Geology and Ore Deposits of East Shasta Copper-Zinc District Shasta County, California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 338

Prepared in cooperation with the State of California, Department of Natural Resources, Division of Mines

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By JOHN P. ALBERS *and* JACQUES F. ROBERTSON

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GEOLOGY AND ORE DEPOSITS OF EAST SHASTA COPPER-ZINC DISTRICT, SHASTA COUNTY, CALIFORNIA

By JOHN P. ALBERS and JACQUES F. ROBERTSON

ABSTRACT

Introduction.—The East Shasta copper-zinc district in central Shasta County, northern California, lies largely in the southern Klamath Mountains and includes the eastern part of what has long been known as the Shasta copper belt. The principal base-metal mines are the Bully Hill, Rising Star, and Afterthought mines. The area mapped includes about 90 square miles. A large part of Shasta Lake, which was formed by the impounding of the waters of the Sacramento, McCloud, and Pit Rivers, and of Squaw Creek behind Shasta Dam, is within the boundaries of the area mapped. Maximum relief is about 3,500 feet. The highest mountains are Horse and Town Mountains, which rise to altitudes of more than 4,000 feet.

General geology.—The area is underlain by interbedded sedimentary and volcanic rocks that range in age from probable Middle Devonian to Late Triassic. These rocks were laid down in a eugeosynclinal trough that was elongate in a north-south direction. The thickness of the stratigraphic section totals about 20,000 feet, of which 50 to 60 percent is volcanic rock. During Late Jurassic or Early Cretaceous time the layered rocks were folded and faulted, and were intruded by a small stock of granodiorite, by an irregular elongate mass of mafic quartz diorite, and by many dikes and sills of fine-grained mafic igneous rocks. The assemblage of sedimentary, volcanic, and intrusive rocks listed above are the basement rocks of the area. In places in the southeastern part of the area the basement rocks are overlain unconformably by a poorly lithified tuff breccia of Pliocene age and by basaltic lava of Pliocene or Pleistocene age. Recent slope wash, talus, landslide debris, and alluvium obscure the bedrock in much of the area.

Copley greenstone, consisting of 2,000 feet or more of intermediate lavas (keratophyre) and pyroclastic rocks is the oldest rock unit exposed. The age of the Copley is not precisely known but this formation underlies rocks of Middle Devonian with apparent conformity and is presumed to be Devonian.

The Balaklala rhyolite, a series of silicic lava flows and pyroclastic rocks altered to quartz keratophyre, overlies and is interbedded with the Copley greenstone on the west side of O'Brien Mountain. The Balaklala, which is highly lenticular and of small areal extent, has a maximum thickness of about 1,000 feet in the East Shasta area.

Overlying the Balaklala rhyolite and Copley greenstone with structural conformity is the Kennett formation, composed of shale, tuff, and limestone. The thickness of the Kennett ranges from 0 to about 400 feet. It is the oldest formation exposed that contains fossils and is of Middle Devonian age.

The Bragdon formation of Mississippian age and consisting of shale, mudstone, conglomerate, and minor tuff, overlies the Kennett with probable unconformity. The Bragdon ranges in thickness from a thin film to about 3,000 feet.

The Baird formation of Mississippian age overlies the Bragdon in the stratigraphic column. These two units are probably separated by a disconformity but the evidence is inconclusive. The Baird is 3,000 to 5,000 feet thick and it consists of mafic to intermediate pyroclastic rocks and flows, mudstone, and minor limestone and chert. The formation contains abundant fossils of Mississippian age.

The McCloud limestone is next above the Baird formation but the two units are almost everywhere separated by intrusive rocks. The McCloud consists of medium-gray limestone with chert lenses and nodules. It contains abundant fusulinids and other fossils of Permian (Hueco) age. The thickness of the McCloud is difficult to determine because the formation is not everywhere present and is separated into discrete blocks by faults filled by intrusive rocks. The maximum thickness is probably about 2,500 feet.

The Nosoni formation, also of Permian age, is the next younger unit above the McCloud limestone but the two formations are separated by a fault along which mafic quartz diorite is intruded. Probably owing in part at least to this fault the Nosoni is missing in some places. The Nosoni, which contains abundant fossils of Permian (Leonard or Guadalupe) age, consists chiefly of mudstone and fine-grained tuffaceous rocks. The maximum thickness of the Nosoni is about 2,000 feet.

Overlying the Nosoni formation with probable erosional discordance is the Dekkas andesite, which consists chiefly of mafic to intermediate lava flows and pyroclastic rocks now altered to spilite and keratophyre, and lenses of mudstone. Some of the mudstone lenses in the lower part of the Dekkas contain fusulinids of late Permian (Guadalupe) age. The upper part of the Dekkas, which consists chiefly of lava flows, may be of Triassic age. The thickness of the Dekkas andesite ranges from 1,000 to 3,500 feet.

The Dekkas andesite is overlain by the Bully Hill rhyolite, a series of silicic lava flows and pyroclastic rocks largely altered to quartz keratophyre. Silicic rocks typical of the Bully Hill rhyolite are locally interbedded with the Dekkas andesite, and mafic rocks typical of the Dekkas andesite are likewise interlayered in places with the Bully Hill rhyolite. This interlayering indicates that the volcanism which gave rise to the Dekkas andesite continued intermittently after extrusion of silicic lavas of the Bully Hill rhyolite had commenced. The thickness of the Bully Hill rhyolite ranges from about 100 feet to possibly 2,500 feet.

The Pit formation, which conformably overlies the Bully Hill rhyolite, consists principally of shale, mudstone, and pyroclastic rocks, and subordinate limestone and siltstone. The pyroclastic rocks are lithologically similar to those in the Bully Hill rhyolite, indicating that the volcanism that give rise

to the Bully Hill rhyolite continued sporadically after deposition of the Pit began. The Pit formation contains fossils of Middle and Late Triassic age and reaches a thickness of about 5,000 feet.

The Hosselkus limestone of Late Triassic age conformably overlies the Pit formation. The Hosselkus, which forms the northeastern boundary of the area, was not studied in detail.

A small stock of granodioritic rock, referred to in this report as the Pit River stock, partly altered to albite granite intrudes the above sequence of sedimentary and volcanic rocks. Many dikes of altered fine-grained mafic quartz diorite, metadiabase, and dacite porphyry also intrude the sequence. These intrusive rocks were emplaced after the sedimentary and volcanic rocks were deformed and are of probable Late Jurassic age.

Rock alteration.—Practically all the basement rocks in the district have undergone some form of alteration. Most of the volcanic rocks and the majority of the intrusive rocks are mineralogically reconstituted to a great or less extent but retain their original texture and structure. Only locally in the extreme southeastern part of the area and in the vicinity of Bully Hill where the rocks have a secondary foliation are the original texture and structure largely obliterated. Sedimentary rocks, because of their more stable mineral assemblages, have undergone less alteration than volcanic and intrusive rocks.

Alteration processes that have been operative in the area include dynamic, igneous, and hydrothermal metamorphism. The alteration of rocks with secondary foliation, mainly in the eastern part of the district, is ascribed in part to dynamic metamorphism but this process was relatively unimportant for the district as a whole. Igneous metamorphism has resulted in the local recrystallization of rocks adjoining the Pit River stock to hornfels, and in the recrystallization of the McCloud limestone to marble near the Shasta Iron mine. Bodies of skarn, consisting of lime silicate minerals and magnetite, have formed by contact metasomatism locally in rocks adjacent to the quartz diorite along the McCloud fault. Hydrothermal metamorphism was the most important alteration process in the area. It resulted in widespread metasomatic albitization, chloritization, and silicification, and in somewhat more restricted hydrous mica alteration and calcitization. Sodium and silicon were the main constituents added during the alteration process and calcium was the main constituent removed.

Structure.—The sedimentary and volcanic components of the basement rocks are complexly deformed by folding and faulting. The oldest formations are exposed in the core of a large anticline, the O'Brien Mountain anticline, in the western part of the area, and successively younger rocks crop out toward the east in a sequence that is homoclinal. The trend of the O'Brien Mountain anticline and of major rock units in the homocline is north-northeast. A few small folds, and a fault between the McCloud and Nosoni formations along which mafic quartz diorite is intruded, disrupt the homocline in the western part of the area. In marked contrast to the north-northeast structural trend shown by the outcrop pattern of major rock units, a northwest trend, defined by a series of northwestward-trending folds and a steeply dipping secondary foliation predominates in the eastern and southeastern parts of the area. Lineations and observed plunges indicate that these northwestward-trending folds plunge alternately northwestward and southeastward. Weakly developed northwestward-trending cross folds are superimposed on the north-northeastward-trending anticline and homocline in the western part of the area.

The sedimentary and volcanic basement rocks are also disrupted by a series of high-angle faults and shear zones in addition to the preintrusive fault that separates the McCloud and Nosoni formations. In the eastern and southeastern parts of the area these high-angle faults strike predominantly northwestward, but from Bully Hill and vicinity westward faults that strike northeast are about as abundant as those that strike northwest and are probably of greater importance. The high-angle faults are subdivided into strike and transverse faults. On most of the high-angle faults the hanging wall is displaced downward with respect to the footwall, but most of the larger faults show either strike-slip or reverse movement. Because of the lack of reliable reference beds and parallelism of many faults to the strike of rock units, the displacement could be determined on only a few of the high-angle faults. The Main fault in the Afterthought mine, a reverse fault with a probable dip-slip displacement of 450 to 500 feet, has the largest determinable displacement, but is probably not the largest fault. In the central and extreme southeastern parts of the area the Bully Hill rhyolite and Pit formation are cut by shear zones consisting of crushed and highly schistose rock. These zones are as much as 1 mile long and 200 feet thick. Thin sections show that a good deal of distributed movement has taken place within the shear zones, but adjacent rock units seem to be displaced very little by the shear zones.

Folding occurred in two stages. The north-northeast folds were formed first, followed by the formation of the northwest folds at a later stage. Most of the faulting occurred during the latter part of the later stage. The Pit River stock was probably emplaced after the northeast folds were formed but the mafic quartz diorite and related rocks occupy faults and fractures formed mostly during the later stage of deformation when the northwest folds and the McCloud fault were formed. Mineralization postdated most rock deformation, as shown by the fact that sulfide bodies are localized mostly along shear zones and faults.

Although many unconformities and an abundance of volcanic material and orogenic sediments indicate that the East Shasta area was tectonically unstable at least from Devonian through Triassic time, all the recognizable folding and faulting, as well as igneous intrusion, rock alteration, and mineralization, probably took place during Late Jurassic or possibly Early Cretaceous time.

Postorogenic history.—The Tuscan formation of Pliocene age, consisting of poorly lithified tuff breccia, overlies the basement rocks in the eastern part of the area with marked unconformity. The Tuscan is overlain in turn locally by basaltic lava flows.

The basement rocks are also masked in places by slope wash, talus, landslide debris, and alluvium.

Weathering extends to depths ranging from a fraction of an inch to as much as 300 feet, but in most places it extends to depths of only a few feet. Feldspathic rocks are weathered most easily and commonly yield a rotten rock with a red or buff coloration.

The area lies mostly in the Klamath Mountain geomorphic province but that part of the area south of the Pit River arm is in the Cascade Range province. Two of the five main streams, the Sacramento and McCloud Rivers, are nearly parallel to the gross structure but the other three—Little Cow Creek, the Pit River, and Squaw Creek—are transverse to the structure. Since the Tuscan formation was deposited, Little

Cow Creek has incised itself into the basement rocks 600 to 800 feet, and the Pit River has cut its canyon 375 feet into the basement rocks. This indicates that the area has been uplifted since Pliocene time.

Mineral deposits.—From 1900 through 1952 nearly 60 million pounds of copper, 50 million pounds of zinc, and significant amounts of silver, gold, and lead were produced from the district. The total value of these metals is about $16 million, of which copper has accounted for about half. The district has also yielded several hundred thousand tons of iron ore the value of which is not known. Mining activity, which began in 1853 with the discovery of placer gold in Town Creek east of Bully Hill, has been sporadic. The principal periods of activity were from 1900 to 1910 when copper was the principal metal produced, and from 1922 to 1927 when zinc was produced. The most recent production from the district was from 1949 to 1952, when copper-zinc ore was produced.

Three types of deposits in the district are (a) massive sulfide replacement deposits (b) contact metasomatic magnetite deposits, and (c) gold-bearing quartz veins. Virtually all the base and precious-metal production has been from the massive sulfide deposits.

The massive sulfide deposits are lenses ranging from a few inches to 400 feet in greatest dimension. They are localized along shear zones in the Bully Hill rhyolite and along fault contacts between the Bully Hill and Pit formations. The sulfide replaces either sheared and altered quartz keratophyre or shale. Sulfide lenses are commonly closely grouped along shear zones, but isolated lenses are not rare. Contacts between massive sulfide and country rock are in most places sharp but in a few places gradational. Typical ore is an intimate mixture of fine-grained pyrite, sphalerite, and chalcopyrite, and smaller amounts of galena, tetrahedrite-tennantite, and bornite. Gangue minerals, which are intimately mixed with the ore minerals, include barite, quartz, clay minerals (mainly hydrous mica), chlorite, anhydrite, gypsum, and calcite. Anhydrite and gypsum occur only at the Bully Hill and Rising Star mines. Much of the ore is banded parallel to foliation or bedding in the host rock. Typical ore assays 15 to 20 percent zinc, 3 percent copper, 1 or 2 percent lead, 5 ounces of silver, and 0.03 ounce of gold. Although reversals are not uncommon the general paragenetic sequence among the principal ore minerals is, from oldest to youngest: pyrite, sphalerite-chalcopyrite, bornite, and tetrahedrite-galena. The gangue minerals are mostly older than the ore minerals and there seems to be no consistent age relation among them. In general, microcrystalline quartz is oldest, calcite and anhydrite are youngest, and barite, hydrous mica, and chlorite are intermediate in age. In places stringers and veinlets of quartz, calcite, barite, and anhydrite or gypsum cut sulfides, indicating at least two stages of deposition for these gangue minerals.

Rocks in the vicinity of sulfide deposits are in general more strongly silicified and altered to clay minerals, mainly hydrous mica, than elsewhere, but no distinctive alteration envelope surrounds individual sulfide lenses.

The structural environment indicates that the sulfide lenses were localized mainly along zones of crushed, brittle, silicified Bully Hill rhyolite but partly along fault contacts between the Bully Hill and Pit formations. The faults and shear zones served as feeder channels. Deposition in some places occurred beneath the intersection of a feeder channel and a fault that cuts the feeder channel at a considerable angle and formed an impermeable barrier that retarded the ascending mineralizing fluids. In other places, deposition of sulfide ore occurred where the dip of the feeder channel flattens slightly or where drag folds in shaly beds retarded the mineralizing fluids.

The massive sulfide lenses are of replacement origin, as shown by: (a) the unsupported masses of country rock within sulfide lenses; planar structures in many of these masses are demonstrably concordant with those in the rock enclosing the sulfide lens, showing that the horses of country rock were not moved during mineralization; (b) banding in the sulfide at places parallels bedding or schistosity in the country rock; the banding is nowhere crustified as might be expected if the deposits were fissure fillings; (c) the presence, in some places, of a gradational contact between massive sulfide and country rock.

The deposits probably formed from ascending hydrothermal fluids. Two possible sources of these fluids and the substances they carried were: (a) a subjacent igneous mass of which the Pit River stock may be a cupola; and (b) the volcanic and sedimentary rocks that lie beneath the Bully Hill rhyolite and the Pit formation.

A subjacent igneous mass of trondhjemite and quartz diorite beneath the East Shasta district seems highly probable. The Pit River stock is probably one cupola of this mass, and others, outside the boundaries of the district, include the Mule Mountain stock in the West Shasta district and a small body of quartz diorite about 5 miles southeast of the East Shasta district. The location of sulfide deposits near the Mule Mountain stock in the West Shasta district suggests a genetic relation to the stock. No similar spatial relation between sulfide deposits and the Pit River stock can be demonstrated in the East Shasta district. Nevertheless, the possibility that the mineralizers were derived from the postulated subjacent mass cannot be dismissed.

Quantitative spectographic analyses show that the copper contained in samples of volcanic rocks from the Dekkas and Baird formations remote from mineralized areas is about 0.01 percent, or about the average for the earth's crust. The zinc content of these rocks is about 0.030, which is 2 to 3 times greater than the average of 0.013 percent for the basic igneous rocks. No quantitative data are available for the Copley greenstone but because of its lithologic similarity to the greenstone of the Dekkas and Baird it seems fair to assume that it contains similar amounts of copper and zinc. Using the most conservative values for copper and zinc content, the Dekkas and Baird formations, and probably the Copley as well, contain about 1 million tons of copper and 2½ million tons of zinc per cubic mile. Thus it seems that these rock units would have been a more than adequate source for the 30,000 tons of copper and 25,000 tons of zinc that the district has so far produced.

Assuming that the mafic volcanic rocks of the eugeosyncline were the source of the mineralizing fluids, two mineralization mechanisms are suggested. One would require that by an increase in temperature and pressure during orogenesis, sea water held in pore spaces of the rocks was mobilized and thereby made a vehicle of transport for the mineralizing substances. These hydrothermal fluids moved generally toward areas of lower pressure such as provided by faults and shear zones, carrying in solution small amounts of metals and sulfur derived from the rocks through which the fluids passed. The faults and shear zones served as collecting channels for the mineralizers, and finally, in siliceous, much fractured rock such as the Bully Hill rhyolite, as loci of deposition. This mechanism requires a pervasive movement of fluids through the pore spaces of the rocks but the regional metasomatic

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albitization and chloritization by hydrothermal processes indicates that such pervasive movement has taken place in the district.

An alternative mineralization mechanism might result from the granitization of mafic volcanic rocks buried deep in the geosyncline. In the formation of a granitic rock by replacement processes the valuable elements of ore deposits are concentrated in inverse ratio to the extent to which they are incorporated by isomorphous substitution in the common rock forming minerals. Consequently, in the granitization of mafic rocks rich in metals such as copper and zinc, the metals cannot all be incorporated into the granitic rock by isomorphous substitution but are expelled into the surrounding rocks. There is evidence suggesting that some granitic rocks in the district formed in part by replacement processes. Thus the possibility exists that a significant volume of Copley greenstone and other mafic rock deep in the geosyncline was replaced or assimilated by granitic rocks, or converted to granitic or quartz dioritic magma by palingenesis. If so, the copper and zinc expelled would have been available for concentration in structurally favorable places higher in the crust.

The depth at which the sulfides formed was not greater than 11,500 feet, as this is the maximum thickness of the stratigraphic sequence that could have overlain the Bully Hill rhyolite. Inasmuch as deformation largely preceded sulfide mineralization it seems probable that considerable erosion of the stratigraphic sequence took place before mineralization; thus the deposits may have formed at depths much less than 11,500 feet.

Five blocks of ground are outlined as geologically favorable for prospecting. High-grade sulfide lenses may be present in these areas. However, judging from known deposits, they will be small and hard to find. Detailed mapping of shear zones and faults and prospecting by geophysical methods should precede diamond drilling in any search for hidden sulfide deposits.

The principal base-metal mines and prospects in the district are described.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The area described in this report includes about 90 square miles in west-central Shasta County, Calif. (fig. 1). It lies in the southern Klamath Mountains and includes the eastern part of what has long been known as the Shasta copper belt. Inasmuch as sulfide deposits in the eastern part of the Shasta copper belt contain at least as much zinc as copper the area is here called the East Shasta copper-zinc district.

The area mapped measures about 17 miles in an east-west direction by 5 miles in a north-south direction and includes parts of the Lamoine, Bollibokka Mountain, and Millville 15-minute quadrangles. The area mapped is bounded on the west by long 122°22½′ W., and on the south by lat 40°45′ N., although the extreme southeastern part extends about 3 miles south of that parallel.

U.S. Highway 99, and the Southern Pacific railroad cross the western part of the area, and U.S. Highway 299E crosses the southeastern part. A large part of Shasta Lake lies within the boundaries of the area and much of the central part including the Shasta Iron mine and most of the area west of Horse Mountain, is accessible only by boat. The Bully Hill mine is accessible by boat or via U.S. Highway 299E and a good dirt road.

TOPOGRAPHY

The topography ranges from that of a partly dissected plain with a few hundred feet of relief in the southeastern part of the area, to that of a rugged, maturely dissected surface with more than 3,500 feet of relief in the north-central part (pl. 1).

North of Backbone Ridge the canyons of Squaw Creek and the Pit, McCloud, and the Sacramento Rivers, now inundated by the waters of Shasta Lake, are the dominant topographic features. The highest peaks are O'Brien Mountain, altitude 2,709 feet, on the divide between the Sacramento and McCloud arms of Shasta Lake, Horse Mountain, altitude 4,025 feet, and Town Mountain, altitude 4,325 feet, on the divide between the McCloud River and Squaw Creek arms, and Brock Mountain, altitude 2,724 feet, on the divide between the Squaw Creek and Pit River arms. The waters of Shasta Lake have a maximum altitude of 1,065 feet but generally are at an altitude of 1,000–1,050 feet. The maximum depth of the lake is about 350 feet.

South of Backbone Ridge, the canyon cut by Little Cow Creek, about 800 feet deep, dominates the topography. The uplands on either side of Little Cow Creek canyon have gentle relief.

CLIMATE AND VEGETATION

The climate is characterized by hot, dry summers, and cool wet winters. A weather station near the junction of the Pit and McCloud River arms of Shasta Lake was established by the U.S. Bureau of Reclamation in 1947. Records for the 5-year period from January 1, 1948 through December 31, 1952 show a mean annual temperature of 60.78°F, and a mean annual precipitation of 61.79 inches.[1] The mean average temperature during the coldest month, January, was 42.04°F for the 5-year period, and a minimum of 22°F was recorded on January 25, 1950. The mean average temperature in July, the hottest month, was 80.86°F for the 5-year period. The highest reading, 111°F, was recorded on September 2 and 3, 1950.

Most hill slopes in the area are brush covered, principally with manzanita (*Arctostophylos* sp.). Several species of scrub oak and chaparral are other common types of brush, one of which generally predominates on a given hill side. At higher altitudes, especially on

[1] Weather data furnished by U.S. Bureau of Reclamation, (written communication, 1948–52).

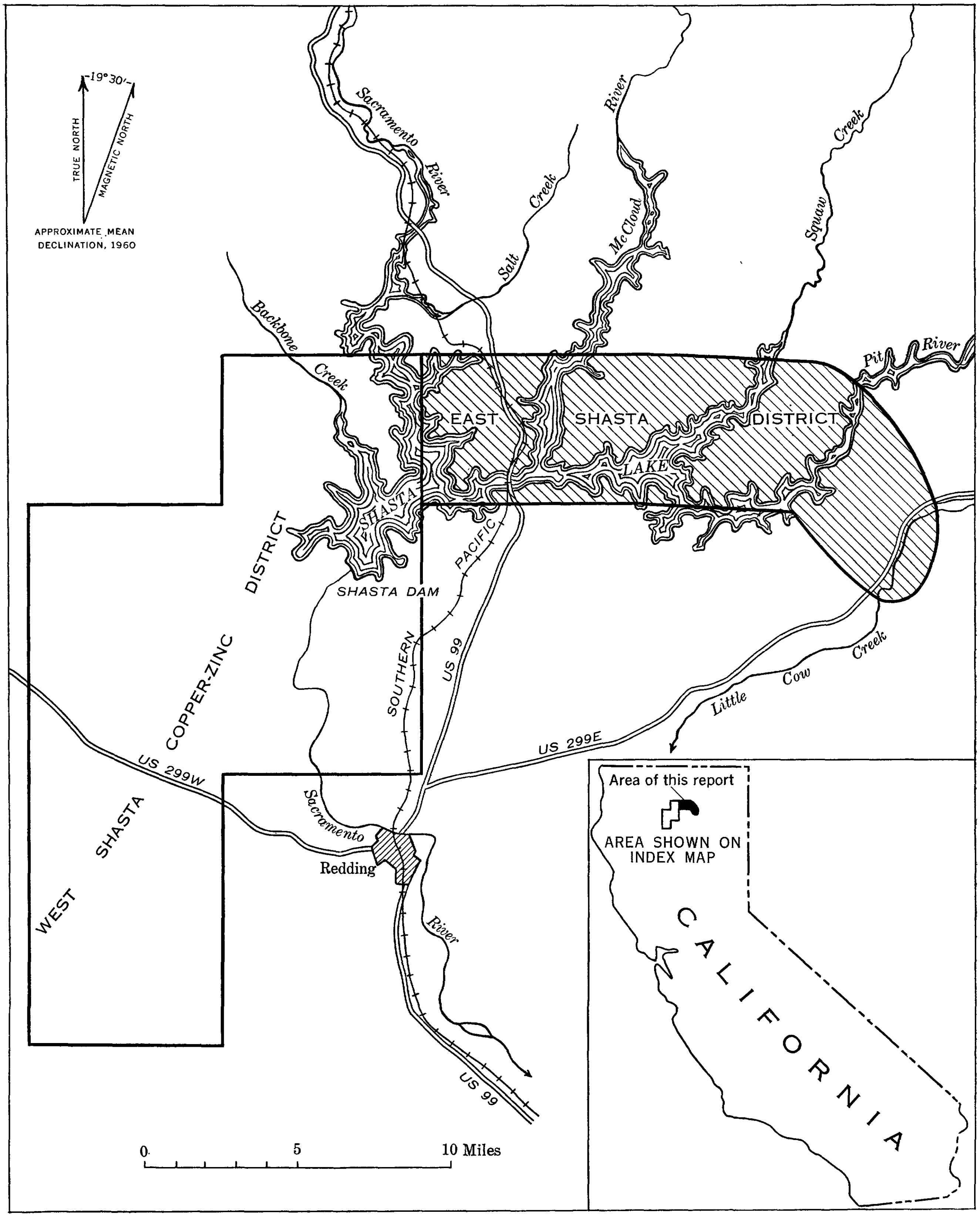


FIGURE 1.—Index map showing location of the East Shasta copper-zinc district.

north hill slopes, groves of sugar pine (*Pinus lambertiana*), and ponderosa pine (*P. ponderosa*) stand out in marked contrast to the surrounding brush-covered areas. At lower altitudes, especially in the southeastern part of the area, digger pine (*P. sabiniana*), and oak (*Quercus douglassi*), and (*Q. wizlezenii*) dot many of the low, grassy hills.

PREVIOUS WORK IN DISTRICT

Many geologists have worked in the area covered by this report and geologic literature is abundant; however, most earlier reports were based on reconnaissance surveys.

The earliest reference to the geology of the area is in a report by Trask (1855), in which, referring to the formation now called the McCloud limestone, he mentions the "Carboniferous limestone" that forms the "limestone mountains" along the McCloud River.

After Trask's reconnaissance, no further geologic work was done in the area until the early 1890's but from 1893 to 1906 several geologic reports were published. A broad-scale geologic map of northern California by Diller (1893), and a report on the geology and mineralogy of Shasta County by Fairbanks (1893) were published in 1893. Included in Fairbanks' report is a map of the county, showing large-scale geologic features.

Smith (1894) reported on the stratigraphy and paleontology of the deformed rocks and described part of the stratigraphic column. Hershey (1901), in a report describing the metamorphic formations of northwestern California, briefly mentions the rocks east of the Sacramento River in the present area.

The general stratigraphy of the Klamath Mountains, and also the geology of the copper deposits in the Redding area, were reviewed by Diller in 1903 (1903a, 1903b); in 1906 the Redding folio, also by Diller (1906), was published. The excellent geologic map and descriptive text in the Redding folio has served as a basis for practically all geologic work done in the Redding area since 1906.

In a report by Graton (1910) on the copper deposits of the Shasta region brief reference is made to the Bully Hill, Copper City, and Afterthought mines. The geology of the Bully Hill mining district was described by Boyle (1914).

More recent literature on the geology of the area includes reports by Hinds (1932) on the "Paleozoic eruptive rocks" of the southern Klamath Mountains, Hinds (1933) on the geologic formations in the Redding and Weaverville quadrangles, Hinds (1935) on "Mesozoic eruptive rocks" of the Klamath Mountains, and Hinds (1940) on the Paleozoic section in the southern Klamath Mountains. Wheeler (1940) refers to the Dekkas andesite in a discussion of Permian volcanism in western North America. The geology of the Shasta Iron mine is described in a report by Lamey (1948), and the geology of the Afterthought mine is described in a report by Albers (1953). A report by Kinkel and others (1956) [1957] describes the geology and base-metal deposits of the West Shasta copper-zinc district, which adjoins the area on the west.

In addition to the literature mentioned above short references to mining activity and to local aspects of the geology appear in reports published by the California State Division of Mines after 1900.

PURPOSE OF THIS REPORT AND METHODS OF INVESTIGATION

A study of the East Shasta copper-zinc district was undertaken in 1949 by the U.S. Geological Survey in cooperation with the California State Division of Mines for a fourfold purpose: (a) to work out the stratigraphy and structure of the area in detail; (b) to determine the stratigraphic, structural, and alteration environment of the known sulfide deposits; (c) to locate geologically favorable areas to prospect for hidden sulfide deposits; and (d) to tie the geology of the East Shasta copper-zinc district to the geology of the West Shasta copper-zinc district.

Mapping of the part of the area south of Backbone Ridge was done on aerial photographs and compiled on a topographic base at a scale of 1:24,000. The remainder of the area was mapped on a topographic base on enlargements of the Lamoine and Bollibokka Mountain 15-minute quadrangles at a scale of 1:24,000. The lithology of formations and small-scale structural features were mapped in as much detail as the mapping scale would allow. Age of the rock units are determined by fossils and by stratigraphic relations.

The accessible workings of the Afterthought and Bully Hill mines were mapped at a scale of 1 inch to 40 feet. The surface geology of the areas of the Afterthought and Bully Hill-Rising Star mines was mapped by planetable methods at a scale of 1 inch to 100 feet.

The writers studied about 300 thin sections and 65 polished sections by conventional petrographic methods. Chemical analyses were made of 11 rock samples, and samples of sulfide ore were analyzed spectroscopically for minor elements in the laboratories of the U.S. Geological Survey.

