for considerable distances commonly exhibit a sort of en echelon offset every 500 or 1000 ft. The offsets are usually about 20 to 30 ft., and at these points the veins

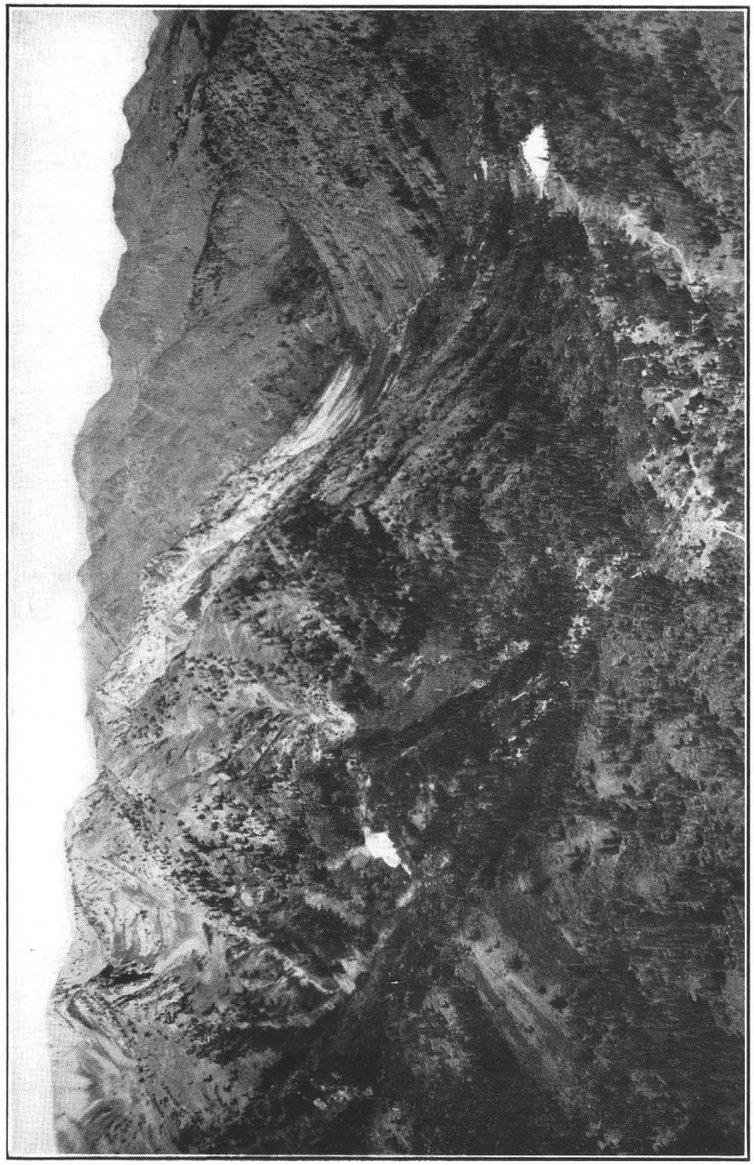

Fig. 2.—General view of Cornucopia, Oregon.
Hornfels and biotite schist are the predominant dark colored rocks excluding the basalt dikes, which show in the photograph as irregular dark bands. Note scattered irregular patches of grayish rock transitional between hornfels and the light colored granodiorite.

impregnated with iron pyrite, so that they are stained a brownish color by surface weathering. Schistosity, many joint planes, and local brecciated zones testify to the shearing stresses accompanying the

