The Geology and Ore Deposits of the Bully Hill Mining District, California

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DISCUSSION OF THIS PAPER IS INVITED. It should preferably be presented in person at the New York meeting, February, 1914, when an abstract of the paper will be read. If this is impossible, then discussion in writing may be sent to the Editor, American Institute of Mining Engineers, 29 West 39th Street, New York, N. Y., for presentation by the Secretary or other representative of its author. Unless special arrangement is made, the discussion of this paper will close Apr. 1, 1914. Any discussion offered thereafter should preferably be in the form of a new paper.

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BY A. C. BOYLE, JR., LARAMIE, WYO.

(New York Meeting, February, 1914)

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I. Introduction

The geological field work of the Bully Hill district, upon which this paper is based, was begun July 1, 1908, and covered a period of three months. The time was found too short for a complete report and the district was again visited in the early part of July, 1912, from which time detailed study of the locality continued until September of the same year. This paper is the result of observations made in the mines in the immediate vicinity of Winthrop, Shasta county, Cal., during these two periods of study.

The preparation of this report has been greatly facilitated by various courtesies rendered the writer by D. M. Riordan, President of the Bully Hill Copper Mining & Smelting Co., and by John B. Keating and Herbert R. Hanley, managing officers actively in charge at the mines. The elaboration and further study of the notes and collections were carried on in the laboratories of the Departments of Geology and Mining at Columbia University, and the writer takes pleasure also at this point in expressing his acknowledgments to Profs. James F. Kemp, A. W. Grabau, Charles P. Berkey, and William Campbell, for advice and assistance.

In order that one may appreciate at first reading the significance of some of the details which follow, and for the sake of clearness, a brief outline of the geological relationships is here given, together with certain conclusions which have been reached regarding the genesis of the ores and the gypsum masses.

In the Bully Hill mining district an associated series of Triassic lavas and tuffs, chiefly andesites, is preceded as well as followed by sediments. The entire system is tilted so that the original bedding planes dip in general to the southeast. The surrounding region has been greatly disturbed, and in the immediate vicinity of the mines close folding of the later sediments and extreme shearing of the igneous rocks locally is a striking feature.

Into the nearly vertical shear zones have been intruded post-Triassic dikes of various rock types in the following order: alaskite-porphyry and andesite-porphyry. Outside the area under consideration diorite dikes are known, but they will not receive attention further than to note that they probably represent a differentiation product of the same magma from which the other two dikes came. In this connection all the dikes have an important bearing on the origin of the ores and of the gypsum found in the mines.

The intrusion of the alaskite-porphyry as well as the later andesite was accompanied by the emission of magmatic waters and metal-bearing solutions. As these solutions passed upward they wrought important changes in the rocks within their influence, and were directly responsible for the introduction of the various ore minerals, as well as some of the

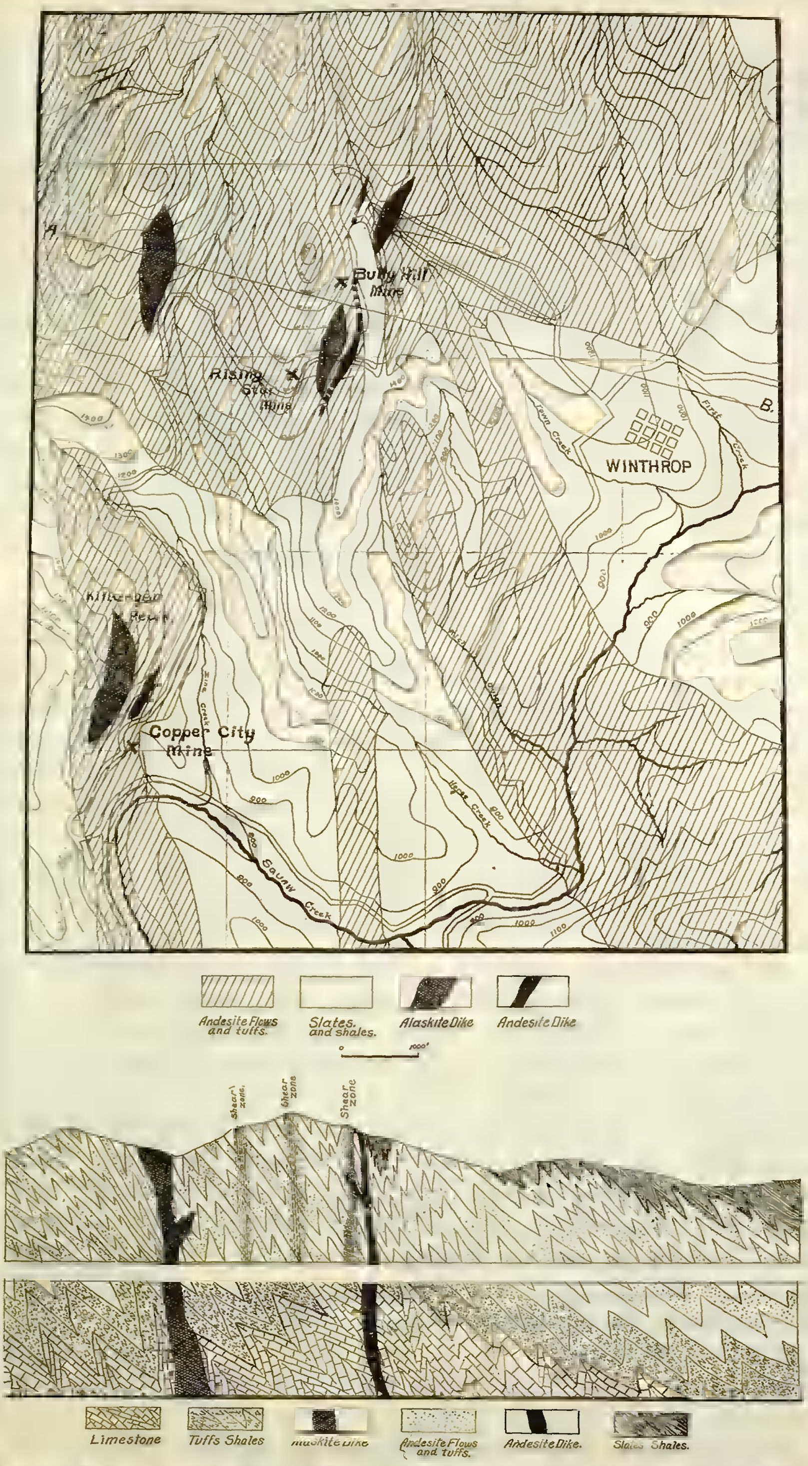

FIG. 1.—MAP OF BULLY HILL MINING DISTRICT, WITH GENERALIZED SECTION ON LINE A–B.
The lower structural section is below sea level and involves the McCloud Limestone.

gangue. By secondary changes which involved alteration, the ores became enriched so that in some cases a copper content of 8 per cent. was produced.

Of considerable interest in this district are the relationships between the shear zones and the various dikes; the shape, extent, and genesis of the ore bodies; the occurrence of large masses of sulphate of lime, which suggests formation by a process not heretofore recognized of great importance. Of great economic significance are the association of copper ores with the alaskite-porphyry, and the interpretation of some facts established in prospecting the extensive masses of gypsum.

The area covered by the map, Fig. 1, extends 2 miles east and west and 3 miles north and south. It is embraced in the *Redding Folio* of the U. S. Geological Survey, which was prepared by J. S. Diller, to whose careful observations the writer is deeply indebted. The recent development of the mines has naturally revealed, however, some points of interest which were not accessible when Mr. Diller's observations were made, and as a result some modification of his views will be supported.

II. Location of the District

The Bully Hill district is one of several mineral belts situated in a moderately elevated area in the western central part of Shasta county, Cal. This county lies at the extreme northern end of the Great Valley of California and embraces a range of mountains which is chiefly formed by the northward convergence of two important mountain chains, the Sierra Nevada on the east, which has a general north and south trend, and the Coast Range on the west, which has a decided northeast trend. The actual junction consists of short irregular ranges.

The section of the country is roughly in the shape of a flat-lying U with the opening to the south. The Coast Range and the Sierras form the limbs, while the high slope of the Sierras, bearing westward, rapidly merges with the eastern slope of the Coast Range and produces the gentle curve of the U at the north.

Irregular east and west ridges parallel to the curve of the U succeed one another to the north, and present a relatively steep front to the south. The Southern Pacific railway, connecting Sacramento with Portland, passes up the Great Valley and crosses this range by following along the course of the Sacramento river and its tributaries. At a distance of 10 miles north of Redding it passes through the station of Pit, from which the Sacramento Valley & Eastern railway extends to the east 15 miles so as to tap the copper belt at Copper City. The branch finally ends 3 miles farther to the north at the Bully Hill mine, near the town of Winthrop.

The productive area which has attracted attention for the past 13 years and which is now under consideration lies in the immediate vicinity of the town. There are three local mining centers, designated as Bully hill to the north, Copper City to the south, and the Rising Star between these, but somewhat nearer to Bully Hill.

History of the Mining Development

The existence of copper ores in this part of the mineral belt was known in the first decade of the '50's. It was encountered in small quantities in tunnels which were opened primarily for the gold and silver veins which yielded the placer values. In 1853 placer gold was discovered in the vicinity of Bully Hill[1] and in 1862 gold was found in the altered surface rock near the present site of Copper City.[2] The copper deposits were neglected for the time being, and little of importance happened before 1895.

Oxidized ores from the surface soon failed to yield acceptable returns, and tunneling was employed with the hope of discovering sources which presumably supplied surface values. Tunnel No. 1, on the east slope of Bully Hill about 500 ft. from the top, was driven a short distance. Since the surface somewhat to the west and north had yielded profitable returns in gold and silver, this tunnel was driven with the view of striking the gold-bearing rock in depth. As the working face advanced, the gossan which had yielded the values changed into very base ore. This condition of affairs so discouraged the operators that in a comparatively short time their workings were abandoned, as it was the general belief that such base ores could not be reduced successfully.

About this time Iron Mountain, some 20 miles to the southwest, was located as an iron mine by William Magee and Charles Camden. The surface rocks throughout the entire country were more or less stained by iron oxide; the gossan was thick and usually carried gold values. Practically the same gossan occurred at the abandoned claims on Bully Hill. Since sufficient time had elapsed for the timbering in Tunnel No. 1 of Bully Hill to rot, the property was relocated and later passed into the possession of Alvin Potter, in 1877. The tunnel was reopened and retimbered. Some ore was taken out, but it exhibited such a base character that active work was discontinued, and subsequently the property passed into the hands of the Extra Mining Co.

It now appeared for the first time that the enterprise was on a firm basis, and in 1877 the first ore-dressing mill in Shasta county was erected near the present site of Copper City by C. M. Peck. The mill was erected on the west bank of Squaw creek and was known as the Northern Light mill.

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[1] *Bulletin No.* 23, *California State Mining Bureau*, p. 32 (1902).

[2] *Idem*, p. 33.

It is reported that in three years the company extracted nearly $650,000 from the ores. The rich values soon began to decrease or change in character to such an extent that this mill was abandoned after a comparatively short period of operation. The equipment became the property of Messrs. Potter and Hall, who had purchased some of the adjoining claims, but, like the Extra Mining Co., they were forced to discontinue operations because of the complex nature of the ores.

The entire milling industry was established on the basis of returns from a 250-ton shipment of local ore sent to Swansea in 1863. It is reported that the ore assayed 8 per cent. in copper, and showed a value of $40 in gold and $20 in silver to the ton. The copper content was considered of no value.

In 1879 James Salee passed through this section of the country and incidentally visited Iron Mountain. He was a miner of wide experience, and in samples of the gossan which he had collected he found gold and silver values. He became the sole owner of the property at Bully Hill. Years passed and occasionally new finds would be reported, which boomed the Copper City district and gave a new impetus to speculation. Little was done, however, until the latter part of the '90's, when the property was transferred to the Bully Hill Mining & Smelting Co. Such is, in part, some of the early history of the camp.

Topography

The district shown on the map, Fig. 1, is embraced by the Klamath mountains and shows a well-dissected portion of the Klamath plateau. The elements of relief are not many and are easily distinguished. Topographically the most important feature of this region is a ridge of igneous rock formed by the upturned edges of surface flows of andesites and intimately associated tuffs. This complex has been metamorphosed to such an extent that it resists erosion to a greater degree than the limestones to the northwest, on which it rests, and than the shales and tuffs which flank it on the south and east. This ridge is continuous outside the limits of the map for a distance of 30 miles and has approximately a north and south direction.