FIELDWORK AND ACKNOWLEDGMENTS

Fieldwork was begun by Albers in July 1949 and completed in September 1952. Robertson joined the project in February 1950 and took part in all phases of the fieldwork until its completion. E. M. MacKevett and C. D. Rinehart assisted in the field mainly with planetable mapping for about 1 month each during 1949 and 1951, respectively. A total of about 30 man months was spent in the field.

Fossil collections were identified by R. C. Douglass, Helen Duncan, J. T. Dutro, Jr., L. G. Henbest, C. W. Merriam, S. W. Muller and J. B. Reeside. Messrs. Merriam and Muller also spent 4 days with the writer collecting fossils. Robert L. Smith determined the optical properties of fine-grained white mica in specimens of the Bully Hill rhyolite and identified the mineral as hydrous mica. H. E. Hawkes determined the copper, lead, and zinc content of 20 limonite samples by geochemical prospecting methods.

Chemical analyses were made by Harry F. Phillips, Katrine White, Joseph Dowd, Harry M. Hyman, and W. Pollard, all of the U.S. Geological Survey. Quantitative spectrographic analyses were made by Harry Bastron, also of the Geological Survey.

The logging of diamond-drill core and mapping of underground workings at Bully Hill was done by J. F. Robertson and R. G. Reeves under the auspices of the Defense Minerals Exploration Administration.

The main part of the report was written by Albers. Robertson wrote the section on the Bully Hill and Rising Star mines. The writers are indebted to Drs. C. O. Hutton, Adolph Knopf, Eleanor Bliss Knopf, B. M. Page, and C. F. Park, Jr., of Stanford University, and to L. D. Clark, W. E. Hall, A. R. Kinkel, Jr., and C. W. Merriam of the Geological Survey for valuable advice concerning stratigraphic, structural, and petrologic problems. Photomicrographs were taken by James A. Denson of the U.S. Geological Survey.

The California State Division of Mines, under Dr. Olaf P. Jenkins, chief, and J. C. O'Brien, district engineer for northern California, kindly provided office space and stenographic service at Redding from 1949 to 1951.

Thanks are due officials of the Glidden Co., particularly Mr. E. L. Ralston, for allowing access to the Bully Hill and Rising Star properties, for furnishing and allowing the publication of mine maps and production data, and for other courtesies. Officials of the Coronado Copper and Zinc Co., especially Messrs. R. W. Moore, K. C. Richmond, Lyttleton Price, and M. G. Grant, were equally cooperative in allowing access to the Afterthought mine, in furnishing and permitting the publication of mine maps and production data, and in providing many other courtesies.

The U.S. Bureau of Reclamation provided mooring space for a U.S. Geological Survey boat for several months during two field seasons and furnished barge service for transporting packhorses and supplies across Shasta Lake.

GENERAL GEOLOGY AND GEOLOGIC HISTORY

The East Shasta area is underlain by sedimentary, volcanic, and intrusive rocks that range in age from probable Middle Devonian to Late Jurassic or possibly Early Cretaceous. These rocks constitute what will henceforth be referred to as the "basement rocks." In general, except for intrusive units, the oldest formations in the basement-rock sequence crop out in the western part of the area and successively younger units crop out toward the east.

About 50 to 60 percent of the layered basement rocks are of volcanic origin, irregularly distributed through the stratigraphic column. Virtually all are hydrothermally metamorphosed and they now range in composition from mafic spilite to silicic quartz keratophyre. A noteworthy stratigraphic feature is the occurrence of two markedly similar lithologic sequences in different parts of the column. The Copley greenstone of probable Devonian age, and the Balaklala rhyolite and Kennett formation of Devonian age, are similar lithologically to the Dekkas andesite of Permian age, and the Bully Hill rhyolite and Pit formation of Triassic age. Mafic and intermediate volcanic rocks make up the lower part of each of these two sequences; silicic volcanic rocks overlain by shale and tuff make up the middle and upper part; and limestone occurs in the upper part. The existence of two different sequences rather than a single repeated sequence is conclusively shown by paleontologic, lithologic, and structural data.

Intruding the layered basement rocks is a small stock composed of granodiorite and albite granite, an irregular, elongate, dikelike mass of mafic quartz diorite, and many dikes and sills of fine-grained igneous rocks, chiefly of mafic character.

The thickness of the sedimentary and volcanic basement rocks could not be accurately measured owing to the lenticular nature of most of the units, to marked facies changes within short distances, to recurrent lithologic types, to complex structure, and to poor outcrop. Thicknesses shown in figure 2 are estimated mainly from map measurements. The total mean thickness of the basement rocks, computed from map measurements, is about 19,000 feet, of which about 12,400 feet are rocks of Paleozoic age and about 6,800 feet are rocks of Mesozoic age. These mean thicknesses cannot be measured, however, along any one line of section. The approximate thickness along section *A–A′* (pl. 1) is 22,500 feet, including about 12,500 feet of Paleozoic rocks and 10,000 feet of Mesozoic rocks.

The outstanding feature in the geologic history of the East Shasta area is the dominant and persistent role played by volcanism in the buildup of the strati-

Formation	Age	Thickness in feet	Lithologic description	Economic value	Number on diagrammatic section
Unconsolidated deposits	Quaternary	0-100	Includes alluvial material in stream valleys, rock and soil mantle on hill slopes, talus, local terrace deposits, and landslide debris.	None	16
	UNCONFORMITY				
Basalt	Pleistocene or Pliocene	0-200	Small bodies of basalt that locally cap hilltops and ridges in southeastern part of the map area.	None	15
	UNCONFORMITY(?)				
Tuscan formation	Pliocene	0-360	Tuff breccia, consisting of poorly lithified aggregate of blocks, lapilli, and volcanic ash.	None	14
	UNCONFORMITY				
Quartz diorite and related rocks	Early Cretaceous(?) or Late Jurassic(?)		Includes fine-grained mafic quartz diorite, medium-grained augite quartz diorite, fine-grained diorite, albite diabase, and minor granodiorite.	None	13
Igneous rocks of the Pit River stock	Early Cretaceous(?) or Late Jurassic(?)		Leucocratic granodiorite, albite granite and quartz diorite, with minor aplite.	None	12
	UNCONFORMITY				
Hosselkus limestone	Late Triassic	0-250	Thick- to thin-bedded light-gray limestone containing abundant fossils.	Potential source of lime products.	11
Pit formation	Middle and Late Triassic	2000-4400	Predominantly medium-gray to black shale and siltstone, with abundant lenses of metadacite tuff and quartz keratophyre tuff. Also includes lenses of limestone and lava flows.	Host rock for sulfide deposits.	10
Bully Hill rhyolite	Triassic	100-2500	Chiefly quartz keratophyre lava flows and pyroclastic rocks but includes metadacite, keratophyre, and shaly tuff. Also includes quartz keratophyre dikes in the Dekkas andesite.	Host rock for sulfide deposits.	9
Dekkas andesite	Permian	1000-3500	Chiefly keratophyre and spilite lava flows and pyroclastic rocks, with lenses of siliceous mudstone and quartz keratophyre in upper part.	None	8
	UNCONFORMITY(?)				
Nosoni formation	Permian (Leonard or Guadalupe)	0-2000	Chiefly tuffaceous mudstone and tuff interlayered with subordinate tuff breccia. Fossils abundant in some tuffaceous mudstone beds.	None	7
	UNCONFORMITY				
McCloud limestone	Permian (Hueco and Leonard?)	500-2500	Thin- to very thick-bedded light-gray limestone, with local layers of chert and chert nodules. Many beds contain abundant fossils.	Host for contact metasomatic magnetite deposits. Potential source of lime products.	6
	UNCONFORMITY				
Baird formation	Mississippian	3000-5000	Lower part consists dominantly of pyroclastic rock with subordinate mudstone and keratophyre flows; middle part chiefly siliceous mudstone, with subordinate tuff and minor limestone; upper part is keratophyre, lava and volcanic breccia.	None	5
	UNCONFORMITY(?)				
Bragdon formation	Mississippian	0-3000	Mainly shale and mudstone, with numerous lenses of grit and chert conglomerate; locally a few lenses of tuff and sandstone.	None	4
	UNCONFORMITY				
Kennett formation	Middle Devonian	0-400	Chiefly dark gray siliceous mudstone, tuff, and brownish-gray tuffaceous mudstone containing fossils; small lenses of light gray limestone in upper part.	Potential source of lime products.	3
Balaklala rhyolite	Middle Devonian	1000±	Quartz keratophyre lava flows and pyroclastic rocks.	Host for massive sulfide deposits in West Shasta copper-zinc district.	2
Copley greenstone	Devonian(?)	2000±	Keratophyre and spilite lava flows and breccias; includes minor quartz keratophyre tuff.	None	1

Diagrammatic section

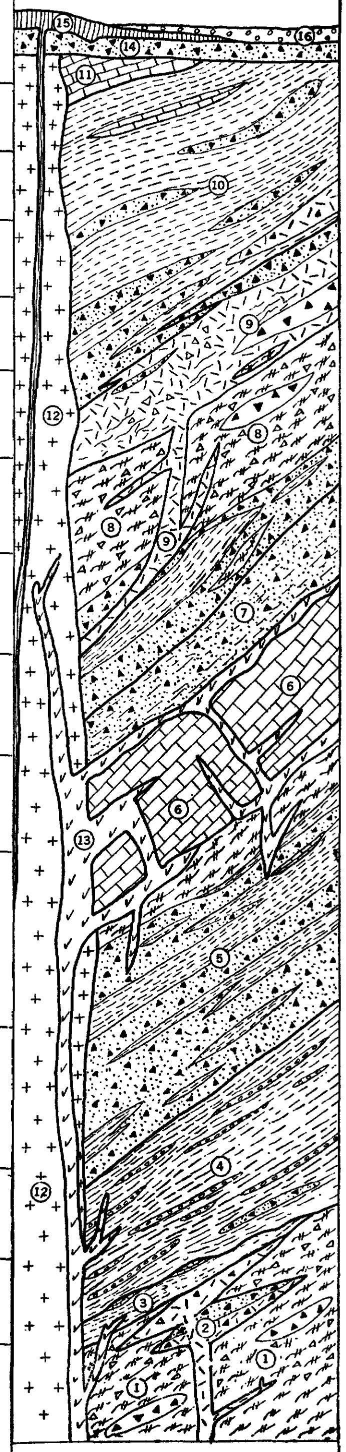


FIGURE 2.—Generalized diagrammatic section showing the principal rock formations in the East Shasta district.

graphic column. Volcanic rocks occur in 10 of the 12 geologic units exposed within the area, and according to Diller (1906, columnar section), they also occur in 3 of the 4 formations of Triassic and Jurassic age exposed east of the area. Only the McCloud and Hosselkus limestones, of the basement-rock sequences are lacking in volcanic constituents. Much of the volcanic material was extruded into the sea as indicated by the intimate interbedding of volcanic rocks with sedimentary rocks containing marine fossils in many parts of the column.

The great thickness of the stratigraphic column—about 30,000 feet if rocks of Triassic and Jurassic age exposed east of the area are included—and the character of the rocks, indicate deposition in a eugeosynclinal trough. Regional distribution of rocks of Paleozoic and Mesozoic age, indicates that the trough was probably elongate in a north-south direction. Within the trough, there were probably volcanic island archipelagos, and from vents on these islands lava flows and pyroclastic rocks were ejected intermittently.

Unconformities record at least five disturbances during Paleozoic and early Mesozoic time but folding and faulting, as well as igneous intrusion and hydrothermal metamorphism, occurred mainly during Late Jurassic or possibly Early Cretaceous time.

The basement rocks are overlain with marked unconformity in the southeastern part of the area by poorly lithified tuff breccia of Pliocene age. Small bodies of basalt, probably also of Pliocene age, overlie the tuff breccia with erosional unconformity. Quaternary deposits include slope wash, talus, terrace deposits, alluvial fan deposits, landslide debris, and alluvium.

The earliest recognizable event in the history of the area was the extrusion probably during Early and Middle Devonian time, of the lavas and pyroclastic materials that make up the Copley greenstone and the Balaklala rhyolite. The intertonguing of these two units in places shows that lavas and pyroclastic rocks of mafic, intermediate, and silicic composition were being erupted penecontemporaneously. The mixing of fragments of keratophyre and quartz keratophyre in pyroclastic rocks in the Waters Gulch area as well as the local interlayering of intermediate and silicic flows at the same locality suggests that both intermediate and silicic material was being erupted intermittently from the same vent or vents. One possible vent was in the western part of sec. 20, T. 34 N., R. 4 W.

During late Middle Devonian time at least the western part of the area was submerged beneath a shallow sea and the shaly rocks that form the lower part of the Kennett formation were deposited. Volcanoes were still active, at least during early Kennett time, but tuffaceous material on the flanks of the volcanoes was being reworked, giving rise to the tuffaceous sediments in the Kennett. During late Kennett time coral reefs probably grew on seamounts formed by eroded volcanoes. A warm shallow sea is inferred during late Middle Devonian time from the abundance of corals in sedimentary rocks of the Kennett formation.

During Late Devonian or Early Mississippian time the area was uplifted and the Kennett formation was in part eroded. Later, during Mississippian time, at least part of the area subsided rapidly and was covered with several thousand feet of mud, silt, and poorly sorted gravel comprising the Bragdon formation. This formation was derived partly from erosion of the Kennett.

Deposition of the Bragdon was followed by minor uplift and erosion, after which there was renewed subsidence and a resumption of volcanic activity. The eruptions produced many hundreds of feet of andesitic pyroclastic rocks that make up most of the lower part of the Baird formation. During middle Baird time volcanic activity diminished and fossiliferous mudstone and minor limestone were deposited in a shallow sea. However, the youngest rocks of the Baird are greenstone and breccia, showing that volcanism again prevailed during the latter part of Baird time.

The Pennsylvanian seems to have been a period of nondeposition as no rocks of Pennsylvanian age are known in northern California. Probably the area stood slightly above sea level and underwent some erosion during Pennsylvanian and possibly during the earliest part of Permian time. Early in Permian time the area was submerged and most of the McCloud limestone was deposited. Most of the McCloud is of Hueco age, but deposition of the youngest beds of McCloud limestone possibly took place during Leonard time. Emergence, northward tilting, and partial erosion of the limestone followed.

Resubmergence and a renewal of volcanic activity took place during Guadalupe time in the Permian period, giving rise to the tuffaceous mudstone, mafic lava and pyroclastic material of which the Nosoni formation is comprised. Uplift, tilting, and erosion followed deposition of the Nosoni but before the end of the Paleozoic era the region was again submerged and the Dekkas andesite, a great thickness of intermediate pyroclastic rocks, with intercalated lenses of andesitic lava and fossiliferous mudstone was deposited. This volcanism seems to have continued into the Mesozoic era but the evidence is inconclusive. The lower part of the Dekkas andesite contains fossils of Permian age but the upper part may be Triassic. In Triassic time the character of the lava and pyroclastic material erupted changed from andesitic to dacitic and the

Bully Hill rhyolite was formed. A large part of the lava and pyroclastic material forming the Dekkas andesite and Bully Hill rhyolite was probably erupted into the sea. Possible vents for the Bully Hill rhyolite were in the NW¼ sec. 4, T. 33 N., R. 2 W. and in the NE¼ sec. 16, T. 34 N., R. 3 W. A possible vent for the Dekkas andesite was in the NW¼ sec. 9, T. 34 N., R. 3 W.

During Middle Triassic time the intensity of volcanism decreased and the area slowly subsided. Mudstones were deposited, first in basins between volcanoes, and eventually, as a result of continued subsidence and contemporaneous erosion, layers of mudstone were deposited over the crests of most but not all volcanoes. Intermittent volcanism, chiefly of the explosive type, continued throughout deposition of the Pit formation, forming layers of dacitic pyroclastic rocks interbedded with the mudstone of the Pit. The area remained largely submerged throughout late Middle and early Late Triassic time, permitting deposition of the upper part of the Pit as well as the Hosselkus limestone.

Profound orogeny, including folding, faulting, igneous intrusion, metamorphism, and widespread metasomatic albitization and chloritization, and mineralization, occurred probably during Late Jurassic or possibly Early Cretaceous time.

No record of sedimentation or volcanism exists within the immediate area between Late Triassic and Pliocene time. However, marine sedimentary rocks as well as volcanic rocks of Late Triassic and Early and Middle Jurassic age crop out just east of the area. These rocks show that sedimentation and volcanic activity continued, with possibly one or more periods of uplift, until Middle Jurassic time.

Extensive erosion of newly formed mountain ranges followed the orogeny. Relations outside the area suggest that the region was again submerged and covered with sedimentary rocks during Cretaceous time. This was followed by further uplift and by the deposition during Eocene time of coarse gravels at least locally east of the area. Erosion was dominant during Oligocene and Miocene time and a surface of low relief was formed in the southeastern part of the area. The Tuscan formation was deposited on this surface during Pliocene time. Because of the higher and more rugged topography the mudflows of the Tuscan extended only a little way north of the Pit River. Minor uplift and erosion of the Tuscan was followed by the extrusion of basaltic lavas in the eastern part of the area during late Pliocene or possibly early Pleistocene time. A small body of diabase near the south edge of sec. 26, T. 34 N., R. 2 W. may mark one vent from which these lavas were extruded.

During the Pleistocene and Recent epochs uplift and erosion have been dominant. Little Cow Creek has incised its canyon about 600 to 700 feet into the pre-Tuscan erosion surface. The Pit River, meanwhile, has deepened its canyon about 350 feet. Remnants of a thin layer of limonite at an altitude of about 1,700 feet in the First Creek area northeast of Bully Hill marks a high-water level during probable Pleistocene time. Alluvial gravels at an altitude of 1,000 to 1,100 feet on several small benches along the canyon of Squaw Creek mark another and more recent high-water level. Landslides have occurred on Horse and Town Mountains and an alluvial fan has formed downslope from the toe of one large landslide on Town Mountain. The area is presently undergoing vigorous erosion.

SEDIMENTARY AND VOLCANIC DEPOSITS

COPLEY GREENSTONE

DISTRIBUTION, STRATIGRAPHIC RELATIONS, AND THICKNESS

The Copley greenstone (Kinkel and Albers, 1951, p. 4), formerly called the Copley meta-andesite (Diller, p. 7, 1906), is the oldest formation exposed. It crops out over an area of about 5 square miles in the western part of the area and forms the core of a large anticline that passes through O'Brien Mountain (pl. 1). On the west, north, and east sides of O'Brien Mountain the Copley is overlain in some places by the Kennett formation of Middle Devonian age, and in other places by the Bragdon formation of Mississippian age. On the southwest flank of O'Brien Mountain, west of the mouth of Waters Gulch, the Copley is overlain by the Balaklala rhyolite of Devonian age and east of Waters Gulch it intertongues with the Balaklala rhyolite. The intertonguing of the Copley greenstone with the Balaklala rhyolite shows that the two formations are at least in part contemporaneous.

The base of the Copley greenstone is not exposed, and therefore the thickness is indeterminable. Section *B–B′* through O'Brien Mountain (pl. 1) suggests a minimum thickness of 2,000 feet or more.

LITHOLOGY AND PETROGRAPHY

The Copley greenstone consists chiefly of fragmental and nonfragmental mafic lava and mafic pyroclastic rocks. These rocks have undergone low-grade metasomatism, with the result that most primary igneous minerals are replaced by albite, chlorite, and other secondary minerals. The primary igneous textures and structures are preserved, however, so that the original volcanic character of the rock can readily be recognized in most places.

Although several lithologic types are recognized in the Copley, gradation between the different types is common and in many places it is difficult or impossible to accurately draw lithologic contacts. Blocky lava grades into massive lava in many places and into coarse volcanic breccia of probable pyroclastic origin in a few places. Likewise, coarse pyroclastic rocks grade into fine pyroclastic rocks, amygdaloidal lava grades into nonamygdaloidal lava, and porphyritic lava grades into nonporphyritic lava.

Bedding is rare and secondary foliation is absent in the Copley.

The chief lithologic types of the Copley greenstone are described below.

NONFRAGMENTAL MAFIC LAVA

The nonfragmental mafic lava is a dark greenish-gray to greenish-black aphanitic rock that contains sparse to locally abundant feldspar phenocrysts ranging from 1 to 6 mm in diameter. Amygdules are common, and in a few places they are as much as 1 cm across. White quartz, calcite, and dark-green chlorite are the most common minerals filling amygdules.

Thin sections show that most of the mafic lava consists of about 50 to 60 percent albite (An_4) and 20 to 25 percent chlorite. Other components, of irregular distribution, include calcite, pumpellyite, epidote, zoisite(?), celadonite, fine-grained white mica, sphene, leucoxene, quartz, kaolinite, and limonite. The texture is commonly porphyritic. Phenocrysts are of albite pseudomorphous after original, more calcic plagioclase. Groundmass textures are pilotaxitic or felty. According to petrographic evidence most of the mafic lava is classified as keratophyre, derived from andesitic rocks by hydrothermal alteration. A small percentage of the mafic lava may be spilite similarly derived from rock of basaltic composition.

BLOCK LAVA

As used here the term "block lava" applies to fragmental volcanic rocks of monolithologic composition. It is similar to aa, and according to Macdonald (1953, p. 182), is characteristic of lavas more salic than basalts and basaltic andesites.

The block lava in the Copley greenstone consists of angular to subrounded fragments of massive dark greenish-gray porphyritic keratophyre in a slightly darker matrix. The fragments, or blocks, range from 2 to 15 inches in diameter, although the majority range from 6 to 10 inches. The mineralogy and texture of the block lava are identical to the mineralogy and texture of the nonfragmental lava described above and contacts between the two types of rock are commonly gradational.

PYROCLASTIC ROCKS

The classification of pyroclastic rocks used herein is virtually that of Wentworth and Williams (1932), slightly modified:

Volcanic breccia consists chiefly of angular and (or) spherical fragments greater than 32 mm in diameter and of heterogeneous texture and composition. Fragments predominate over the matrix. The heterogeneity of the fragments is the chief criterion by which volcanic breccia is distinguished from block lava.

Tuff breccia is similar to volcanic breccia except that the matrix predominates over the fragments. Tuff breccia and volcanic breccia are commonly gradational one into the other. These rocks are well indurated.

Tuff is indurated pyroclastic rock consisting of particles smaller than 4 mm in diameter. It may consist predominantly of crystal clasts of quartz, feldspar, and ferromagnesian minerals, in which case it is called "crystal tuff;" or it may consist predominantly of fragments of lava and sedimentary rocks, containing subordinate crystal clasts, in which case it is called "lithic tuff." In some places lithic tuff and crystal tuff grade into one another.

Lapilli tuff consists of fragments ranging from 4 to 32 mm in diameter in a fine tuff matrix. Lapilli tuff grades on the one hand into tuff, and on the other hand into tuff breccia.

Tuffaceous sandstone and tuffaceous mudstone are mineralogically similar to tuff but are better sorted and more distinctly bedded. In thin section the constituent particles are commonly subangular to subrounded.

The fragmental rocks of presumed pyroclastic origin in the Copley greenstone are more heterogeneous than the block lavas, as shown mainly by the heterogeneity of composition and texture of the fragments. Volcanic breccia, tuff breccia, and tuff are the chief size categories of pyroclastic rock in the Copley.

Volcanic breccia is abundant in the southwestern part of the Copley greenstone outcrop area and is much less common in the northern part (pl. 1). Much of the breccia consists of subrounded and subangular fragments of mafic lava, closely packed, in a subordinate matrix. The fragments average 4 to 12 inches in diameter and include porphyritic and nonporphyritic mafic lava, amygdaloidal and nonamygdaloidal lava, and flow-banded lava. In some places, especially where the Balaklala ryholite is interlayered with the Copley greenstone, the volcanic breccia contains fragments of porphyritic and nonporphyritic quartz keratophyre. The quartz keratophyre [2] is a light-gray rhyolitic rock that commonly weathers buff, and fragments of it stand out in marked contrast to the neighboring dark-colored keratophyre fragments. The matrix of volcanic breccia containing quartz keratophyre

[2] Quartz keratophyre, as used in this report, applies to fine-grained siliceous rocks composed largely of quartz and albite. The albite is a pseudomorphous replacement of originally more calic plagioclase. Some quartz keratophyre is porphyritic, whereas some is nonporphyritic. The groundmass is aphanitic.

fragments is commonly keratophyre but in a few places it is quartz keratophyre.

Tuff and tuff breccia are subordinate to volcanic breccia in the Copley greenstone but are lithologically important in that they commonly show bedding. The tuff and tuff breccia beds range from a few feet to about 100 feet in thickness. These rocks are commonly medium gray or dark greenish gray and consist of volcanic rock fragments and crystal clasts of feldspar and quartz. The lithic fragments are generally less than a centimeter in diameter but in some place sparse fragments as much as 6 inches across are unevenly distributed in a tuffaceous matrix.

ORIGIN AND AGE

The character of the rocks that make up the Copley greenstone shows that the formation is of extrusive volcanic origin. Whether the volcanic rocks were extruded into the sea or onto dry land is not known although small lenses of bedded tuff suggest that part of the Copley in the O'Brien Mountain area was deposited in water. In the West Shasta copper-zinc district (Kinkel and others, 1956 [1957], p. 54) abundant pillow lava and tuffaceous mudstone in the Copley suggest that much of the formation was extruded into the sea. The great areal extent of the Copley greenstone in northern California (Hinds, 1933, geol. map) suggests that the formation was ejected from several volcanic centers.

No fossils have been found in the Copley greenstone and its age must be deduced from its relation to the overlying rocks. It is interbedded with rocks typical of the Balaklala rhyolite and is overlain with apparent conformity by the Balaklala rhyolite in the West Shasta district. The Kennett formation and the Balaklala rhyolite are of Middle Devonian age (Kinkel and others, 1956, p. 16). Therefore the Copley greenstone is probably also of Middle Devonian age or older.

BALAKLALA RHYOLITE

DISTRIBUTION, STRATIGRAPHIC RELATIONS, AND THICKNESS

About 1 square mile in secs. 19, 20, 29, and 30, T. 34 N., R. 4 W. on the south flank of O'Brien Mountain is underlain by siliceous quartz keratophyre, quartz keratophyre breccia, and tuff. These siliceous volcanic rocks are correlated on the basis of lithology and stratigraphic relations with the Balaklala rhyolite, which was named by Diller (1906, p. 7) from exposures at the Balaklala mine in the nearby West Shasta copper-zinc district. The Balaklala rhyolite is the host rock for massive sulfide deposits in the West Shasta district and is lithologically similar to the Bully Hill rhyolite of Triassic age, which is the chief host rock for sulfide deposits in the East Shasta district.

The Balaklala rhyolite overlies and intertongues with the Copley greenstone. On the south flank of O'Brien Mountain (pl. 1), the Balaklala is overlain in part by the Kennett formation but in part by a tongue of the Copley greenstone. In the West Shasta district, where the Balaklala rhyolite is more extensive than in the East Shasta district, the main body of Balaklala overlies the Copley greenstone but in places the contact is transitional, with sheets of quartz keratophyre locally interbedded with volcanic rocks of the Copley greenstone, and layers of mafic rocks interbedded locally with the Balaklala rhyolite. Interbedding is common not only in the vicinity of the contact between the two formations but also occurs in places hundreds of feet above or below the contact. Moreover, where the upper part of the Copley and the lower part of the Balaklala are made up of pyroclastic rocks, fragments of quartz keratophyre and fragments of mafic lava are commonly intermixed (Kinkel and others, 1956, p. 20). This relation was seen near the mouth of Waters Gulch and in other places on the south flank of O'Brien Mountain. The contact between the Balaklala and the Copley is purely arbitrary in such places and its position depends upon whether quartz keratophyre fragments or fragments of mafic volcanic rocks predominate. It seems from the above described relations that the Balaklala rhyolite is at least in part contemporaneous with the Copley greenstone.

The maximum thickness of the Balaklala rhyolite is about 1,000 feet as measured from a cross section drawn normal to the strike in the eastern part of sec. 30, T. 34 N., R. 4 W. However, as is apparent from the map pattern, the thickness differs markedly from place to place. The absence of the Balaklala in much of the O'Brien Mountain area is attributed to the original discontinuity of the formation.

LITHOLOGY AND PETROGRAPHY

The Balaklala rhyolite consists of siliceous, light-colored lava flows, block lava, volcanic breccia, tuff, and minor mafic lava. These rocks are interbedded, and in many places gradational into each other. Insofar as it was possible to do so the rock types listed above are differentiated on the geologic map. The tuffaceous rocks, which crop out mainly east of the mouth of Waters Gulch, commonly show bedding but the other lithologic types do not. Most of the lava contains quartz and feldspar phenocrysts in an aphanitic groundmass. Crystals and crystal clasts of quartz and feldspar are commonly visible in the tuffaceous rocks. The quartz phenocrysts and clasts and the generally lighter color are the main features by which the Balaklala rhyolite is distinguished from the Copley greenstone. The main lithologic types are described below.

NONFRAGMENTAL QUARTZ KERATOPHYRE

Most of the quartz keratophyre is light olive gray to medium gray on fresh surface and weathers to whitish gray, or buff. Commonly it is porphyritic, and contains phenocrysts of quartz and feldspar, although in some places it is nonporphyritic. Phenocrysts in the porphyritic facies range from 0.5 to 6 mm in diameter, and are quantitatively subordinate to the groundmass. Quartz phenocrysts, although less abundant, are more conspicuous than those of feldspar. Commonly individual flows contain phenocrysts that fall within a particular size range. Phenocrysts range from 1 to 3 mm in diameter in some flows, and as much as 6 mm in diameter in others; a few flows are nonporphyritic or contain only sparse phenocrysts less than 1 mm in diameter. In general, flows containing the largest phenocrysts occur in the upper part of the Balaklala rhyolite.

Thin sections show that quartz and albite commonly make up about 90 percent of the quartz keratophyre. Fine-grained white mica and chlorite are minor components in almost all thin sections studied, and celadonite, apatite, fine-grained biotite, and leucoxene occur locally in very small amounts. The texture is commonly porphyritic (pl. 17*A*); in some slides albite phenocrysts are grouped in clusters, giving a glomeroporphyritic texture. Groundmass textures include felty, microgranular, and granophyric.