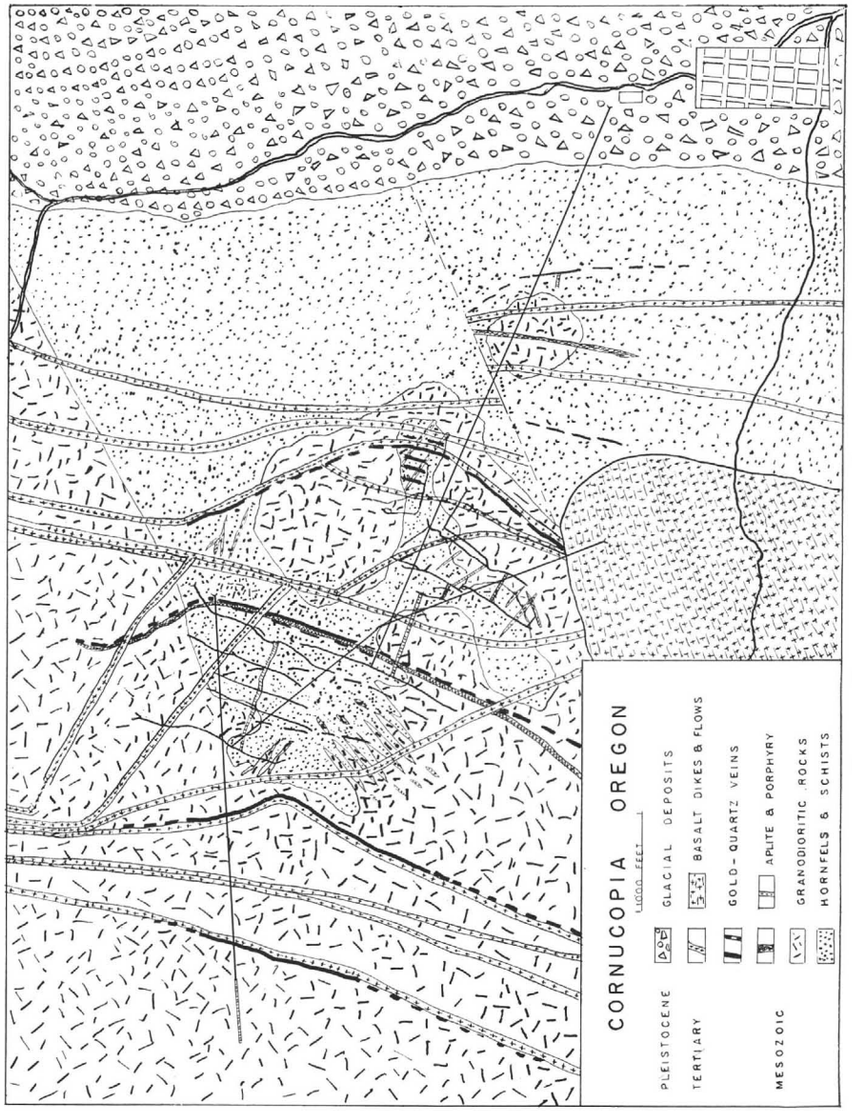

FIG. 3.—SURFACE GEOLOGY AT CORNUCOPIA.

late Mesozoic orogeny. Field and microscopic evidence also indicates that the original material has been changed, in places very considerably, by additive metamorphism.

BASIN RANGE STRUCTURE

After the successive outpourings of basalt, this region was subjected to block faulting similar to that in the Basin Range. Some of these faults had displacements of perhaps as much as 5000 ft., and are reflected in the present-day topography.[23] Pine Valley is a typical fault valley and the fault-line scarps are evident.

A very well marked normal fault was observed in the Coulter tunnel. Its position indicates that the upper part of the Whitman vein is on the downthrow side and the fault plane probably cuts the vein just above the level of the Coulter tunnel. What appears to be the vein in the upthrow portion of the fault was intersected by the tunnel 4000 ft. from the portal. If this is the Whitman vein on the upthrow side of the fault (and petrographic evidence appears to substantiate the field observation) the movement along this fault plane has been about 800 ft. Although probably much greater displacements have taken place in this region, yet in the Cornucopia mines, with the above exception, the amount of postmineral dislocation as at present disclosed has been only a few feet.

After these presumably late Pliocene dislocations, the uplifted blocks were subjected to extensive stream erosion culminating in the Pleistocene with severe mountain glaciation. Numerous erosional and depositional features incident to alpine glaciers are to be found in the Wallowa Mountains. Many of the steep-walled U-shaped glacial valleys have afforded excellent geological cross sections, and at Cornucopia have exposed some of the gold quartz veins for a considerable extent along both their dip and their strike. The southern slopes of some of the mountains have a mantle of weathered material, while the deep cirques and glacial valleys have been carved in unweathered rock.

WEATHERING

Since the Pleistocene, the amount of surface rock weathering has been relatively slight except where there has been an abundance of easily decomposed minerals such as sulphides. Some of the hornfels have been stained brown by limonite derived from disseminated pyrite, and the outcrops of the gold quartz veins are oxidized. On most of the veins there is an irregular downward penetration of oxidation for several hundreds of feet and in some of the veins narrow oxidized zones are found at a depth of over 2000 ft. from the outcrop. The water courses formed by the sheared veins readily permit the draining of ground water from the surface, which is 1500 ft. or more above the valley floor.

The yearly precipitation at Cornucopia is about 45 in., a large part of which is in the form of snow. Although the soil mantle is meager, the numerous joints in the rocks provide ample opportunity for the downward

Columbia River Basalt

During the Tertiary, and particularly during the Miocene, this region was subjected to profound tensional fracturing, and was traversed by many prominent fissures, which followed in part the existing planes of structural weakness. Through these fissures, many of which were from 40 to 50 ft. wide and several miles long, poured out floods of hot basaltic lava in a series of widespread flows known as the Columbia River basalt. The aggregate thickness of these flows was several thousand feet, enough to completely cover the old mature land surface. At Cornucopia the dike feeders for the basalt flows are especially well exposed and form distinctive surface features, particularly where the dark basalt is in striking contrast to the light colored granodioritic rocks. Since the dikes follow planes of weakness, their course has been controlled by the gold quartz veins, especially when approaching the old land surface. Near this surface they may also follow a system of conjugate jointing and so have variable dips. At greater depths, as shown in the lower workings of the mines, the dikes are more nearly vertical, indicating that the increasing load nullified the joint control.