In general, the drainage of the district is to the southwest until the Sacramento river is reached, after which it is entirely south. To the east of the ridge is Squaw creek, which flows southwesterly and joins Pit river near the southern border of the map. The west slope of the ridge is drained entirely into the McCloud river. This ridge is traversed by a series of narrow and steep gulches separated by steep ridges of a minor order.

Bully Hill may be regarded as an elevation of secondary importance, scarcely more than 2,000 ft. in height. The elevations decrease progressively toward the southern limits of the map. The topography is intimately related to the general geological structure of the district and results from differential erosion of the various rock formations.

The lower portions of the larger gulches have been partly filled with detritus from the higher slopes, and in many parts of the district these have been worked as placers.

III. Stratigraphy

It is not the purpose of this paper to enter into an elaborate detailed discussion of the stratigraphy of the region, for it has received great care and special attention from J. S. Diller,[3] J. P. Smith,[4] and H. W. Fairbanks.[5] In order, however, that the geological relations of the eruptive rocks and the ore bodies may be fully comprehended, a brief outline of the separate formations is here introduced. (See Fig. 2.)

The oldest rocks in the Bully Hill district which outcrop on the surface consist of a series of volcanics, everywhere tilted at a high angle decidedly to the southeast, although locally beds may vary so as to be nearly flat.

This series consists of alternate flows and tuffs which together measure roughly 1,500 ft., and has been named by Diller[6] Dekkas andesite. Above this and apparently conformable are the crumpled massive to thin-bedded shales of the Pit series. Only the lower part of fully 2,000 ft. of the Pit shales is embraced by the eastern boundary of the map.

Description of the Rocks

Triassic Lavas and Tuffs.—Andesite flows and related tuffaceous beds, now greatly metamorphosed, are seen to cover most of the western part of the area under consideration. The shape and areal distribution are shown on the map, Fig. 1. It is a matter of some difficulty, however, to fix the precise divisional planes that separate the earlier from the later flows. This comes about from the fact that one grades into the other. In many instances the flows succeed each other with apparent regularity, and at times were followed by accumulations of tuffaceous materials. The present metamorphosed condition of the tuff beds and the flows makes it difficult in the hand specimen to draw definite divisional planes. From the manner in which this andesite series weathers it is possible to describe two different varieties, but because of limited space the andesites collectively will be described as a single unit.

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[3] *Redding Folio, No.* 138, *U. S. Geological Survey* (1906).

[4] The Metamorphic Series of Shasta County, California, *Journal of Geology*, vol. ii, No. 6, p. 588 (Sept.–Oct., 1894).

[5] Geology and Mineralogy of Shasta County, *Eleventh Report of the California State Mineralogist*, p. 24 (1892).

[6] *Redding Folio, No.* 138, *U. S. Geological Survey*, p. 7 (1906).

The freshest specimens are dark gray, with numerous small glistening phenocrysts of labradorite, showing best on fractured surfaces. The rock exhibits a greenish tinge, due to the presence of chlorite, epidote, and similar secondary minerals derived from pyroxenes (probably augite). On alteration the rock usually becomes lighter colored, and in many places on first sight resembles rhyolite. Occasionally sparsely scattered vesicles which have been filled with calcite occur, and the presence of these gives

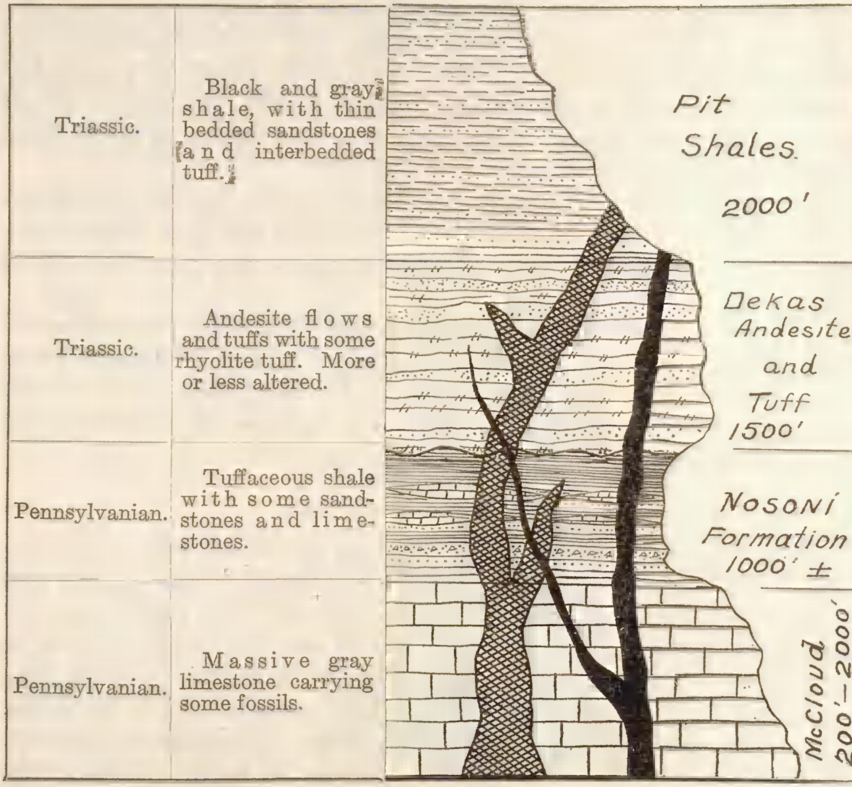

FIG. 2.—GENERALIZED COLUMNAR SECTION IN BULLY HILL DISTRICT, SHOWING THE INTRUSIONS.

to the rock mass a mottled appearance. Where the rock is found thoroughly altered it is characterized by a red stain derived from iron-bearing silicates. The secondary minerals are sericite, quartz, kaolin in large amount, and minor quantities of calcite and iron oxide. The alteration is often attended by leaching by which the rock changes to a nearly white mass, roughly schistose.

In the valleys where this andesitic material has accumulated characteristic red gravelly soil results, which because of the red color makes it impossible to trace the series where the outcrops are obscured. The massive character of some of the flows is evidenced from the presence of numerous large rounded boulders, which are to be seen in the gulches as placer gravels.

Triassic Sediments.—The Pit Shales.—The youngest formation in the district with which this paper is immediately concerned is an extensive series of shales, interbedded occasionally with various volcanic tuffs. In general these shales are fine-grained, dark gray to black, characteristically thin-bedded, and frequently provided with remains of minute marine organisms.

This terrane is by far the most extensively developed of any formation in the district and covers the entire area of the eastern part of the map. These shales underlie a limestone having an abundant and well-preserved fauna which is known to be Middle or Upper Triassic.[7] Because of this relationship the age of the shales is placed in Middle Triassic.

The average strike is north and south when large areas are considered, but on the map it will be noted that the strike varies. The dip is decidedly to the southeast, in common with the previous series, and in amount it is not far from 28°. Variable dips are encountered in the southeastern part of the map.

Where the shales exist the topography is well rounded, and usually low lands result. This is not because the series is characteristically soft, for there are some members making up the deposit which are hard and resistant; but because a few soft layers or beds exist. These are usually tuffs, and as they are washed away the harder parts, because of insufficient support, break away and the entire formation is thus weakened and the topography is thereby subdued.

The rock types include brownish red to yellowish red shales and tuffs. The shales alter to lighter shades, browns and grays predominating. Because of folding the entire formation is jointed and shattered, and overturned folds are not uncommon.

Areal Geology

The area mapped consists of Triassic rocks, which can be deciphered into several distinct types. Along the southern and eastern border of the map are found sediments, chief of which are shales, sandstones, and interbedded tuffs. The area embraced shows only a small part of a widespread series which extends north and south for many miles, and stretches over a distance of 10 miles or more in width to the south. The western border of the area is rather irregular, a condition produced in part by stream cutting, but largely by complex folding and erosion.

West of the sedimentary portion is an extensive area of igneous rocks

[7] *Professional Paper No.* 40, *U. S. Geological Survey*, p. 16 (1905).

comprising andesites and andesitic tuffs. These rocks cover the entire west half of the area under consideration. Irregular masses and long strips extend south and east from the main area. The entire area has been sheared so that the rocks are usually of a pronounced and thinly foliated type. Into the sheared country rock have entered dikes, which tend to complicate the structure. Natural outcrops are abundant and form sharp ridges, persistent for long distances. The hilly tract containing the mines embraces this igneous complex and has abundant evidences of mineralization. The ledges of altered andesite and dikes rise many feet above the general profile, and obviously present what physiographers term a "young" topography. The rocks over wide areas are greatly decomposed, and, except where exposed as already described, have weathered to a mantle of soft, reddish brown, chalky débris; and again they have become so thoroughly silicified that their original character is entirely obliterated. The extent and general areal relationships are given on the map, Fig. 1.

Structure

The rock formations, which have a general southeasterly dip, are complicated by folds, faults, shear planes, igneous intrusions, and metamorphism to such an extent that in the immediate vicinity of the mines these secondary features are of more importance, in the solution of the problems later discussed, than the rock types in which they are so conspicuously found.

In order that the significance of these relations may be fully comprehended, and also that the reader may have at the outset a working knowledge of the local features, it becomes necessary particularly to appreciate the character of the various metamorphic processes involved. There is a very intimate relation between all these elements and the origin of the ore deposits. No single feature when taken by itself explains the situation, but when all are taken together, in proper sequence, they are directly responsible for all the facts observed with regard to the ore genesis. For convenience and emphasis these will be discussed separately.

Folds.—The best preserved folds are to be seen in the sedimentary rocks which flank Bully hill on the south and east. In these rocks the compressive forces have produced a great variety of folds, ranging from those in which the flexure is just perceptible to those where overturning is pronounced. The folds are complicated, variable, and at times very obscure. The simplest type, Fig. 3, is found in the south and east part of the area, and the folds become progressively more complicated north and west until at the contact with the igneous rocks they are apparently lost by grading into another structure later to be discussed.

The prominent phase of deformation especially noticed in the vicinity

Fig. 3.—Open Folding in the Pit Shales.

Fig. 4.—Close Folding in the Pit Shales.

of the mines is that which follows from compression. Within this zone the strata have shortened and the greater length of the various beds, previously listed and described, has been taken up by folding. The bending became complex and later reached a condition in which the units yielded easier to the applied stresses by breaking than by further crumpling. As a result, in the western part of the Pit shales, the adjustment is characterized by numerous breaks in the strata. Since the strata of the Pit formation consist of shales, sandstones, and limestones, there is reason to suspect widely differing structures.

The composition and thickness of the various beds determined in a large way the behavior of the series under the applied stresses. The units varied greatly in thickness, and as a rule the thicker portions yielded by breaking rather than by bending. On the other hand, where the strata were thin and the composition favorable, complex folding and contortion resulted. These finally became more pronounced and were later replaced by thrust and dislocation.

Everywhere the Pit shales are folded, and so prominent is this feature that the formation can be detected for great distances. These strata were not originally deposited in this position, but have been subsequently deformed by lateral thrusts which crumpled the units and caused the folds. As might be expected, folds occur of every degree of complexity. Some are broad and open, others are narrow and compressed; in some the strata are but slightly disturbed, in others the beds are actually twisted, contorted and confused in the most extraordinary manner. (See Fig. 4.)

The whole process is not difficult to imagine, and it is furthermore an absolutely necessary step to follow if one wishes to understand the structural relations in the mines as they now exist. Many of the local complexities observed in the working places are easily understood and can be explained by a knowledge of the structures.

It should be stated that in few places only, in the field directly related to the mines, are there good examples of complex folds in the tuffs. This is not because these have in any way escaped the deformation, but chiefly because extreme shearing and metamorphism have obliterated all evidences of such features.

The greater part of the hill in which the mines are located consists of a series of interbedded andesites, and associated tuffs. Although there is a wide range between these products they show a common behavior in the development of shear and foliation. Over the entire region, of which the area mapped is a small part, there is a likeness in the results that argues similarity of causes and materials.