The albite phenocrysts have negative relief with respect to canada balsam and are weakly twinned according to albite, Carlsbad, and pericline-acline twinning laws. Most albite phenocrysts are subhedral to euhedral. Maximum symmetrical extinction in the zone normal to 010 is 16°. The optic sign is (+), and the optic angle is large. These properties correspond to plagioclase at least as sodic as An_5. Albite of about the same composition forms laths in the groundmass of the quartz keratophyre.

Quartz forms bipyramidal phenocrysts ranging from 0.5 to 6 mm in diameter and microcrystalline grains intergrown with albite in the groundmass. The phenocrysts are commonly rounded and show marked undulatory extinction, although some are euhedral and show uniform extinction. A few phenocrysts showing undulatory extinction, or strain shadows, are fractured and sheared. In some slides the groundmass quartz occurs as spherulitic intergrowths with albite. The radiating fibers of these spherulites commonly have negative elongation and indices of refraction slightly greater than 1.54. This material may be chalcedony.

BLOCK LAVA

Block lava is a common constituent of the Balaklala rhyolite although it is not easily recognized except in weathered exposures. It commonly consists of porphyritic quartz keratophyre fragments ranging from about an inch to a foot in diameter, in a matrix of similar rock. Although the fragments are of the same composition and texture as the matrix they are of slightly different color and show sharp contacts with the matrix in weathered outcrops. The block lava grades in many places into massive quartz keratophyre; in a few places it seems to grade into volcanic breccia of probable pyroclastic origin.

VOLCANIC BRECCIA

The diversity of lithologic types in the volcanic breccia distinguishes it from the block lava. Most commonly several textural varieties of quartz keratophyre, including porphyritic, nonporphyritic, flow banded, and massive, occur as fragments; in some places fragments of mafic lava are mixed with the fragments of light-colored quartz keratophyre. The fragments range from less than 1 to about 15 inches in diameter. They predominate over the matrix, which generally has the composition of quartz keratophyre except in some places near contacts with the Copley greenstone where it consists of more mafic material. The close time relation between the Copley greenstone and the Balaklala rhyolite is shown by the intimate mixture of siliceous and mafic rock fragments in much of the volcanic breccia.

TUFF AND TUFF BRECCIA

Tuff is a prominent constituent of the Balaklala rhyolite along the east shore of the Waters Gulch arm of Shasta Lake in secs. 29 and 30, T. 34 N., R. 4 W. It forms lenticular beds as much as 100 feet thick interstratified with quartz porphyry and volcanic breccia. The tuff is medium gray or dark greenish gray, distinctly bedded, and composed of fragments of volcanic rocks, together with crystals and clasts of quartz and feldspar. In most tuffs the lithic fragments are less than 1 cm in diameter, but in a few places fragments as much as 6 inches in diameter are found in tuff breccia.

In thin section the tuff consists of lithic fragments and crystal clasts in about equal amounts. The lithic fragments include several textural varieties of quartz keratophyre and keratophyre. Quartz and albite form crystals and crystal clasts. The matrix is in most places a mixture of fine-grained white mica, biotite, and quartz.

ORIGIN

The origin of the Balaklala rhyolite has long been a matter of controversy. Diller (1906, p. 7) recognized it as a series of lava flows and tuffs lying chiefly between the Copley greenstone (meta-andesite) and the Kennett formation but in part interlayered with the Copley. Graton (1910, p. 81–85), from a study of the mining district west of the Sacramento River, believed the unit to be an intrusive mass and renamed it alaskite porphyry. The character of the Balaklala rhyolite in the East Shasta area, and the lack of intrusive relations to adjoining rock units show that Diller was correct in his interpretation that the formation is largely of extrusive origin. A more complete discussion of the origin of the Balaklala rhyolite is given in a report on the West Shasta copper-zinc district by Kinkel and others (1956 [1957], p. 31–32).

AGE

No fossils were found in the Balaklala rhyolite in the area, but it has been shown by Kinkel and others (1956 [1957]), that in the West Shasta district the formation is overlain conformably by the Kennett formation of Middle Devonian age. Presumably the Balaklala rhyolite is also of Middle Devonian age.

KENNETT FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Kennett formation, which is the oldest fossiliferous unit in the area, was named by Smith (1894, p. 591–593) from exposures between Squaw and Backbone Creeks in the West Shasta copper-zinc district. At the type locality on Backbone Creek the Kennett formation consists chiefly of dark, siliceous shale, tuff, and thick-bedded limestone containing fossils (Kinkel and others, 1956 [1957], p. 32).

In the East Shasta area the Kennett formation forms a discontinuous belt as much as 1,800 feet wide on the flanks of the O'Brien Mountain anticline (pl. 1). Dark-gray siliceous shale, light brownish-gray fossiliferous shale, pyroclastic rocks, tuffaceous sandstone, and lenticular limestones are the chief lithologic constituents. The Kennett is recognized in the field mainly by the dark siliceous shale and the lenses of limestone.

STRATIGRAPHIC RELATIONS AND THICKNESS

The Kennett formation overlies the Copley greenstone except west of Waters Gulch where the Balaklala rhyolite lies between the Kennett and the Copley. Poor exposures and faulting obscure the details of the relation between the Kennett and the underlying formations. However, from relations seen in the West Shasta district (Kinkel and others, 1956 [1957], p. 33) it appears likely that the Kennett was deposited conformably on the underlying volcanic rocks. Absence of the Balaklala rhyolite in much of the O'Brien Mountain area is probably due to the original discontinuity of the Balaklala rhyolite rather than to partial erosion of the formation prior to deposition of the Kennett.

The Kennett, which reaches a maximum thickness of 400 feet, maintains a uniform thickness of 300 to 400 feet where it is present. This uniformity is a puzzling feature in view of the heterogeneous lithology and local absence of the formation.

LITHOLOGY

No well-defined stratigraphic sequence was recognized in the Kennett formation within the area. In general tuff and coarse pyroclastic rocks interbedded with siliceous shale make up the lower part of the formation, and light-brown fossiliferous shale, overlain by small lenses of limestone make up the upper part. Only the limestone is differentiated on the geologic map (pl. 1).

DARK-GRAY SILICEOUS SHALE

One of the most characteristic rocks in the Kennett formation is dark-gray siliceous shale that forms units ranging from a few feet to about 100 feet in thickness. The shale is in layers ranging from 1 to 6 inches in thickness and separated by planes of parting. Only rarely was a color difference observed between adjacent layers. The hardness of the shale differs from place to place, apparently reflecting differences in the silica content. The most siliceous phases commonly weather medium bluish gray and in a few places contain megascopically visible radiolaria, which stand out in relief on weathered surfaces. In many places the dark, siliceous shale is greatly contorted and veined with milky quartz. This highly contorted siliceous shale may mark a low-angle fault between the Kennett and the underlying volcanic units.

PYROCLASTIC ROCKS AND TUFFACEOUS SANDSTONE

Interbedded with shale in the lower part of the Kennett formation are tuff, coarse pyroclastic rocks, and tuffaceous sandstone. Most of the tuff is crystal-lithic tuff of keratophyric and quartz keratophyric composition; it is similar to the tuff in the Copley greenstone and the Balaklala rhyolite. Fragments of volcanic rocks and crystals and crystal clasts of quartz and feldspar are the principal constituents. The grain size ranges from less than 1 to about 2 mm. Most of the tuff is poorly stratified.

Lenses of coarse fragmental rock are common in the Kennett formation, chiefly in the lower part. Some of the fragmental material is pyroclastic rock and some is flow breccia. In sec. 9, T. 34 N., R. 4 W., along the old highway near O'Brien Creek a lense of agglomerate about 50 feet thick consisting of rounded porphyritic keratophyre fragments ranging from 2 to 6 inches in diameter in a tuffaceous matrix is overlain by light-brown fossiliferous shale and underlain by gray shale.

In sec. 29, T. 34 N., R. 4 W., a layer of flow breccia similar to flow breccia in the Copley greenstone is interbedded with shale and tuff.

A few beds in the Kennett formation consist of subrounded and partly sorted particles of feldspar, quartz, and rock. This material is classed as tuffaceous sandstone probably formed largely from reworked tuff.

FOSSILIFEROUS SHALE

A bed of light brownish-gray fossiliferous shale about 50 feet thick, overlies the dark siliceous shale and tuff in most places. Commonly this rock is soft and deeply weathered. Bedding planes are marked in some places by layers of fossils and in other places by partings spaced a fraction of an inch to about a foot apart. It is a lithologically important unit because it is the oldest rock in the East Shasta area that has been dated by fossils. The best exposure is in the cut of an abandoned road in the NW¼ sec. 9, T. 34 N., R. 4 W.

LIMESTONE

The youngest lithologic unit of the Kennett formation is massive to poorly bedded, fine-grained, light-gray limestone. This unit forms several discrete bodies ranging from 100 to 325 feet in length and 40 to 50 feet in thickness on the east side of O'Brien Mountain. Locally, chert is a minor component. Sparse, poorly preserved fossils, mainly corals, were seen in a few places. The absence of recognizable clastic material suggests that the limestone is autochthonous. The presence of corals shows that it must have been formed in shallow, warm seas, and probably, as was first suggested by Diller and Schuchert (1894, p. 418), that it is at least in part a reef deposit. Kinkel and others (1956 [1957], p. 35) from studies in the West Shasta district reached a similar conclusion.

CONDITIONS OF DEPOSITION

Corals in sedimentary facies of the Kennett formation suggest shallow-water deposition in a warm sea. The interstratification of volcanic material with the sedimentary rocks indicates intermittent volcanism. That volcanic activity gradually diminished and finally ceased in the immediate area during late Kennett time is suggested by the gradual decrease in volcanic rocks from the lower to the upper part of the unit and the virtual absence of volcanic rocks in the upper part. The volcanoes that give rise to the tuffs and fragmental rocks in the lower part of the Kennett may have been in or near the map area. Erosion of these volcanoes and the reworking of tuff deposits probably supplied the materials constituting the tuffaceous sandstones.

AGE AND FAUNA

The Kennett formation has long been known to be of Devonian age (Diller and Schuchert, 1894, p. 416). Age is determined chiefly by material collected from limestone in the Backbone Creek locality of the West Shasta district, and from shaly rocks near the submerged settlement of Morley, sec. 19, T. 34 N., R. 4 W., in the East Shasta district. The relative stratigraphic position of the limestone on Backbone Creek and the shaly rocks at Morley is not definitely known but lithologic evidence indicates that the limestone overlies the shaly rocks. The present investigation has shown that the fossiliferous shale beds exposed near Morley also crop out on the east side of O'Brien Mountain where they underlie small bodies of limestone. If these bodies are stratigraphically equivalent to the limestone on Backbone Creek the underlying fossiliferous shale is the oldest fossil-bearing rock in the district.

During the summer of 1951 C. W. Merriam and S. W. Muller spent several days with the writers making collections from some of the better fossiliferous shale of the Kennett formation at several places in the East Shasta district and from the limestone in the Backbone Creek area of the West Shasta district. C. W. Merriam, who examined this material and who has otherwise given much attention to the Devonian problem of northern California reports on the age and correlation of Devonian rocks as follows:

> Fossils in the past identified as Devonian (Diller and Schuchert, 1894, Stauffer, 1930) occur in the two distinct depositional facies in the Redding district. Limestones represented on Backbone Creek in the West Shasta district yield a poorly preserved coral fauna assigned with qualification to Devonian; specific relationships of these corals are unknown and the general facies and character of the assemblage is not unlike certain western coral assemblages of Silurian age. Brachiopods of the genera *Atrypa* and *Cryptonella* are much less common. The *Atrypa* could be Silurian but the *Cryptonella* belongs to a genus generally regarded as restricted to Devonian. While a Devonian age appears probable it is believed that this assignment should be viewed with reservation pending possible discovery of better fossil material and until the relationships of the corals can be worked out. It should be mentioned that certain of the limestones with similar but actually different faunas in Siskiyou County, California are rather confidently referred to the Silurian. In several instances the limestones in question rest like the Kennett Devonian? on dark shales, the age of which has not been determined with assurance.
>
> The light tan or grayish brown Devonian shales of the East Shasta district, representing the second facies, contain *Atrypa* and the coral *Cladopora* in abundance, most localities apparently yielding few other fossils. While the abundance of these two genera as such does not eliminate possibility of Silurian, the *Atrypa* is a medium to large form which may be compared with Middle Devonian forms from the Great Basin. One assemblage from these shales near Morley (Merriam, 1940, p. 48) is more diverse including a small *Schizophoria*, *Cyrtina*

sp. and *Stropheodonta* sp. It is believed to be Devonian and possibly late Middle Devonian.

Whereas several rather lengthy fossil lists have in the past been published and reported to have come from the Kennett limestones, actually almost none of the listed forms are known to be conspecific with other western Devonian types and as a matter of fact cannot yet be identified as to species. Following are a few of the commoner Kennett limestone fossils:

Cyathophyllid corals, several types
Cystiphyllid corals
Cladopora
Heliolites
Alveolites
Stromatoporoids
Small trilobites, undetermined
Atrypa sp.
Cryptonella cf. *C. planirostra* (Hall)

BRAGDON FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Bragdon formation, named by Hershey (1901, p. 236–238), underlies about 6 square miles of the East Shasta area. It wraps around the nose and forms the flanks of the O'Brien Mountain anticline. On the west flank and on the nose of the anticline the Bragdon crops out for a width of several miles, extending beyond the limits of the mapped area, but on the east flank of the anticline the maximum outcrop width is about 3,000 feet (pl. 1). The belt of Bragdon formation on the east flank of the anticline is cut out by a fault near the divide between Goat Creek and Packers Gulch, but it reappears a few hundred feet farther southwest and crops out continuously to the north edge of Shasta Lake. It is absent on the south side of the lake opposite the present mouth of Packers Gulch and just south of the map boundary. The Bragdon consists principally of shale, mudstone, and conglomerate, but also includes subordinate sandstone, siltstone, and pyroclastic rocks. The most reliable criterion for recognizing the Bragdon formation is the conglomerate beds consisting mainly of chert pebbles.

STRATIGRAPHIC RELATIONS AND THICKNESS

The Bragdon formation overlies the Kennett formation in most places, but in secs. 8 and 9 on the north side of O'Brien Mountain it apparently overlies the Copley greenstone. The contact between the Kennett and Bragdon formations is poorly exposed but can be mapped fairly accurately on the basis of lithology. The lower part of the Bragdon is very thinly bedded, dark-gray shale and siltstone that commonly weathers brownish gray, whereas the Kennett formation consists of siliceous, more thickly bedded shale, fossiliferous shale, and lenticular limestone. Conglomerate, the most characteristic rock of the Bragdon, is absent near the base of the formation.

Diller (1906, p. 3, geol. map, and columnar section) concluded from regional mapping that the Kennett and Bragdon formations are separated by an unconformity. He points out that in many places the Kennett formation is missing and assumes that it was completely eroded locally before deposition of the Bragdon. He also notes that conglomerate beds in the Bragdon formation contain much material derived from the Kennett, and that fossils indicate a Mississippian age for the Bragdon, whereas the Kennett is Middle Devonian.

Kinkel and others (1956 [1957], p. 34–35) interpret the Bragdon and Kennett in the West Shasta copper-zinc area to be virtually conformable. According to this interpretation, differences in the lithology of the Kennett immediately beneath the Bragdon are due to facies changes, and places where the Kennett formation is absent were topographic highs where deposition did not occur. The fragments of fossiliferous limestone in conglomerate beds of the Bragdon were derived from the Kennett formation beyond the limits of the area where erosion was taking place.

In the East Shasta area the contact between the Kennett and Bragdon formations is so poorly exposed and the two units are so disrupted by faulting that their stratigraphic relations could not be definitely ascertained. An unconformity is suggested by the absence of the Kennett in some places (pl. 1) and by the different lithologic features of the Kennett immediately beneath the Bragdon. However these features can also be explained by faulting. The fragments of limestone containing characteristic Kennett fossils in conglomerate beds in the Bragdon suggests an unconformity.

The Bragdon formation ranges in thickness from a thin film near the mouth of Packers Gulch to 3,000 feet or more in the extreme northwestern part of the area, but the top of the formation is not exposed. Therefore the maximum thickness is without doubt greater than 3,000 feet. Along the east side of O'Brien Mountain the maximum thickness is about 1,600 feet and the average thickness is about 1,000 feet.

LITHOLOGY

The Bragdon formation is principally shale, mudstone, and conglomerate, but includes a minor amount of siltstone, sandstone, tuff and volcanic breccia. On the geologic map (pl. 1) beds of conglomerate and beds of pyroclastic rock are differentiated from shale, mudstone, siltstone, and sandstone.

SHALE AND MUDSTONE

About 75 percent of the Bragdon formation is shale and mudstone. On fresh surfaces these rocks are dark gray to black but they commonly weather to light brownish gray or medium gray. The shale is platy and in most places it is thin bedded to laminated, whereas the mudstone is flaggy, and the beds are several inches thick. In both the shale and the mudstone bedding is marked by slight differences in color and locally by slight differences in grain size.

SILTSTONE AND SANDSTONE

Siltstone and sandstone form thin and inconspicuous layers throughout the Bragdon formation and make up about 5 percent of the unit. In many places thin beds of siltstone, sandstone, or interstratified siltstone and sandstone, are interlayered with shale and mudstone. In a few places conglomerate grades upward through grit, sandstone, and siltstone, into shale or mudstone.

Most sandstone beds are medium gray but some are light brownish gray or brownish gray. Quartz, forming subangular grains, is the dominant mineral. The siltstone is commonly medium gray to dark gray and is also composed mainly of quartz.

CONGLOMERATE

Conglomerate, the most distinctive rock of the Bragdon formation, occurs as lenticular beds throughout the formation and constitutes about 15 to 20 percent of its volume, but is absent at the base. The beds form hard, light-gray or medium-gray outcrops that stand out in marked contrast to the adjoining shale and mudstone. They are common north and west of O'Brien Mountain but are sparse east of the mountain.

These conglomerate beds range from about 2 to 50 feet in thickness, but most are 10 to 20 feet thick. The conglomerate beds maintain a fairly uniform thickness for as much as several thousand feet along strike, only to end abruptly. On the other hand, a few of the beds lens out gradually along strike.

The conglomerate consists largely of chert fragments, but includes sparse fragments of limestone, greenstone, shale, white quartz, and sandstone. The fragments in most conglomerate beds range from grains a few millimeters to cobbles about 4 inches in diameter. In general, the conglomerate beds are poorly sorted, with pronounced maxima near the ends of the size-distribution curve. The matrix of most conglomerate beds is sandy or silty material so firmly cemented that the rock breaks smoothly across the pebbles. A few beds grade upward from cobble or pebble conglomerate to sandstone or to siltstone. The bases of almost all these beds are sharp, smooth, and conformable but the effects of scouring and channeling were observed in a few places. The chert pebbles are angular to rounded. The degree of roundness shows no consistent relation to stratigraphic position or to grain size. Fragments of rock types other than chert are much more rounded than those of chert.

A few dark-gray conglomerate beds, composed chiefly of subangular pebbles of chert and cherty mudstone in a dark, mudstonelike matrix, crop out in the lower part of the Bragdon formation. One bed, about 50 feet above the base of the formation, crops out in sec. 16, T. 34 N., R. 4 W. on the east side of O'Brien Mountain. It averages about 5 feet in thickness and was traced for about half a mile. A similar bed crops out at about the same stratigraphic position on the west side of the mountain in sec. 17, T. 34 N., R. 4 W. Other beds of similar rock occur at stratigraphically higher positions in the Bragdon but they are sparse. Thin sections show that the dark-gray conglomerate consists of subangular to subrounded granules of chert, cherty shale, mudstone, and quartz in a subordinate matrix of microcrystalline quartz, carbonaceous material, and a small amount of chlorite. The fragments are poorly sorted and range from about 1 to 10 mm in diameter. The dark color of the rock is due principally to carbonaceous material.

TUFF AND VOLCANIC BRECCIA

Tuff is a minor constituent of the Bragdon formation and was seen in only three places. The thickest and most extensive bed is in the extreme northwest corner of the area (pl. 1). This tuff bed, which lies about 3,000 feet above the base of the Bragdon formation, is dark greenish gray and massive. It contains feldspar crystals averaging about 1 mm in diameter, sparse, small crystals of ferromagnesian minerals, and sparse fragments of greenstone as much as half an inch in diameter. The matrix seems to be chiefly chlorite. Locally, this lithic crystal tuff grades into fine-grained silty tuff.

Tuff was also seen near the present mouth of Packers Gulch, where at least two beds of tuff are interbedded with the epiclastic rocks. One bed is about 100 feet above the base of the Bragdon formation and lies a few feet above a 5-foot-thick bed of chert conglomerate. Except in one place where it grades into volcanic breccia this tuff is similar in composition and texture to that described previously.

A third tuff locality is in sec. 16, T. 34 N., R. 4 W., just west of U.S. Highway 99. This tuff, which forms a bed too small to be shown on the map, lies at about the same stratigraphic position as the bed in Packers Gulch. It is interbedded with shale but the underlying shale is only a few feet thick and is in turn underlain by dark-gray, muddy conglomerate.

A study of thin sections reveals that the tuff in sec. 16 is lithic crystal tuff of two distinct petrographic types, one of andestitic or basaltic composition, containing labradorite feldspar clasts, and the other of keratophyric composition, containing clasts of albitized feldspar.

CONDITIONS OF DEPOSITION

Much too small an area of Bragdon formation was mapped during the present study to permit much speculation regarding source rocks and conditions of sedimentation but several features suggest its source and mode of deposition. Most of the chert and all the limestone debris in the conglomerate was probably derived from the Kennett formation, and may thus have been of local origin. The marked angularity of most chert pebbles in the conglomerates also suggests short transport and therefore local origin but does not necessarily imply deposition in shallow water. The sediments of the Bragdon probably were deposited in the bathyal depth zone, near steep shores, in a tectonically active eugeosyncline. Pyroclastic rocks in the formation indicate that the volcanoes were active intermittently. One shore of the earliest Bradgon seas may have been near the now submerged mouth of Packers Gulch where shale of the Bragdon seems to lens out between the Copley greenstone and the Baird formation.

AGE

The stratigraphic position of the Bragdon formation between the Kennett and the Baird formations establishes it as Late Devonian or Early Mississippian age. Diller (1906, p. 3), on the basis of fossils found near Lamoine, a few miles north of the present mapped area, dates the Bragdon formation as early Carboniferous, and a Mississippian age is retained for this report.

BAIRD FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Baird formation crops out on both sides of the McCloud River arm of Shasta Lake and is assumed to be continuous beneath the submerged McCloud River valley. The outcrop width of the formation ranges from about 1 to a little more than 2 miles and dips generally eastward. Mudstone, pyroclastic rocks, and greenstone make up the bulk of the Baird formation. Tuffaceous sandstone, limestone, and chert are minor constituents. The formation is intruded by the Pit River stock of light-colored granodiorite and is also intruded in many places by tabular bodies of mafic quartz diorite.

The Baird formation is named from exposures near the now submerged Baird fish hatchery, which was located on the McCloud River near the junction with the Pit River. The formation was originally called the Baird shale by Smith (1894, p. 594–599) but Diller (1906, p. 3) changed the name to Baird formation. The Baird shale of Smith included about 500 feet of black, metamorphic, siliceous shale, and subordinate beds of diabase and other eruptive rocks at the top. Diller, in renaming the unit the Baird formation, extended the lower limits of the Baird shale to include "the tuffaceous rocks and adjoining sandstones and shales which overlie the topmost Bragdon conglomerate."

STRATIGRAPHIC RELATIONS AND THICKNESS

The contact between the Baird and the underlying Bragdon formation is drawn at the upper limit of the platy shale which characterizes the Bragdon. Overlying this platy shale are pyroclastic rocks and interlayered mudstone lenses assigned to the Baird. It is possible that the Bragdon and Baird formations are separated by a disconformity although this could not be proved because of poor outcrop and minor faulting. The sparse conglomerate and thinness of the Bragdon on the east flank of O'Brien Mountain suggests that only the lower beds of the formation are present at that locality. The upper beds were either never deposited, were removed by erosion before deposition of the Baird, or have been faulted out. There seems to be no reliable evidence to prove which of these conditions is true.

The thickness of the Baird formation cannot be measured accurately owing to lack of data on the submerged part of the formation. It is also difficult to estimate the thickness because the formation is cut by many small faults and by tabular intrusive bodies. If the unknown influence of faults is neglected, but allowance is made for folds and intrusive bodies, a line of section drawn just north of Bailey Creek (pl. 1) shows a maximum thickness of about 3,000 feet. A similar section, drawn just north of the junction between the McCloud River and Pit River arms of Shasta Lake, shows a thickness of about 5,000 feet.

LITHOLOGY AND PETROGRAPHY

The Baird formation consists chiefly of pyroclastic rocks interbedded with tuffaceous sandstone, mudstone, and mafic flows in the lower part; siliceous mudstone, and minor amounts of limestone, chert, and tuff in the middle part; and greenstone in the upper part. The formation is intruded in many places by tabular bodies of mafic quartz diorite many of which are nearly parallel to bedding and are difficult to distinguish from mafic flows.

PYROCLASTIC ROCKS

West of Goat Creek the pyroclastic rocks in the lower part of the Baird formation include greenish-gray to greenish-black volcanic breccia, tuff breccia, and tuff. The fragmental character of this material is difficult to recognize on fresh surface but is brought out clearly by weathering. Bedding is rare. Most of the lithic fragments in the coarse pyroclastic rocks are of porphyritic rocks containing phenocrysts of ferromagnesian minerals and plagioclase; the fragments range from a fraction of an inch to about a foot in diameter. Plagioclase, and in some places quartz, form crystals and clasts. Irregular clots of ferromagnesian minerals and quartz clasts are common constituents of the tuffaceous matrix of the coarse pyroclastic rocks.

Thin sections show that tuffaceous rocks west of Goat Creek consist of angular to subangular fragments of volcanic rocks and mudstone, and clasts of quartz and feldspar in a matrix of green acicular amphibole and plagioclase. Most fragments of volcanic rocks are porphyritic and contain plagioclase ($An_{43\text{-}53}$) phenocrysts and pyroxene crystals replaced pseudomorphously by uralite in a groundmass of green amphibole, plagioclase, chlorite, stilpnomelane, epidote, magnetite, sphene, and leucoxene. Commonly the uralite crystals contain small remnants of unreplaced augite. Most plagioclase phenocrysts are subhedral and range from 0.25 to 2.0 mm in diameter. They show normal oscillatory zoning, and the cores are slightly more calcic than the rims. Albite, fine-grained white mica, chlorite, pumpellyite, and stilpnomelane are common alteration products in plagioclase phenocrysts. Groundmass textures of the fragments of porphyritic volcanic rocks range from microgranular to intersertal. Most porphyritic rock fragments are meta-andesite. Some lithic fragments in the pyroclastic rocks have about the same mineralogic composition as the fragments of porphyritic rock but differ from the latter in that they contain no phenocrysts.

East of Goat Creek, along the west side of the McCloud River arm to the north edge of the area, tuff interbedded with subordinate tuffaceous sandstone and mudstone is the dominant lithologic constituent of the Baird formation. Commonly the tuff forms beds ranging from a few feet to about 50 feet in thickness. The tuff is poorly stratified, rarely shows bedding, and ranges from light greenish-gray through brownish-gray, to greenish-black. Lithic tuffs are more common than crystal tuffs but all gradations occur.

Under the microscope the tuffs show great diversity in composition but three main compositional types, meta-andesite tuff, keratophyre tuff, and quartz keratophyre tuff, were recognized.

The meta-andesite tuff is commonly a dark-greenish-gray to greenish-black rock containing angular fragments of meta-andesite and clasts of slightly albitized intermediate plagioclase, hornblende, and augite in a matrix of celadonite, chlorite, sphene, leucoxene, epidote, and fine-grained white mica. In some places the meta-andesite tuff contains sparse fragments of mudstone and devitrified volcanic glass in addition to the materials listed above.

The keratophyre tuff is similar to the meta-andesite tuff except that the feldspar in lithic fragments as well as the feldspar forming crystal clasts is albite rather than intermediate plagioclase.

Quartz keratophyre tuff is interbedded with the more mafic tuffs and in a few places it is interbedded with mafic flows in the lower part of the Baird formation. Commonly the quartz keratophyre tuff is a light greenish-gray to light-gray rock consisting of quartz and feldspar clasts as much as 3 mm in diameter in an aphanitic matrix. Bedding is rare. In thin section the quartz keratophyre tuff commonly consists of anhedral crystals and clasts of quartz and albite, and fragments of keratophyre, in a matrix of albite, stilpnomelane, microcrystalline quartz, chlorite, epidote, sphene, leucoxene, fine-grained white mica, and pyrite. Striking features of the quartz keratophyre tuff are the rounded and lobate quartz crystals and crystal clasts. In detail the edges of the quartz grains show narrow, microscopic overgrowths of the microcrystalline groundmass quartz.

TUFFACEOUS SANDSTONE

Tuffaceous sandstone forms beds as much as 10 feet thick interlayered with tuff and mudstone in the lower part of the Baird formation along the west side of the McCloud River arm. The tuffaceous sandstone in contrast to tuff is a well-bedded rock and commonly has a high proportion of mineral clasts to lithic fragments. Subrounded clasts of quartz and feldspar, fragments of mafic volcanic rocks, and black opaque minerals are the most common constituents. The opaque minerals are chiefly magnetite concentrated in discrete layers generally about a half an inch apart. A thin section of a typical tuffaceous sandstone consists of clasts of albite, quartz, and magnetite, and fragments of keratophyre, in a matrix of chlorite, microcrystalline quartz, fine-grained white mica, and limonite. The sandstone contains detrital grains of albitized feldspar as much as 2 mm in diameter. These make up 50 percent of the rock. Quartz clasts and lithic fragments are mixed with the albite. Magnetite in layers averaging about 1 mm in thickness forms about 10 percent of the rock.