Where the dikes intersect the veins at other than a right angle, the veins are offset because of the dilation of the dike fissure. Therefore, in development work it is in general necessary to drive across a dike at right angles to the strike of the dike. Since actual dike contacts may be irregular; the recognition of columnar structure at right angles to the dike wall is of considerable practical aid.

The Tertiary basaltic dikes at Cornucopia may be placed in two groups, an earlier one, which is diabasic in character, and a later one distinctly basaltic. The outcrops of the diabasic rocks show rounded surfaces due to spheroidal weathering, while the finer grained basaltic dikes appear to be more resistant. Columnar structure is also more evident in the basaltic dikes. It is not unusual to find compound dikes.

Although the temperature of the basaltic lava was probably about 1000° C.,[21] the extent of optalic metamorphism is not great. Probably the quickly chilled selvedges acted as an insulating medium. However, where dikes of sufficient size were injected parallel to the gold quartz veins, the heat was sufficient to change pyrite to pyrrhotite. This is especially noticeable on some of the upper levels of the Union Companion vein. Along the bottom of a basalt flow, as exposed in the intermediate or Clark adit, detrital quartz from the Union Companion vein has been picked up by the quickly chilled lava. The wash from the vein may well have been in some old creek bed, since the alteration products suggest aqueous chilling.[22] Assay of this material shows some gold content, due to contamination.

Relation of Hornfels and Granodiorite

In the Coulter tunnel there are zones of brecciated hornfels that appear to have been partly replaced by granodioritic material in irregular block-like forms.[6] Here metasomatic action was apparently intensified in local patches of finely crushed material. The angularity of the granodioritic blocks was due presumably to the margins of the more resistant larger fragments of hornfels. The borders of these blocks are in part sharp and in part gradational into the hornfels. Some of the blocks exhibit veinlike extensions of the granodiorite into the hornfels, and some contain delicate undisturbed inclusions of hornfels, which still retain

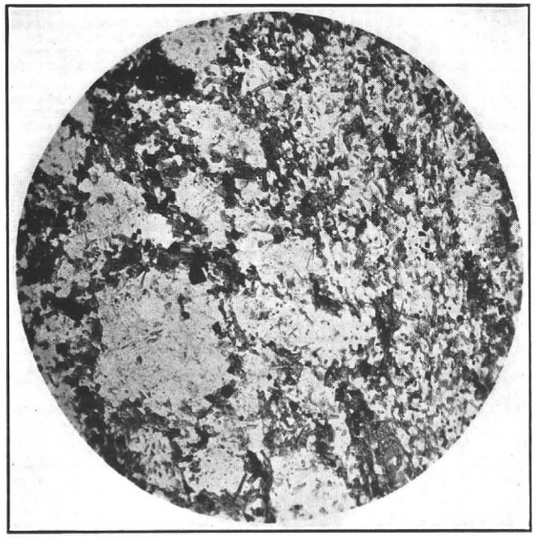

Fig. 4.—Partly feldspathized hornfels.

original structures. Alternative hypothesis of magmatic injection or of faulted granitic bodies are not in harmony with all the facts. The lack of crushing within the blocks, and the lack of chilled borders or evidence of flow structure, coupled with the positive evidence of crystalloblastic extension of plagioclase along some of the contacts, suggest the mechanism of metasomatism (Fig. 6).

Although striking in appearance, such occurrences are not as common as replacement dikes and replacement breccias.[7] Such features might casually be interpreted as ordinary dilation dikes or as swarms of xenoliths that became included in a hot, liquid magma. However, they exhibit many characteristics that point definitely to a gradual process of granitization rather than to the solidification of a hot liquid melt (Fig. 5).[8]

At Cornucopia, transitional hornfelsic granodioritic facies are so common, and the field and petrographic evidence so abundant and con-

clusive, as to warrant the suggestion that most of the granodioritic rocks have been formed as the end stage of progressive metamorphism.[9] The