The units varied greatly in thickness from point to point and often the tuffs were mixed in and incorporated with the flows. The fragmental volcanic rocks appear to have been very abundant and may even have been predominant in this particular locality. As such they consisted mainly of fine dust particles, but there is evidence also that large amounts of ash, as well as some glassy fragments, constituted part of the accumulations.

The massive brittle rocks were originally the flows and these have furnished the angular fragments of the breccias, while the tuffs, because of their porous texture, permitted adjustment to take place between the individual particles without apparent crush. In extreme zones of shear and brecciation, however, all traces of former structures have been obscured, if not completely obliterated. The composition and form of the volcanic rocks determined to some extent their behavior under the applied stresses. Since there is such an abundance of folded structures in the sedimentary formations on top of the igneous rocks, and a short distance to the west in formations stratigraphically lower, it follows that these deformations exist in some form, however badly preserved, in the igneous rocks as well, because the entire series was subjected to the same stresses and behaved as a structural unit. Just how far these deformations extend in depth is a matter purely conjectural, but it is believed that they have affected rocks very early in the geological column.

As noted above, the general structure of the district is comparatively simple, but there are minor features which tend to complicate it. As a result of the degree of folding, beds which were in the beginning far below have been brought near to the surface. These relationships are shown on the structural section taken along the line *A–B*, Fig. 1. Actual measurements at depth could not be made, but the surface relationships are mainly correct. As will be seen, the structural section is made in a line which is parallel to the direction of thrust and consequently the axes of the folds in the slates and the more complex shear zones in the igneous rocks trend northeast and southwest. Furthermore, the axes of the folds pitch, so that the tendency is for the ore bodies to pass into deeper rocks going northward.

Faults.—The structure of the district is affected only in a very subordinate way by faults, but where these do occur they are a source of further complexity. Since the readily distinguishable beds found in the immediate vicinity of the mines show no evidence of extensive faulting, it is safe to infer that no dislocation has taken place since these were laid down. It is possible, however, for faults to have taken place in the earlier rocks and yet not be registered in the sediments within the area mapped, but field study does not reveal any. There are numerous minor slips and dislocations in the rocks, but these are attributed to shearing processes.

Such slips have been encountered in prospecting work, but they are too local to be recognized as being important in the larger structural features, and they are too numerous to be shown on the map. In the mine workings the older fractures have been rehealed, while the later cracks are still open and furnish circulation channels.

At only two points has faulting taken place on a scale that merits attention, and even here the data are somewhat obscure, so that the actual amount of dislocation is questionable. Further developments may reveal some interesting relationships. The shear zones which stand up as silicified ledges on the hill-top apparently end in the south slope of the hill. It is quite possible, however, that these shear zones are local; but there are several dikes, which will receive attention under "Intrusives," which also outcrop on the south slope of the hill, and these also end rather abruptly. After apparent shifting to the west about 100 ft., they continue in their normal direction southward and finally disappear under the shales. This is very suggestive of a fault when taken in connection with the dikes and the shear zones, but the shales only a short distance to the east show no evidence whatever of any dislocation.

Another possible fault, which is better characterized by being a "crush zone," is seen on the north slope of the hill where it crosses Town creek just northwest of the main tunnel entrance and back of the company houses. Here the rocks are badly brecciated and the zone is apparently vertical and at right angles to the foliation planes of the rock masses on each side. This zone has been partly explored in depth and some ore obtained. Aside from these two instances (and they are rather obscure) no faults of importance were found in the district.

Shear.—A structure which is intimately related to the folds and thrusts is that of shear. It may be regarded as the limiting phase of combined folding and thrusting processes. In this district sheared structures are prominent and are almost wholly restricted to the igneous rocks. While the massive igneous rocks show this structure to some extent, it is best developed in the tuffs, and in some of these it is so persistent that the rock in places may be regarded as typically schistose.

Just as the shales are characterized by being folded rocks, in like manner the igneous members can be considered as sheared rocks. Just where folding ends and shear begins is not always easily determined, since one passes by gradual transitions into the other. In a general way shear is characterized by being a finer structure and represents a greater degree of crush, and involves changes other than those of purely dynamic character. That folds and thrusts preceded shear in the igneous rocks there can be little doubt, but the persistent type structure now seen is shear alone.

The shear has developed mainly at right angles to the direction of pressure and has a general trend corresponding to a north and south plane. In the district under consideration the shear has taken place on a small scale in all the rocks and is widespread, but there were conditions which favored localized shear zones, and as a result Bully hill is characterized by three independent zones which are approximately parallel to each other but separated by intervals of several hundred feet. These zones are nearly vertical and have a north and south direction. They are seen as irregular ledges which project above the general profile of the hill and are shown in Fig. 5. The material constituting the rock of these ledges is mainly silicified andesite tuffs and flows. In this hardened condition it resists the weathering processes and gives rise to rugged, steep slopes. In spite of the rock being hard it splits easily in a plane parallel to the foliation and is often characterized by an abundance of long parallel cracks trending north and south.

FIG. 5.—LOOKING NORTH FROM KILLANGER PEAK AT BULLY HILL.
The picture shows the three shear zones.

The Intrusions

From observation of the succession and character of the intrusives of the district they present in their structural relations one single type—dikes, which are found well exposed on the southeast slope of Bully hill. They may be divided into two distinct varieties, an earlier acidic (alaskite-porphyry), and a later one of andesitic characteristics.

Alaskite Dike.—The alaskite dike, Fig. 6, is found in detached masses on the east slope of Bully hill and apparently ends at the Rising Star mine, 0.75 mile farther to the south. The rock is medium even-grained and contains a few small phenocrysts of quartz and feldspar in a fine-grained ground mass of mottled gray color. The freshest specimens have practically no dark silicates. Most of the outcrops exhibit alteration and intense bleaching, so that the weathered, rough, projecting masses are colored by iron oxide, the colors ranging usually from yellows through reds to pinks.

In the hand specimen the actual dimension of the grains is seldom greater than 5 mm. Much of the rock is fine-grained and may be regarded as felsite-porphyry. Of economic significance are the nearly vertical foliation planes and the cracks along which ore-bearing solutions have deposited ores in notable amounts.

The time of the intrusion is not definitely known, but since the

Fig. 6.—View Showing the Rugged Character of the Alaskite-Porphyry.

country rock is believed to have accumulated in Middle Triassic time, it follows that the intrusion is as young at least as the late Triassic.

Andesitic Intrusion.—A later intrusive of decidedly andesitic affinities, mostly decomposed to a reddish brown exfoliated mass, is exposed on the south slope of Bully hill and extends in a more or less continuous mass in a northerly direction for a distance of 0.75 mile. Because of the readiness with which this dike rock alters, it is mostly obscured, and at times it is difficult to distinguish it from the country rock through which it passes. Were it not for the exposures in ravines and gulches one would notice little difference between this rock and the normal weathered country rock.

The main body of the dike is nearly vertical, irregular, parallel or nearly so to the alaskite dike, and at several points it is coincident in course with the direction of the main ore bodies. In the deeper workings of the mines it is known to have a thickness of approximately 300 ft. To the south of the Rising Star mine it pitches under the shales and disappears.

In the hand specimen it is greenish to grayish in color and is usually very fine-grained, although at times it is coarse enough to show distinct phenocrysts. It frequently exhibits amygdaloidal structure. The cavities in all cases are filled with calcite.

In common with the alaskite this dike sends off branches which undergound give considerable trouble and annoyance in mining operations. Some of the smaller branches are finely felsitic in texture.

The dike has been changed by shearing and alteration, so that in the mines the dike material exactly resembles sheared masses of ore. With reference to the age of this intrusion, it is the youngest igneous outbreak found in the district mapped, and although a definite age cannot be assigned to it, it is known to intersect the lower members of the Pit shales and therefore must be as young at least as the series, which is considered as Upper Triassic.

IV. Petrography of the Rock Types

The chief object of the microscopic study of the rock types has been to identify them and to suggest processes directly connected with the genesis of the deposits. Although the metamorphism is complex and the processes of mineralization have persistently overlapped other stages, it is believed that the best results will be obtained by attempting, as far as possible, to treat the various stages as individual and separate phases even though the several processes have been simultaneous.

The specimens of rock have been collected in a systematic study of the Bully Hill district, and represent quite fully the range of types. In the set of rocks which has been selected as typical, microscopic study shows the following: (1) andesites, andesite tuffs, and some rhyolite tuffs among the pyroclastics; (2) alaskite and andesite as the representatives of the intrusives.

Tuffs, of both the andesitic and the rhyolitic varieties, are the dominant types and include 11 specimens of the total 24. Next in importance are the andesitic flows which give rise to the breccias. Then follow the intrusives, which can be grouped into two main types: extremely acid and moderately basic.

The phases of mineralization may be listed under several different heads, but this arrangement does not mean that the processes necessarily followed one another in definite sequence. Aside from dynamic changes, a study of thin sections shows that all of the following processes have been operative in producing the present characters in the rocks and ores.

They are: sulphatization, carbonatization, sulphidation, chloritization, serpentinization, and silicification.

Andesite Flows

The andesites range in texture from distinctly porphyritic to finely felsitic and glassy varieties. The characteristic andesite is a close-textured, dense, grayish to greenish rock containing visible phenocrysts of feldspar in a greenish ground mass. The representatives of this class accumulated as thick flows, in some of which crystallization was well advanced before movement ceased.

The felsitic and glassy varieties are without doubt those which were poured out on the surface as thin flows and sheets. In some of these the escaping gases have left the mass porous, but this feature is not always prominent. The microscopic features show the porphyritic varieties to consist of labradorite with some hornblende in a felsitic ground mass. The feldspars are large and contain numerous scattered inclusions, presumably ilmenite. In the finer-grained varieties the feldspar and hornblende wane and in the glassy facies these minerals entirely disappear.

Only fragmentary evidences of biotite remain and in the highly altered types this is often indicated by the arrangement of grains of magnetite.

The transition of the porphyritic types to the finer-grained varieties is gradual but distinct. The alteration of the andesites is a very salient characteristic. Aside from the ordinary weathering to chlorite, kaolin, and epidote, some sericite was noticed, especially where the rocks were badly crushed. Some of the larger phenocrysts of feldspar show internal strain, as seen in the wavy extinction. Where the crush has been extreme the phenocrysts are badly broken and comminuted. The glassy types show only irregular areas traversed by numerous cracks and fissures. For the most part such areas show advanced divitrification, so that in the present form they resemble mottled patches with irregular boundaries. Under the high power of the microscope such areas resolve into an aggregate of quartz and feldspar. In cases where devitrification has not progressed too far characteristic glassy textures are still to be seen.

Tuffs

Only a small number of types belong to this group and each is designated according to the kind of lava fragments it contains. As a whole these rocks do not possess great petrographical interest. In the hand specimen they are not conspicuously fragmental, but if examined with a pocket lens they will be found to contain lighter and darker colored grains imbedded in a gray ground mass. Numerous small specks of magnetite are present. The following types seem to deserve mention:

Andesite Tuff.—The andesite tuff includes all the rocks composed of volcanic detritus which is clearly andesitic in composition. The texture is therefore of wide range and includes rocks made up of lapilli as well as those consisting of sand and dust. Under the microscope the clastic character of the rock is easily recognized and the mass is seen to be composed of intermingled fragments of feldspars and glass. The andesite tuffs are badly altered or decomposed and this feature renders them very difficult to study. Although the alteration is well advanced and the particles are very fine, yet the microscope shows traces of porosity. Many of the fragments still show evidence of original glassy texture. The tuffs alter to kaolin and sericite, and where the ferro-magnesian minerals have been prominent these have given rise to considerable amounts of chlorite and iron oxide.

Rhyolite Tuff.—In the essential features the rhyolite tuff does not differ markedly from the andesitic variety except in the presence of quartz phenocrysts imbedded in a large amount of dust-like material. This dust may have been in part glassy, but the present metamorphosed condition of the products makes any trustworthy statement of the original condition uncertain. The range in size of fragments is variable. Rarely do the particles exceed 5 mm. in diameter and three-quarters of the entire mass is less than 1 mm. in diameter. The presence of quartz grains makes the identification of the rock comparatively easy. This rock involves glassy fragments as well as mineral grains, all of which are sharp, angular particles, exactly analogous to volcanic detritus. Although the macroscopic evidence indicating that the rock is tuffaceous is strong the microscopic evidence is still stronger and demonstrates completely its volcanic origin. Numerous stringers of partly devitrified glass are to be seen, together with numerous small grains of magnetite. Like the andesite tuffs, these rocks are also porous, and when altered give rise to sericite kaolin, and some leucoxene. The kaolin occurs as irregular earthy patches and in some slides makes up a large part of the rock mass. The sericite had its origin in the feldspars and usually occurs as fine aggregates.