MUDSTONE

About 25 to 30 percent of the Baird formation is mudstone. It is the principal lithologic constituent of the middle part of the formation and forms lenses interbedded with pyroclastic rocks, tuffaceous sandstone, and mafic lava in the lower part. Most of the mudstone is dark gray and siliceous. A smaller amount is tuffaceous. The siliceous mudstone is generally not laminated and is in beds ranging from 4 to 12 inches in thickness. Some beds contain abundant fossils. The tuffaceous mudstone commonly shows faint bedding and in a few places shows crossbedding.

In thin section the siliceous mudstone consists chiefly of microcrystalline quartz, but includes minor clay minerals, stilpnomelane, fine-grained white mica, chlorite, feldspar, and carbonaceous material. A faint lamination is discernible in some slides owing to a slightly different concentration of colored components in adjacent layers. The average grain size is about 0.01 mm.

The tuffaceous mudstone commonly consists of 65 to 75 percent plagioclase and 10 to 20 percent quartz. Stilpnomelane, fine-grained white mica, chlorite, and pyrite are minor components. The grain size of most of the rock is about 0.01 mm, but in some thin sections layers consisting of detrital grains of plagioclase as much as 0.5 mm in diameter were seen.

LIMESTONE AND CHERT

Limestone partly replaced by chert crops out at an altitude of 1,950 feet on a ridge at the north edge of sec. 3, T. 33 N., R. 4 W. This body of limestone, which is about 25 feet thick, has an outcrop width of about 200 feet on the crest of the ridge. The limestone is light gray and contains abundant lithostrotionoid corals and other fossils characteristic of the Baird formation.

About 50 percent of the limestone is replaced by chert, which forms lenses, nodules, and irregular masses. Some chert layers parallel bedding in the limestone whereas others cut across the bedding. Locally, masses of chert several feet thick contain irregular, unreplaced remnants of limestone and silicified fossils identical to those in the limestone.

GREENSTONE AND BRECCIA IN THE UPPER PART OF THE BAIRD

The dark greenish-gray fine-grained porphyritic greenstone and associated breccia that crops out along the east side of the McCloud River arm and in secs. 34 and 35, T. 34 N., R. 4 W. probably is volcanic material in the upper part of the Baird formation. These rocks apparently overlie mudstone containing fossils characteristic of the Baird and lie stratigraphically below the McCloud limestone although they are almost everywhere separated from the limestone by intrusive mafic quartz diorite.

Diller (1906, geol. map) apparently regarded these rocks as a facies of the quartz augite diorite intrusive mass. This interpretation cannot positively be refuted as certain features of these rocks, notably their massive character and the marked lack of continuity of breccia facies, suggest an intrusive rather than extrusive mode of origin. On the other hand, the continuity of this rock unit through the area as a layer of rather uniform thickness, the lack of crosscutting relations to adjacent rock units and the local lenses of pyroclastic-like breccia (pl. 1) suggest an extrusive origin.

The greenstone closely resembles the mafic flows of the Copley greenstone, but differs from the Copley in that it is more massive in outcrop, contains few if any amygdules and contains as much as 15 percent primary quartz. In some places the greenstone seems to grade into mafic pyroclastic rock and flow breccia and in other places sheets of quartz keratophyre tuff are intercalated with the greenstone.

Thin sections show that plagioclase, epidote, chlorite, and quartz are the chief mineralogic constituents of the greenstone; and apatite, amphibole, sphene, leucoxene, celadonite, leptochlorite, biotite, fine-grained white mica, pumpellyite, pyrite, and magnetite are the minor constituents. Groundmass textures range from trachytic to hypidiomorphic microgranular.

The plagioclase forms phenocrysts ranging from 1 to 10 mm in diameter and forms laths in the groundmass. In some slides the feldspar is calcic andesine (An_{45-50}) but in other slides it is poorly twinned and much altered albite (An_{5-10}).

Epidote makes up as much as 20 percent of the greenstone in places. It replaces plagioclase and forms small grains and irregular clots in the groundmass. In some slides epidote is altered to chlorite, which in turn is altered to leptochlorite. Pale-green chlorite is common in the groundmass. Quartz, which forms 5 to 15 percent of the rock, is interstitial to plagioclase laths in the groundmass and in places encloses several plagioclase laths poikilitically. It forms 5 to 15 percent of most thin sections.

Fibrous, blue-green amphibole, probably actinolite, was seen only in slides containing andesine feldspar. The amphibole forms radiating clusters, surrounds a few plagioclase phenocrysts, and is interstitial to plagioclase laths in the groundmass.

CONDITIONS OF DEPOSITION

The stratigraphic distribution of volcanic and sedimentary components of the Baird formation shows that volcanism was dominant during early Baird time and again during late Baird time. Marine sedimentation was dominant during the intervening periods. As suggested by the interbedded pyroclastic rocks, tuffaceous sandstone, and mudstone, the lower part of the formation was probably deposited in a sea dotted with volcanoes or in a sea adjacent to a volcanic high-land. The well-sorted tuffaceous sandstone beds composed of slightly abraded feldspar grains and cleanly segregated layers of heavy minerals indicate that the water in which these sediments were deposited was probably shallow. Abundant shallow-water marine fossils including corals in the mudstone and limestone likewise show that the middle part of the Baird was deposited in warm, shallow water. The greenstone in the upper part of the formation may have been extruded onto dry land.

AGE AND FAUNA

The mudstone and limestone in the middle part of the Baird formation contain abundant invertebrate fossils. The type locality for the Baird is now submerged, but its fauna was reported by Smith (1894, p. 595–597) and assigned to the Lower Carboniferous.

During the present study fossil collections were made from two localities in the Baird. One collection is from limestone and chert in the NW¼, sec. 3, T. 33 N., R. 4 W. (colln. E779), and the other is from beds in sec. 14, T. 34 N., R. 4 W. Mr. J. Thomas Dutro and Miss Helen Duncan have studied collection E779 from sec. 3 (USGS 14983) in detail. Mr. Dutro examined the brachiopod-molluscan part of the assemblage, and Miss Duncan examined the bryozoans and coral Mr. Dutro (written communication, 1953) states:

This collection contains a fauna which is typical of the Baird formation * * * The fauna includes:

crinoid columnals
Orbiculoidea aff. *O. damanensis* Sokolskaja
Orthotetes sp.
Isogramma cf. *I. pachti* (Dittmar)
Chonetes sp.
Linoproductus? sp.
"*Cancrinella*" cf. "*C.*" *undata* (de France)
Dictyoclostus cf. *D. scabriculoides* Paeckelmann
"*Productus*" aff. "*P*". *keokuk* Hall
Echinoconchus aff. *E. punctatus* (Martin)
Spirifer cf. *S. brazerianus* Girty
  sp.
Torynifer? sp.
Parallelodon aff. *P. reticulatus* (McCoy)
  P. cingulatus (McCoy)
  P. verneuilianus (deKoninck)
  sp.
Schizodus sp.
Aviculipecten aff. *A. fimbriatus* (Phillips)
  A. dissimilis (Fleming)
  sp.
Amusium? sp.
Pinna? sp.
Pteronites? sp.
Straparollus (*Straparollus*) sp.
bellerophontid gastropod, genus indet.
pleurotomarian gastropod, genus indet.
pseudozygopleurid gastropod, genus indet.
murchisonid (?) gastropod, genus indet.
Mooreoceras? sp.
ostracodes, genus indet.

The Baird fauna previously has been considered of Meramecian or Viséan age. Some faunal elements in this collection are similar to the fauna from the Brazer formation in Idaho (*Spirifer* cf. *S. Brazierianus* Girty, "*Productus*" cf. "*P.*" *keokuk* Hall, the chonetid, and certain of the pelecypods). Other species are found in the upper Viséan of central Russia, specifically in the C_1^{st} (Steshevskiy) horizon. These include:

Orbiculoidea aff. *O. damanensis* Sokolskaja
Isogramma cf. *I. pachti* (Dittmar)
"*Cancrinella*" cf. "*C.*" *undata* (de France)
Echinoconchus aff. *E. punctatus* (Martin)
Dictyoclostus cf. *D. scabriculoides* Paeckelmann

Gigantoproductid brachiopods similar to those found in the Baird, but not present in this collection, are also found in the Upper Viséan of western Europe, Russia, and Alaska.

The pelecypod assemblage is typical of lower Carboniferous faunas described by Hinds (1896–1905).

There seems little doubt that the shale fauna is of Viséan age, related to the Brazer, Alaskan, and European faunas of approximately that same age.

Concerning bryozoans and corals from the same locality (USGS 14983) in sec. A, T. 33 N., R. 4 W. (colln. E779), Miss Duncan (written communication, 1952) reports:

This collection contains indications of several types of bryozoans. Many of the specimens are so poorly preserved, however, that they are not generically determinable, and none of the material is identifiable as to species. The following genera have been recognized: *Fenestella*, *Polypora*, "*Thamniscus*," and *Rhabdomeson*. Most of the ramose forms are crushed and cannot be accurately placed; they appear to belong to the group ordinarily called rhomboporoid bryozoans. All the genera identified range through the Carboniferous and Permian, but the general aspect of the assemblage is Carboniferous rather than Permian because several generic types that almost invariably occur in western Permian bryozoan faunules are not present. The specimens I am calling "*Thamniscus*" appear to be very much like a bryozoan I collected in the Mississippian (probable Brazer equivalent) of north central Nevada. The bryozoan material in this collection, however, is not adequate for discrimination of Mississippian from Pennsylvanian.

The fragment of colonial coral found in associated limestone is *Lithostrotion* aff. *L. pauciradiale* (McCoy). Forms that are identical with or closely related to this species are widely distributed in the upper Mississippian rocks of western North America and in the upper part (Viséan) of the Lower Carboniferous of other continents.

The collection from sec. 14, T. 34 N., R. 4 W., has not been examined in detail, but C. W. Merriam (oral communication, 1953) reports a fragment of a gigantoproductid brachiopod in this material. *Gigantoproductus* is a formation characteristic of the Baird and is indicative of a Mississippian age.

McCLOUD LIMESTONE

GENERAL CHARACTER AND DISTRIBUTION

The McCloud limestone is the most prominently exposed formation in the area. It consists mainly of light-gray limestone that forms large cliffs along the east side of the McCloud River arm of Shasta Lake from the Shasta Iron mine in sec. 26, T. 34 N., R. 4 W. northeastward to the boundary. It also crops out south of the Pit River arm in secs. 34 and 35, T. 34 N., R. 4 W., and in secs. 2 and 3, T. 33 N., R. 4 W. The limestone forms discrete masses that are separated from each other by mafic intrusive rock (pl. 1); the smallest masses have an areal extent of only a few hundred square feet, whereas the largest mass underlies an area of about 1 square mile. The McCloud limestone is a potential source of lime for cement and is a host rock for contact metasomatic magnetite deposits.

The first mention of the formation now known as the McCloud limestone was in a report by Trask (1855, p. 50–53) who referred to it as the "Carboniferous limestone" that forms "limestone mountains" along the east side of the McCloud River. Features of the formation were also described by Meek (1864, p. 1–16; pls. 1–2), Whitney (1865, p. 326–327), Fairbanks (1893, p. 35) (1894, p. 28–30), Smith (1894, p. 599–601), and Diller (1906, p. 3–4). Fairbanks (1893, p. 35) first referred to the unit specifically as the McCloud limestone and showed its distribution on a geologic map of Shasta County. Diller, (1906, p. 3–4) believed the McCloud limestone to be of Pennsylvanian (Upper Carboniferous) age. More recently Wheeler,[3] and Thompson, Wheeler, and Hazzard (1946, p. 21–36) have contributed systematic studies of the fauna of the McCloud limestone, especially the fusulinids, which show the formation to be of Permian age.

STRATIGRAPHIC RELATIONS AND THICKNESS

The McCloud limestone lies geographically in a belt between the Baird formation on the west and the Nosoni formation and Dekkas andesite on the east. However, within the area, the limestone is almost everywhere separated from these three formations by mafic quartz diorite. The quartz diorite is intruded mainly along a fault separating the McCloud from the Nosoni and Dekkas formations and partly along the contact between the McCloud and Baird. The only places where the McCloud is not in contact with quartz diorite are in the southeastern part of sec. 12, in the central part of sec. 23, and in the southwestern part of sec. 35, T. 34 N., R. 4 W. (pl. 1). In these localities the McCloud limestone is underlain by greenstone of the Baird formation, but owing to poor exposures and the absence of bedding in the lava the character of the contact could not be determined. The strike of bedding in the limestone in secs. 13 and 23, T. 34 N., R. 4 W. is markedly discordant to the general strike of the McCloud and Baird formations, suggesting the presence of a preintrusive fault between these two formations as well as between the McCloud and Nosoni formations.

Paleontologic evidence and stratigraphic relations in unfaulted sections exposed outside the map area show that the McCloud limestone lies in its correct stratigraphic position between the Baird and the Nosoni formations even though it is probably separated from these two units by preintrusive faults. Fossils indicate that an interval including at least all of Pennsylvanian time separates the McCloud from the Baird. Whether uplift and erosion of the Baird took place during this interval is not known.

Because the McCloud limestone is surrounded by intrusive rocks and broken by many faults its thickness is difficult to estimate. A cross section drawn from near the mouth of Marble Creek northeastward to Curl Creek suggests a thickness of at least 2,500 feet and possibly as much as 5,000 feet, depending on how much of the section is repeated by faulting. A more accurate determination of the thickness of the limestone in the large block north of Marble Creek might be obtained by detailed mapping of fusulinid zones as was done by Wheeler[4] in several places south of Marble Creek. If it is assumed that there is no repetition of beds by faulting, the apparent thickness of the limestone on the ridge between Marble and Potter Creeks is about 2,000 feet. South of the Pit River arm the maximum exposed thickness is about 500 feet but in this locality much of the upper part of the unit has probably been removed by faulting and recent erosion.

LITHOLOGY

LIMESTONE

The McCloud limestone consists of about 95 percent light-gray limestone and about 5 percent chert. The chert forms lenses and nodules throughout the formation but is most common in the lower part.

The limestone forms beds ranging from a few inches to about 10 feet in thickness. Most of the limestone is light bluish gray to medium gray, fine grained, and effervesces freely in cold dilute hydrochloric acid. A few blunt-ended, dark-gray layers ranging from 2 to 6 inches in thickness, react weakly with cold dilute hydrochloric acid. These dolomitic layers probably form less than 1 precent of the formation.

Some limestone beds are richly fossiliferous, and are commonly a fraction of an inch to several feet thick. One type of fossiliferous limestone contains mainly corals, crinoid stems, and brachiopods; a second type contains mainly fusulinids. Most of the fossils are

[3] Wheeler, H. E., The fauna and correlation of the McCloud limestone of northern California: Unpublished thesis, Stanford Univ., p. 1–166.

[4] Wheeler, H. E., op. cit., p. 1–166.

fragmentary and are composed of fine-grained calcite, fine-grained quartz, or a mixture of calcite and quartz. Beds containing abundant fusulinids commonly have a mottled appearance owing to a slightly lighter shade of gray than the matrix. A limestone of similar mottled appearance in the upper part of the McCloud limestone between Marble and Potter Creeks consists of ovoid bodies of calcite, ranging from 1 to 2 inches in diameter. Wheeler[5] regards these ovoid masses as stromatoliths of inorganic origin.

In a few places near mafic quartz diorite the limestone is coarsely crystalline or is altered to tactite. The most altered phases[6] of the McCloud limestone are near the Shasta Iron mine in sce. 26, T. 34 N., R. 4 W. Here a small peak is capped by white, equigranular coarsely crystalline limestone having an average grain size of about 6 mm. Bedding and fossils have been destroyed although a few layers of chert that may be approximately concordant with the bedding are discernible. The marble is underlain by skarn, and is intruded by dikes of fine-grained mafic quartz diorite.

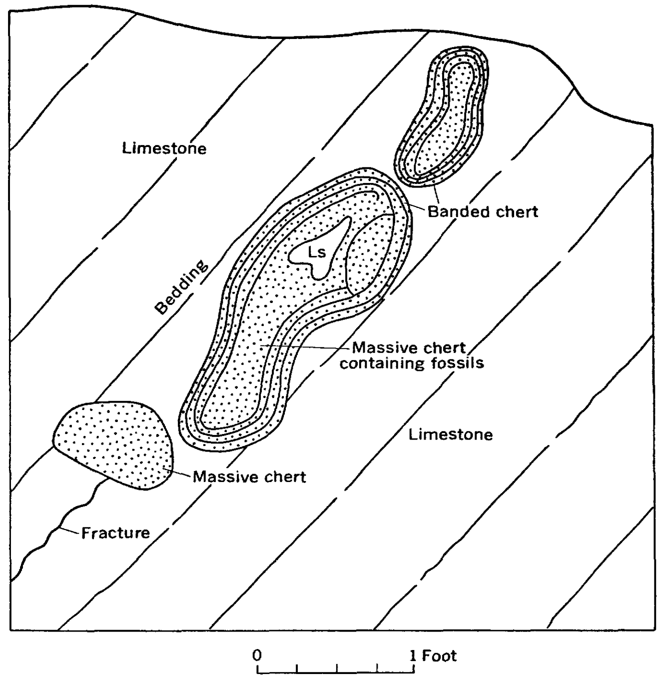


FIGURE 3. Sketch of chert bodies in the McCloud limestone on ridge between Marble and Potter Creeks. Note the concentric banding in the largest body of chert, and the remnant of unreplaced limestone in the central part of the kidney-shaped body.

CHERT

Chert of replacement origin, which comprises about 5 percent of the McCloud limestone, occurs irregularly throughout the formation but is most common in the lower part. The chert forms nodules, irregular lenses as much as 2 feet thick and 100 feet long, and irregular, kidney-shaped bodies as much as 2 feet in diameter. Most chert lenses are nearly parallel to bedding in the limestone but some cut across the bedding. The upper and lower edges of the lenses are commonly very irregular in detail. In places the nodules seem to coalesce into lenses along strike. Locally chert predominates over limestone throughout a stratigraphic thickness of several feet.

A few kidney-shaped bodies of chert are concentrically banded and contain remnants of limestone (fig. 3), and locally, irregular bodies of chert contain silicified fusulinids. The same type of fusulinids are unsilicified in contiguous beds of limestone crosscut by the chert.

CONDITIONS OF DEPOSITION

The abundance of colonial corals and fusulinids, which favored warm, shallow water, indicates that deposition of the McCloud limestone took place in a clear, warm, shallow sea, possibly far from shore. The abundance of fossils in most parts of the formation suggests that the limestone is probably largely of biogenic origin and the fragmental nature of the fossils shows that at least part of the limestone is calcarenite. The absence of biohermal and biostromal structures indicates that the limestone is not a reef. The abundance of fusulinids shows that deposition may have taken place far from shore because, according to Moore and others (1952, p. 63), studies of fusulinid ecology show that these organisms lived chiefly in a clear-water marine environment far from shore.

AGE AND FAUNA

Three collections of fusulinids from the McCloud limestone taken from the ridge between Marble and Potter Creeks were identified by Lloyd G. Henbest and Raymond C. Douglass (written communication, 1952). Their findings are as follows:

Field No.	*USGS collection No.*	*Stratigraphic position (approximate)*	*Age*	*Fauna*
		McCloud limestone:		
31	F-9009	Upper 15–20 ft exposed	Hueco	*Pseudofusulinella* aff. *P. occidentalis* (Thompson and Wheeler). *Schwagerina* sp. *Parafusulina* sp.
28	F-9008	About 1,500 ft above apparent base	---do------	*Pseudoschwagerina* sp.
25a	F-9013	About 250 ft above apparent base	Hueco, possibly Leonard	*Bradyina* sp. *Schwagerina* sp. *Pseudoschwagerina* sp.

[5] Wheeler, H. E., op. cit., p. 1–166.

[6] C. L. and M. A. Fenton (1930, p. 145–153) define the term "phase" as "* * * a local or regional aspect or condition of a stratum of group of strata, as determined both by original nature and secondary change; the latter the determining factor." This usage of the term "phase" is followed in this report.

Two specimens, one a horn coral, and the other a colonial coral, were also collected from beds about 250 feet above the apparent base of the McCloud limestone (field No. 25a). Helen Duncan reports on these as follows: (written communication, 1951 and 1956):

> The fragmentary horn coral was found to be a siliceous mold in which only traces of the septa are preserved. As information on critical structures is not obtainable, the specimen cannot be identified. About all one can say is that the coral appears to have a cardinal fossula and is therefore a Paleozoic form.
>
> Minute fracturing and recrystallization have obscured and obliterated diagnostic internal characters of the colonial coral. The specimen is probably one of the forms that have been referred to *Waagenophyllum*. At present, five genera are distinguished in the group of corals formerly included in *Waagenophyllum*. Unfortunately, the characters needed to determine which genus is represented are not preserved in this altered specimen. Meek described (under the name *Lithostrotion*) some species from the McCloud limestone that are believed to be "waagenophyllids," and corals of this type are fairly widely distributed in the rocks of Permian age in the Pacific Coast region.

Faunal data indicate that most of the McCloud limestone is of Hueco (Wolfcamp) age although the F-9013 collection may be of Leonard age.

Thompson, and others (1946, p. 22) classify the lower part of the McCloud limestone as Wolfcamp in age, but believe that the development of certain fusulinids strongly suggests a Leonard age for the upper part of the formation.

NOSONI FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Nosoni formation, the next stratigraphic unit above the McCloud limestone, consists mainly of mudstone and fine-grained tuffaceous rocks. It has two areas of outcrop. One area extends from the northwestern part of sec. 25, T. 34 N., R. 4 W. northward to the west-central part of sec. 24, T. 34 N., R. 4 W. (pl. 1). The other extends from the northwestern part of sec. 18, T. 34 N., R. 3 W. northeastward to the edge of the area. Elsewhere the Nosoni is missing, due in part to faulting and possibly in part to an erosional unconformity at the top of the Nosoni.

The Nosoni formation was named by Diller (1906, p. 4) from exposures on Nosoni Creek about 6 miles north of the East Shasta area. As defined by Diller the Nosoni included all the sedimentary and volcanic rocks between the top of the McCloud limestone and the top of the uppermost bed containing fossils of Paleozoic age. The Dekkas andesite, which overlies the Nosoni formation, was considered by Diller to be of Triassic age. The present fieldwork has shown, however, that between Horse and Town Mountains (pl. 1) lenses of tuffaceous rock containing Paleozoic fossils interfinger with lavas and pyroclastic rocks that are characteristic of the Dekkas andesite. Moreover, the fossil-bearing lenses of tuffaceous rock are at different stratigraphic positions so that they cannot be used as a formation boundary. Therefore, in this report the contact between the Nosoni and Dekkas is drawn several hundred feet stratigraphically below the highest fossil-bearing lens, in a zone where predominantly fine grained tuffaceous sedimentary rocks are overlain by generally coarser grained pyroclastic rocks and mafic lava characteristic of the Dekkas andesite. As thus delimited the Nosoni formation consists mainly of mudstone and fine-grained tuffaceous rock but includes some coarse pyroclastic rock and lava.

STRATIGRAPHIC RELATIONS AND THICKNESS

Within the mapped area the Nosoni formation and the McCloud limestone are separated by intrusive rock and by a preintrusive fault (pl. 1) so that the stratigraphic relations between the two units are indeterminate. Paleontologic data and stratigraphic relations observed by Wheeler [7] outside the area, where the two units are in contact indicate that the Nosoni formation succeeds the McCloud limestone in the stratigraphic column.

The Nosoni is probably separated from the McCloud by a disconformity as is suggested by: (a) the absence of fossils of early Leonard age in rocks above the McCloud limestone; (b) the observation of Wheeler that southward from Potter Creek successively lower strata are absent from the McCloud limestone, implying uplift, northward tilting, and erosion of the limestone before deposition of the Nosoni; and (c) the finding of Wheeler that:

> Basal conglomerate of the Nosoni formation resting on the McCloud limestone, and containing boulders and pebbles of the McCloud is exposed * * * in an old magnetite prospect in the SW¼ sec. 22, T. 33 N., R. 4 W.

This locality is about 4 miles south of the East Shasta area.

The maximum thickness of the Nosoni formation on the ridge between Marble and Potter Creeks, in sec. 24 and 25, T. 34 N., R. 4 W., is about 900 feet. However, on the northwest flank of the ridge between Horse and Town Mountains the thickness, assuming an average southeast dip of 30° and no repetition of beds by faulting, is estimated to be about 2,000 feet.

LITHOLOGY AND PETROGRAPHY

The principal lithologic components of the Nosoni formation are mudstone, tuffaceous mudstone, tuffaceous sandstone, and tuff. The formation also includes

[7] Wheeler, H. E., 1934, The fauna and correlation of the McCloud limestone of northern California: Unpublished thesis, Stanford Univ., p. 1–166.

minor conglomerate, mafic lava, and mafic tuff breccia. These rock types are so closely interbedded and in most places are so poorly exposed that they could not be delineated on the map.

MUDSTONE AND TUFFACEOUS MUDSTONE

About half of the Nosoni formation is mudstone and tuffaceous mudstone. In most places these rocks are interbedded with each other and with tuffaceous sandstone and tuff. Many beds of mudstone and tuffaceous mudstone are fossiliferous. Fusulinids are common in some beds, whereas brachiopods, bryozoans, and other fossils are common in other beds. Fusulinids rarely occur in the same bed with other kinds of fossils.

Thin sections show that quartz, chlorite, and fine-grained white mica are the chief mineral components of the mudstone and that plagioclase, chlorite, calcite, quartz, and minor sphene are the most common mineral constituents of the tuffaceous mudstone. The plagioclase is andesine or labradorite in part replaced by albite. Calcite commonly occurs as a replacement of other minerals.

TUFF AND TUFFACEOUS SANDSTONE

Tuff and tuffaceous sandstone make up about 40 to 45 percent of the Nosoni formation. These rocks range from olive gray to greenish black, are poorly bedded, and in most places could not be distinguished from each other in the field. As shown by thin section, the tuffs are commonly composed largely of albite clasts and keratophyre fragments in a matrix of pale-green chlorite. Fragments of mudstone and chert, and leucoxene, epidote, fine-grained white mica, clay minerals, limonite, and calcite are minor components. Albite is the most common feldspar but andesine and labradorite were seen in a few slides. The tuffaceous sandstone, in thin section, consists of plagioclase and quartz clasts, fragments of volcanic rocks, and irregular masses of calcite, in a matrix of chlorite. The plagioclase and quartz clasts generally are slightly abraded. The abrasion of feldspar clasts and the generally better development of bedding are the main criteria by which tuffaceous sandstone was distinguished from tuff.

MAFIC LAVA AND TUFF BRECCIA

Dark-greenish-gray porphyritic lava and mafic tuff breccia make up about 5 percent of the Nosoni formation. Commonly the lava is massive or slightly brecciated and contains plagioclase phenocrysts 1 to 3 mm in diameter in an aphanitic groundmass. It is similar in hand specimen and in thin section to the keratophyre of the Copley greenstone, the Baird formation, and the Dekkas andesite. The tuff breccia is composed of fragments of keratophyre as much as 10 inches in diameter in a tuffaceous matrix.

CONGLOMERATE

A bed of conglomerate about 5 feet thick, consisting of rounded to angular pebbles and cobbles of siliceous mudstone in a tuffaceous mudstone matrix, is exposed at the apparent base of the Nosoni formation on the ridge between Marble and Potter Creeks. Whether this conglomerate is actually at the base of the formation is not known because the conglomerate is separated from the McCloud limestone by about 15 feet of intrusive rock. Probably none of the fragments in the conglomerate were derived from the McCloud limestone. However, Wheeler,[8] found basal conglomerate of the Nosoni formation resting on the McCloud limestone and containing boulders and pebbles of the limestone in several places south of the East Shasta area.

CONDITIONS OF DEPOSITION

Volcanic rocks interbedded with mudstone containing shallow-water marine fossils indicate that Nosoni time was characterized by intermittent volcanism, and that between volcanic episodes marine organisms lived in shallow waters in the general region of the volcanoes. During periods of quiescence pyroclastic material that had fallen on land was eroded and redeposited in nearby seas as tuffaceous mudstone and tuffaceous sandstone. The abundance of fusulinids suggests that the waters of the Nosoni seas were probably warm.

AGE AND FAUNA

Fossils were collected from the Nosoni formation at two localities. Locality 58 is in sec. 24, T. 34 N., R. 4 W., on the ridge between Marble and Potter Creeks, 200 feet above the apparent base of the Nosoni formation. Locality 33 is in the same section, on the same ridge, 500 feet above the apparent base of the formation.

Messrs. L. G. Henbest and R. C. Douglass (written communication, 1952–1953) report that the fusulinids in the collection taken from locality 58 (USGS F-9010) include:

?*Parafusulina californica* (Staff)
nosonensis Thompson
Schwagerina sp.
Parafusulina sp. advanced type, probably at least as late as upper Leonard, and possibly Word age.

With regard to other fossils in the collection from locality 58, James Steele Williams (written communication, 1953) reports:

The collection consists mostly of molds of incomplete single valves of brachiopods. Detailed features of the ornamentation are preserved on few of them. The molds were studied from rubber casts made from the molds. A few natural casts are present.

Tentatively identified from the molds were a *Punctospirifer* that is close to if not identical with *P. pulcher* (Meek), two

[8] Wheeler, H. E., op. cit., p. 16.

undetermined species of spiriferinoid shells, a *Hustedia?*, a *Chonetes?*, a piece of shell that resembles a *Neospirifer*, and a *Leiorhynchus*-like shell (possibly the same as the leiorhynchoid in collection D from the Dekkas andesite), and a productoid shell. There are also indeterminate fenestrate bryozoans and a fragment of a gastropod shell.

I believe that this collection is of Permian age, possibly of nearly if not precisely the same age as the Phosphoria formation. I would be inclined to assign it to the age equivalent of the Nosoni formation.