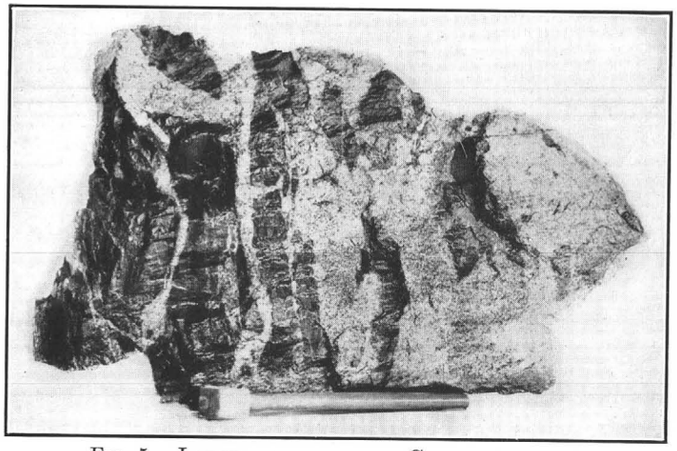

FIG. 5.—LARGE SPECIMEN FROM COULTER TUNNEL.
Note gradual transition from dark hornfels to light colored granodioritic rock. Numerous parallel stringers of "porphyry," of which the phenocrysts are in reality porphyroblasts accompanying an initial stage of metasomatic replacement while the phantomlike shadows of hornfels inclusions mark a later stage of granitization.

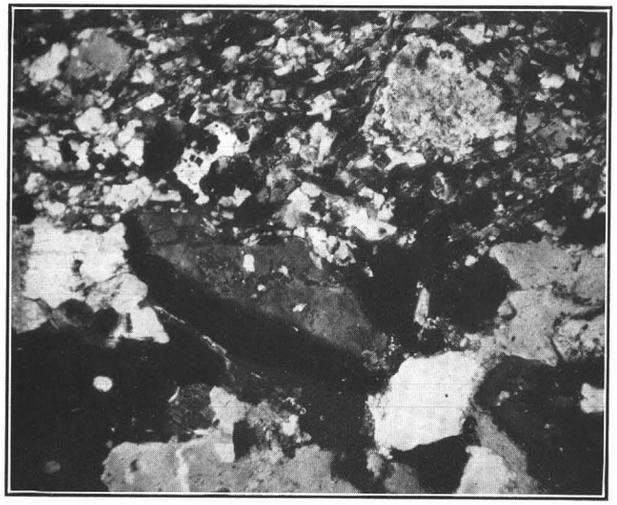

FIG. 6.—CONTACT BETWEEN GRANODIORITIC BLOCK (LOWER HALF OF CUT) AND HORNFELS.
Note incipient feldspar porphyroblast in hornfels and inclusion of hornfelsic material within and around feldspars of granodioritic block.

usual interpretation for the emplacement of a granitic batholith is based upon the assumption that the granitic rock crystallized from a hot, liquid silicate melt or magma.[10] However, it has been shown recently that in

some batholiths replacement processes may play a most important role.[11–16] In England, also, the origin of certain plutonic rocks has recently been ascribed to metasomatic processes.[17]

ORIGIN OF APLITES AND QUARTZ VEINS

From the standpoint of the origin of ore deposits, the genetic relation of metamorphic differentiation instead of magmatic differentiation should be stressed.[18] Several years ago, it was noticed that some small quartz veinlets apparently were found as the product of the recrystallization of a xenolith.[19] The formation of quartz as a released mineral incident to recrystallization processes may perhaps give a clue as to the source of part of the quartz associated with the later hydrothermal solutions.

Regional field evidence indicates that shearing stress was prevalent preceding, concomitant with, and succeeding granitization. Some facies of the hornfels are veritable crush breccias and cataclasites. In some of these sheared rocks, fracturing, solution, replacement, and recrystallization have had varied sequences. In general the interlocking decussate texture of the granulites or the hypidiomorphic granular intergrowth of the granodioritic rocks does not appear to have favored the innumerable shear planes that characterize some of the hornfels and schist. Instead, these even-grained rocks have broken along either single planes of shear or narrow zones of very closely spaced shear planes.

The rise of hydrothermal solutions along these shear planes appears to have produced various effects. In the field, all gradations may be seen from mineralized fracture planes to quartz veins or aplite dikes. Hydrothermal origin has recently been suggested for some aplites in Ontario.[20] In like manner, at Cornucopia these dikes, even when of considerable magnitude, appear to be definitely formed by replacement rather than by magmatic origin. This is indicated by the fact that the dikes include locally undisturbed remnants of schist or hornfels, and have failed to cause an offset in the structural features of the wall rock. Petrographic examinations of the marginal contacts of the dike substantiate this conclusion, for the irregular penetration of the crystals of the dike into the wall rock indicates crystalloblastic encroachment.

The field evidence at Cornucopia strongly suggests that the gold quartz veins are genetically associated with the later or retrogressive phase of the intensive hydrothermal metamorphism to which the granodiorite is genetically related. They appear essentially to be due to replacement along lines of fracture that developed in the closing stages of late Jurassic orogeny. The quartz veins formed brittle zones of weakness, which controlled subsequent movements. The recurrent fracturing permitted the continued rise of the hydrothermal solutions.

has been a product of the alteration reactions. Studies of the Mother Lode veins of California have in fact suggested that most of their quartz has been derived from the wall rocks by the latter procedure.[26] In either case, however, there has been an increase in the actual amount of quartz.