The tuffs as a whole are mineralized and this phase will be described in detail on a later page.

Eleven specimens out of the 24 are fragmental in character and were originally composed entirely of volcanic detritus. They are the tuffs. The fragments vary in size from 3 mm. down to fine dust. Two specimens of the 11 are best classified as andesite tuff, while the remaining ones are decidedly rhyolitic in general make-up. Nine of the 11 specimens show pyrite in varying amounts from fine sprinklings of dust-like particles, not exceeding 3 per cent. of the mass, to those in which the sulphide runs as high as 20 per cent. or more. One specimen shows blende in minor amounts. Seven show the presence of chlorite and serpentine, while two show notable amounts of carbonate. Seven show the presence of gypsum and all show traces of silicification.

Of the tuffs there is one specimen that deserves special comment since it shows some interesting features not commonly seen in the rest but which are believed to be general throughout the entire class of tuffs. This particular feature is to be noted when the sulphate encroaches upon and entirely replaces the quartz grains, Fig. 7. In the same section pyrite is seen encroaching upon quartz grains and completely replacing them. It appears from these slides that the conditions under which the solutions existed were such that silica was dissolved and a sulphide as well as a

FIG. 7—DARK AREA IS A QUARTZ GRAIN IN RHYOLITE TUFF.
The quartz is being replaced by gypsum, shown in the upper right-hand area. × 50 diameters.

sulphate was deposited. It is well known[8] that the solubility of gypsum decreases with increase of temperature above 100° C., and that silica is dissolved with increase of temperature. It is quite possible that the limits for the solubility of gypsum were closely approached, so that the sulphate already in solution was thrown out and silica taken up. Clarke[9] states that "Hot waters, charged with sulphuric or hydrochloric acid,

[8] Seidell: *Solubilities of Inorganic and Organic Substances* (New York, 1911).
[9] *Bulletin No.* 491, *U. S. Geological Survey*, p. 459 (1911).

attack nearly all eruptive rocks, dissolve nearly all bases, and leave behind, in many cases, mere skeletons of silica."

Two specimens of the 24 are typical breccias, the fragments of which are angular in character, greenish in color and cemented together with gypsum. These rocks are of such unusual petrographic character that they well merit special description. The fragments, although originally sharply angular, are now conspicuously sheared and at first sight resemble

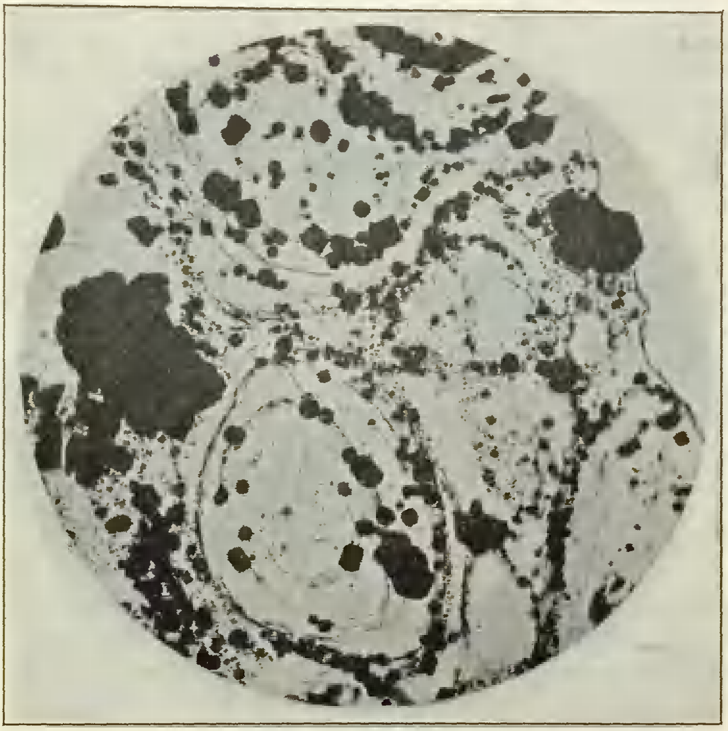

FIG. 8.—THIN SECTION OF A GREENISH FRAGMENT FOUND IN GYPSUM.

The curved lines, accentuated in part by the arrangement of the black sulphide grains, are interpreted to be perlitic cracks of a glassy rock. $\times$ 50 diameters. Transmitted light.

pieces of serpentine. They are usually very soft and at times are fissured with carbonate and sulphate of lime.

Scattered through many of the other specimens are greenish areas which closely resemble the fragments of the breccia in hand specimen, but a study of thin sections shows that the fragments of the breccia were originally glassy. In spite of the degree of shearing that is in evidence in most of the surrounding rocks, and also in these specimens as well, many details of their original texture are preserved with a sharpness scarcely to be looked for in rocks which have had such a history.

It is generally agreed that dynamic action is a powerful agent in completely obliterating all such structures, but in this instance it does not appear to hold true. Glassy rocks are known to be more easily attacked than many others and are subject to either alteration or complete destruction, so that preservation of the glassy breccia without apparent loss of its original earmarks and quick-chill characteristics must be regarded as very

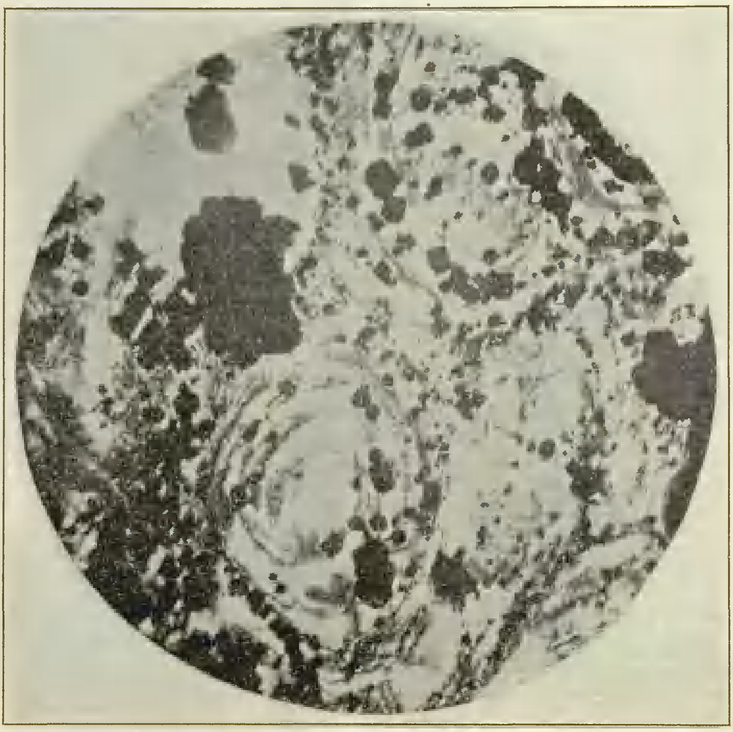

FIG. 9.—SAME SECTION AS FIG. 8, BUT UNDER POLARIZED LIGHT.

interesting, if not exceptional. In the hand specimen the rock presents a uniformly sheared crystalline matrix in which are imbedded greenish fragments varying in size from an inch in diameter downward to microscopic dimensions. Most of the fragments are heavily pyritized and the individual grains of pyrite are conspicuously arranged along curved lines which are exactly analogous to perlitic cracks, Figs. 8 and 9. Many of the fragments show distinct flow lines under the moderate power of the microscope. In the hand specimen they often show how the fragments have been drawn out into "Augen." In some types this arrangement of the fragments gives to the larger rock masses a distinctly banded appearance.

In thin section the greenish grains are either isotropic or else they show devitrification changes. No chemical analysis of the greenish fragments has been made, but since they are closely related to flow rocks they are provisionally classed as acid glasses. In one thin section the greenish patches show original porphyritic habit. These areas generally represent original glassy rocks and they are certainly being replaced by the gypsum. Stringers and shreds of such material are being encroached upon from all sides, and they remain as cores. Like the breccia, these greenish areas are heavily charged with sulphides, and the conclusion is made that the same mineralizers which introduced the sulphates were influential in introducing the sulphides as well. The sulphate was introduced as a vein filling, and this feature establishes its secondary character. As in the case of the breccia, these rocks were originally flows and are best regarded as acid glasses.

One specimen out of the entire series is classed as a rhyolite flow. It is badly sheared, and under the microscope shows corroded and embayed grains of quartz. Secondary carbonate has replaced some of the ferro-magnesian minerals, and this feature gives to the rock a mottled appearance. There are a few patches of divitrified glass which still show pronounced flowage. There is no evidence of introduced sulphate or sulphide. Small amounts of secondary silica are to be seen in microgranular patches.

The remaining specimens are grouped as dikes, and out of the total number of rock types there are eight representatives which can be described under two types.

Under this head are included only those dikes which are intimately related to the ore deposits. There are others in various parts of the area mapped, but they all have a striking similarity in structural relationships. For convenience they will be described in order of age.

Alaskite-Porphyry

This is the most conspicuous dike rock in the district. It is generally light colored, very acid, and is at times mottled. The phenocrysts oi the rock consist of quartz and feldspar, the feldspar generally slightly predominating. The ground mass is seen to consist of a microgranular mixture of quartz and feldspar. Some of the larger phenocrysts of feldspar, because of orientation, do not show the usual twinning. The chief accessory minerals are magnetite in small grains, apatite, and rarely zircon.

The quartz phenocrysts are embayed and heavily corroded, as seen in Fig. 10. The feldspars are altered in part to kaolin. There is little or no sericite, and the specimen is notably free from mineralization. The rock mass has been fractured but has been later recemented by quartz. The alteration products are chlorite and epidote in small amount, derived in all probability from original flakes of mica. The dike varies in thickness and on thin edges it is relatively fine grained, while in the center of the larger masses the texture is rather coarsely grained.

Although in places the rock shows conchoidal fracture it contains no glass. Diller[10] regarded this rock as a surface flow and recorded it as being

FIG. 10.—CORRODED PHENOCRYST IN ALASKITE-PORPHYRY.
Light area, quartz; dark area, unaltered ground mass. × 50 diameters. Crossed Nicols.

older than the sedimentary formations apparently resting upon it. From his various published statements regarding these relationships it may be inferred that such a conclusion was not reached without some hesitation. Recent study of the structural relations in depth shows that all such masses can best be regarded as intrusives, and this idea was entertained by H. W. Fairbanks.[11]

[10] *Redding Folio, No.* 138, *U. S. Geological Survey*, p. 8 (1906).
[11] *Eleventh Report of the California State Mineralogist*, p. 32 (1892).

Andesite Dike

In appearance the andesite dike is a dark gray to greenish fine-grained rock, sometimes showing a tendency to amygdaloidal structure. The microscope proves that the rock consists of phenocrysts of orthoclase imbedded in a fine-grained ground mass of lath-shaped feldspars. The chief accessory minerals are magnetite and rarely rutile. The rock appears more basic than is actually the case. It varies in composition from point to point and shows in its northernmost outcrop the presence of some pyroxenes. Like the alaskite dike, it also sends off branches into the country rock, and these are finely felsitic. Both dike rocks have been sheared and have been replaced in part by sulphides, sulphates, and carbonates. Although the dikes vary from point to point the following analyses made on typical specimens of the freshest material will give an idea of their chemical character.

Analyses of Alaskite-Porphyry and Andesite Dike

	(A)	(B)	(C)
SiO_2	78.50	81.25	49.85
Al_2O_3	11.50	9.03	17.00
Fe_2O_3	0.11	0.63	4.02
FeO	1.82	0.40	5.51
MgO	0.46	2.48	7.65
CaO	0.50	trace	1.18
Na_2O	6.04	0.25	4.78
K_2O	none	1.82	none
H_2O at 105°	0.30	1.09	2.16
H_2O above 105°	0.82	2.81	6.65
TiO_2	0.27	0.08	0.97
P_2O_5	0.03	trace	0.10
S	0.13	0.35	0.07
SO_3	none	none	none
CO_2	none	none	none
MnO	0.03	trace	none
BaO	none	0.05	trace
ZrO_2	none	none	none
Totals	100.51	100.24	99.94

(A) and (B), Alaskite-porphyry dike rock near Bully Hill mine, rich in porphyritic quartz. (A) analyzed by George Steiger, (B) by E. T. Allen.