Concerning the bryozoans in the collection from locality 58 Miss Helen Duncan (written communication, 1953) reports:

This collection exhibits a great many indications of bryozoans, but as the fossils are preserved almost exclusively as molds or impressions, the bryozoan component is almost unidentifiable. Fenestrate, ramose, and bifoliate zoaria are present. A very few fenestrate specimens show enough structure to distinguish the genera *Polypora* and *Fenestella*. The ramose and bifoliate forms are generically indeterminate. About all that can be safely said about the bryozoan assemblage is that it is indicative of Paleozoic age. It is hoped that better preserved bryozoa from the Nosoni may eventually be found as the material examined suggests that the ramose and bifoliate forms in particular might provide useful information for correlation of the western Permian.

Concerning collection from locality 33, which is about 300 feet stratigraphically above locality 58, James Steele Williams (written communication, 1953) states:

It consists mainly of remains of brachiopods but a few indeterminate molds may be of pelecypods. Many of the forms are indeterminate even as to genus. Noted were a productoid shell that may represent a lino-productid, an indeterminate spiriferinoid form, and smooth forms that do not retain surface ornamentation, which may be Dielasmas or phricodothyrid brachiopods. The above forms are sufficient to indicate a Carboniferous or Permian age but are not sufficient for any closer age determination. There would be no conflict to its assignment to Nosoni.

DEKKAS ANDESITE

GENERAL CHARACTER AND DISTRIBUTION

The Dekkas andesite consists chiefly of mafic fragmental laval flows and pyroclastic rocks but includes beds of mudstone and tuffaceous sandstone. The formation was named by Diller (1906, p. 7) from exposures on Dekkas Creek about 3 miles north of the East Shasta area.

Within the area the Dekkas andesite is prominently exposed in a belt as much as 2 miles wide extending from the vicinity of Cove Creek northeastward through Horse and Town Mountains (pl. 1). Mafic volcanic rocks correlated with the Dekkas andesite also crop out in the cores of anticlines in the southeastern part of the area. Altogether, the Dekkas andesite is exposed throughout an area of about 10 square miles within the map boundaries.

STRATIGRAPHIC RELATIONS AND THICKNESS

The Dekkas andesite overlies the Nosoni formation in secs. 24 and 25, T. 34 N., R. 4 W. and in secs. 7, 8, and 18, T. 34 N., R. 3 W. Elsewhere the Nosoni formation is missing and the lowest part of the Dekkas andesite exposed is in contact with quartz diorite.

The contact between the Nosoni formation and the Dekkas andesite is difficult to determine owing to the presence of rocks of similar lithology and fauna in both formations and to the lenticular character of most mappable lithologic units. As stated in the section on the Nosoni formation, Diller (1906, p. 4) placed the contact at the top of the uppermost bed containing fossils of Paleozoic age. However, during the present mapping it was found that the uppermost beds containing Paleozoic fossils are small lenses a few hundred to a few thousand feet long that are at different stratigraphic positions. Moreover, between Horse and Town Mountains these lenses interfinger with and are underlain by mafic lava and coarse pyroclastic rocks similar to material that makes up the bulk of the Dekkas andesite. Because of these relations the contact between the Dekkas and Nosoni formations, as defined by Diller, could not be used during the present mapping. Instead, the contact is here drawn at the lower limit of the main mass of lava and coarse pyroclastic rock that characterizes the Dekkas andesite. Beneath this volcanic rock in most places is dominantly fine grained tuffaceous mudstone and mudstone typical of the Nosoni formation, interbedded with a minor amount of lava and coarse pyroclastic rock.

The absence of the Nosoni formation between the Dekkas andesite and the McCloud limestone southwest of Horse Mountain and in sec. 35 south of the Pit River arm (pl. 1) probably results mainly from a preintrusive fault along the east side of the McCloud limestone (pls. 1 and 2) but may in part be due to an erosional unconformity between the Nosoni formation and the Dekkas andesite.

The thickness of the Dekkas andesite, as measured in cross section, ranges from about 1,000 to 3,500 feet.

LITHOLOGY AND PETROGRAPHY

Dark-greenish-gray to olive-gray keratophyre and spilite lava containing sparse plagioclase phenocrysts is the chief constituent of the Dekkas andesite. Much of the lava is fragmental or blocky. Intercalated with the lava are sheets of mafic pyroclastic rocks, lenses of mudstone, and a few small lenses of porphyritic quartz keratophyre. Intrusive spilitic rock correlated with the Dekkas andesite crops out in the northwestern part of sec. 9, T. 34 N., R. 3 W.

The volcanic character of the Dekkas andesite is readily recognized in most places because original textures and structures have not been destroyed by deformation and metamorphism. Only in the extreme southeastern part of the area, where the andesite is weakly foliated, is the original character of the rock obscure.

KERATOPHYRE AND SPILITE

Thin sections and chemical analyses show that the lava constituting most of the Dekkas andesite is chiefly keratophyre. A minor amount is spilite. These two petrographic types could not be differentiated in the field and are difficult to distinguish even in thin section.

The spilites are dark-greenish-gray, aphanitic rocks containing albite phenocrysts with an average diameter of about 2 mm and sparse amygdules as much as 5 mm in diameter. Much of the spilite is fragmental. Thin sections show that the spilites consist commonly of 40 to 50 percent albite in the form of phenocrysts and microlites, 25 to 40 percent chlorite, which is mainly interstitial to the albite, and magnetite, sphene, leucoxene, calcite, fine-grained white mica, and epidote. Commonly the albite phenocrysts contain abundant inclusions of chlorite. Some specimens of spilite contain 15 to 20 percent augite, which forms microphenocrysts averaging about 0.5 mm in diameter. The texture is commonly porphyritic; in places it is glomeroporphyritic (pl. 18*A*). The groundmass texture in some specimens is pilotaxitic (pl. 18*B*). In other specimens it is intersertal.

A chemical analysis of a spilite is given in table 2, and the analysis of an average spilite, as computed by Sundius (1930, p. 9) is given for comparison. The analysed spilite contains no modal augite.

The keratophyres, like the spilites, are dark greenish gray, porphyritic, and slightly amygdaloidal and are commonly blocky or fragmental. The microscope shows that the keratophyres contain the same minerals as the spilites but the proportion of albite, the chief mineral, to mafic constituents, is greater. Albite makes up 50 to 65 percent of the keratophyres but only 40 to 50 percent of the spilites. Typically, the albite forms phenocrysts as much as 4 mm in diameter and microlites in a pilotaxitic or intersertal groundmass. Chlorite, sphene, leucoxene, magnetite, calcite, epidote, and fine-grained white mica are other common minerals in the keratophyres. The chlorite is interstitial to albite microlites; locally it replaces albite phenocrysts. Of the other minerals, one or all may be absent in a given specimen. An analysis of a keratophyre sample from along the Horse Mountain trail in sec. 20, T. 34 N., R. 3 W., is given in table 2, and the analysis of a keratophyre from Cornwall (Dewey and Flett, 1911) is given for comparison. A thin section of this keratophyre contains about 10 percent secondary quartz as microscopic veinlets and irregularly shaped masses.

TABLE 1.—*Analyses of spilite and keratophyre samples*

[An asterisk (*) indicates that the analyses were made by rapid methods]

	*1	2	3	4
SiO_2	52.3	51.22	65.52	66.05
Al_2O_3	17.6	13.66	14.90	13.29
Fe_2O_3	3.1	2.84	6.25	3.22
FeO	5.8	9.20	1.55	5.07
MgO	6.4	4.55	1.10	1.36
CaO	2.8	6.89	.64	.50
Na_2O	6.2	4.93	4.85	6.67
K_2O	.15	.75	1.97	.87
H_2O-	(1)	(1)	.39	.96
H_2O+	(1)	1.88	2.03	1.88
TiO_2	.64	3.32	.47	.49
CO_2	1.64	.94	.00	(?)
P_2O_5	.16	.29	.16	.09
MnO	.16	.25	.05	(?)
Total	97	100.72	99.88	100.45
Bulk density	2.68	(1)	2.65	(1)
Powder density	2.72	(1)	(1)	(1)

[1] Not determined.

1. Laboratory No. 52–1655. Spilite from upper Norton Gulch, southeast of Little Cow Creek, Shasta County, Calif., (Dekkas andesite). Analysts, Harry F. Phillips, Joseph Dowd, and Katrine White.
2. Average spilite, according to N. Sundius, 1930, Geol. Mag., v. 67, p. 9.
3. Laboratory No. ID–2116 CD. Keratophyric lava from exposures near Horse Mountain trail in sec. 20, T. 34 N., R. 3 W., Shasta County, Calif. Analyst, Harry M. Hyman.
4. Keratophyre, Tervennen, Cornwall, Dewey and Flett, 1911, no. 2, p. 209. Analyst, W. Pollard.

Most of the spilites and keratophyres contain amygdules. In a few places amygdules are abundant and conspicuous but in general they are sparse and erratically distributed. The amygdules, which are more common in the spilites than in the keratophyres, range in maximum diameter from a fraction of a millimeter to more than an inch; those less than 5 mm in maximum diameter are most common. The shape of the amygdules ranges from spherical to prolate; the smaller ones are nearly spherical, whereas the larger ones have ratios of length to width as great as 10 to 1.

Chlorite is the most common mineral in the amygdules but quartz, calcite, pumpellyite, albite, barite, and celadonite also occur. Commonly two, or even three minerals, occur in separate layers of a single amygdule. Typical combinations of this sort include: (a) albite crystals oriented normal to and lining the wall of amygdules whose central part is filled with chlorite; (b) quartz linings with chlorite in the centers; (c) chlorite linings with an intermediate layer of a different type of chlorite, and pumpellyite in the center; (d) quartz lining with calcite in the center; and (e) chlorite linings with celadonite in the center. Several of the above combinations are shown in some slides. Evidence suggesting possible feeders to the amygdules was found in one thin section. In this section veinlets lined with microcrystalline quartz, containing calcite in the center of the veinlet, join amygdules filled with quartz and calcite.

INTRUSIVE SPILITE

A body of intrusive spilitic rock that is possibly part of the Dekkas andesite is exposed in the northwestern part of sec. 9, T. 34 N., R. 3 W. near the summit of Town Mountain. It underlies an irregular area of about 100 acres. Locally well developed prismatic columns oriented normal to a steep unfaulted contact with gently dipping mudstone indicate that the mass is of intrusive origin. Also, a few angular fragments of mudstone are enclosed in the intrusive rock near its borders.

In hand specimen this spilite is dark olive gray, very finely granular, and nonporphyritic. It contains a few greenish-black chlorite amygdules. A thin section shows that lathlike crystals of albite, having an average length of 0.5 mm, make up about 50 percent of the rock. Other components are fresh augite, pale-yellowish-green chlorite, sphene, leucoxene, and pumpellyite. The albite laths show a marked fluidal arrangement, thus giving the rock a trachitic texture. Augite, which makes up about 20 percent of the rock, is nearly colorless and occurs as microphenocrysts as much as 0.5 mm in maximum dimension and as small grains averaging 0.1 mm in diameter. Some crystals are twinned. The optic angle is about 55°. The augite is remarkably fresh in spite of its close association with chlorite and with weakly twinned albite.

Augite also occurs as unaltered to partly altered microphenocrysts in some flows of the Dekkas andesite. The most notable occurrence of augite is in a spilite flow that directly overlies the prominent mudstone layer extending between Horse and Town Mountains. This spilite flow is cut by the intrusive spilite described above. The close spatial relation of the augite-bearing instrusive spilite with an augite-bearing spilite flow lithologically similar suggests that the intrusive body may mark the vent from which the flow was extruded.

The chlorite in the intrusive spilite is pale yellowish green. It fills amygdules, is a main constituent of the groundmass, and occurs as a replacement of albite. In the amygdules the chlorite forms rosettes that show a deep anomalous blue interference under crossed nicols. Its optic sign is negative and the mean index of refraction is 1.605.

Sphene, including its alteration product leucoxene, occurs as cloudy patches and constitutes about 2 percent of the rock. Pumpellyite locally lines amygdules.

QUARTZ KERATOPHYRE

Quartz keratophyre correlated with the Dekkas andesite crops out in the extreme southeastern part of the area and in a few other places. This rock is similar mineralogically and chemically to the quartz keratophyres forming the Bully Hill rhyolite, which overlies the Dekkas andesite, but is darker, and in most places enclosed by the mafic lavas of the Dekkas andesite. The rock, which is dense, siliceous, and dark gray, contains feldspar phenocrysts as much as 4 mm across, and sparse rounded quartz phenocrysts. Thin sections show that albite, forming subhedral phenocrysts and microlites, makes up about 70 percent of the quartz keratophyre. Quartz, as highly corroded phenocrysts, forms about 5 percent and chlorite makes up 10 to 15 percent. Fine-grained white mica, calcite, epidote, leucoxene, and magnetite are found in some sections. The porphyritic quartz keratophyres have a felty groundmass.

PYROCLASTIC ROCKS

Pyroclastic rocks, including volcanic breccia, tuff breccia, and tuff, make up about 20 percent of the Dekkas andesite. These rocks occur as lenticular bodies in all parts of the formation but are most common in the upper part.

Volcanic breccia crops out prominently on the south slopes of Horse and Town Mountains, and locally in the extreme southeastern part of the area. The breccia generally consists of fragments of several textural types of keratophyre and spilite. In a few places fragments of granitic rocks and quartz keratophyre are in a subordinate tuffaceous matrix. The fragments are commonly angular and average about 6 inches in maximum dimension. The mixture of lithologic types contained as fragments, and a matrix of tuff rather than lava distinguishes volcanic breccia from blocky lava. The volcanic breccia grades into tuff breccia.

The tuff of the Dekkas andesite ranges from fine silty tuff to lapilli tuff, and forms beds ranging from 2 to 100 feet in thickness. The thinnest beds persist for less than 100 feet along strike but the thicker beds continue for several thousand feet. The fine-grained tuff is commonly dark gray or dark greenish gray and closely resembles mudstone in outcrop. Within some tuff layers bedding is shown by slight differences in color, or in grain size, but more commonly internal bedding structure is absent. The attitude of the layer is defined by its contacts with the enclosing rocks. Thin beds of fine-grained tuff are exposed in the upper part of Seaman Gulch and near the upper part of Norton Gulch in the southeastern part of the area, and on the south slopes of Town and Horse Mountains.

In most places the fine-grained tuffs are interbedded with coarser pyroclastic rocks. Fusulinids and other marine invertebrate fossils are abundant in lenses of tuff that crop out in the area between Horse and Town Mountains.

MUDSTONE

Gray, siliceous mudstone is interbedded with the volcanic rocks of the Dekkas andesite on the upper slopes of Horse and Town Mountains. The most continuous mudstone bed was traced from the southwest side of Horse Mountain northeastward to the top of Town Mountain, about 3½ miles (pl. 1). The mudstone is olive black on fresh surface but weathers to light brownish gray, and has a faint color lamination in some places. It commonly parts along planes spaced 8 to 12 inches apart. Thin sections show that microcrystalline quartz, clay minerals, chlorite, biotite, and feldspar are the chief minerals. The average grain size is about 0.005 mm but sparse grains of plagioclase, quartz and magnetite are as much as 0.1 mm in diameter.

ORIGIN

The lithology of the Dekkas andesite shows that the formation is largely of volcanic origin. Layers of mudstone and tuff containing marine fossils, interbedded with the lava and coarse pyroclastic rocks, indicate that at least part of the volcanic material was extruded into the sea. The lenticular nature of the tuff beds suggests that the environment of deposition was a series of shallow basins, probably interconnected, rather than a large, continuous body of water.

On the other hand, the absence of pillow structure in the mafic lavas, while not conclusive, suggests deposition on dry land. Possibly the lavas and some of the pyroclastic material were extruded onto dry land, whereas the finer grained, well-sorted and well-bedded tuffs were deposited in shallow basins in the volcanic field.

AGE

Fossils were found in tuffaceous beds in the Dekkas andesite in the east-central part of sec. 8, T. 34 N., R. 3 W. (loc. D–207), and near the north edge of sec. 1, T. 33 N., R. 4 W. (loc. F–142). Locality D–207 is several hundred feet above the base of the Dekkas andesite as here mapped; the stratigraphic position of locality F–142 in sec. 1 is unknown. The rocks at both localities were mapped as Dekkas andesite by Diller (1960, geol. map and p. 4), although according to his description of the Nosoni formation he might have included them in the Nosoni had the fossils come to his attention.

Concerning the collection from locality D–207 (USGS F–9010b), L. G. Henbest and R. C. Douglass of the U.S. Geological Survey (written communication, 1953) state that:

> This collection contains at least two species of *Parafusulina* or possibly of *Polydiexodina*. The Guadalupian epoch of the Permian is indicated. These fusulinids are possibly as late as Capitan age.

James Steele Williams (written communication, 1953) examined the fossils other than fusulinids contained in the collection from locality D–207 and reports that:

> It contains a specimen tentatively referred to *Dictyoclostus* cf. *D. occidentalis* (Newberry), a *Meekella?* sp. indet., chonetid brachiopod, possibly a new genus, and other brachiopods not generically determinable. The form tentatively identified as *D. occidentalis* is somewhat crushed, smaller than typical forms of that species, and may represent a closely related species. There is enough evidence in this collection to refer it to late Paleozoic, very probably Permian age. My impression is that it is as young or younger than the Leonard formation of West Texas.

Mr. Williams also studied collection F–142 from the northern part of sec. 1, T. 33 N., R. 4 W. and reports as follows:

> This collection contains many crinoid columnals and many molds of fossils. Rubber casts were made from many of these molds and tentative identifications were made from these casts. None of the casts showed completely preserved specimens. A productoid of the same general configuration and structure as *Dictyoclostus occidentalis* (Newberry) occurs in the collection. This is smaller and narrower than typical forms of this species. Many molds and a few imperfect casts of interiors belonging to one or more species of brachiopods generally referred to *Leiorhynchus* (*Nudirostra* of recent authors) are also present. These may belong to closely related genera distinguishable only by characters not revealed on these specimens. The average specimen is rather large and I cannot identify the species represented. There is also a fragment of a dorsal valve of a large *Dictyoclostus*. From the general aspect of the fauna I believe that the age is Permian and that it is very probably of Leonard or younger age.

A single indeterminate *Fenestella* was also noted by Miss Helen Duncan (written communication, 1953) in collection F–142.

Fossil evidence indicates that the lower part of the Dekkas andesite is of late (Capitan) Permian age. The fusulinids from sec. 8, T. 34 N., R. 3 W., suggest that the Dekkas is somewhat younger than the Nosoni formation, according to Henbest and Douglass (written communication, 1953) but not significantly younger.

Diller (1906, p. 8) states that the Dekkas andesite is conformable with and interbedded with shale of the Pit formation, which is of Triassic age. He concludes that the Dekkas andesite was extruded largely during the early part of the Mesozoic and is therefore Triassic but notes that this volcanic activity actually began during the latter part of the Carboniferous.

No evidence was found by the writers to indicate that the upper part of the Dekkas is uncomformable beneath the Pit formation and it seems probable that the volcanic activity that gave rise to the Dekkas andesite began during late Permian and perhaps continued intermittently into the Triassic.

BULLY HILL RHYOLITE

GENERAL CHARACTER AND DISTRIBUTION

The Bully Hill rhyolite, named by Diller (1906, p. 8) from exposures on Bully Hill, crops out in the central and extreme southeastern parts of the area. It also forms the cores of several anticlines east of the junction between the Squaw Creek and Pit River arms. The Bully Hill consists principally of silicic lava flows and pyroclastic rocks, but includes subordinate hypabyssal intrusive bodies. Much of the Bully Hill rhyolite is porphyritic, and contains phenocrysts of quartz and plagioclase in a dense aphanitic groundmass. A subordinate amount is nonporphyritic. The comparatively light color and common presence of quartz phenocrysts are the chief features that distinguish the Bully Hill rhyolite from the underlying Dekkas andesite. The Bully Hill rhyolite is economically the most important formation in the area because most of the sulfide deposits occur as a replacement of its siliceous rocks.

The Bully Hill rhyolite is most prominent in the central and extreme southeastern parts of the area (pl. 1). The outcrop width of the belt of Bully Hill rhyolite that underlies Bully Hill ranges from about 100 feet west of Horse Creek to about 1½ miles in the upper reaches of Second Creek where the formation occupies a dipslope. In the southeastern part of the area the Bully Hill rhyolite occupies the troughs of synclines and the flanks and noses of two large anticlines.

STRATIGRAPHIC RELATIONS AND THICKNESS

The Bully Hill rhyolite overlies the Dekkas andesite and is overlain by the Pit formation of Middle and Late Triassic age. Rocks lithologically similar to the Bully Hill rhyolite are also interbedded with the Dekkas andesite and with the Pit formation in many places, so that the limits of Bully Hill rhyolite are difficult to define. In most places the contact between the Bully Hill rhyolite and the Dekkas andesite is drawn at the lower limit of the main mass of siliceous, light-colored volcanic rocks that characterize the Bully Hill rhyolite. However, in places where mafic lavas typical of the Dekkas andesite are interbedded with siliceous rocks typical of the Bully Hill rhyolite, correlation is based on which type of rock predominates. In sec. 30, T. 34 N., R. 3 W., for example, (pl. 1) siliceous, light-colored lava and tuff interbedded in subordinate amounts with mafic volcanic rocks are mapped with the Dekkas andesite. On the other hand, subordinate mafic lavas in the upper part of Seaman Gulch interbedded with silicic lavas are included with the Bully Hill rhyolite.

The Bully Hill rhyolite is also interbedded with the overlying Pit formation, which as a whole, consists mainly of shale and siltstone. The contact between these two formations is drawn at the base of the lowest bed of shale. However, in many places above the contact, as near the end of the peninsula between the Squaw Creek and Pit River arms of Shasta Lake, silicic volcanic rocks are almost as abundant as shaly sedimentary rocks. Here some ambiguity exists as to the position of the Bully Hill–Pit contact.

Interbedding of volcanic rocks of the Bully Hill rhyolite type with the underlying Dekkas andesite and the overlying Pit formation is interpreted to mean that the Bully Hill rhyolite is virtually conformable with the enclosing units.

The thickness of the Bully Hill rhyolite ranges from about 100 feet in sec. 21, T. 34 N., R. 3 W. (pl. 1) to possibly 2,500 feet in the extreme southeastern part of the area (section *A–A′*). In the Bully Hill area the maximum thickness is estimated to be about 1,500 feet.

LITHOLOGY AND PETROGRAPHY

The chief lithologic components of the Bully Hill rhyolite are lava flows and pyroclastic rocks of quartz keratophyric composition. Subordinate components include metadacite pyroclastic rocks, intrusive bodies of quartz keratophyre, mafic lava flows, mafic pyroclastic rocks, and shaly tuff. In most places the lithologic components of the Bully Hill rhyolite can be distinguished from one another with confidence, but in the extreme southeastern part of the area shearing and alteration are locally so intense that the distinction between lava flows and pyroclastic rocks is impossible. Therefore, some highly sheared and altered phases of the formation, shown as nonfragmental quartz keratophyre on the geologic map (pl. 1), may be pyroclastic material.

A consistent lithologic sequence, applicable throughout the district, was not recognized in the Bully Hill rhyolite. A reliable correlation of an individual lava flow or pyroclastic layer in a given locality with a rock of similar lithology elsewhere cannot be made because rocks of a given lithology occur at many stratigraphic positions in the Bully Hill rhyolite. The most persistent lithologic sequence recognized is in sec. 15, T. 34 N., R. 3 W., northeast of Bully Hill. Here a flow of partly fragmental, porphyritic quartz keratophyre several hundred feet thick overlies mafic pyroclastic rocks of the Dekkas andesite and is overlain by quartz keratophyre with faint flow banding and sparse quartz phenocrysts 1 to 2 mm in diameter. This quartz keratophyre with faint flow banding is in turn overlain by quartz keratophyre showing marked flow banding and containing large quartz phenocrysts as much as 6 mm in diameter. Finally, on top, is volcanic breccia consisting chiefly of slightly porphyritic quartz keratophyre fragments of mixed sizes. This sequence was traced for about one-half mile along strike. Other sequences of lithologic types, sufficiently persistent and distinctive to be utilized in mapping structure in small areas, were recognized in the Bully Hill-Rising Star mine area and in a few other places in the district.

A description of the main types of rock forming the Bully Hill rhyolite follows:

PORPHYRITIC QUARTZ KERATOPHYRE

Porphyritic quartz keratophyre is the most common petrographic type in the Bully Hill rhyolite. It occurs as massive and blocky lava flows, as dikes and irregularly shaped intrusive bodies in the Dekkas andesite and in the lower part of the Bully Hill rhyolite, and as fragments in pyroclastic rocks. Most commonly the porphyritic quartz keratophyre is light-greenish-gray to gray, siliceous rock containing quartz and feldspar phenocrysts in an aphanitic groundmass. The size and abundance of phenocrysts differ markedly among the units but at no place do phenocrysts predominate over groundmass. Individual flows commonly are characterized by the size and abundance of the quartz phenocrysts. Some flows contain only sparse quartz phenocrysts about 1 mm in diameter, whereas others contain abundant quartz phenocrysts ranging from 1 to 6 mm in diameter. In general, the largest phenocrysts are in the facies that contain the most abundant phenocrysts. Quartz keratophyre containing phenocrysts ranging from 1 to 3 mm in diameter is most common.

Feldspar phenocrysts are generally about the same size and are more abundant than quartz phenocrysts, but are much less conspicuous and therefore not as useful in the field as distinguishing lithologic features. Moreover, in some places the quartz keratophyres are so sheared and altered that the feldspar phenocrysts are completely obliterated and the quartz phenocrysts alone testify to the original petrographic character of the rock.

Thin sections show that the porphyritic quartz keratophyres consist chiefly of quartz and albite. Both minerals occur as phenocrysts and in the groundmass. The albite ranges in composition from Ab_{90} to nearly Ab_{100}, most of which is more sodic than Ab_{95}. Fine-grained white mica, calcite, chlorite, stilpnomelane, clinozoisite, epidote, leucoxene, and pyrite are sparse secondary minerals of irregular distribution.

Groundmass textures in the porphyritic quartz keratophyres include felty, microspherulitic, and trachitic. In many speciments the groundmass consists of anhedral microcrystalline quartz and fine-grained white mica. Flakes of fine-grained white mica are arranged subparallel in schistose facies.

Albite phenocrysts are commonly euhedral in unsheared and slightly altered phases of porphyritic quartz keratophyre but in altered phases the phenocrysts are partly replaced by microcrystalline quartz, fine-grained white mica, or calcite, or by combinations of these minerals. In some places albite crystals are completely replaced pseudomorphously by these secondary minerals.

Quartz phenocrysts range from euhedral bipyramids to very irregular crystals with lobate outlines. Most commonly the quartz crystals are rounded and slightly embayed. The rounded and lobate shapes of a few quartz phenocrysts may result in part from corrosion by the magma, but many of the most irregular grains are optically continuous quartz that has replaced plagioclase phenocrysts probably in the late magmatic stage. In some facies quartz and feldspar phenocrysts are fractured and fragmented into discrete clasts that are strung out in trains. The fracturing and fragmentation of the quartz phenocrysts are attributed in part to shearing in very viscous magma, and in part to shearing during orogenesis. Analyses of the quartz keratophyres are given in table 2.

NONPORPHYRITIC QUARTZ KERATOPHYRE

About 25 percent of the Bully Hill rhyolite is nonporphyritic quartz keratophyre. The nonporphyritic facies is most common in the Little Cow Creek area but also occurs in the Copper City mine area and in a few other places. It is not restricted to a particular stratigraphic position in the Bully Hill rhyolite. Locally it seems to form individual flows, but more commonly it grades into porphyritic quartz keratophyre containing very sparse quartz phenocrysts as much as 1 mm in diameter. The nonporphyritic quartz keratophyre cannot be used as a marker unit even in small areas.

In thin section the nonporphyritic quartz keratophyres are mineralogically and texturally similar to porphyritic facies containing sparse phenocrysts. Most slides show a few microphenocrysts of quartz and albite generally about 0.5 mm in diameter, in a felty or microspherulitic groundmass of quartz and albite. Fine-grained white mica, chlorite, pyrite, and limonite after pyrite are sparse minerals irregularly distributed.

TABLE 2.—*Analyses of quartz keratophyres from the Bully Hill rhyolite*

[An asterisk (*) indicates that the analyses were made by rapid methods]

	*1	2	3	4
SiO_2	76.3	72.83	81.69	70.45
Al_2O_3	12.4	12.77	10.66	14.47
Fe_2O_3	1.1	2.55	1.74	1.25
FeO	1.9	1.15	.09	2.07
MgO	.69	1.45	.59	1.38
CaO	.74	2.07	.06	.85
Na_2O	6.0	4.38	.14	5.99
K_2O	.26	.80	2.44	1.70
H_2O-	--------	.12	.27	.06
H_2O+	.61	1.35	2.00	1.13
TiO_2	.20	.35	.11	.36
CO_2	.39	.18	.00	.22
P_2O_5	.02	.10	.04	.10
MnO	.06	.04	.01	.05
Totals	101.00	100.14	99.84	100.08
Bulk density	2.67	2.66	2.57	2.66
Powder density	2.67	(1)	(1)	(1)

[1] Not determined.

1. Laboratory No. 52–1651. Porphyritic quartz keratophyre (possibly intrusive rock) from lower Seaman Gulch in the southeastern part of the East Shasta area. Analysts, Harry F. Phillips, Joseph Dowd, and Katrine White.
2. Laboratory No. ID–2114 CD. Medium-dark-gray, porphyritic quartz keratophyre from northwest corner of sec. 15, T. 34 N., R. 3 W. Analyst, Harry M. Hyman.
3. Laboratory No. ID–2115 CD. Silicified, flow-banded, slightly porphyritic quartz keratophyre from east-central part of sec. 16, T. 34 N., R. 3 W. This rock contains virtually no feldspar because of intense silicification and sericitic alteration. Analyst, Harry M. Hyman.
4. Laboratory No. ID–2117 CD. Quartz keratophyre from north-central part of sec. 16, T. 34 N., R. 3 W. Analyst, Harry M. Hyman.

FRAGMENTAL QUARTZ KERATOPHYRE

About half of the Bully Hill rhyolite is fragmental rock. Approximately 50 percent of the fragmental rock is block lava or flow breccia, and the remainder is pyroclastic rock, including volcanic breccia, tuff breccia, and tuff. A very small amount of the fragmental rock seems to be of tectonic origin. On the geologic map (pl. 1) block lava is differentiated insofar as possible from pyroclastic rock.