The mechanism of formation of gold quartz veins has been given many interpretations, but perhaps the most common is that of a filled fracture or true fissure vein.[27] There are many gold quartz veins for which this interpretation is wholly adequate; but certain quartz veins, especially those of great lateral and vertical extent, exhibit evidence that is definitely against such an interpretation. The Cornucopia gold quartz veins are in this category. It is very difficult to reconcile the interpretation of fissure filling with such features as: the extension to depth at a relatively low angle, the multiplicity of slickensides and slipping planes, and the petrographic evidence of microbrecciation.[28] On the other hand, the presence in the vein of long, thin inclusions of the wall rock, the gradational contacts with the quartz of these inclusions and of the walls themselves, suggest metasomatic replacement processes as the most applicable mechanism. It has been maintained by some that unsupported inclusions denote the actual injection of a viscous ore magma, so that quartz veins would really be vein dikes.[29] Some of these inclusions, however, are 15 to 20 ft. long, with a maximum width of 3 in. Even where they thin down to a fraction of an inch, these elongated inclusions show no evidence of being distributed by magma flow. This fact should be sufficient to disprove the magmatic hypothesis without the petrographic evidence such as the lack of a chilled border and the presence of relics in all stages of replacement from actual rock fragments through partial silicification to complete replacement with but a mere ghost of the fragment.

The zones of alteration adjacent to the larger veins usually exhibit a coarse network of lenticular joints, which locally are followed by minute veinlets of quartz. They also, however, may contain as gouge, kaolinitic and sericitic material, surrounding cores of highly altered rock. These minor veinlets often enlarge to segregations, which increase in size and number as the vein is approached. The vein itself may contain a network of lenticular joints that have a close resemblance to the joints in the altered zones. Many of these joints within the quartz vein contain gouge, kaolinitic and sericitic material, which appears to have been derived from remnants of the initial alteration stage of vein formation.

Petrography of the Quartz Veins

One of the most noticeable microscopic characteristics of the vein quartz is a pronounced turbidity due to inclusions formed of very finely divided material and minute vacuoles. The vacuole inclusions are from 0.05 to 0.001 mm. in diameter; some with angular boundaries may be considered negative crystals; others, however, are rounded, amoebalike

or tubelike in form. Vacuole inclusions locally extend from a partly replaced mineral into quartz, hence their formation may be connected with replacement processes. The concentration of the finely divided included material is commonly defined by an angular outline suggesting a ghost-relic of an original rock fragment, which is in contrast with the clearer later quartz.

Another striking microscopic feature of the Cornucopia vein is that of microbrecciation. This may be in the form of a miniature angular brecciation or it may take the form of minute shear fractures accompanied by recrystallization of the quartz to a finer grain. The usual lack of turbidity in the zones of microbrecciation may result from the filling of vacuole-inclusions by later quartz. In addition to later quartz, calcite and later ore minerals are found in zones of microbrecciation. The shearing stresses that produced the microbrecciation were particularly effective on a brittle mineral like the earlier pyrite. In some of the veins this mineral has been so crushed that it crumbles readily to very small fragments.

Ore Minerals

Successive stages of microbrecciation permitted the continued passage of hydrothermal solutions, which cemented the fragments (Fig. 8). Under suitable physical-chemical conditions the metallic salts of these hydrothermal solutions were precipitated as later ore minerals. In general their paragenesis beginning with the earlier formed mineral is: earlier pyrite, sphalerite, galena, later pyrite, chalcopyrite, tetrahedrite, tellurides and native gold. Idiomorphism is a distinguishing feature of later pyrite. Probably the two main factors causing the precipitation of the later ore minerals were decrease in temperature consequent upon the upward rise of the solutions and the chemical effect of the earlier minerals. Petrographic studies show that these ore minerals replace the earlier quartz and the earlier pyrite. Inclusions in the quartz may have had some bearing on the precipitation. Some thin sections show what appears to be a vacuole by vacuole advance of later ore minerals through earlier quartz adjacent to fractures and zones of microbrecciation. The replacement of the earlier pyrite ranges from incipient filmlike coatings along minute fracture planes to a complete change of the earlier mineral to the later one. That such changes have taken place is proved by the crystallographic form inherited from the earlier mineral and by relics of the earlier mineral. Sections of the veins indicate that physical-chemical conditions may be quite complex, as, for instance, the dissolving of earlier quartz by later sulphide solution and at the same time the release of later quartz as a product of the reaction. This may be due to slight changes in the hydrogen-ion concentration of the solutions.[30]