(C), Andesite dike forming the east wall of Bully Hill mine. Analyzed by E. T. Allen. *Bulletin No.* 228, *U. S. Geological Survey*, p. 210 (1904).

The various specimens of the andesite dike show pronounced shear effects and along such planes there is evidence of introduced carbonates and sulphides. The carbonates fill irregular cavities, and while the sulphide is often found along the borders of the calcite areas it is not confined to these alone. The cracks and fissures are most heavily mineralized, although in one specimen the sulphide appears to be uniformly scattered throughout the mass. In only one specimen of the andesitic dike rock was sulphate found. One specimen shows introduced copper carbonate.

It is in the andesite dike and its apophyses that the greatest amounts of chlorite and serpentine are found. In all cases these products have been produced by hydrous alteration from former ferro-magnesian pyroxenes as well as amphiboles.

More than half of the specimens contain ores, which are confined to the tuffs. Where the gypsum is found it appears also to favor the fragmental rocks, especially the tuffs. In some of the specimens all original structures are obscured in the various processes of sulphatization, sulphidation, and silicification. In a few there are satisfactory evidences of original minerals and structures that prove the tuffaceous character of the original rock. In the rhyolites the phenocrysts have resisted alteration where all other structures have been destroyed. In such cases the ores are essentially replaced rhyolites and rhyolite tuffs. Some of the specimens show marked crushing and these have been preserved as breccias. The sulphides and the sulphates were deposited in some specimens simultaneously, and in others the sulphides alone are promiscuously distributed through the rocks.

V. Description of the Mines

The descriptions are presented according to the geographic position of the three properties in three major groups. The chief producing mines have been divided into the southern, middle, and northern, and comprise the Copper City, the Rising Star, and the Bully Hill, respectively. The writer was permitted personally to visit each of the properties, where ample opportunity was enjoyed for studying both surface and underground geology. Under present conditions such good opportunities are not afforded.

The most southerly of the properties is the Copper City. Although the first property to be extensively worked it is now the smallest. The ore is more difficult to treat than that of the others. The mine is situated about 1,000 ft. west of Zinc creek, and just south of Killanger peak. A tunnel a few feet above the level of Squaw creek has been driven to a distance of 1,000 ft. or more in a northwest direction, and for the greater part of the distance it is in a contact zone between shale on the east and alaskite on the west.

These broad relationships have been modified, however, by extensive fracturing and fissuring, with some shearing, so that while the zone of mineralization is somewhat irregular, it is roughly northeast in direction and has a nearly vertical dip. The shear zone has been richly mineralized and ore shoots of lenticular shape have resulted. The thickness of these bodies varies from a thin edge on the margins to 14 ft. or more near the middle. The width of the shoots varies from 30 to 150 ft. The central part of the shoot is generally the thickest. The longer axes coincide with the general foliation of the inclosing rocks. Where the walls have been mineralized they have also been mined, but in no instance have they been so productive as to be regarded as important sources of ore.

The principal ore bodies have resulted from the complete replacement of the country rock. The mine is, however, in the early stages of its development, and no very extensive shoot has been mined out. The ore consists of a mixture of pyrite, bronite, chalcopyrite, and an abundance of sphalerite. There are also minor amounts of galena scattered through the masses. In later years the sphalerite has become so abundant as to make the extraction of the copper difficult. The workings have also revealed a badly sheared intrusive dike, containing copper minerals, apparently not original. They are subsequently described.

The next property is about 2 miles to the north of Copper City, and although it is the latest of all to be worked, it is nevertheless of great importance. The mine is called the Rising Star and is situated near the head of Buck gulch, which has its source in the south slope of Bully hill.

The andesites, alaskite-porphyry, and andesitic dike are well exposed. So far as known the andesite dike lies wholly to the east of the principal ore body, and, as already stated, is faulted so that detached portions are shifted to the west. The main lodes are lenticular in shape, with their longer axes pitching 60° or more to the north, and having a general strike of N. 10° E. The shoots have been formed by replacement of the sheared rock.

The ores are mixtures of sulphides, chief of which are pyrite, chalcopyrite, and bornite, with small quantities of sphalerite. Of special interest in this mine are masses of gypsum and anhydrite, with minor amounts of barite, the latter being sparingly present in the ores. The workings are extensive and have reached a depth of approximately 1,000 ft. The surface geology presents rocks which consist almost entirely of sheared andesites and tuffs highly stained with iron oxide. The andesite dike, although not conspicuous, is known to exist to the north and east of the main tunnel. At the time of this writing no commercial ore has been found east of the dike.

The northernmost property comprises the Delamar lode of Bully Hill. This mine is the most extensively developed of all. It is situated on the south slope of Town creek, which has its source in the northeast slope of Bully hill and the southeast slope of Town mountain. The workings are entered by means of a tunnel, Fig. 11, 1,400 ft. long, which passes into the hill in a general southwest direction. The shaft near the end of the tunnel is more than 1,000 ft. deep and connects with a number of drifts and cross-cuts.

The geology is similar to that of the Rising Star mine. The general structure is simple, but the details of the structure and the deformation which produced it are not only complex but in some instances are beyond exact determination. This is due to the complex folding of the igneous members.

The ore bodies are strikingly lenticular in shape and conform perfectly to the foliation of the sheared country rock. The lodes lie much nearer

Fig. 11.—The Main Portal of Bully Hill Mine, Looking Southwest. Alaskite-porphyry seen immediately above the right-hand end of building.

the andesite dike than those in the Rising Star mine. They are richer nearer the dike and leaner as they are followed toward the west. From detailed study there is no doubt that the shoots represent completely replaced sheared rock, which may be andesites, tuffs, or alaskite porphyry.

The lenticular bodies range in size from masses a few inches in dimensions to those of hundreds of feet in length. The thickness appears to be controlled, in part at least, by the width of the more completely sheared, and therefore the more easily replaced, country rock.

Gypsum and anhydrite occur here substantially in the same way as in the Rising Star mine, and will receive discussion under the topic, "The Gypsum Masses."

Summary.—It is plain from the preceding statements that the mines are located in a line corresponding closely with the shear zone. The shoots are strikingly lenticular in shape, with their longer axes parallel to the foliation of the inclosing rock masses; their longer axes also pitch steeply to the north, and the deposits in places attain a thickness of 30 ft. or more. Additional descriptions of the ore bodies will be given under "Metalliferous Deposits."

VI. Metalliferous Deposits

The metalliferous deposits of the Bully Hill district, so far as known, are simple and uniform, and constitute three principal tracts intimately related to an igneous intrusive (alaskite-porphyry) locally known as Bully Hill quartzite. These tracts are represented on the map and roughly embrace an area of 1 by 3 miles.

The Bully Hill and Rising Star mines form a group comprising the most important ore bodies of the district, and although ore is known at Copper City, and the mines have been operated at irregular intervals for many years, the composition of the ores has until recently made the mine of small importance. Detailed study of the ore bodies shows disconnected but often overlapping masses varying in size from mere flattened nodules several inches in diameter to large masses hundreds of feet in length and 30 ft. or more in width.

These characteristically lenticular masses, which are roughly parallel to the andesite dike previously mentioned, and which lie between it and the alaskite-porphyry, pitch steeply to the north and are longest in that direction. The crushed rock contiguous to the ore bodies and wholly within the shear zone is generally, but not always, impregnated with sulphides. It follows, therefore, that there exist in the mines theoretically two distinct masses of ore, one having a roughly lenticular shape, the other somewhat irregularly replaced brecciated rock. The latter is an important source of ores, and at times is characterized by more or less complete secondary enrichment. It might be stated that while there are two distinct modes of ore occurrence, there is rarely any distinction between the minerals common to both. Occasionally there are residuary cores of rock in the ore which indicate replaced fragments. Aside from this the only distinction is based on sparsely distributed minerals in the country rock.

As the ore bodies lie wholly within a metamorphosed area of igneous rocks, the individual members of which have been sheared and disturbed, it follows that the shoots themselves may likewise be disturbed. Careful study shows that subsequent to the original deposition of the major ore bodies several later dynamic movements have taken place, each producing fractures which have affected the mineral deposits.

Although the movements have for the most part been of the minor order, the subordinate fracturing has taken place mainly parallel to the foliation of the country rock. It is also believed, upon good evidence in the field, that important shifting has resulted at approximately right angles to the existing shear zone. Because of the number and character of the fractures it is impossible to determine definitely the ages of the different movements.

This condition is therefore favorable to the existence of faulted parts of the main ore body, and applies especially to the north end of the Delamar lode in Bully Hill. The evidence—though obscured by the badly sheared country rock, and therefore of rather unsatisfactory character—shows that in all probability the faulted portion can be looked for farther to the east than the main lode in Bully Hill. The strongest evidence bearing on such interpretation is twofold: first, the isolated mass of alaskite-porphyry near the eastern end of Bully Hill dump, which is thought to be shifted from a position which it once had near the main tunnel, eastwardly to its present position; secondly, the brecciated zone and otherwise ground-up material just above the wagon road leading to the Rising Star mine and directly back of the company houses as one goes south. This broken and fractured zone is axially in line with an escarpment produced by an abrupt ending of alaskite-porphyry just west of the main portal. Such brecciated zones, within the mineralized area, have received secondary enrichment by copper-bearing solutions.

In a broad way the general distribution of the productive ore zones with reference to the various rock formations has been indicated in a previous part of this paper. In all cases the deposits occur in or in close association with altered igneous rocks, generally alaskite-porphyry, which because of fracture and partial alteration exhibit various stages of replacement. The occurrence of the ore in depth is indicated on the surface by a reddish, usually porous, iridescent gossan, and is coextensive with it.

When the ore bodies had been finally completed, and when by dynamic movements they were placed above the level of ground water, oxidation resulted and the subsequent production of the gossan began. It is believed that a very great vertical extent of ore was in this manner affected, and it is quite certain that the solutions which leached the surface rocks migrated downward, carrying with them the salts which they could hold in solution, until they came in contact with the reagents which would cause precipitation. It follows, therefore, that the leaner masses below would receive contributions from above and thus become enriched.

The vertical distribution of the ore bodies at present (1913) is known to be 1,000 ft., and at this depth oxidized minerals exist but as compared with upper levels their amount is waning. The downward limit of the copper ores has not been determined.

The areal distribution is shown on the map, but because of the characteristic weathering of the surface rocks, and the subsequent spreading of the gossan, there is no sharp distinction between the country rock and the mineralized rock. In very general terms it might be stated that the Delamar lode can be traced on the surface for a half mile, and the Anchor lode of the Rising Star mine for a quarter mile. The width of the mineralized zone varies, but in round figures it is not far from 300 to 500 ft.

Character of the Ores

In a number of instances pyrite appears to be the chief mineral, with chalcopyrite as a very common and characteristic associate. More rarely, and chiefly in the zones where oxidation and enrichment have been in progress, we find chalcocite, bornite, covellite, and native copper. The typically oxidized ores if followed down to sufficient depth invariably give way to secondary enriched products, and, when these are not prominent, to the unaltered sulphides. Although some grains of metallic copper are found in the superficially changed rock, the decrease in assay values, going downward in the rocks, is doubtless to be explained by the well-known fact that along open, water-bearing, shear and fracture zones, under the action of surface waters, copper minerals suffer rapid alteration and transportation, and only in the uppermost parts of the sheared zone, especially where reducing agents have had play, do we find grains of metallic copper.

At present the deposits of commercial value are mainly those which are below the gossan and are confined to that part of the zone where enrichment has taken place. Wherever the products of enrichment are present chalcopyrite, chalcocite, covellite, etc., associated with zinc blende are found.

Some shipping ore in the Bully Hill district carries as much as 6 per cent. of copper, but the smelting ores, which furnish the bulk of the output, range from 3 to 5 per cent. of copper, and a few ounces of the precious metals, mostly silver, to the ton. The ores of the various mines, as well as different parts of the same mine, exhibit a considerable range in tenor. In the outcrop, where the gossan is in great abundance, small nuggets of gold have been found. It is from this source chiefly that gold has been derived for the placers.