The principal criterion used to distinguish block lava from pyroclastic rock in the field is the composition and texture of the fragments. Pyroclastic rocks are made up of a mixture of several varieties of quartz keratophyre, whereas block lava contains but a single variety. Generally a slight difference in color or texture enables one to distinguish fragments from matrix in both block lava and pyroclastic rocks. The character of the matrix cannot be utilized to distinguish block lava from volcanic breccia in the field because the matrix is so intensely silicified and otherwise altered in most places that its original character, whether holocrystalline, glassy, or clastic, cannot be determined.

Block lava.—Block lava, or flow breccia (pl. 17*B*), forms about 25 percent of the Bully Hill rhyolite. It has no stratigraphic significance and cannot be utilized as a marker unit, even in small areas. It grades into massive lava in many places, and into pyroclastic rock in a few places. Petrographically, the block lava is identical to the quartz keratophyres described above.

Volcanic breccia.—Volcanic breccia occurs throughout the Bully Hill rhyolite but is most common in the upper part of the formation. It consists of angular to rounded fragments of different types of quartz keratophyre as much as a foot in diameter in a subordinate quartz keratophyre matrix. Textural varieties of quartz keratophyre that occur as fragments include flow-banded porphyritic, flow-banded nonporphyritic, massive nonporphyritic, and several facies of massive porphyritic types. In some places fragments of mafic lava are present. Commonly the matrix of volcanic breccias is a slightly different color than the fragments but is virtually the same composition. Thin sections show what much of the matrix consists of nests of albite and quartz that probably were introduced into a highly porous matrix. In many places volcanic breccia grades into tuff breccia.

The best exposures of volcanic breccia are about three quarters of a mile southeast of Sugarloaf, directly beneath the Pit formation.

Quartz keratophyre tuff breccia.—Much of the pyroclastic rock in the upper part of the Bully Hill rhyolite consists of fragments of several types of quartz keratophyre in a tuffaceous matrix that predominates over the fragments. This type of fragmental rock, classed as tuff breccia, grades from volcanic breccia to tuff. It is not differentiated from tuff on the map (pl. 1).

The principal mass of tuff breccia is a sheetlike body underlying 2 to 3 square miles on the southeast flank of Town Mountain. This sheet of pyroclastic rock is about 200 feet thick and forms the upper part of the Bully Hill rhyolite northeast of Bully Hill. It is probably correlative with the tuff breccia in the cores of anticlines between Brushy Canyon and Green Mountain, as well as with metadacite tuff breccia along the east and southeast sides of Bully Hill, which is described on pages 91–92.

The tuff breccias have a poorly defined bedding structure that is conspicuous in outcrops viewed from a distance but is difficult to discern at close range. On the southeast flank of Town Mountain this bedding is parallel to bedding in the overlying shale of the Pit formation.

In thin section the quartz keratophyre tuff breccia is chiefly quartz and albite. Most commonly lithic fragments of silicified quartz keratophyre are cemented by an aggregate of secondary quartz and albite. The secondary albite of the matrix is in the form of anhedral grains averaging 0.05 to 0.1 mm in diameter. Many grains show imperfectly formed Carlsbad twins whose exact position of extinction is difficult to determine. Albite and pericline-acline twins were not observed. In a few places the diversely oriented grains of secondary albite seem to have recrystallized to untwinned albite porphyroblasts as much as 0.5 mm across sieved with tiny blebs of quartz. A few albite porphyroblasts, which apparently achieved a more advanced stage of growth, show checkerboard twinning.

The quartz phenocrysts, which are probably the only original mineral remaining in the rock, are commonly fractured and strung out in trains. The fragmented quartz crystals are cemented by secondary quartz whereas fractured albite crystals are cemented by albite. Partial replacement of abite phenocrysts by optically continuous quartz of probable late magmatic origin, forming vermicular intergrowths of quartz and albite, is common. In its replacement of the albite the quartz seems to have been guided to some extent by crystallographic directions in the feldspar.

Tuff.—Tuff and lapilli tuff make up about 5 percent of the Bully Hill rhyolite, forming lenticular beds and poorly defined bodies that grade vertically into tuff breccia.

Tuff is mapped separately on the geologic map but lapilli tuff either forms bodies too small to be mapped separately or is so intimately mixed with tuff breccia that it could not be differentiated.

Tuff beds, some of which are well bedded and others that are poorly bedded, range from a few inches to about 50 feet in thickness and are as much as half a mile in strike length. In color they range from light brownish gray to dark gray. The tuff is most common in the southeastern part of the mapped area and in the Bully Hill area.

In well-bedded tuff the bedding is shown by slight differences in grain size and color between adjacent layers. Clasts of quartz and tiny pellets of lava, each crudely concentrated in discrete layers, are the principal components of most tuff.

Lapilli tuff occurs in close association with and is commonly gradational into coarse-grained tuff.

Metadacite tuff and tuff breccia.—Possibly 5 percent of the pyroclastic rock in the Bully Hill rhyolite approximates the composition of metadacite. This rock cannot be distinguished from quartz keratophyre pyroclastic rocks in the field and is not delineated on plate 1. Thin sections show that it occurs mainly along the east and southeast sides of Bully Hill in a zone about parallel to the stratification. Metadacite pyroclastic rocks may occur elsewhere in the Bully Hill rhyolite but have not been found.

The metadacite fragments in these pyroclastic rocks are olive gray to medium greenish gray. Microscopic examination shows that they consist of quartz, albite, plagioclase ranging in different specimens from calcic oligoclase to calcic andesine An_{27-49}, chlorite, fine-grained white mica, sphene, and leucoxene. The texture is commonly porphyritic, with a xenomorphic microcrystalline groundmass. Quartz and plagioclase form phenocrysts; some vermicular intergrowths of quartz and plagioclase resemble phenocrysts in hand specimen. The plagioclase commonly shows oscillatory zoning, and the cores are slightly more calcic than rims. In all slides, veinlets and irregular masses of clear, untwinned albite partly replace the plagioclase phenocrysts. The groundmass of the metadacite pyroclastics is commonly anhedral microcrystalline quartz.

Mafic lava and pyroclastic rock.—A few lenses of mafic lava and pyroclastic rocks are interstratified with the light-colored siliceous rocks of the Bully Hill rhyolite but make up less than 5 percent of the formation. Most of the mafic lava is in the southeastern part of the area between Little Cow Creek and Backbone Ridge (pl. 1). This mafic lava is indistinguishable petrographically from the mafic lava of the Dekkas andesite. Amygdaloidal structure is common. Chlorite, albite, sphene, leucoxene, and calcite are the chief minerals.

Mafic pyroclastic rocks, including volcanic breccia and tuff breccia, are interbedded with silicic rocks in the upper part of Seaman Gulch, on the east flank of Town Mountain, and in the vicinity of Brushy Canyon. Fragments in these pyroclastic rocks are chiefly keratophyre; a few light-colored fragments are quartz keratophyre. The matrix of some mafic pyroclastic rocks contains clasts of quartz.

COLUMNAR STRUCTURE

Columnar structure, consisting generally of 4-, 5-, and 6-sided columns occurs locally in the porphyritic and nonporphyritic quartz keratophyres. It is most conspicuous in nonporphyritic quartz keratophyre in the Afterthought mine area and in porphyritic quartz keratophyre on the south flank of Town Mountain (pl. 1).

The columns are of two sizes. Some columns have cross-sectional diameters averaging about 6 inches; others, which are more common, have diameters ranging from 1 to 2 inches. Larger columns show an internal fracture pattern that causes them to break down into columns in the smaller size range. The columns are rarely straight but commonly have a sinuous form. In some outcrops the orientation of neighboring groups of columns differs by as much as 90° within a few feet. Individual columns or groups of columns are as much as 10 feet long but most columns fade out or become fragmented and brecciated within a few feet. Petrographically, the quartz keratophyres with prismatic structure are identical to those in which the structure is absent.

Presumably the prismatic columns formed in response to the contraction of cooling lava and are oriented normal to the surface of cooling. The sinuous form of many columns and the markedly diverse orientation of neighboring groups of columns within short distances may have resulted of slight movements in the lava when it was nearly consolidated. Or, if the Bully Hill rhyolite was extruded partly into the sea as seems probable, the diversely oriented columns may have resulted from many different cooling centers that would likely occur in the extruded lava under submarine conditions. Slight fragmentation and brecciation of the columns in many places may also be in part attributed to minor movements of the lava after it was almost solidified, but intensely brecciated phases of quartz keratophyre with columnar structure probably result mainly from shearing during orogenesis.

VERMICULAR INTERGROWTHS OF QUARTZ AND PLAGIOCLASE

The porphyritic facies of the Bully Hill rhyolite contains vermicular intergrowths of quartz and plagioclase that commonly have euhedral outlines. In thin section these intergrowths consist of discrete vermiform masses of quartz that extinguish simultaneously under crossed nicols. The largest vermicular intergrowths may consist of two or three such masses of quartz, each mass extinguishing at a different position. Discrete bodies of plagioclase interstitial to vermiform masses of quartz also extinguish simultaneously and represent single crystals in which twinning and even oscillatory zoning is preserved. In quartz keratophyres the plagioclase is albite, whereas in metadacites it is oligoclase or andesine. Plate 19 *A*, *B* show typical quartz-feldspar intergrowths.

Evidence suggests that the vermicular quartz is a replacement of plagioclase rather than an eutectic intergrowth owing to the exceedingly irregular pattern of the quartz in the plagioclase and the vastly different proportions of quartz and plagioclase in the intergrowths (pls. 19; *A*, *B*; 20). Many intergrowths consist of only 20 to 25 percent quartz, whereas others are at least 90 percent quartz. A few plagioclase phenocrysts may be completely replaced by quartz.

A late magmatic rather than hydrothermal origin for the vermicular quartz is postulated because it occurs in rocks having both silicified and unsilicified groundmasses. There is no correlation between the degree of replacement of a feldspar crystal by vermicular quartz and the intensity of silicification of the groundmass. Moreover, inasmuch as vermicular intergrowths and clasts thereof are common in pyroclastic rocks, it seems likely that the intergrowths formed before the material was ejected from the volcano (pl. 20).

In silicified phases of the Bully Hill rhyolite the feldspar of vermicular intergrowths, as well as the groundmass, is commonly replaced by secondary, microcrystalline quartz, leaving vermiform quartz masses that extinguish simultaneously, surrounded by microcrystalline quartz. Key thin sections (pl. 19*A*) show that the microcrystalline quartz has actually replaced plagioclase.

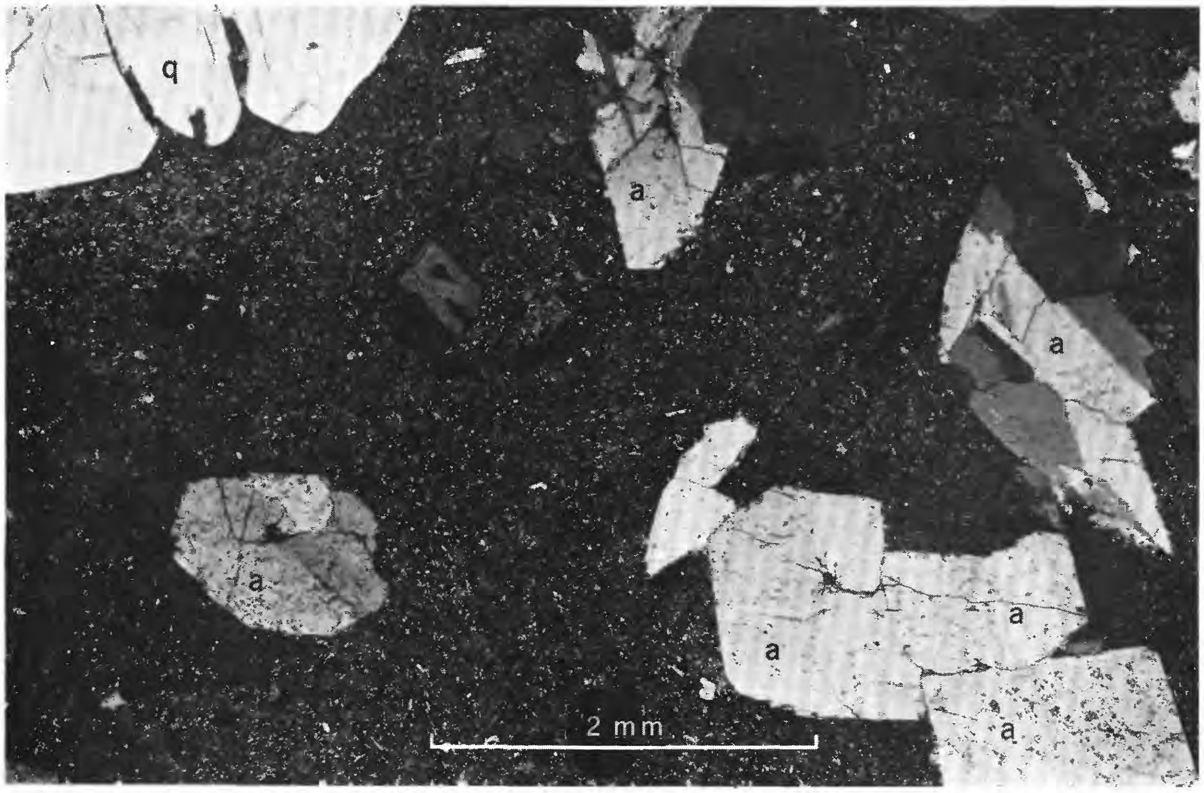
ORIGIN

The origin of the Bully Hill rhyolite, like the origin of the Balaklala rhyolite, has been a subject of controversy among geologists who have worked in the area. Diller (1906, p. 8) described the formation as a series of flows and tuffs that dip beneath shale of the Pit formation; but he states that the Bully Hill rhyolite locally cuts the shale and envelopes its fragments. Fairbanks (1893, p. 32) also noted the tuffaceous character of the rock later named the Bully Hill rhyolite and he also believed it to be mainly extrusive.

Graton (1910, p. 82), after making a study of the mines in the Shasta copper district, concluded that the Bully Hill rhyolite, as well as the Balaklala rhyolite, intruded their surrounding rocks; he refers to the siliceous rocks comprising these two formations as "alaskite" and "alaskite porphyry." Most geologists who have worked in the area since Graton (Boyle, 1915, p. 69; Hinds, 1933, p. 107–109; and others) regarded Bully Hill rhyolite and the Balaklala rhyolite as intrusive masses of similar age and character.

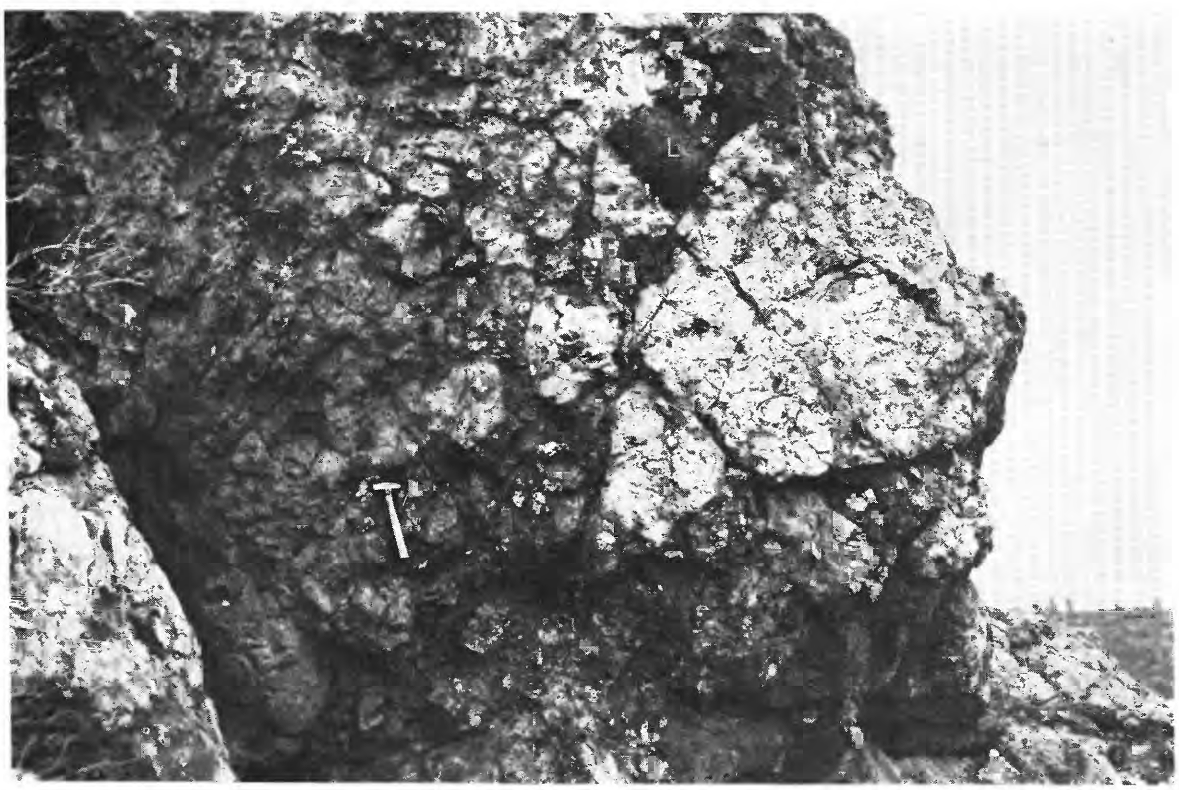
The writers conclude that the Bully Hill rhyolite, like the Balaklala rhyolite, is chiefly of extrusive origin. The main reasons for this conclusion are:

1. The abundance, throughout the section, of bedded pyroclastic rock interlayered with fine-grained rocks many of which are flow banded.
2. The general lack of intrusive contact relations to the enclosing sedimentary and volcanic formations, especially to the overlying Pit formation. Bodies of quartz keratophyre that are demonstrably of intrusive origin are restricted to the Dekkas andesite and to the Bully Hill rhyolite itself. They do not occur in the overlying Pit formation although pyroclastic rock and lava typical of the Bully Hill rhyolite is interstratified with shale in the Pit formation. If the Bully



A. PHOTOMICROGRAPH OF PORPHYRITIC QUARTZ KERATOPHYRE FROM EASTERN PART OF SEC. 30, T. 34 N., R. 4 W.

Note the angular albite phenocrysts (*a*), and embayed quartz phenocrysts (*q*) in groundmass of albite laths, microcrystalline quartz, and minor fine-graned white mica.

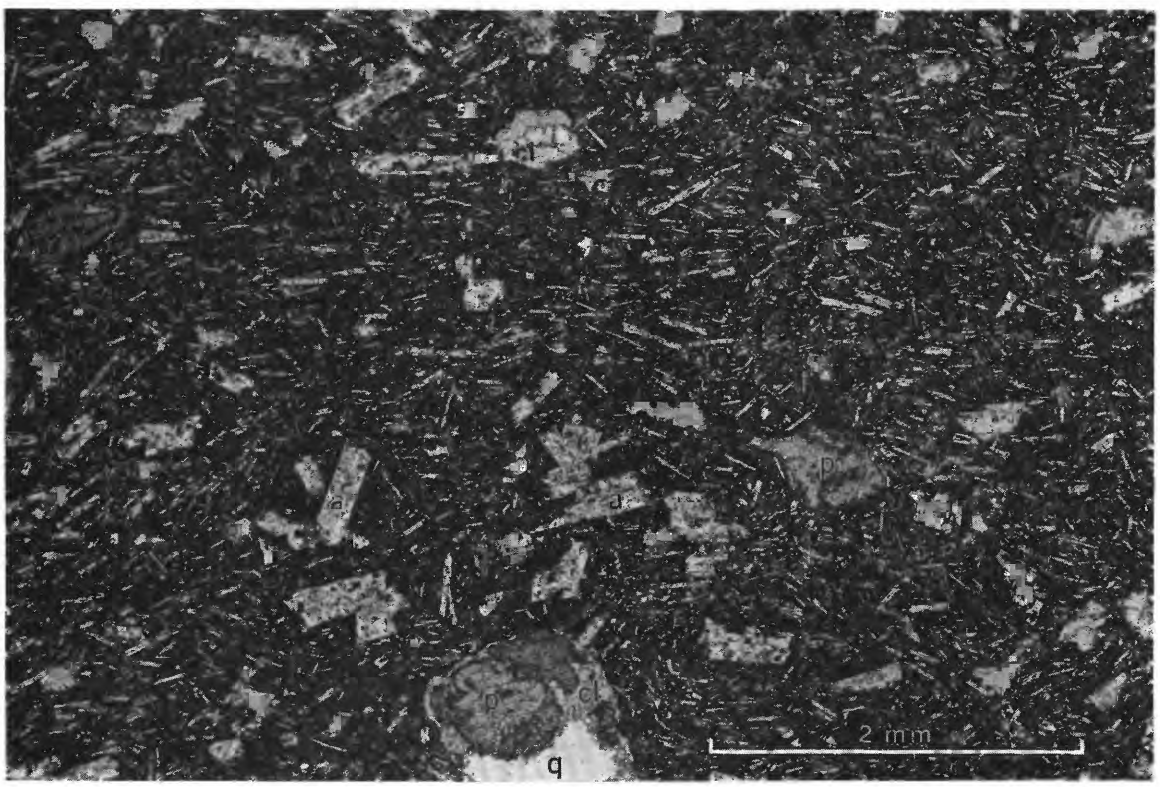


B. BLOCKY NONPORPHYRITIC QUARTZ KERATOPHYRE

On ridge above the Copper City mine in the SW¼ sec. 21, T. 34 N., R. 3 W. Dark material (*L*) is limonite that replaces discrete blocks as well as the breccia matrix.

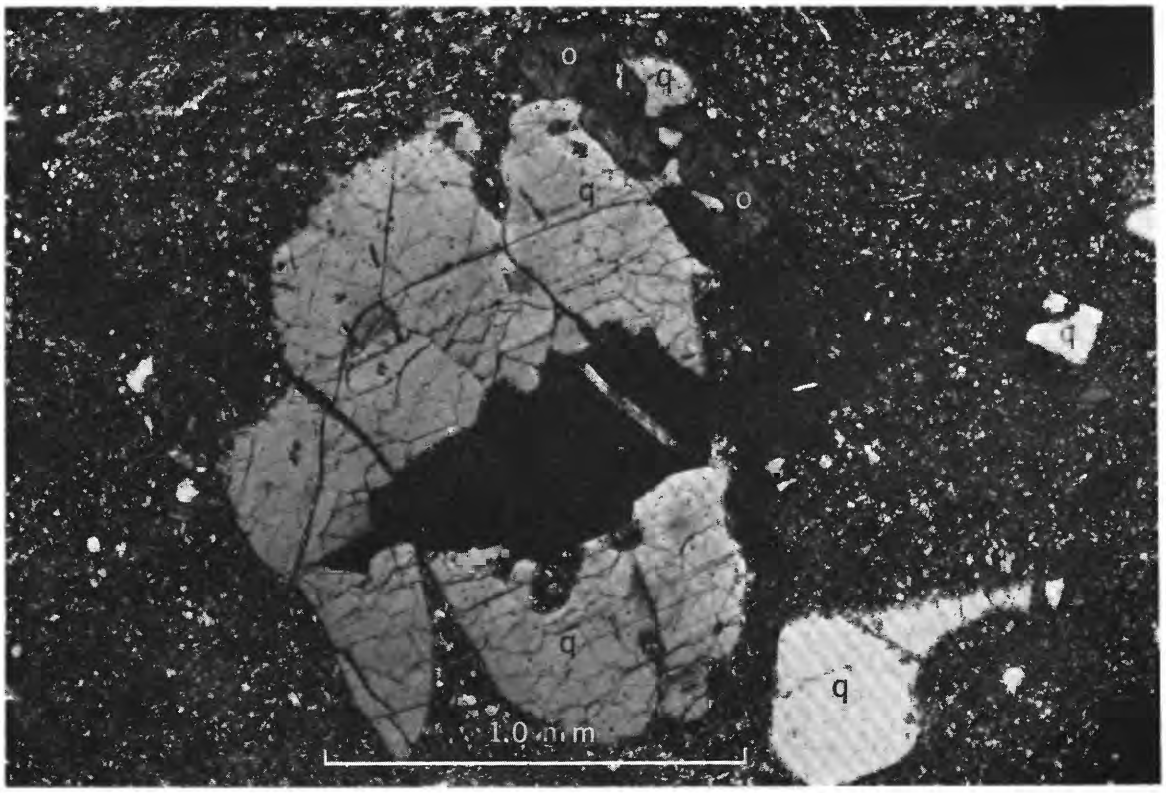
A. PHOTOMICROGRAPH OF GLOMEROPORPHYRITIC KERATOPHYRE

Phenocrysts are nearly pure albite. Groundmass is albite laths with interstitial chlorite.



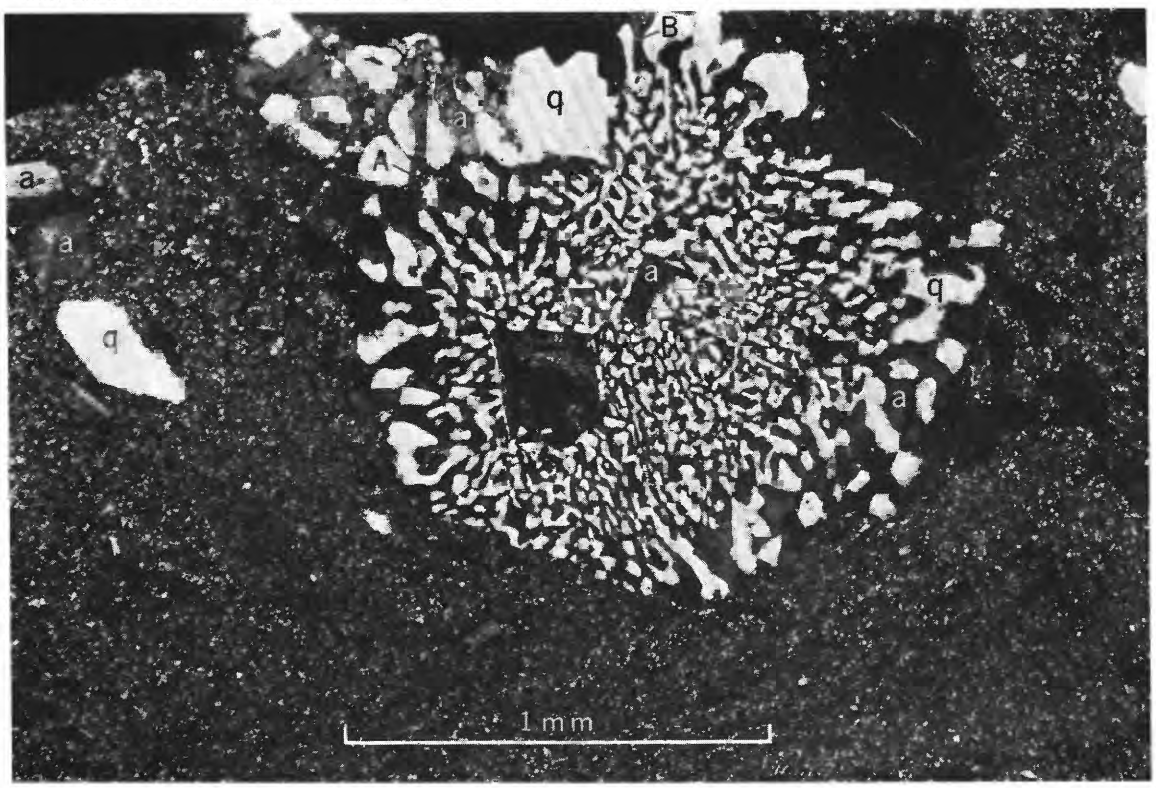
B. PHOTOMICROGRAPH OF PORPHYRITIC, AMYGDALOIDAL SPILITE WITH PILOTAXITIC GROUNDMASS

Principal minerals are albite (*a*), chlorite (*cl*), pumpellyite (*p*), and quartz (*q*) which fills centers of amygdules. Black grains are magnetite, which is disseminated throughout the rock. Some calcite is present.



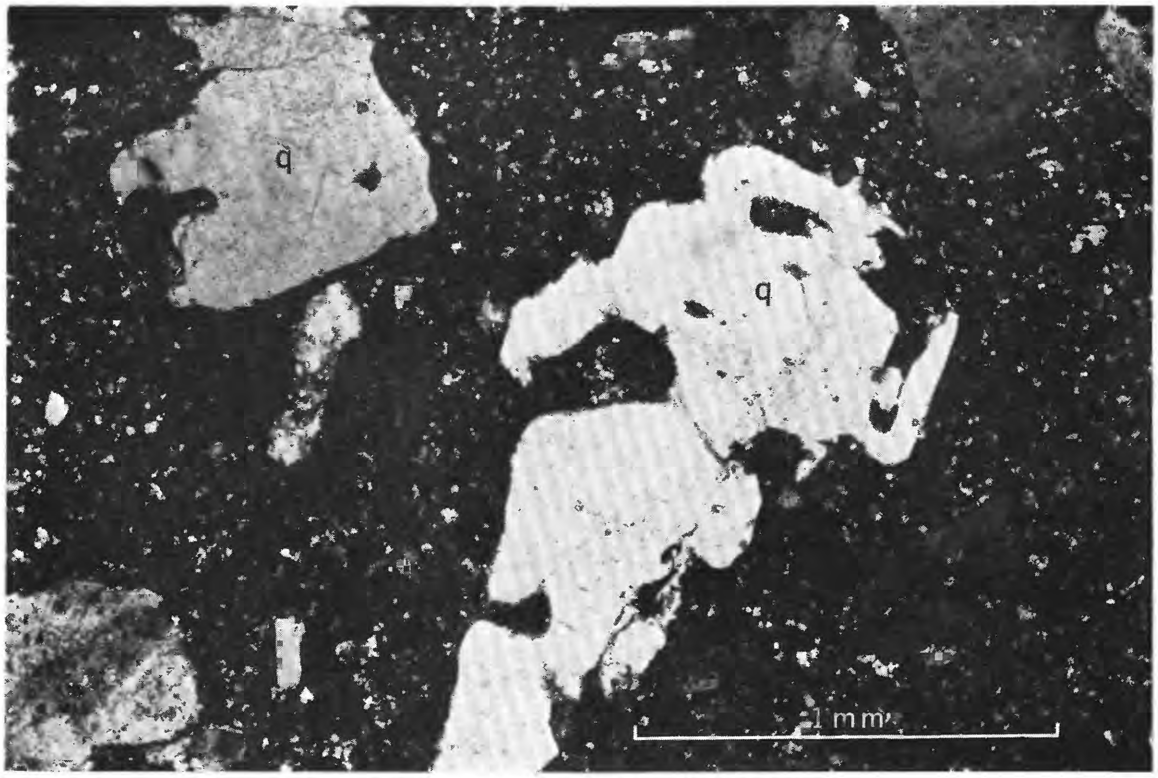
A. PHOTOMICROGRAPH OF METADACITE PYROCLASTIC ROCK

Phenocrysts are quartz (*q*),calcic oligoclase (*o*), and vermicular intergrowths of the two minerals. The vermicular quartz, a replacement of plagioclase, is probably late magmatic. Groundmass is anhedral microcrystalline quartz of hydrothermal origin that replaces plagioclase of vermicular intergrowths. leaving vermicular quartz embedded in a groundmass of microcrystalline quartz.