Tellurides have been found in many of the Cornucopia veins and in greatest amounts in the Red Jacket and Last Chance veins.[31] Hessite, petzite and sylvanite have been identified, a most common occurrence being an intimate intergrowth of hessite and petzite with a little sylvanite and some free gold. These minerals have been the last to form and replace the earlier sulphides. They favor zones of microbrecciation and are associated with later quartz, calcite, and sometimes chlorite. In the Red Jacket mine and in the upper levels of the Last Chance mine they form bunches or pockets several inches in diameter, but of irregular distribution (Fig. 9). Although they are most characteristic of the upper

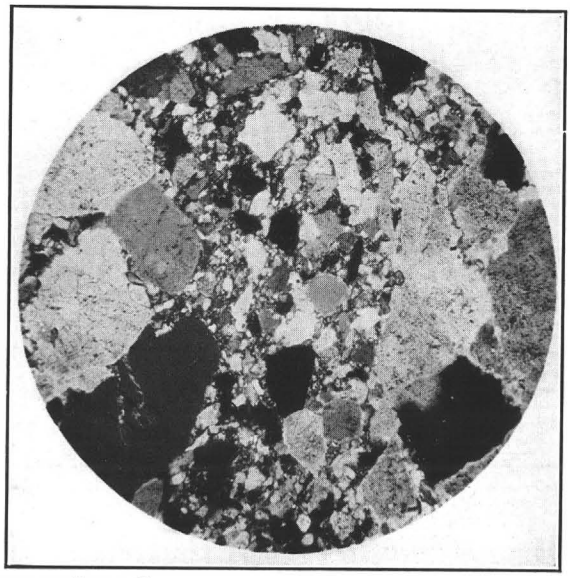

FIG. 8.—SECTION OF LAST CHANCE VEIN SHOWING ZONE OF MICROBRECCIATION AND RECEMENTATION BY LATER QUARTZ.

portions of the veins, they have a range of over 2000 ft. below the outcrop in the Last Chance vein. Near the surface the tellurides are commonly oxidized to tellurite and the gold-bearing ones furnish a mustard colored secondary gold.

Pyrrhotite is common on the 300-ft. level below the Clark adit. In an earlier paper this was interpreted to signify higher temperature conditions of vein formation and it was expected that pyrrhotite would be one of the dominant ore minerals at depth. But when the Coulter tunnel intersected the Union vein on the 2000 level, pyrite and tetrahedite with some galena and sphalerite were found to be the dominant ore minerals, and pyrrhotite was absent. However, during subsequent development some pyrrhotite was found adjacent to a basalt dike. Moreover, this pyrrhotite had the crystallographic form of pyrite. It is assumed therefore that the pyr-

rhotite in this vein was formed by optalic metamorphism caused by the heat of the basalt dike. In all probability the same deduction will hold true for the upper levels of this vein, since that portion is paralleled by a basalt dike.

In general, however, the ore and gangue minerals place the Cornucopia veins in the upper mesothermal zone, although some of the upper veins such as the Red Jacket may be considered as leptothermal.[32,33] Structurally the veins occupy shear planes, which are in alignment with the tectonic features belonging to the late Mesozoic orogeny. Their characteristic microstructure is cataclastic. This microstructure is not

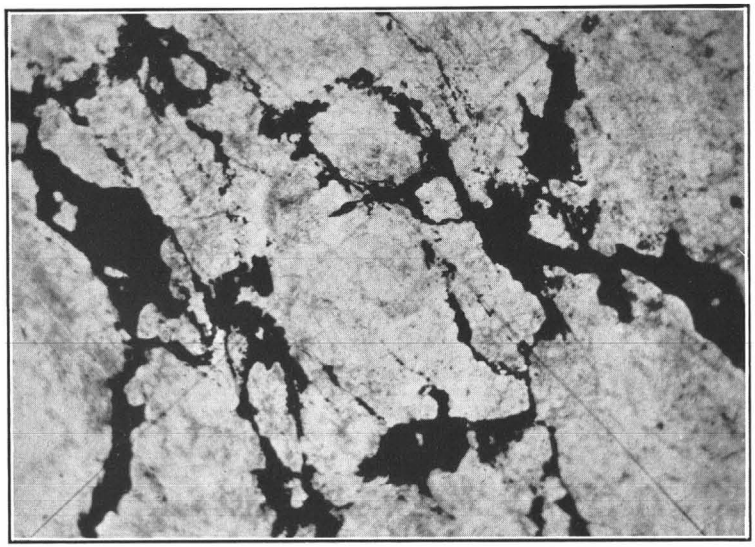

FIG. 9.—SECTION OF RED JACKET VEIN, SHOWING TELLURIDES IN ZONE OF MICROBRECCIATION.

present in some of the connecting gash veins, which are of limited extent. Such gash veins, although belonging to the same hydrothermal zone as is indicated by their mineralogy, might be termed *aclastic* in contrast to the *cataclastic* veins of great lateral and vertical extent.