There are many surface outcrops which still yield gold after the rock is crushed and panned. It follows, therefore, that the gossan carries higher values in gold than the ore extracted at depth.

Mineralogy of the Ores

Metallic Minerals (*Metals*).—Filaments of native copper occur in greatly altered and much-bleached country rock, detailed study of which indicates that originally the masses were rhyolites or rhyolite breccias. The surface rocks by early mining methods yielded notable amounts of native copper, but at present such materials are not an important source of the metal. Just how the copper accumulated is not known, but in all probability the presence of organic compounds played an important part in its reduction.

Practically all the gold obtained by hydraulic mining occurs in the native state. Although the particles are uniformly small they are usually visible on close inspection in all the detrital accumulations.

In the oxidized ore the gold occurs in a siliceous, limonitic matrix, which, without doubt, contributed to the placers of local areas. From the intimate relation of the gold with the gossan it is evident that a very close association exists between it and the original sulphur-bearing minerals. In the pyrites, however, the gold is in such a state of fine subdivision and is present in such small quantity that it has not been recognized under the microscope. While most of the gangue runs high in iron oxide, the gold is frequently closely associated with cryptocrystalline quartz. In the mine workings, and particularly in the vicinity of the basic dike, there appears to be a genetic relation and close association with barite and sulphides in which the gold is apportioned evenly through the mass. On the surface this mass alters to limonite, quartz, barite, kaolinite, and in a few places to hematite.

Native silver of delicate filiform and more solid shapes has been reported from the upper levels of the mine workings. It is commonly associated with the gold in the iron-stained capping rock, and occasionally with minute quantities of malachite and azurite. The largest and richest masses are found wholly within the oxidized zone quite near the surface. It decreases with depth and is generally accompanied by an increase in zinc and galena, minerals which seriously interfered with the early amalgamation methods adopted at Copper City. It may be stated that in general the occurrence of silver is less common than native copper.

Microscopic Characters of the Ores.—The material for microscopic examination was collected for the purpose of establishing the sequence of ore deposition. In order to study these problems, a series of selected specimens were polished and examined by reflected light, the general procedure following that of the recent researches of Prof. William Campbell and others.

The chief opaque minerals of interest which enter into the composition of the ores of the Bully Hill mining district are, in order of their importance, pyrite, chalcopyrite, blende, bornite, galena, and covellite, with minor amounts of chalcocite. Not infrequently transparent minerals also are present in the specimens, chief of which are quartz, calcite, and gypsum. These minerals, because of the close resemblance to each other when observed by this method, are best identified in sliced sections rather than by reflected light.

Pyrite.—Detailed studies show that in the freshest specimens of alaskite-porphyry there are no metallic sulphides which crystallized from fusion as did the other components constituting the rock mass. Pyrite is indeed found disseminated through the alaskite, but it is believed that it was formed at a time after the alaskite had solidified. In this occurrence the mineral usually forms aggregates and grains. Individual crystals of free growth and sufficiently large for recognition of the crystal

Fig. 12.—Lean Pyrite Ore with Veins of Chalcopyrite.
Reflected light. × 50 diameters.

habit are comparatively rare. Such faces as are visible indicate that the prevalent form is the pyritohedron, variously modified. When the crystals have been able to grow without mutual interference, which frequently happens in places filled with soft massive gypsum or kaolinite, the usual form assumed is a sharply defined cube, in some instances modified by octohedral and dodecahedral faces. Such forms have been noted particularly in the Delamar lode of Bully Hill. Some brilliant crystals have been found imbedded in a quartzose matrix just to the north of Bagster shaft. These studies show that pyrite was the first of the ore minerals to crystallize. Whether or not the pyrite is auriferous is not easily determined. That it is not highly so is certain, since tests of the most pyritous matter often show little or no gold, and an abundance of pyrite is generally a sign of poor rather than of rich ore.

Where the pyrite is in masses innumerable branching cracks traverse the specimen in every direction (Fig. 12). As far as could be determined, no other metallic mineral of importance could be seen. This fact does

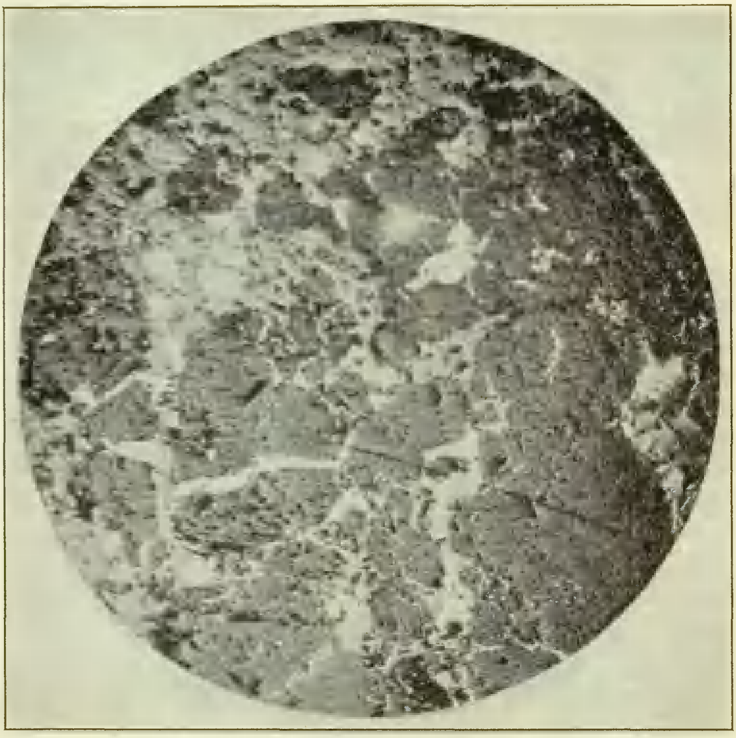

FIG. 13.—BRECCIATED COUNTRY ROCK.
Filling material chalcopyrite. Reflected light. × 50 diameters.

not fully coincide with the results of chemical investigation, because it is almost impossible to select any sample of lean pyrite that will not give traces of copper. Whether the pyrite contains minute grains of a copper mineral as a mechanical inclusion, or whether the pyrite is a lean chemical compound of copper and iron, could not be determined by this method of reflected light. Aside from the chemical tests the pyrite appears to be pure, and its deposition for convenience has been designated as the pyrite phase.

Chalcopyrite.—The second stage of ore deposition is apparently characterized by the introduction of chalcopyrite (Fig. 13). This primary mineral closely followed pyrite, although in rare instances, as stated by L. C. Graton,[12] "small grains of chalcopyrite. . . are inclosed in the pyrite individuals." Studies made by the writer point to the conclusion that chalcopyrite has been the last mineral to enter. This mineral completely surrounds the pyrite grains and in some instances enters the minutest fissures of the partly crushed pyrite masses. At times the pyrite and the chalcopyrite are so inextricably mingled that their physical appearances are almost identical, and it becomes difficult if not impossible to distinguish, in the hand specimen, one mineral from the other. In such cases simultaneous deposition may be employed to explain these complex relationships, although from the examination of many specimens the evidence indicates chalcopyrite as being later than the pyrite.

Sphalerite.—Like pyrite and chalcopyrite, sphalerite is one of the primary minerals and is everywhere crystalline. Sphalerite is later than pyrite and is seen to surround particles of this mineral. Unlike the pyrite with which it is so intimately related, it does not form well-bounded crystals even where conditions of free growth appear to have been favorable. The blende is so common throughout some of the ores, especially those near Copper City, that a zinc-extraction plant is now being constructed for its recovery. Near the surface it is easily oxidized, and, aside from a few occurrences, its products appear as sulphates on the walls of the mine workings.

Bornite.—The isometric sulphide of copper (peacock copper ore, Cu_5FeS_4), though moderately abundant as a secondary mineral, is very sparingly found in the primary ore of the district. It is always massive with a recognizable crystalline structure, and is generally met in forms irregularly rounded, closely related to the other sulphides. In no instance is it entirely isolated, but according to microscopic study it is intimately associated with pyrite and chalcopyrite, and in some cases clearly shows close association with sphalerite.

Galena.—Primary sulphide of lead occurs sparingly in the copper ores of the Bully Hill district. It is rarely isolated, but occasionally it is found sparsely disseminated through country rock at the Bagster shaft. It occurs in massive form, both cleavable and granular, rarely crystalline and never crystallized. It is not widespread in any of the mines studied and is found intimately associated with primary chalcopyrite, pyrite, and blende. It has been noted especially in the high-grade sulphide ores of the Delamar lode (Fig. 14) with the other sulphides. It does not occur, so far as known, in the workings of the Copper City or Rising Star mines. Since galena is rarely encountered in depth its alteration products

[12] *Bulletin No.* 430, *U. S. Geological Survey*, p. 103 (1910).

on the surface were not observed. It is quite probable that the galena as well as the blende is argentiferous, and that would explain the presence of high silver values in the gossan as well as in the regular mine-run of ore. It is plain from a detailed study of the relationships of the minerals that galena favors rich sulphides, especially where blende is in large amount.

Chalcocite.—The cuprous sulphide is not a common mineral in any of the ores of the district. It occurs as dotted masses intimately associated with bornite. Mr. Graton[13] states that chalcocite and bornite apparently

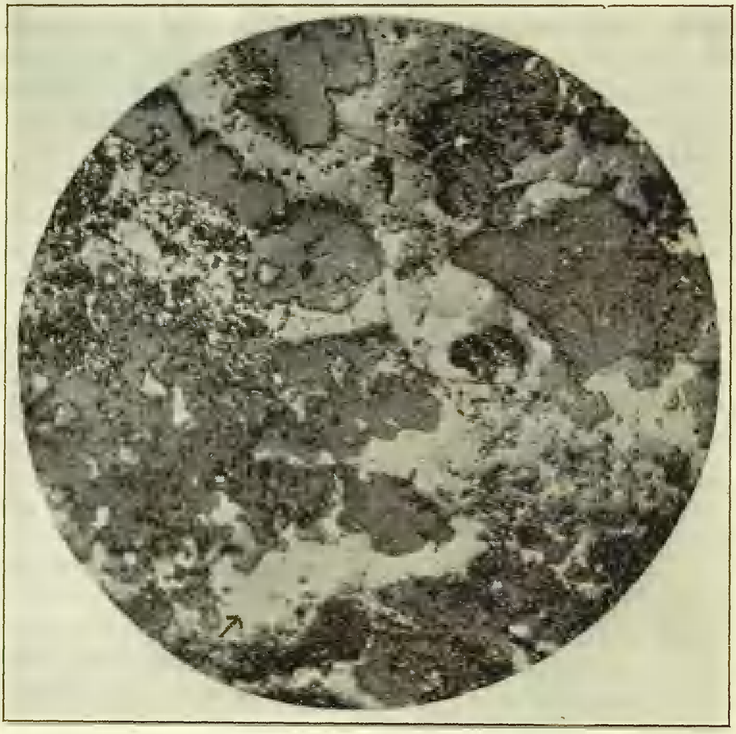

FIG. 14.—RICH COPPER ORE.

White areas, galena; darker, bornite and chalcopyrite; black, quartz. Reflected light. × 50 diameters.

take the place of chalcopyrite as an irregular network through and around the other sulphides. Chalcocite was found in small amounts in the deepest workings of the Bully Hill mine and has been regarded by Graton[14] as primary as well as secondary. From recent studies made by the writer, although not rigidly limited, it is generally confined to the upper levels in close association with other enriched sulphides.

[13] *Bulletin No.* 430, *U. S. Geological Survey*, p. 104 (1910).
[14] *Idem*, p. 105.

Secondary Enrichment

The oxidized zone in the Bully Hill district continues, in general, to unusual depths. The lower limit is known to be as low as the 1,000-ft. level. The ore in this zone is considerably enriched, and the enrichment was materially favored by the openness of the mass because of the abundance and relative size of the cracks and fissures, these being possible only in materials which are brittle, such as quartz and pyrite.