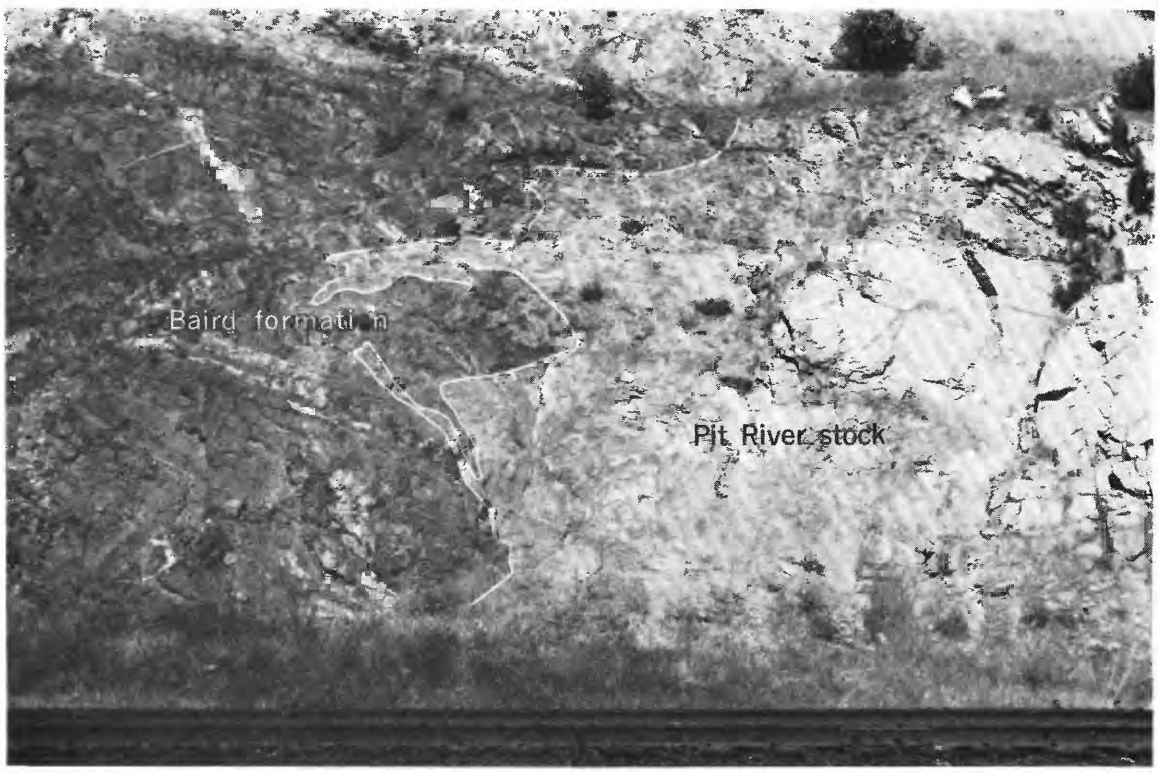
B. VERMICULAR RELATION BETWEEN QUARTZ (*q*) AND ALBITE (*a*) IN QUARTZ KERATOPHYRE

Near *A* and *B* the microcrystalline groundmass has partly replaced the albite of the intergrowth. Compare with (*A*), photomicrograph of metadacite pyroclastic rock.



A. VERMICULAR QUARTZ IN QUARTZ KERATOPHYRE TUFF

Groundmass is secondary quartz and albite that partly replaces ragged albite crystals. The vermiform quartz (*q*) is a replacement of plagioclase (*a*). The plagioclase of the intergrowth has been replaced by the secondary groundmass, leaving the irregular quartz. Compare with plate 19.



B. CROSSCUTTING, IRREGULAR CONTACT BETWEEN THE PIT RIVER STOCK AND THE BAIRD FORMATION

Bedding in the tuffaceous rocks of the Baird dips gently to the right. Blocks of the Baird are enclosed in the stock a few hundred feet to right of photograph. Railroad cut is about 30 feet high.

Hill rhyolite were of intrusive origin one would expect to find apophyses in the overlying formation.

3. The Bully Hill rhyolite is not thick compared to its great lateral extent. Including the part that is presumably covered by the Pit formation, the Bully Hill rhyolite must have an areal extent of at least 35 to 40 square miles in the map area, and judging from Diller's regional map (1906, geol. map) it probably underlies a total of at least 100 square miles. The thickness, however, ranges from less than 100 to about 2,500 feet. A tabular intrusive body of this size and shape, and consisting of such heterogeneous lithology, seems highly improbable. On the other hand, consideration of the Bully Hill rhyolite as a volcanic pile of silicic lavas and pyroclastic rocks or more probably a group of interfingering and overlapping piles of volcanic rocks, with subordinate feeder dikes and plugs, seems much more reconcilable with the facts.

Kinkel and others (1956 [1957], p. 31–32), after mapping the Balaklala rhyolite in the West Shasta copper-zinc district at a scale of 1:24,000 and studying its lithologic and structural relations in commensurate detail, have also concluded that the Balaklala is largely of extrusive origin.

Differences in thickness and lithology suggest that the lavas and pyroclastic rocks of the Bully Hill rhyolite were probably ejected from more than one vent. In the Bully Hill-Town Mountain area the volcanic rocks may have come from a vent about a half a mile northeast of Bully Hill. This is suggested by (a) the heterogeneous lithology (pl. 1), (b) by the abundance of pyroclastic material, (c) by the great thickness in the vicinity of Bully Hill compared to the thickness in nearby areas, and (d) by the presence in the north-central part of sec. 15, T. 34 N., R. 3 W., of a mass of flow-banded quartz keratophyre the banding of which dips mostly inward toward the center of the mass suggesting a cumulo dome. A second volcanic center may have been about a mile southwest of Sugarloaf where pyroclastic material is also abundant and where a great variety of rock types is present.

AGE

The Bully Hill rhyolite overlies the Dekkas andesite which is at least partly of Permian age, with apparent conformity and is overlain conformably by the Pit formation of Middle and Late Triassic age. These relations indicate that silicic volcanic material of the Bully Hill rhyolite was being erupted intermittently through a long interval of time. The Bully Hill rhyolite is considered to be of Triassic age.

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PIT FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Pit formation, which consists principally of shale, mudstone, and pyroclastic rocks, and includes subordinate siltstone, limestone, and lava, underlies a crudely triangular area covering about 25 square miles in the northeastern part of the area (pl. 1). As originally defined by Fairbanks (1894, p. 28) and Smith (1894, p. 601–604) the "Pitt formation" included all sedimentary rocks that lay stratigraphically between the McCloud limestone and the Hosselkus limestone, whereas the "Pitt shale" applied to the sedimentary rocks of Triassic age beneath the Hosselkus limestone. Diller (1906, p. 4) restricted the Pit formation to the sedimentary and pyroclastic rocks lying above the Bully Hill rhyolite and Dekkas andesite and beneath the Hosselkus limestone. Diller's definition of the Pit formation is followed in this report, except that three small bodies of limestone and one mass of lava near the east-central edge of the area, which Diller correlates with the Hosselkus limestone and with the Bully Hill rhyolite, respectively, are here included in the Pit formation.

STRATIGRAPHIC RELATIONS AND THICKNESS

The Pit formation overlies the Bully Hill rhyolite everywhere in the area except in the vicinity of Cove Creek where it overlies the Dekkas andesite with apparent structural discordance (pl. 1). The contact between the Pit formation and the underlying volcanic units is drawn at the base of the lowest bed of shale. In many places, however, shale intertongues with pyroclastic rocks of the Bully Hill rhyolite, showing that the Pit formation and Bully Hill rhyolite are at least in part contemporaneous in age.

The intertonguing of the Pit formation and the Bully Hill rhyolite leads locally to ambiguity and uncertainty in determining the contact between the two units. This is especially true on the lower part of the peninsula between the Squaw Creek and Pit River arms of Shasta Lake and it is not known with certainty whether the quartz keratophyre breccias and tuffs exposed in the cores of anticlines (pl. 1) belong to the Bully Hill rhyolite or whether they are merely layers of pyroclastic material in the Pit formation underlain by more shale. The large mass of metadacite and quartz keratophyre about a mile northeast of the Afterthought mine is mapped as a flow in the Pit formation but it may be part of the Bully Hill rhyolite. However, the pyroclastic rock in the cores of these anticlines consists mostly of coarse fragmental material more typical of pyroclastic rocks in the Bully Hill rhyolite and therefore is correlated with that formation.

The apparent structural discordance between the Pit formation and the Dekkas andesite in the Cove Creek area is a local feature contradictory to relations seen in other parts of the area that suggest structural concordance between the Dekkas andesite and the Bully Hill rhyolite and between the Bully Hill rhyolite and the Pit formation. A possible explanation for the local structural discordance in the Cove Creek area is that volcanic material of the Dekkas andesite was deposited with steep initial dips and later was covered discordantly by sediments of the Pit formation.

The thickness of the Pit formation is difficult to estimate because the rocks are closely folded in most places and because of the intertonguing of the Bully Hill rhyolite with the Pit. However, a section drawn from Second Creek east to Gray Rocks, the only place where the top of the Pit formation is exposed, suggests a thickness of about 5,000 feet (pl. 1, section *B–B′*). Diller (1906, p. 4) estimated the thickness to be "somewhat over 2,000 feet."

LITHOLOGY

SHALE, MUDSTONE, AND SILTSTONE

About 60 to 70 percent of the Pit formation is shale, mudstone, and siltstone, undifferentiated on plate 1. These rocks occur throughout the formation but they are probably more abundant in the upper than in the lower part. Shale and mudstone form beds that range from a fraction of an inch to about 2 feet in thickness; individual beds are separated by planes of parting or by slight color differences. Siltstone, which is much less abundant than shale and mudstone, forms beds as much as 6 feet thick. The color of the shale, mudstone, and siltstone ranges from medium gray to black on fresh surfaces; weathered exposures are commonly medium dark gray. Some shale beds have a faint lamination. Poorly preserved fossils are fairly common in some of the darker shale beds. Round or oblate concretions as much as 3 inches in diameter occur locally in fossil-bearing beds.

At least two beds of mud-pellet conglomerate are interbedded with shale west of Green Mountain. These beds range from 1 to 3 feet in thickness and have a strike length of about 1 mile.

Thin sections show that the beds of shale and mudstone are composed principally of anhedral microcrystalline quartz, carbonaceous material, and fine-grained white mica. Quartz commonly makes up more than 50 percent of most thin sections. Much of the quartz occurs in irregular clots. Dark-brown to black carbonaceous material forms cloudy masses that locally coalesce into larger elongate masses along bedding planes. Fine-grained white mica, kaolinite, leucoxene, chlorite, pyrite, hematite, and limonite, are minor components of irregular distribution. In addition, a few beds of shale and mudstone contain sparse, tiny clasts of quartz and feldspar. The clasts average about 0.05 mm across, are markedly angular, and are subordinate to the matrix in all slides examined. Rocks that contain as much as 10 or 15 percent of clastic quartz and feldspar clasts are classed as siltstones. In some siltstones the feldspar clasts are albite, whereas in others they are andesine or labradorite. One type of siltstone, which forms a bed about 25 feet thick, contains abundant evenly distributed oval white spots about 1 mm in diameter, composed of aggregates of anhedral microcrystalline quartz.

PYROCLASTIC ROCKS

About 20 percent of the Pit formation is pyroclastic rock, including crystal and lithic tuff, and tuff breccia. These volcanic rocks form beds ranging from a few inches to more than 100 feet in thickness. They are interlayered with shale, mudstone, and siltstone throughout the formation, and with quartz keratophyre and metadacite lava locally in the lower part. It was not possible to separate the lavas from the pyroclastic rocks everywhere in the field, and therefore some lava is included with the pyroclastic rocks shown on plate 1, especially in the lower part of the formation southwest of Bully Hill and also northeast of the Afterthought mine. In the Susanville Canyon-Brock Mountain area the outcrop pattern of volcanic rocks in the Pit formation could not be determined owing to poor outcrop and marked lensing of the beds.

The pyroclastic rocks are commonly medium gray to dark greenish gray on fresh surface but weather to tannish gray or light gray. The tuff breccias and lithic tuffs consist chiefly of quartz keratophyre, keratophyre, metadacite, shale, and mudstone fragments in a tuffaceous matrix. The fragments of volcanic rocks range from well rounded to angular, whereas most shale and mudstone fragments are elongate. Volcanic rock fragments range from a fraction of an inch to about 6 inches in diameter, whereas some shale and mudstone fragments are as much as several feet in maximum dimension. Bedding is uncommon in most tuff breccias and lithic tuffs.

The crystal tuffs and lithic-crystal tuffs consist chiefly of plagioclase clasts and also contain sparse quartz crystal clasts and lithic fragments in a siliceous or chloritic matrix. The crystal clasts are as much as 5 mm in diameter in some beds but the average grain size of most beds is about 1 mm. Within a given bed the clasts are predominantly the same size, although a few beds show graded bedding. Plagioclase and quartz clasts greatly predominate over the matrix in all the crystal tuffs.

Thin sections show that the crystal tuffs and lithic-crystal tuffs are of two main compositional types, metadacite and quartz keratophyre. These compositional types cannot be differentiated in the field. A metadacite crystal tuff from the NW¼ of sec. 22, T. 34 N., R. 2 W., which is typical of the group, consists largely of plagioclase clasts mixed with a few quartz crystal clasts and sparse lithic fragments, in a matrix of chlorite, fine-grained white mica, microcrystalline quartz, calcite, sphene, leucoxene, pyrite, and limonite. The plagioclase clasts range in composition from An_{30} to An_{53}. Many show normal oscillatory zoning; others are extensively veined and replaced by untwinned albite.

The quartz keratophyre crystal tuffs differ from the metadacite tuffs in that the feldspar clasts are poorly twinned albite rather than plagioclase of intermediate composition partly replaced by albite, and the matrix is commonly microcrystalline quartz or microcrystalline albite. Other secondary minerals in the matrix are chlorite, fine-grained white mica, calcite, leucoxene, sphene, pyrite, and limonite. The proportion of quartz crystal clasts to feldspar clasts is about the same in the quartz keratophyre tuffs as in the metadacite tuffs. One specimen of crystal tuff from the upper part of Norton Gulch is unusual in that albite clasts are clouded with tiny grains of clinozoisite.

LAVA FLOWS

Quartz keratophyre and metadacite lava forms 5 to 10 percent of the Pit formation exposed in the area. The largest body of lava underlies about 1 square mile centering in sec. 2, T. 33 N., R. 2 W.; several smaller bodies crop out near the end of the peninsula between the Squaw Creek and Pit River arms of Shasta Lake. Other lava flows, not separable from pyroclastic rocks, are in the lower part of the Pit formation south of Bully Hill and north of the Afterthought mine.

The mass of lava, centered mostly in sec. 2, T. 33 N., R. 2 W., is principally massive rock containing abundant, unevenly distributed feldspar phenocrysts as much as 6 mm in diameter, and less abundant quartz phenocrysts in a medium-gray to dark greenish-gray, aphanitic groundmass. Sparse, subrounded fragments of mafic lava measuring a few inches in diameter are irregularly distributed throughout the mass. Locally, the rock is composed entirely of fragments.

Thin sections show that the mineralogy of the volcanic rock underlying sec. 2 and adjoining areas differs markedly from place to place but the textures remain about the same. Near the northwest end of the unit the rock contains albite and quartz phenocrysts as much as 5 mm in diameter, and augite microphenocrysts as much as 0.5 mm in diameter, in a felty groundmass of albite laths, chlorite, sphene, and leucoxene. Minor amounts of calcite, prehnite, and pyrite replace other minerals in some slides.

About 1,000 feet north of U.S. Highway 299E, in the north-central part of sec. 2, the lava contains phenocrysts of oscillatory zoned plagioclase (composition about An_{50}), a few quartz phenocrysts, 20 to 25 percent chlorite, 10 to 15 percent calcite, and a small amount of sphene and leucoxene. Albite, chlorite, and calcite replace plagioclase phenocrysts; anhedral, microcrystalline albite forms part of the groundmass. Specimens showing similar mineralogy were collected from the extreme eastern part of sec. 2 and from the western part of sec. 1, T. 33 N., R. 2 W.

Thin sections of material from road cuts along U.S. Highway 299E, in the same body of lava, consist chiefly of quartz and albite phenocrysts in a groundmass of anhedral, microcrystalline quartz and chlorite.

Some of the quartz keratophyre lava flows near the end of the peninsula between the Squaw Creek and Pit River arms are underlain by shale (pl. 1) and are therefore mapped as part of the Pit formation. They are light-green to light-olive-gray rocks containing sparse, tiny quartz phenocrysts, and rounded feldspar crystals as much as 3 mm in diameter. Much of this lava has a closely spaced, platy parting that parallels the bedding in adjoining shale beds.

Thin sections show that this lava contains sparse, strongly corroded quartz and albite crystals in a trachitic groundmass of albite laths and interstitial quartz. Minor components include chlorite, celadonite, sphene, leucoxene, fine-grained white mica, and limonite. The feldspar forming phenocrysts is nearly pure albite.

LIMESTONE

Several lenses of light-gray limestone containing abundant fossils are exposed in the extreme east-central part of the area, north of U.S. Highway 299E. The limestone lenses range in size from beds 1 foot thick and 10 feet long to beds 100 feet thick and at least 2,000 feet long. Individual lenses are separated by shale. Some beds within the limestone lenses are as much as several feet long, and are composed chiefly of small brachiopods, ammonites, and belemnites.

The limestone was correlated with the lithologically similar Hosselkus limestone by Diller (1906, p. 4–5) but it is here considered as part of the Pit formation because: (a) the limestone is interbedded with shales and tuffs that are indistinguishable from those of the Pit formation; (b) the age of fauna in the limestone lenses is Middle Triassic, whereas the Hosselkus limestone according to Diller (1906, p. 5) is of Late Triassic age.

CONDITIONS OF DEPOSITION

Deposition of the Pit probably took place in the neritic depth zone as is indicated by ammonites and other shallow-water marine organisms throughout the formation. The abundance of volcanic material, especially the viscous silicic flows in the lower part of the formation, necessitates the proximity of vents, and therefore a sea of deposition containing scattered volcanoes is postulated. The distribution and composition of volcanic rocks suggest that the same vents from which the Bully Hill rhyolite was extruded were the source of the volcanic material in at least the lower part of the Pit formation. One vent was probably in the vicinity of Bully Hill, another was northeast of the Afterthought mine, and a third was near the end of the peninsula between the Squaw Creek and Pit River arms of Shasta Lake. Whether these same volcanoes were intermittently active throughout Pit time is not known.

AGE AND FAUNA

Collections of fossils from shale and limestone beds in the Pit formation are reported by John B. Reeside (written communication, 1951) as follows:

> The preservation of much of the material is such as to leave identification uncertain. Nevertheless, it is my best judgment that it is of Middle Triassic age. J. P. Smith reports both Upper and Middle Triassic from the Pit shale, but I do not find here the forms he reports for Upper Triassic.

A list of the fossils determined by Reeside follows. Numbered localities are shown on plate 1.

Locality No.	*USGS No.*	*Lithology*	*Fauna*
C–120	23313	Mudstone fragments in tuff.	Juvenile ammonites, undetermined.
C–213	23314	Limestone	Small rhynchonellid brachiopods, unnamed. *Eutomoceras*? sp. *Arcestes* (*Proarcestes*) sp. *Ceratites*? cf. *C. occidentalis* Smith. *Ceratites*? sp.
C–214	23315	Limestone	*Ceratites* (*Paraceratites*)? sp. *Arcestes* (*Pararcestes*)? sp.
C–435	23316	Shale	*Daonella* sp.
C–856	23317	do	*Arcestes* (*Proarcestes*)? sp.
D–273	23318	do	Indeterminable fragments of ammonites.
D–572	23319	do	*Eutomoceras*? sp.
D–646	23320	do	Undetermined impressions of ammonites.
E–139	23321	do	Algae(?), undetermined. *Monotis*? sp. *Arcestes* (*Proarcestes*)? sp. *Tropigastrites*? sp.

Two additional collections from the SW¼ sec. 36, T. 34 N., R. 4 W. (loc. E–434 and E–437) were examined by S. W. Muller (oral communication, 1951) of Stanford University, who reported the following fauna:

Halobia
Trachyceras
Trachyceras?

Dr. Muller believes the evidence to be fairly substantial that this material is of Late Triassic age. Therefore, the general area about sec. 36 may have been a topographic high during Middle Triassic time for the beds containing these fossils are less than 50 feet above the base of the Pit formation at this locality.

HOSSELKUS LIMESTONE

The Hosselkus limestone, of Late Triassic age (Diller, 1906, p. 5), is exposed at the northeast boundary of the area, where it seems to conformably overlie the Pit formation. Superficially, the Hosselkus resembles the limestone in the Pit formation near the southeast edge of the area, north of the Afterthought mine, but the Hosselkus lithology was not studied in detail.

INTRUSIVE ROCKS

Intrusive rocks in the East Shasta area include, in addition to the minor intrusive phases of the Balaklala rhyolite, Bully Hill rhyolite, and Dekkas andesite already described; (a) a small stock of coarse-grained light-colored rock called the Pit River stock; (b) an elongate irregular mass of medium- and fine-grained quartz diorite that surrounds the McCloud limestone; (c) abundant tabular bodies of quartz diorite, diorite, and metadiabase; and (d) a few tabular bodies of granodiorite and aplite. Virtually all the intrusive rocks except a few dikes at Bully Hill are west of the belt of volcanic rocks underlying Horse and Town Mountains.

PIT RIVER STOCK

LOCATION AND RELATION TO ADJACENT ROCKS

The Pit River stock (Hinds, 1933, p. 106) is a plutonic body about 3 miles long and 1 mile wide, extending into the area from the south. The northern part of the stock underlies about 1½ square miles near the Pit bridge. The stock consists chiefly of coarse-grained, light-colored granodiorite and albite granite. In some places it contains abundant inclusions of mafic hybrid rocks having the composition of hornblende quartz diorite. The Pit River stock is part of the quartz hornblende diorite of Diller (1906, p. 8) and is lithologically similar to a much larger plutonic body, the Mule Mountain stock (Hinds, 1933, p. 105; Kinkel and others, 1956 [1957]) in the West Shasta copper-zinc district.

The stock cuts the Baird formation with a transgressive contact. This contact is well exposed in railroad cuts just north of the Pit bridge where bedding in slightly hornfelsed mudstone and tuff of the Baird dips gently southeast, and the irregular, crosscutting contact dips north. Small apophyses of the stock extend at least 50 feet into the Baird, and blocklike bodies of mudstone and tuff protrude into the plutonic rock (pl. 20*B*). In some places the plutonic body is slightly finer grained near the contact but more commonly it is not.

An extension of the Pit River stock to the north beneath O'Brien Mountain is suggested by the northward dip of the contact at the Pit bridge, and by the abundant dikes of quartz diorite, granodiorite, dacite porphyry, and aplite, and abundant quartz veins on O'Brien Mountain.

LITHOLOGY AND PETROGRAPHY

The Pit River stock is principally light colored, granitoid rock composed of feldspar, quartz, and subordinate ferromagnesian minerals. The average grain size is 2 to 3 mm, but some facies have a pseudoporphyritic texture formed by the occurrence of irregular bodies of milky quartz as much as 1 cm across containing poikilitic inclusions of feldspar. The microscope shows that most of the light-colored rock is granodiorite and albite granite. These two phases are transitional and not distinguishable in hand specimen.

South of the Pit bridge the stock contains abundant xenoliths of intermediate and mafic holocrystalline rocks ranging from about 1 inch to as much as 50 feet in diameter. Most of the xenoliths are well rounded but a few are subangular. They show marked variations in mineralogy, grain size, and fabric. Most have the composition and texture of hornblende quartz diorite but some are inclusions of the Baird formation recrystallized to hornfels, and there are many intermediate types. All the inclusions could have been derived from the Baird formation.

Sharp-walled aplite dikes, ranging from a few inches to a foot in thickness, cut marginal parts of the stock and adjacent wallrocks.

GRANODIORITE

Thin sections show that the granodiorite is typically 30 to 40 percent plagioclase (An_{25}–An_{37}), 10 to 20 percent microperthite, 35 to 45 percent quartz, 10 percent hornblende and biotite, and minor apatite, magnetite, chlorite, fine-grained white mica, and epidote. The texture is hypidiomorphic granular, poikilitic, with tendency toward porphyritic development of the plagioclase.

The plagioclase occurs as subhedral grains that commonly show normal oscillatory zoning, with slight difference in composition between cores and rims. Some crystals, however, have irregular rims of nearly pure albite, and others are slightly veined by albite. The origin of the albite is probably either deuteric or hydrothermal.

Microperthite, consisting of orthoclase containing tiny veinlets of albite parallel to crystallographic directions is interstitial to and forms a rim around some plagioclase crystals and occurs as unreplaced remnants in quartz.

TABLE 3.—*Analysis of partly albitized granodiorite from the Pit River stock*[1]

[Lab. No. 52-1657; field No. B-76. Analysts, Harry F. Phillips, Joseph Dowd, and Katrine White]

	Percent		Percent
SiO_2	74.0	Na_2O	3.8
Al_2O_3	13.4	K_2O	2.0
Fe_2O_3	1.3	TiO_2	.30
FeO	1.2	P_2O_5	.01
MgO	.62	MnO	.04
CaO	3.0	Ignition[2 3]	.69
		Total	100
Bulk density	2.61	Powder density	2.66

[1] Analysed by rapid methods.
[2] Includes gain due to oxidation of FeO.
[3] Includes 0.06 percent CO_2.

Quartz forms poikilitic crystals as much as 1 cm across and shows diverse relations to other minerals, especially feldspar. Optically continuous quartz is interstitial to and encloses small euhedral crystals of plagioclase. Much of the quartz seems to replace feldspar. It encroaches on feldspar crystals as lobe-shaped embayments and encloses irregular remnants of microperthite that have a common orientation.

Green hornblende and brown biotite are about equal in over-all abundance but their relative abundance differs greatly from place to place. The biotite is in part an alteration after hornblende. Some grains of hornblende show blotches of blue especially near their ends in the Z' vibration direction. This suggests an appreciable amount of Na_2O in the amphibole. Minor chlorite and epidote are alteration minerals after biotite and hornblende.

HORNBLENDE QUARTZ DIORITE

Hornblende quartz diorite occurs in the Pit River stock mainly as inclusions in different stages of assimilation and recrystallization, and hence the varietal name hornblende quartz diorite includes diverse textural and mineralogical types. Thin sections show that most coarser grained inclusions consist of 40 to 50 percent plagioclase (An_{35}–An_{46}), 25 to 35 percent quartz, 25 to 35 percent hornblende, and minor orthoclase, biotite, magnetite, fine-grained white mica, chlorite, and epidote. The texture is hypidiomorphic granular, poikilitic; irregular-shaped quartz crystals as much as 1 cm across enclose plagioclase, hornblende, and magnetite. The plagioclase is in the form of euhedral and subhedral crystals many of which show normal oscillatory zoning. Hornblende forms subhedral grains and has the following optical properties: Extinction angle $Z \wedge c$ 11°; optically (−); $2V=82°$; X pale green, *Y* moderate green, *Z* brownish green. Chlorite and epidote are minor alteration products of the amphibole.

Some specimens of hornblende quartz diorite are partly albitized. In a porphyritic facies containing phenocrysts 2 to 3 mm across and smaller crystals 0.3 to 0.5 mm across the smaller grains are nearly pure albite, poorly twinned, and clouded with white mica, whereas the phenocrysts show oscillatory zoning and have an average composition of An_{45}. In a few places around the edges of phenocrysts the andesine is replaced by albite.

ALBITE GRANITE

Granodiorite locally grades into albite granite, a light-colored rock similar in hand specimen to the granodiorite. Thin sections show that the albite granite consists of about 45 percent albite, 40 percent quartz, 5 percent biotite, and minor chlorite, epidote, sphene, leucoxene, celadonite, fine-grained white mica, kaolinite, and rutile. The texture is xenomorphic granular. The albite is twinned according to Carlsbad, albite, and pericline-acline twinning laws, but some grains are very poorly twinned, with irregularly spaced, discontinuous lamellae. Extinction angles $X' \wedge c$ in the zone normal to (010) range from 15° to 16½°, and indices of refraction for all optical orientations are less than canada balsam. These properties indicate that the feldspar is at least as sodic as Ab_{95}.

Quartz forms bizarre-shaped blebs, lobes, and vermiform masses extensively replacing albite. In some places it forms a pseudographic intergrowth with albite, and in other places it replaces albite along crystallographic directions. Locally, the quartz is interstitial to albite.