The upper portions of the Cornucopia veins are extensively oxidized for about 500 ft. below the outcrop, while at great depths some of the more fractured portions of the veins show the effect of supergene alteration. Portions of the Last Chance vein over 2000 ft. below the outcrop are partly oxidized. Limonite is the chief supergene product, although some malachite and sooty chalcocite have been found. Since the highly fractured portions of the vein usually bear the best values, the oxidation to which they are susceptible is sometimes a reliable guide in locating ore shoots.

Summary of Formation and Metallization of Veins

1. Alteration, sericitization and carbonatization along joints or lines of fracture preceding the quartz-forming period.

2. Continued fracturing and shearing, especially along the closely spaced joints, permitting a continuous flow of solutions and a gradual replacement of the altered material by quartz, or a filling of open fractures which for the most part were probably of very small dimensions.

3. The formation of ore shoots by the recurrent fracturing and shearing of relatively large masses of brittle quartz and a continued upward penetration of hydrothermal solutions through zones of microbrecciation as well as through actual fractures and shear planes, enabling the ore-bearing solutions to come into intimate contact with the earlier formed minerals.

4. Postmineral effects include the intrusion of Tertiary basaltic dikes, a slight amount of cross faulting, and some movement along the planes of the veins as well as oxidation.

Conclusions

The recurrent fracturing of the veins is the essential characteristic that suggests their persistence to depth. This conclusion has been substantiated by the low-level Coulter tunnel, which was driven over 6000 ft. to intersect the Union Companion vein on the 2000-ft. level. At this level the cataclastic nature of the vein is even more evident than it is in the upper levels, with no diminution in average width. Hence it is expected that the other major veins of similar character will have a comparable downward extension. In contrast to the accuracy of these long-range predictions, it is very difficult to be sure of the size and shape of an irregular lenticular ore shoot. For this reason, a large number of working faces are necessary to ensure continued profitable operations.