The profound modification resulted chiefly through the action of descending waters which in their downward course traversed zones in which small but important amounts of copper-bearing sulphides existed. The following equation illustrates the probable chemical reaction:

$$CuSO_4 + 2\ FeS = CuFeS_2 + FeSO_4.$$

As an illustration of the principles of ore deposition, or, rather, ore concentration, this chemical reaction can hardly be overestimated, and since the conditions assume the presence of copper minerals near the surface, this phenomenon is usually related to the second concentration. The first is believed to have been brought about chiefly through the action of ascending hot waters, while the second concentration is almost exclusively related to cool descending waters. It follows from this that if the concentration processes be regarded as cycles the first is far the more important, and as suggested was directly related to the intrusion of the acidic (alaskite) dike. Copper-bearing rock which probably contained less than 1 per cent. of copper will now show from 6 to 8 per cent. in the oxidized zone. Where the replacement has been complete more or less calcite, quartz, and barite are found. It should be stated, however, that while barite has been found in the ores it is not at all important. J. S. Diller[15] regards the barite as a primary constituent of the ores. Calcite and quartz are wholly secondary and occur more or less abundantly at all levels of the various mines.

In most cases observed the mineral relations are fairly definite and leave little room for question. In other relations there is room for more than one inference. The order given is believed to be correct in the main. The disturbing element in most instances is alteration. In no specimen is there any suggestion of a distinctive silver mineral, although the ores yield several ounces to the ton. The presence of other sulphides, notably arsenic and antimony, was not detected. The enriched sulphides taken from the deepest levels of the mines are indicative that the lower limit of descending circulating ground water has not been reached, and therefore that the zone of lean sulphides has not been entered.

One other mineral of great importance and intimately associated with

[15] *Redding Folio, No.* 138, *U. S. Geological Survey*, p. 12 (1906).

the ores, especially of the Bully Hill and Rising Star mines, is the hydrated sulphate of calcium, gypsum. L. C. Graton[16] reports anhydrite as well, but so far, the examination of many slides has not revealed its presence extensively. The explanation advanced for the gypsum will also account for the anhydrite, and this will be given in "The Gypsum Masses."

Genesis of the Deposits

The preceding pages set forth the problems awaiting solution, and only a brief recapitulation is deemed necessary of some of the most significant facts with which an adequate explanation of the ore genesis must harmonize.

The association of the ore deposits with the intrusives is interesting, and a study of the lean ores is one that promises to give most light on their origin. Due consideration must also be given to the mechanical alteration and subsequent changes wrought in the dike materials through which suitable solutions passed, and by which the concentration and enrichment of the ore bodies were made possible.

The fissures produced a weakened zone which not only permitted the solutions to circulate, but determined also the place where the intrusives (dikes) should pass. While it is believed that chemical alteration has facilitated important surface changes, the larger structures of the rock masses in depth are believed to have been caused primarily by deep-seated agents. As far as the andesite flows are concerned, detailed study shows that they were originally almost entirely free from all sulphides.

The limits of the belt which suffered shear in the area mapped are not definitely known, but from data at hand it appears that a strip which measures 1,000 ft. or more in width and several miles in length, at least, has been affected. This zone, which deviates locally, trends practically north and south over long stretches, and it is characterized from point to point not only by variation in width, but also by the degree of mashing and shearing.

A feature of economic significance and one that should receive attention is the fact that the greatest brecciated and comminuted section is not symmetrically located with reference to the side limits of the shear zone; but is decidedly to the eastern border of the belt. Thus in passing across the outcrop of the belt the first few hundred feet encountered closely resemble schists, while toward the west the degree of schistosity becomes less and less until finally the rock masses on the opposite border are practically free from such induced structures.

Another feature which is very conspicuous, especially in Bully hill, shows that locally there are at least three shear zones comprised within the belt. Together they embrace a total width from east to west of approxi-

[16] *Bulletin No.* 430, *U. S. Geological Survey*, p. 100 (1910).

mately 1,000 ft. They are seen in Fig. 6, looking northward, as a series of ridges in the profile of the hill. The eastern zone incloses the alaskite dike and contains the Delamar lode of Bully Hill.

The rough, rugged ridges are forms which have resisted erosion more effectively than the surrounding materials. With the exception to be noted, all such ridges are referable to silicified sheared rock, chiefly andesite flows and tuffs. It appears that the materials are mainly tuffaceous, of rather wide range with regard to fineness of grain; and it is believed that such materials, because of their porous character, permitted siliceous waters to circulate more freely than the more massive andesite flows. The solutions came from below and are believed to have transferred silica, which was derived from silicate minerals in the deeper parts of the crushed zone, to its present position. Weathering has also influenced the composition of such materials by dissolving out soluble constituents, so that in some areas the mass is rather porous.

The exception referred to above is found in the disconnected masses of alaskite-porphyry. This material, because of its position and external physical appearance, closely resembles the masses in the shear zones. Close inspection, however, shows the latter to contain small phenocrysts of quartz, while the former contains only secondary quartz. In some instances, especially where shearing has been excessive, and the rock is badly stained by iron oxide, identification can be established only by microscopic study. In the field the alaskite is often mottled with darker patches, and in most instances the rock breaks with conchoidal fracture. These serve as a guide, for such earmarks are never seen in the materials of the shear zone.

Attention will be directed first to relationships, and in this connection they will be described as a unit and will embrace the following elements: (1) what relation exists between the rhyolites and the copper ores; (2) between the alaskite and the copper ores; (3) between the andesite dike and the copper ores; (4) and lastly, between all these and the gypsum masses?

(1). The most important changes in the rhyolites previous to mineralization are those referable to mechanical alterations. The rock masses where brittle were broken and a zone of weakness was formed. After long-continued fracturing the intrusion of alaskite-porphyry followed the weakened zone and was accompanied by magmatic emanations which passed along the borders of the intrusive and were otherwise limited to the zone of mashing. These solutions were hot, especially rich in CO_2 at the beginning, and later they carried ore-bearing and silica compounds. It is believed also that these richly carbonated waters as they passed through the various limy strata dissolved large amounts of lime and transported it to the zone where vigorous shattering had taken place. This seems in accord with the facts, as the veins or fissures are chiefly filled with a mixture of calcite inclosing minor amounts of chalcopyrite and pyrite. The fissured rhyolites were thus cemented by these minerals.

(2). Long before the alaskite had completely solidified stresses again became operative, this time breaking the alaskite-porphyry and also disturbing the andesites. Mineralization and impregnation of this rock by metallic sulphides resulted It is therefore logical to make the statement that this is the first stage in the genesis of the copper ores. Accompanying this change, although not definitely connected with the deposition of the ores, was more or less sericitization, silicification, etc., in the rock masses.

The brecciation forces which acted on the alaskite-porphyry finally produced essentially the same shear planes that were observed in the inclosing andesites, so that both rock types behaved practically as a structural unit to all later phenomena. These were important stages in decomposing the constituent minerals, and they were followed by chemical modifications which were later represented by completely altered rock masses and the production of secondary silicates.

(3). Shortly after the production of the foliated structures igneous activity was again characterized by the intrusion of an andesite dike, which also followed the foliation planes, and in places cut across the alaskite-porphyry by intruding into the shear planes developed in its mass. Of all the rocks in the Bully Hill district this andesite dike was the last to appear and it closely followed the alaskite-porphyry. Outside the area mapped an intrusive rock, in composition more basic than those described, is known. From these relationships it is believed that each fraction from the original magma became progressively more and more basic, and that accompanying the last intrusion magmatic solutions rich in calcite and barite, together with metalliferous compounds, were also given off and reached the sheared zones. These solutions started out hot and in their upward journey they received heat and chemical energy from the dikes which had intruded the rocks and had not cooled entirely. They were thus effective agents and at once attacked the rocks which were most crushed and comminuted. The andesite dike in places was thus encroached upon by the carbonated compounds, and frequently entirely replaced.

Since the andesite dike is partly mineralized it follows that some of the economic minerals were deposited after the intrusion of the alaskite-porphyry. It is necessary in treating the genesis of the ores to account for the copper minerals in the alaskite. The most reasonable and logical explanation is that they were transferred by the agency of highly heated solutions. That some of the solutions contained lime is certain, because in the andesite dike numerous cavities filled with calcite exist.

Copper compounds in underground highly heated solutions are doubtless carried in many forms, probably more as acid compounds. Assuming that pressure and temperature are important factors at depth, a decrease in either of these might furnish conditions under which deposition would take place. Whatever the chemical nature of the solutions that transported the metallic sulphides, it is certain that they were deposited in the sheared alaskite-porphyry mass.

The magmatic solutions that followed the andesite dike contributed additional metallic sulphides, chief of which were blende, bornite, and galena. Important amounts of chalcopyrite were also introduced which greatly added to the richness of the ores. It should be stated that in all stages of mineralization the sheared rocks were impregnated indiscriminately. The element of control seems to have been the sheared zone. In several places the andesite dike is partly mineralized, but so far as known the ores appear only as a thin crust or veneer on the dike rock.

Several diamond-drill holes were driven through the andesite dike to ascertain conditions on the opposite side. No ores were found, and so far as known only the hanging-wall side of the dike contains sulphides. In the opinion of the writer the opposite side of the dike rock should be prospected, although it is quite possible that the position of the dike partly influenced the course of the solutions in such a way as to leave the rocks on the other side practically barren. So far, marketable ores have been found only on the west side of the dike.

It is not believed that there were open spaces in the rocks sufficiently extensive to account for the ores as they now appear. A characteristic of many thin sections is compactness rather than porosity, although the porous nature of the tuffs would be adequate to explain ease of circulation in any direction. The interpretation of the available evidence strongly supports the hypothesis of partial to complete replacement, and the facts upon which this view is based may be summarized as follows:

(1). The lodes preserve structures, especially schistosity, which exist in the country rock.

(2). Inclosed masses of partly replaced remnants of the original crush-breccia exist as cores.

(3). In all the ore associations, there is clearly to be seen a gradual transition from rich through lean ore to barren country rock.

The elements involved in the explanation are consistent with the facts and the hypothesis of replacement molecule by molecule of the rock masses by the ores seems to be justified.

In connection with the process of replacement, it is of interest to note how a very acid rock like alaskite, and for that matter the andesites as well, could be partly if not wholly replaced. It has been mentioned that the magmatic waters carried carbon dioxide and that lime was dissolved from strata through which such waters passed. Carbonated waters, as pointed out by Clarke,[17] are solvents for most of the common minerals, including quartz. It is believed that some of the solutions, thus carbonated, in passing through the disturbed zone attacked the acid as well as the basic rocks and left in most instances only the resistant minerals. Carbonate was in this way introduced, as shown in Fig. 15. It was accompanied in some instances by notable amounts of chalcopyrite.

Simultaneously with the introduction of carbonate, mineral hydration and removal went on, and in some rocks, especially the dike, considerable

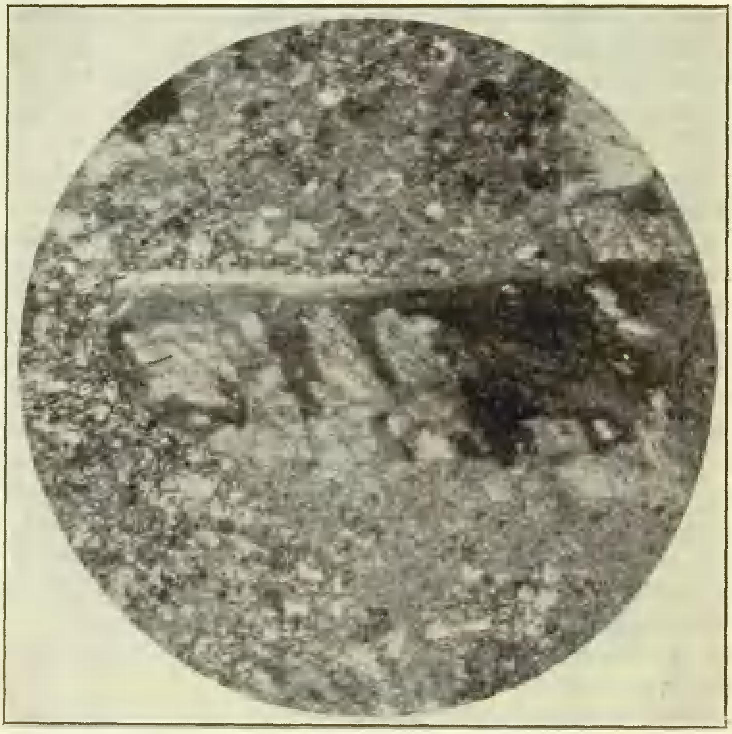

FIG 15.—FELDSPAR IN ANDESITE-PORPHYRY BEING REPLACED BY CALCITE. The felty areas are unaltered ground mass. × 50 diameters. Crossed Nicols.

chlorite was formed. The quartz grains of the alaskite-porphyry were corroded, and in some instances at least were completely removed. The removal of quartz is believed to have taken place through the influence of the alkaline solutions. This phase of the subject will receive detailed discussion under a later heading.