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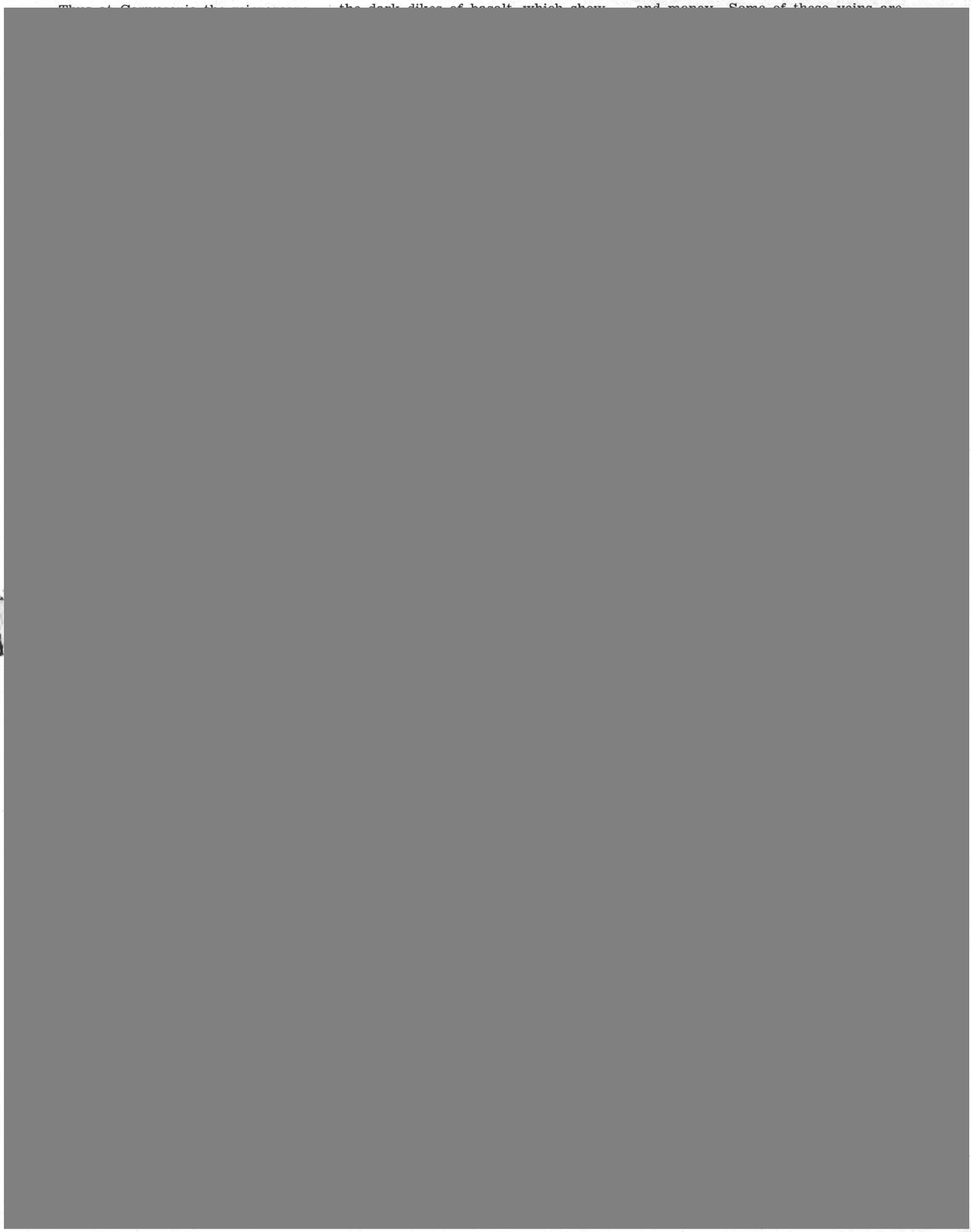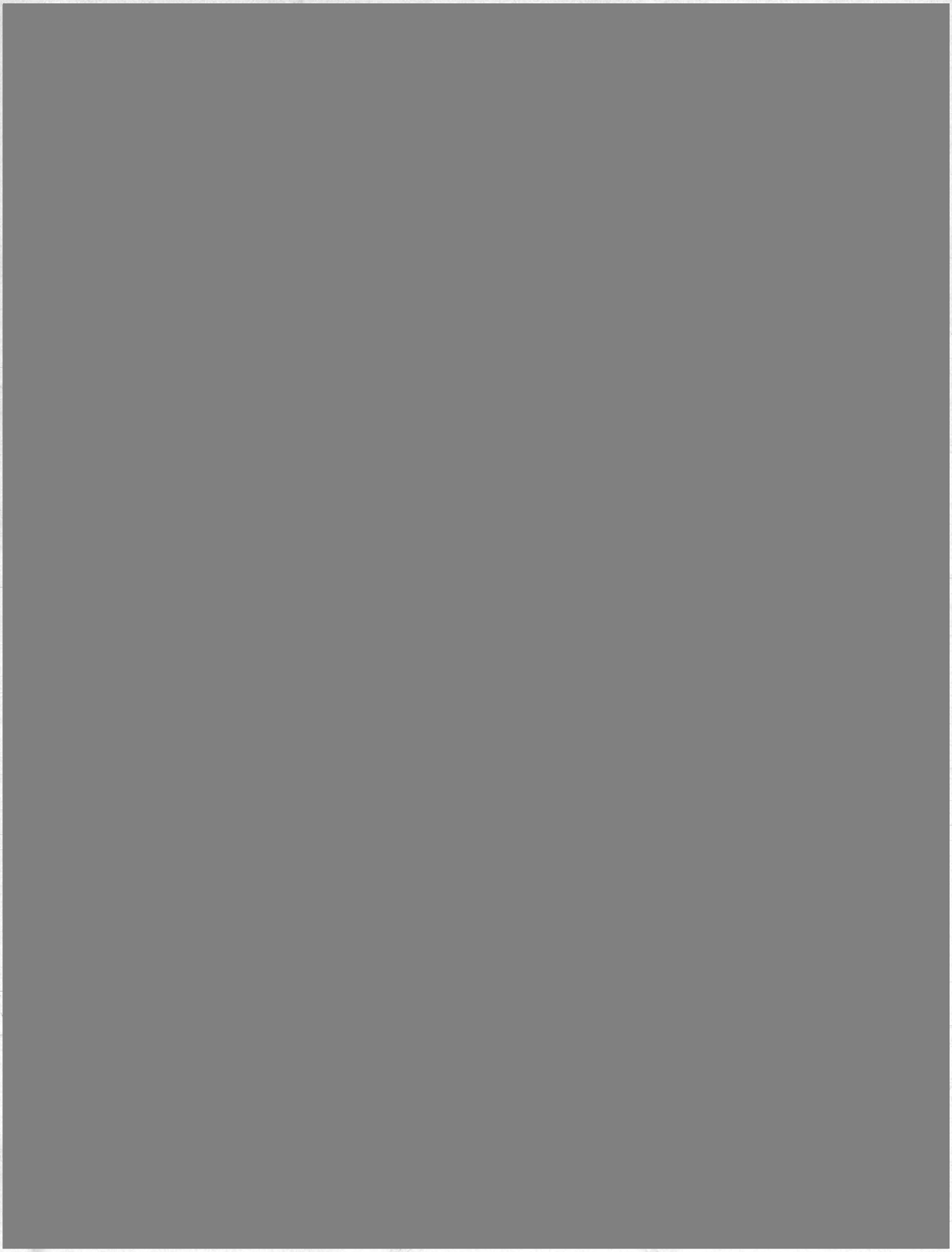
How Microscope Keeps Cornucopia on the Ore