(4). The concordant testimony of a great variety of evidence from a large number of slides suggests several important phases of mineralization

[17] *Bulletin No.* 491, *U. S. Geological Survey*, p. 457 (1911).

processes. The study shows that there was a certain definite order or sequence of deposition, although these relations are partly obscured by the deposition of some compounds which began with the earliest stages and continued persistently through the entire process to the last stage. Such minerals as pyrite and quartz are the most important representatives of this class.

The important phases are those genetically related to carbonatization and sulphatization. From a study of thin sections, the former was a process by itself, while the latter included pyritization in addition to sulphatization.

The presence of certain minerals and their various mutual relationships suggest a common source, and also that the source was rich in the elements which form the compounds now found in the rocks. Carbonates, sulphates, and sulphides are seen in nearly every slide in varying amounts.

The most important geological factor which assisted the circulating solutions was undoubtedly the sheared structure of the rock masses. The solvent power of the solutions, under high temperature and pressure, was very great. The ferro-magnesian minerals were the first to be completely altered, and these changed chiefly to chlorite. The feldspars apparently were the next to yield, and alteration has gone on so completely that in most cases very little remains to suggest their former presence. In some of the ore samples grains of quartz, supposed to be the original phenocrysts, still remain, but these are usually badly corroded. Their relations to the ores are shown in Fig. 14.

VII. The Sulphate Deposits

In the following descriptions of the various types of sulphates, the rocks will be considered in order of their abundance as they have been found in the mine workings up to the time of the writing of this paper. Whether these relationships as they now exist will continue in depth is a matter on which we have no absolute data, and about which we can only speculate.

The sulphates constitute rocks of considerable importance in the mines of this district. Their existence on the surface with the exception of barite is unknown, and their extent in the working places, although conspicuous, is not usually well defined. The occurrence of sulphates underground is not limited to the upper oxidized zone, but these compounds are known to extend as low as the 1,000-ft. level (the lowest point reached in a shaft in 1912). Although, as previously stated, there are indefinite areal and vertical limits to the occurrence of the various sulphates, still there are fragmentary relationships existing between these compounds and the rocks which serve as a working basis for interpretation. The principal sulphates are gypsum, anhydrite, and barite.

Gypsum

The monoclinic hydrous calcium sulphate ($CaSO_4 2H_2O$) is first noticed in the mine workings near the 300-ft. level and from this point it continues downward to the lowest levels of the mine. It is usually of a light gray color, massive to banded, and rarely found in crystals. Its banded appearance is not due to any variation in its composition but is produced by inclusions of other rocks, the fragments of which have been arranged by shearing processes into roughly parallel positions.

At some points it is found in larger masses in a comparatively pure state, but the greater amount in the drifts and tunnels is streaked and locally contains pyrite. The larger masses are soft, usually white and everywhere crystalline. At times the pure fragments are translucent, and it is possible to secure masses several feet in dimensions. Where the rock is in such large masses it is very difficult to mine because of its soft character and its resistance to the action of explosives. For this reason, and also because of the expense of drifting through it, the limits of such masses are not known. Drifts in such bodies are characterized by being noticeably dry.

It is of interest to note that the gypsum as a whole is found limited to the shear zone in depth, and thus far has not been reported from any point on the surface. It is found only in the richest mines, intimately associated with the sheared rocks. In a general way it is seen in the hand specimen to surround masses and fragments of many of the rocks which enter into the structure of the hill.

Anhydrite

The anhydrous calcium sulphate, anhydrite ($CaSO_4$), is found in the rocks in very close association with gypsum. Like gypsum, it has never been found on the surface. In the fresh state it is marble-like in texture and varies in color from a dull white to various shades of light blue. It is never translucent, and is easily distinguished from gypsum in being harder and in having a pseudo-cubic cleavage in which the planes are perpendicular to each other, but of a somewhat differing degree of perfection. It is less abundant than gypsum and optically differs from it in having moderate relief and high double refraction. The rectangular cleavage is also marked. In thin section it is seen to have practically the same relationships as the gypsum.

Barite

Barite, the orthorhombic sulphate of barium, $BaSO_4$, occurs only sparingly in the mines of the district. It is a heavy light-colored mineral having vitreous luster. This mineral is the only sulphate found on the surface and is usually detected by its glistening crystal faces and the relatively great weight. According to Diller[18] the barium had its source in the feldspars of the alaskite-porphyry. After a number of careful tests the writer was unable to detect any barium in the feldspars of this dike rock. It is believed that the barium which furnished the barite had its origin in the same source which supplied the sulphides. Since this mineral is so sparingly present it will not receive further discussion.

Origin of the Deposits, with Special Reference to Gypsum

Before proceeding to a discussion of this subject a summary of the relationships of the gypsum is given. An effort has been made to bring together all the data bearing directly on the problem and also to condense, as far as possible, the descriptions of numerous slides examined. The statements represent facts gathered from the field as well as from detailed microscopic study. A few of the most important relationships are given below:

Field occurrences of gypsum:

1. It is found only in the greatest shear zones.
2. It is never found on the surface in the vicinity of the mines.
3. It begins on the 300-ft. level of the mine and extends to the lowest (1,000-ft.) level.
4. It does not occur outside the zone affected by shear.

Microscopic relations:

1. It replaces quartz grains and glass fragments.
2. It occurs as fissure fillings.
3. It is an alteration product after anhydrite.
4. It completely surrounds rock fragments.
5. It is intimately associated with the sulphides.

In order to explain the conditions given and to account for the origin of the gypsum in this deposit, it will be well first to outline the different theories advanced for the accumulation of gypsum the world over. These are: First, deposition from sea water. Second, deposition through volcanic agencies. Third, deposition by thermal springs. Fourth, deposition through the action of sulphuric acid, derived from pyrites, upon the carbonate of lime. Fifth, Hunt's[19] chemical theory of gypsum formation. This theory is somewhat complex, but Hunt believed it applied to a large part of the gypsum of marine and fresh-water origin. This theory does not apply in this case.

Applying these criteria to the deposit in this district we find that the

[18] *Redding Folio, No.* 138, *U. S. Geological Survey*, p. 12 (1906).

[19] *Quarterly Journal of the Geological Society*, vol. xvi, p. 154 (1860); *Chemical and Geological Essays*, pp. 80 to 92 (1874).

mode of formation as set forth by the first and fifth theories is not applicable. The second and fourth only demand careful consideration, and for convenience of discussion will be taken up in the reverse order.

Deposition through the Action of Pyrites upon Carbonate of Lime.—This method is perfectly possible and has taken place without doubt in an extensive way in nature, but there are certain initial conditions which do not appear in this region. First of all there must be deposits of limestone sufficiently large to form the gypsum deposit as it now appears. That sulphides oxidize to sulphates is well known. If we start with pyrite the final oxidation products are indicated by the following chemical equation:

$$FeS_2 + 7\ O + H_2O = FeSO_4 + H_2SO_4.$$

It is seen that one molecule of pyrite will yield one each of $FeSO_4$ and H_2SO_4. To be on the safe side, it is assumed that both $FeSO_4$ and H_2SO_4 operate to produce sulphate of lime, although it is very doubtful if the ferrous sulphate acts in this manner. The molecular weight of gypsum is 172 while that of pyrite is 120. If these be converted into molecular volumes it is found that for 74.8 volumes of gypsum we require 24 volumes of pyrite, or that for every 100 volumes of gypsum there must be 32 volumes of pyrite, on the basis that H_2SO_4 only goes to make up the sulphate. Under these conditions, and also assuming that the gypsum in territory not yet explored is as thick as that already found, a uniform bed of pyrite approximately 224 ft. thick would be required. If, however, both $FeSO_4$ and H_2SO_4 go to form the sulphate, then one-half of this thickness would suffice. There is no evidence that any such deposit of pyrite ever existed in the district.

By the same method of reasoning it is found that to account for the calcium in the gypsum a bed of carbonate approximately 350 ft. thick would be required. There is no evidence that any such bed of carbonate ever existed in the mine workings. On the other hand, there is distinct proof that clastic volcanic rocks, or their remnants, are the dominant rocks of the district. The failure of this theory to explain the deposits makes it evident that this method of origin could not have been the one to which this deposit owes its existence.

Deposition from Thermal Springs, and Through Volcanic Agencies.—These two theories have been grouped as one, since their effects from a geological point of view are very similar. It is well known that emanations from deep-seated cooling igneous magmas are numerous, and, as shown in an important paper by Lincoln,[20] consist of acids, gases, and sublimates.

By referring to the structural section, Fig. 1, it will be seen that a massive limestone (the McCloud) has been involved in the folded and otherwise compressed strata. Since this limy member was in the crush

[20] *Economic Geology*, vol. ii, No. 3, p. 258 (Apr.–May, 1907).

zone through which the emissions of the igneous magma passed, it is perfectly reasonable that the rock would suffer more or less solution by the acid liquid solutions. These may have been in part water containing CO_2, SO_2, SO_3, or SO_4. Any of these alone would dissolve the lime carbonate and transport large amounts to higher points. Whether the lime was carried as carbonate or sulphate or as a mixture of the two is a matter about which we can only speculate. It is possible that certain solutions were chiefly carbonate while others were sulphate in general composition. That both solutions existed is shown by the presence of carbonate as well as sulphate in the rocks, but since sulphate is in largest amount it follows that solutions of this character were dominant.

Whether the sulphate was deposited as anhydrite or as gypsum is not certain, although Graton[21] from his studies concludes that anhydrite is primary and that gypsum is a secondary product derived from anhydrite. There is room for further study on this point because of the well-known fact that gypsum may be transformed into anhydrite,[22] or that the reverse reaction, anhydrite into gypsum, may readily take place. Furthermore, it is known that anhydrite thus formed may be reconverted into gypsum.[23]

The writer is fully aware, however, that within the limits of experiment the solubility of sulphate increases up to about 38° C. and then decreases for additional increments of temperature. This is somewhat against the theory of transportation of sulphate, but there are so many variable factors which tend to offset this decrease in solubility that we are driven to the conclusion that these sulphate deposits have accumulated by the transportation of lime by magmatic solutions from deep-seated sources.

Considering the origin of the gypsum deposit as well as that of the metallic minerals so closely associated with it, this theory seems to accord most satisfactorily with all the fundamental relations and facts brought out by detailed study.

VIII. Summary

From the previous descriptions and discussions, and also from a detailed study of all available data bearing directly upon the deposits of this character, the following general conclusions seem to be warranted:

1. The structure is conspicuously closely crumpled, and where slightly overturned the folds are accompanied by breaks which result in a tendency to develop weak crush and shear zones along the chief planes of movement.

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[21] *Bulletin No.* 430, *U. S. Geological Survey*, p. 100 (1910).

[22] *American Chemical Journal*, vol. xi, p. 31 (1889).

[23] F. Hammerschmidt: *Mineralogische and Petrographische Mittheilungen, vol.* v, p. 272 (1882–83).

2. The copper ores of the Bully Hill district were originally deposited from magmatic solutions in which the metals were transported as soluble sulphides and were deposited as such.
3. From the character of the metallic sulphides, the associated minerals, and the structural relationships, it appears that replacement has been the dominant process in these deposits.
4. The accumulation and concentration of the ores as they are now found involves secondary enrichment, changes in which precipitation by mingling solutions and reactions on wall rock are of greatest importance.
5. The mineralization processes have apparently taken place under conditions which were entirely independent of rock mass control, as tuffs, flows, and dikes, differing widely in physical and chemical make up, are indiscriminately replaced.
6. The lime as calcite, and the sulphate either as anhydrite or gypsum, had an origin in deep-seated sources, and both these minerals were genetically related to the sulphidation process which has given rise to the ores.

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