Biotite occurs as aggregates of radiating flakes partly altered to chlorite, epidote, and sphene. Fine-grained white mica, celadonite, kaolinite, and epidote are minor alterations of albite.

The albite granite is interpreted as albitized granodiorite. In its texture, mineralogy, and lithogic associations the albite granite here described is similar to the albite granite near Sparta, Oreg., described by Gilluly (1933), and interpreted by him to be of replacement origin. Gilluly recognized zones of cataclastic texture in the albite granite near Sparta and used the cataclastic texture to demonstrate the stage of albitization and the probable channelways. No cataclastic textures suggesting possible channelways for the albitizing solutions and giving a clue to the stage of albitization (whether late magmatic, or hydrothermal), are recognized in the Pit River stock. However, for reasons given in the section on albitization the writers believe that the albite granite resulted from hydrothermal metamorphism.

The milky quartz, which encloses feldspar and ferromagnesian crystals, forms vermicular intergrowth with feldspar and lobe-shaped embayments against feldspar; it is as abundant in the unalbitized or slightly albitized granodiorite and quartz diorite as it is in the albite granite. The quartz encroaches on intermediate plagioclase and albite alike, and seems to have preceded and to be not directly related to albitization. These features suggest that the quartz formed during the last stages of emplacement of the pluton.

CONTACT EFFECTS

The only metamorphism clearly related to emplacement of the Pit River stock is the recrystallization of tuffs of the Baird formation to biotite-oligoclase hornfels in a few places along the periphery of the plutonic mass. The maximum width of the hornfels aureole is about 100 feet, on the peninsula in sec. 33, T. 34 N., R. 4 W.; in most places the aureole is much less than 100 feet wide. During metamorphism little new material was added.

AGE

The age of the Pit River stock cannot be closely determined from relations in the map area owing to the fact that the stock cuts only the Baird formation of Mississippian age. Therefore, from direct observation about all that can be said is that the stock is post-Mississippian. The stock is but slightly deformed by faulting, whereas the Baird formation was folded before the stock was emplaced. Other formations in the region, including those as young as the Potem formation, which according to Sanborn,[9] is of early Middle Jurassic age, have undergone about the same degree of deformation as the Baird, suggesting that the time of deformation and igneous activity did not take place earlier than late Middle Jurassic.

The Pit River stock is correlated by lithologic features with the Mule Mountain stock of the West Shasta district described by Kinkel and others (1956 [1957], p. 43–48). The Mule Mountain stock is intruded by apophyses of the Shasta Bally batholith, which in turn is overlain nonconformably by fossiliferous rocks of Early Cretaceous (Hauterivian and Valanginian) age according to Hinds (1934, p 190), (Hauterivian) age according to Murphy (1956, p. 2098).[10] If allowance is made for the time required by

[9] Sanborn, Albert, 1952, The geology of the Big Bend area, Shasta County, California: Unpublished thesis, Stanford Univ.

[10] Michael A. Murphy (1956) has recently redefined certain Lower Cretaceous stratigraphic units at the north end of the Sacramento Valley. His Rector formation, a thin sandstone and conglomerate unit that lies nonconformably on the Shasta Bally batholith is of Hauterivian age and includes beds referred to as Middle Paskenta and Lower Horsetown by F. M. Anderson (Hinds, 1934, p. 182–192).

erosion to unroof the Shasta Bally batholith before the Cretaceous sediments were deposited, a Late Jurassic rather than Early Cretaceous age for the batholith seems likely. It seems probable from these relations that the Pit River stock was emplaced during Late Jurassic time. Nevertheless, an Early Cretaceous age cannot be positively ruled out.

QUARTZ DIORITE SURROUNDING THE McCLOUD LIMESTONE

The elongate, irregular mass of intrusive rock that virtually surrounds the McCloud limestone (pl. 1) is chiefly finely granular to aphanitic, mafic quartz diorite, but includes subordinate, medium-grained quartz diorite. This mass of intrusive rock is part of the quartz augite diorite of Diller (1906, p. 8), and part of the Redding dike of Hinds (1933, p. 106–107).

Within the area the quartz diorite separates the McCloud limestone into a number of discrete masses and almost everywhere isolates the limestone from adjacent formations of sedimentary or volcanic origin. The shape and location of the intrusive mass, and the apparent structural discordance between the McCloud limestone and adjacent formations (pl. 1), suggest that the intrusive mass in part occupies faults along the limestone. A few dikes of quartz diorite in the limestone also are along faults that predated the intrusion.

LITHOLOGY AND PETROGRAPHY

FINE-GRAINED MAFIC QUARTZ DIORITE

Most of the intrusive rock surrounding the McCloud limestone and separating it into discrete blocks is massive, nonporphyritic, dark-greenish-gray quartz diorite with a finely granular to aphanitic texture. Thin sections show that this rock is composed principally of plagioclase, quartz, and augite. Apatite, magnetite, pyrite, sphene, leucoxene, and uralitic amphibole, are minor constituents. Chlorite, epidote, fine-grained white mica, calcite, prehnite, and celadonite are commonly present and are locally abundant as alteration products. Plagioclase forms about 50 percent of most thin sections of mafic quartz diorite. The plagioclase is poorly twinned albite that is strongly altered to fine-grained white mica. One thin section contains remnants of andesine crystals surrounded and largely replaced by albite. Quartz makes up 5 to 25 percent of the mafic quartz diorite. Augite was seen in one slide, of which it constitutes about 15 percent.

The mafic quartz is altered to differing degrees of intensity. In some specimens most of the original minerals remain except plagioclase, which is altered to albite, whereas other specimens consist almost entirely of secondary minerals. A specimen of a highly altered dike in the McCloud limestone consists of about 90 percent of fine-grained white mica and calcite; remnants of unreplaced quartz and albite constitute the remaining 10 percent.

MEDIUM-GRAINED AUGITE QUARTZ DIORITE

Medium- to light-gray, medium-grained augite quartz diorite crops out mainly south of the Shasta Iron mine in secs. 25 and 26, T. 34 N., R. 4 W. (pl. 1). The rock is holocrystalline and ranges in grain size from 1 to 6 mm. Thin sections show that it consists typically of about 50 percent plagioclase, 20 to 30 percent quartz, 15 to 20 percent augite, and minor uralite, magnetite, ilmenite, leucoxene, apatite, epidote, chlorite, garnet, fine-grained white mica, and kaolinite. The most common texture is hypidiomorphic granular, poikilitic, with optically continuous quartz grains as much as 6 mm in diameter enclosing closely packed euhedral crystals of plagioclase and augite. The plagioclase in almost all specimens examined is of two compositions. The larger crystals range from An_{32} to An_{48}. Many of these crystals show weak oscillatory zoning, with rims only slightly more sodic than cores. The smaller plagioclase crystals in most slides are nearly pure albite clouded with fine-grained white mica, chlorite, and epidote. The albite crystals are weakly twinned. Augite forms subhedral grains as much as 1 mm across, and also occurs as small rounded grains poikilitically enclosed in plagioclase. Its optical properties, determined on the universal stage, are optic sign (+); $2V=52°$; extinction angle $Z \triangle c=42°$. On the basis of optical properties, this augite is a variety containing a high content of lime and iron and a low content of magnesia (Winchell, 1951 p. 408–410). It is partly altered to uralitic amphibole and chlorite. Ilmenite and magnetite form anhedral grains and fill cracks in augite. Some grains are surrounded by leucoxene. Epidote and chlorite are alteration products of feldspar and also occur, commonly together, as fracture fillings. Garnet is a minor mineral in most slides, forming scattered, euhedral crystals.

The distribution and composition of the medium-grained augite quartz diorite suggest that it may be simply a coarser grained phase of the fine-grained mafic quartz diorite.

AGE

Quartz diorite enclosing the McCloud limestone is of probable Late Jurassic age and is presumably younger than the Pit River stock because dikes of fine-grained mafic quartz diorite cut the stock.

DIKES

Many dikes of quartz diorite, diorite, metadiabase, and dacite porphyry, and a few dikes of granodiorite and aplite crop out in the western part of the area, especially west of the intrusive mass enclosing the McCloud limestone. Most dikes are steeply inclined or vertical, but a few dip at low angles. Strikes range from northwest to northeast but the dominant strike is northwest (pls. 1 and 2). Many of the dikes occupy tension faults or joints. The most continuous dikes were traced for about a mile along strike. They range in thickness from about 5 to nearly 500 feet.

FINE-GRAINED QUARTZ DIORITE, DIORITE, AND METADIABASE

Most of the dikes in the O'Brien Mountain area are fine grained mafic quartz diorite. A few that contain no quartz are classified as diorite, and fewer still, although altered, have an intergranular or diabasic texture and are classed as metadiabase. Except for the metadiabase dikes at Bully Hill these dike rocks are undifferentiated on plate 1 and are mapped as mafic quartz diorite.

The fine-grained mafic quartz diorite dikes are lithologically similar to the mafic quartz diorite surrounding the McCloud limestone. They are dark greenish gray; textures in hand specimen range from sugary grained to aphanitic. Thin sections show that plagioclase, augite, quartz, and chlorite are the most common minerals. Apatite, magnetite, leucoxene, epidote, calcite, uralite, biotite, fine-grained white mica, and kaolinite occur in variable amounts. Textures are generally intergranular or granophyric.

A fine-grained mafic dike about 40 feet thick and typical of the mafic fine-grained dikes in the O'Brien Mountain area shows systematic changes in grain size, texture, and mineralogy from the center outward. In the center of the dike the feldspar crystals average 1.0 by 2.5 mm in size, whereas near the border they average about 0.1 by 0.025 mm. Granophyric textures and myrmekitic intergrowths of quartz and plagioclase (An_{10-20}) are commonly superimposed on an intergranular fabric in the central part of the dike, but decrease gradually and ultimately disappear in the peripheral parts of the dike. Likewise, quartz decreases in amount from about 15 percent in the center to a trace near the margin. A similar gradual decrease in calcite from 10 percent in the center to none in the outer part was observed. Sphene increases at the expense of ilmenite from the center outward. Augite, the chief ferromagnesian component, is altered to uralite in the central part, and to biotite in the outer part. Feldspar is partly albitized in all parts of the dike, and no systematic variation in intensity of albitization was observed. Chlorite, fine-grained white mica, and epidote likewise seem to be equally common as alteration products in all parts of the dike.

MEDIUM-GRAINED QUARTZ DIORITE AND GRANODIORITE

Dikes shown by the symbols in plate 1 are in the western part of the area. They are holocrystalline gray to greenish-gray rocks and range in grain size from 1 to 2 mm. Most of these medium-grained rocks are quartz diorite but a few contain sufficient orthoclase to be classed as granodiorite. A typical specimen of quartz diorite from near the south edge of sec. 8, T. 34 N., R. 4 W., consists of about 40 to 50 percent plagioclase (An_{20}), 25 percent hornblende, 15 percent epidote, 10 percent quartz, and minor orthoclase, augite, chlorite, apatite, magnetite, leucoxene, biotite, fine-grained white mica, and kaolinite. The texture is intergranular and locally granophyric.

The plagioclase occurs as subhedral, lath-shaped crystals some of which are strongly replaced by granophyric intergrowths of quartz and orthoclase. It shows maximum extinction angles of 8° in the zone normal to 010, is optically (+), and has a large optic angle. Hornblende, with brown and green pleochroic colors, occurs as euhedral crystals. It has the following optical properties: optic sign (−); $2V=85°$; extinction angle $Z \wedge c=14°$; and $nx'=1.67\pm0.002$. Some hornblende crystals include tiny kernels of augite. Green biotite and chlorite are alteration products after hornblende. Quartz is interstitial to plagioclase, and occurs with orthoclase as granophyric intergrowths replacing plagioclase. Magnetite occurs as tiny kernels surrounded by leucoxene, and apatite forms thin needles. Epidote occurs as large clots and as a coarse-grained replacement of discrete feldspar crystals. In the early stages it replaces feldspar along the 001 crystallographic direction.

METADIABASE

A group of dark greenish-gray to greenish-black metadiabase dikes of heterogeneous character intrude the Bully Hill rhyolite on the east and south flanks of Bully Hill. The majority of the dikes are along a shear zone in the Bully Hill rhyolite and form an anastamosing pattern within this zone. The dikes strike generally northeast and dip at angles ranging from 60° NW. to 75° SE. They range in thickness from 5 to 165 feet and the most continuous dikes were traced for several hundred feet along strike.

In hand specimen the metadiabase is similar to the mafic lavas of the Dekkas andesite except that it is slightly more granular. Some porphyritic facies contain feldspar phenocrysts as much as 4 mm in diameter, whereas other facies are nonporphyritic. The texture commonly ranges from porphyritic to nonporphyritic even within some dikes, and amygdules are common in a few facies. Locally the metadiabase grades into fragmental rock that looks like tuff.

Thin sections show that the metadiabase consists of albite, chlorite, sphene, leucoxene, magnetite, epidote, and calcite. The texture is intergranular or in places diabasic, and the chlorite is interstitial to divergently oriented albite laths averaging 0.3 to 0.4 mm in length. The albite is poorly twinned and a few crystals show a crude zonal structure marked by alteration products. The alteration suggests that the zones were originally plagioclase of different composition but it is now nearly pure albite. Sphene and leucoxene are in small cloudy masses and together make up about 5 percent of the metadiabase. Magnetite forms about 1 percent. Epidote, calcite, and chlorite are irregularly distributed as alteration products on feldspar crystals and in the groundmass. Calcite and quartz-calcite veinlets cut the albite diabase in a few places.

DACITE PORPHYRY

Dikes of dacite porphyry, commonly called birdseye porphyry by local miners, intrude the Bragdon formation in the extreme northwestern part of the area (pl. 1). Most dikes are along faults. Strikes range from N. 75° W. to N. 25° E., and dips are nearly vertical.

A conspicuous feature of the dacite porphyry dikes is the abundant and commonly zoned plagioclase phenocrysts. These phenocrysts generally range from 5 to 10 mm in diameter, but in a few dikes they are as much as 15 mm across. The dikes also contain a few round phenocrysts of quartz.

Thin sections show that the dacite porphyry is composed of oscillatory-zoned plagioclase phenocrysts, sparse, round quartz phenocrysts, and a few hornblende phenocrysts in a groundmass of feldspar, quartz, apatite, and hornblende. The plagioclase ranges from An_{45} to about An_{11} but commonly the cores of the zoned plagioclase crystals are only slightly more calcic than rims. In some slides the plagioclase is extensively veined and replaced by albite. Fine-grained white mica is locally abundant as an alteration of plagioclase.

APLITE

Aplite dikes occur chiefly in and adjacent to the Pit River stock. A notable exception and the only aplite dike mapped is about 30 feet thick and occurs along a fault in the Kennett formation in the SW¼ sec. 16, T. 34 N., R. 4 W. It is a white aphanitic rock containing a few phenocrysts of quartz and feldspar about 1 mm in diameter. Thin sections show the rock to consist of 90 percent albite, 5 percent quartz, and 5 percent clinozoisite. The texture is trachitic.

ROCK ALTERATION

Practically all the basement rocks in the district have undergone some form of alteration since their consolidation. The volcanic rocks as well as the bulk of the intrusive rocks are mineralogically reconstituted to a greater or less degree although they retain their orignal structures and textures. In a few places original structures and textures are obscured by secondary foliation. Rocks of sedimentary origin, probably owing to their more stable mineral assemblages, have in general undergone less alteration than those of volcanic and intrusive origin.

Processes that have brought about alteration include: (a) dynamic metamorphism; (b) igneous metamorphism, including thermal metamorphism and contact metasomatism; (c) hydrothermal metamorphism that is spatially unrelated to any exposed intrusive mass; and (d) weathering. Of these processes, hydrothermal metamorphism, accompanied by metasomatism, has been most important in the East Shasta district. Weathering is discussed in the section on post-orogenic history.

DYNAMIC METAMORPHISM

Dynamic metamorphism, as defined by Turner (1948, p. 5) is the "structural and mineralogical reconstitution of rocks caused by orogenic movements." Turner states that stress is the main factor determining the structure of rocks that have undergone metamorphism of this type but that the mineral assemblage of such rocks is influenced more by temperature than any other condition.

With minor exceptions, the basement rocks throughout the district are mineralogically reconstituted to an assemblage of minerals equivalent in grade to the greenschist facies. But only in the southeastern part of the area and locally in the vicinity of Bully Hill (pl. 1) are the rocks structurally reconstituted. In these areas the basement rocks commonly have a secondary layering that ranges from a weak, discontinuous fracture cleavage to a well-defined schistosity. In the schistose rocks original structures and textures, both megascopic and microscopic, are largely obliterated. In outcrop and hand specimen amygdules and phenocrysts are markedly elongated parallel to schistosity. Some thin sections show strained and fragmented quartz and feldspar phenocrysts (fig. 15), giving a porphyroclastic texture; chlorite or fine-grained white mica are concentrated in layers spaced a fraction of a millimeter to a few millimeters apart marking planes of schistosity.

Inasmuch as the shistose rocks in the southeastern part of the area and in the vicinity of Bully Hill clearly formed under conditions of stress, their alteration is assigned in part to dynamic metamorphism. However, a large-scale metasomatic transfer of materials, notably sodium, silicon, calcium, and aluminum, attributed to hydrothermal activity, has taken place in the rocks of the East Shasta district. This transfer of materials has occurred in nonschistose as well as in schistose rocks as shown by the similarity of the mineral assemblages and chemical composition of schistose and nonschistose rocks of like parentage. Therefore, although dynamic metamorphism effected rock alteration in parts of the district, it was either accompanied or followed by hydrothermal metamorphism and metasomatism.

IGNEOUS METAMORPHISM

THERMAL METAMORPHISM ADJACENT TO INTRUSIVE BODIES

Thermal metamorphism, an isochemical process not involving directed stress, is the simplest type of metamorphism that has been operative in the area. In this type of metamorphism wallrocks adjacent to an intrusive mass tend to recrystallize to an assemblage of minerals stable under the prevailing temperature conditions.

The principal examples of thermally metamorphosed rocks in the are are: (a) coarse-grained marble formed by recrystallization of the McCloud limestone in the NE¼ sec. 26, T. 34 N., R. 4 W., and in a few other places along the contact between the limestone and the mafic quartz diorite; and (b) biotite-oligoclase hornfels formed by recrystallization of tuffaceous beds of the Baird formation adjacent to the Pit River stock in secs. 28 and 33, T. 34 N., R. 4 W. The thickness of marble and hornfels adjacent to intrusive contacts ranges from a fraction of an inch to about 100 feet. The distribution of marble and hornfels along igneous contacts is irregular. At the Shasta Iron mine coarse-grained marble is locally in contact with, and underlain by masses of skarn formed by contact metasomatism.

Thermal metamorphism is relatively unimportant because only a very small volume of rocks has been altered by this process.

CONTACT METASOMATISM ADJACENT TO INTRUSIVE BODIES

Between Marble Creek and the south boundary of the area in sec. 3, T. 33 N., R. 4 W. are small masses of skarn consisting chiefly of lime silicate minerals and magnetite. These masses are metasomatic replacements of limestone, tuffaceous mudstone, pyroclastic rocks, lavas, and quartz diorite. All except two small masses that replace tuffaceous rocks of the Nosoni formation in secs. 24 and 25, T. 34 N., R. 4 W. (pl. 1) are adjacent to, or within augite quartz diorite or mafic quartz diorite.

The skarn masses range from nests a few inches across, or layers a few inches thick, to masses as much as 700 feet in outcrop width. The largest mass centers at the Shasta Iron mine in the NE¼ sec. 26, T. 34 N., R. 4 W. This mass has a maximum outcrop width of about 700 feet and a strike length of about 2,000 feet.

The principal minerals in the skarn bodies are grossular-andradite garnet, epidote, hedenbergite, diopside var. salite, clinozoisite, calcite, and magnetite. Subordinate minerals are ilvaite, quartz, pyrite, chalcopyrite, chlorite, actinolite(?), and serpentine(?). The minerals vary in proportion in different masses and commonly are mixed with remnants of unreplaced country rock. In places south of Marble Creek dikes of fine-grained mafic quartz diorite that cut the McCloud limestone are enclosed by an envelope of coarsely crystalline hedenbergite a few inches to a few feet thick. The hedenbergite crystals are as much as 10 inches long and are oriented perpendicular to the walls of the dikes.

The close spatial relation of nearly all the skarn masses to the augite quartz diorite and mafic quartz diorite indicates that the skarn was formed by contact metasomatic action accompanying the intrusion of the quartz diorite. An introduction of iron, aluminum, silicon, copper, and possibly sulfur was required for the formation of those masses that replace limestone, whereas in the replacement of lava, pyroclastic rocks, tuffaceous mudstone, and quartz diorite by calc-silicate-magnetite rock an addition of iron and lime was probably necessary. The main substances removed during contact metasomatism were probably lime and carbon dioxide from the limestone, and aluminum, potassium, and sodium from the volcanic, sedimentary, and intrusive rocks.

HYDROTHERMAL METAMORPHISM

The principal alteration in the area has resulted in the metasomatic replacement of primary minerals in the basement rocks by secondary minerals, including albite, chlorite, quartz, hydrous mica, calcite, epidote, celadonite, sphene, and leucoxene. These secondary minerals are of widespread distribution but most of them differ greatly in abundance from place to place. Secondary minerals of more restricted distribution than those above include actinolite, anhydrite, gypsum, barite, hematite, pyrite, and base-metal sulfides. All of the above minerals are spatially unrelated to any exposed intrusive mass.

To facilitate discussion, hydrothermal metamorphism is subdivided into discrete processes named from the particular secondary mineral formed. For example, rocks are enriched in albite by the process of albitization, in chlorite by the process of chloritization, and so on. Although these processes are treated separately in the following discussion it is not meant to imply that they necessarily operated independently or at different times. More probably they operated simultaneously.

ALBITIZATION

Practically all the basement rocks of igneous origin contain albite feldspar, and field and petrographic data indicate that virtually all of this albite is of metasomatic origin. One group of rocks, the keratophyres, quartz keratophyres, spilites, albite diabases, and albite granites, which collectively make up 40 to 50 percent of the basement rock, contain albite as the only feldspar. These rocks retain their igneous textures and are characterized chemically by a comparatively high content of sodium and silicon and by a low content of calcium, aluminum, and potassium (tables 1 and 2.) Another group of rocks containing albite includes the meta-andesites, metadacites, metabasalt, and most of the quartz diorites. The latter, strictly speaking, are metaquartz diorite. These rocks, which make up 5 to 10 percent of the basement rock, are lithologically and texturally similar to the keratophyres, quartz keratophyres, spilites, and albite granites, respectively, but contain intermediate plagioclase in addition to albite.

The problem of the origin of keratophyres and related albitic rocks has received much attention, particularly from British and Scandanavian geologists, since Dewey and Flett (1911, p. 202–209, 241–248) proposed that a group of albitic rocks occurring in Cornwall belong to a natural family of igneous rocks, the "spilitic suite." Dewey and Flett visualized the spilitic suite as comparable in importance to the Atlantic and Pacific suites, although they thought the albite to be secondary, formed soon after consolidation of the magma. Many other hypotheses have been advanced to account for the origin of albitic rocks since the work of Dewey and Flett. These hypotheses are well summarized by Gilluly (1935, p. 225–252, 336–352).

According to Turner and Verhoogen (1951, p. 207), there is still no unanimity of opinion on the origin and derivation of sodic albitic rocks. Therefore, it seems worthwhile to record in some detail the relations noted and the conclusions reached on these problems in the East Shasta district.

Field and petrographic relations of the albitic rocks in the area indicate that practically all the albite is of metasomatic origin and that the sodic character of the rocks is a product of hydrothermal activity.

EVIDENCE FOR WIDESPREAD METASOMATIC ALBITIZATION

The thesis that the albite in the keratophyres and other albitic rocks is of metasomatic origin depends largely on evidence furnished by the meta-andesites, metadacites, metabasalts, and metaquartz diorites. These rocks are indistinguishable from the albitic rocks on the basis of color, texture, and structure and therefore could not be differentiated from the albitic rocks in the field. However, the random distribution of these partly albitized rocks suggests that they are not controlled by primary lithology and that they are gradational into the albitic rocks both along and across strike (fig. 4).

Thin sections show that the meta-andesites, metadacites, metabasalts, and quartz diorites or metaquartz diorites contain plagioclase of intermediate composition in addition to nearly pure albite. Other minerals commonly present are augite, uralitic amphibole, quartz, chlorite, sphene, leucoxene, epidote, fine-grained white mica, magnetite, and stilpnomelane. Textures of the volcanic rocks are generally porphyritic. Groundmass textures include pilotaxitic, intersertal, and felty. The texture of the quartz diorites is commonly hypidiomorphic granular, and has a marked tendency toward intergranular texture in many specimens.

The intermediate plagioclase forms euhedral phenocrysts and microlites in the lavas, phenocrysts, microlites, and clasts in the pyroclastic rocks, and subhedral crystals in the intrusive rocks. It ranges in composition from An_{41} to An_{63} in the undifferentiated meta-andesites and metabasalts, from An_{11} to An_{55} in the metadacites, and from An_{13} to An_{55} in the quartz diorites. The crystals are well twinned and the twin lamellae are narrow. Many crystals show normal oscillatory zoning, with rims slightly more sodic than cores. Chlorite, fine-grained white mica, epidote, calcite, and amphibole occur as alteration products in the plagioclase but are not abundant; much of the plagioclase is remarkably free of these alteration products.

Albite in the meta-andesites, metadacites, metabasalts, and metaquartz diorites occurs as a replacement of the intermediate plagioclase and as dilatation veinlets. All the albite is at least as sodic as An_4 and much may be near An_0. Most commonly it is untwinned, but some is poorly twinned. Every stage of replacement of early plagioclase by albite may be seen. Some intermediate plagioclase crystals contain only wisps of albite along cleavage lines or fractures, others are meshed by a network of albite, and a few consist of tiny remnants of the intermediate plagioclase surrounded by albite (fig. 5.) The replacement follows many patterns and has taken place on a volume for volume basis. Boundaries between the intermediate plagioclase and albite are too irregular to be attributed to zonal growth.

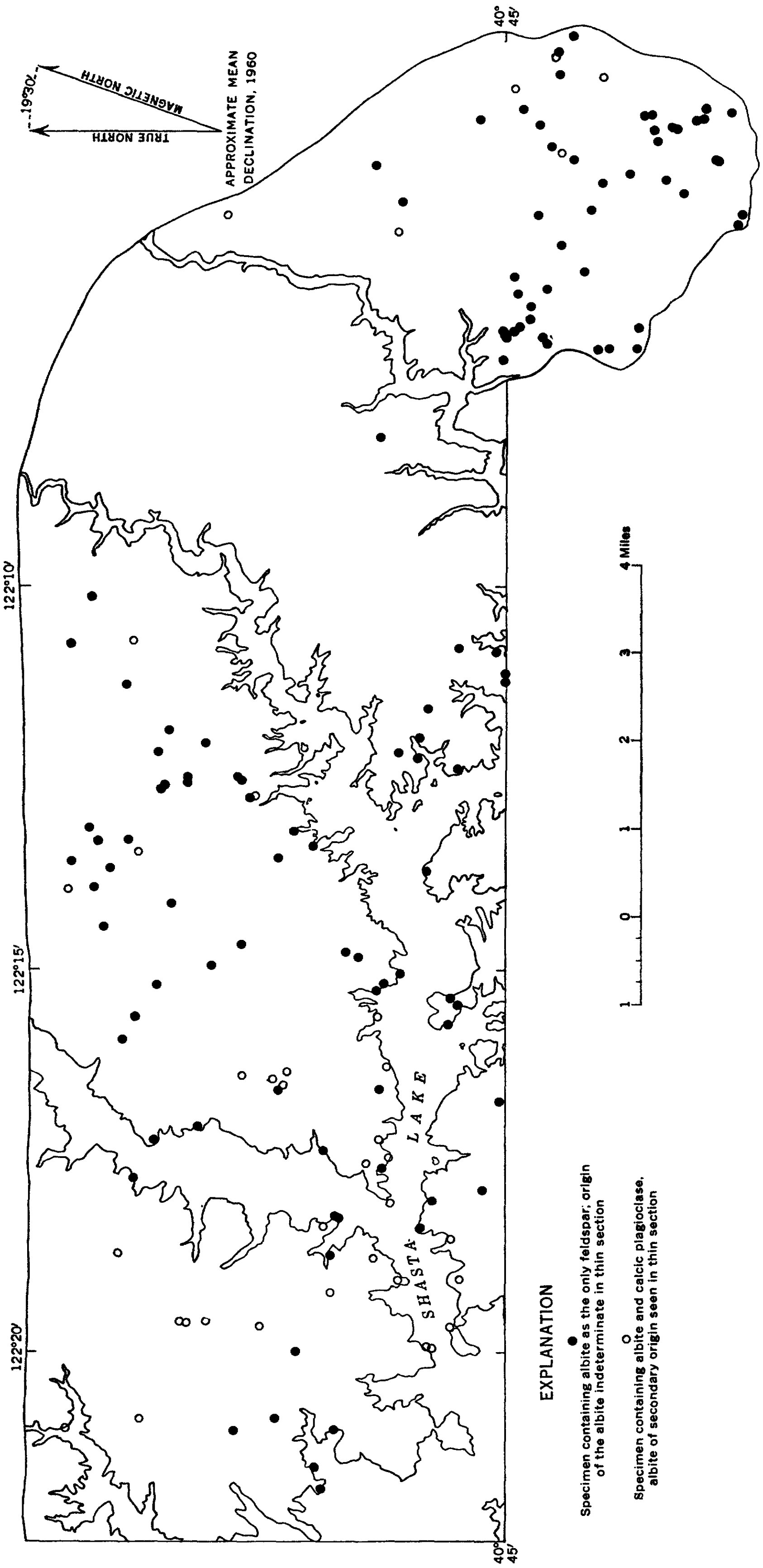

FIGURE 4.—Map of the East Shasta copper-zinc district, California, showing distribution of specimens of feldspathic rock collected at random, containing albite of doubtful origin and albite of demonstrable secondary origin.

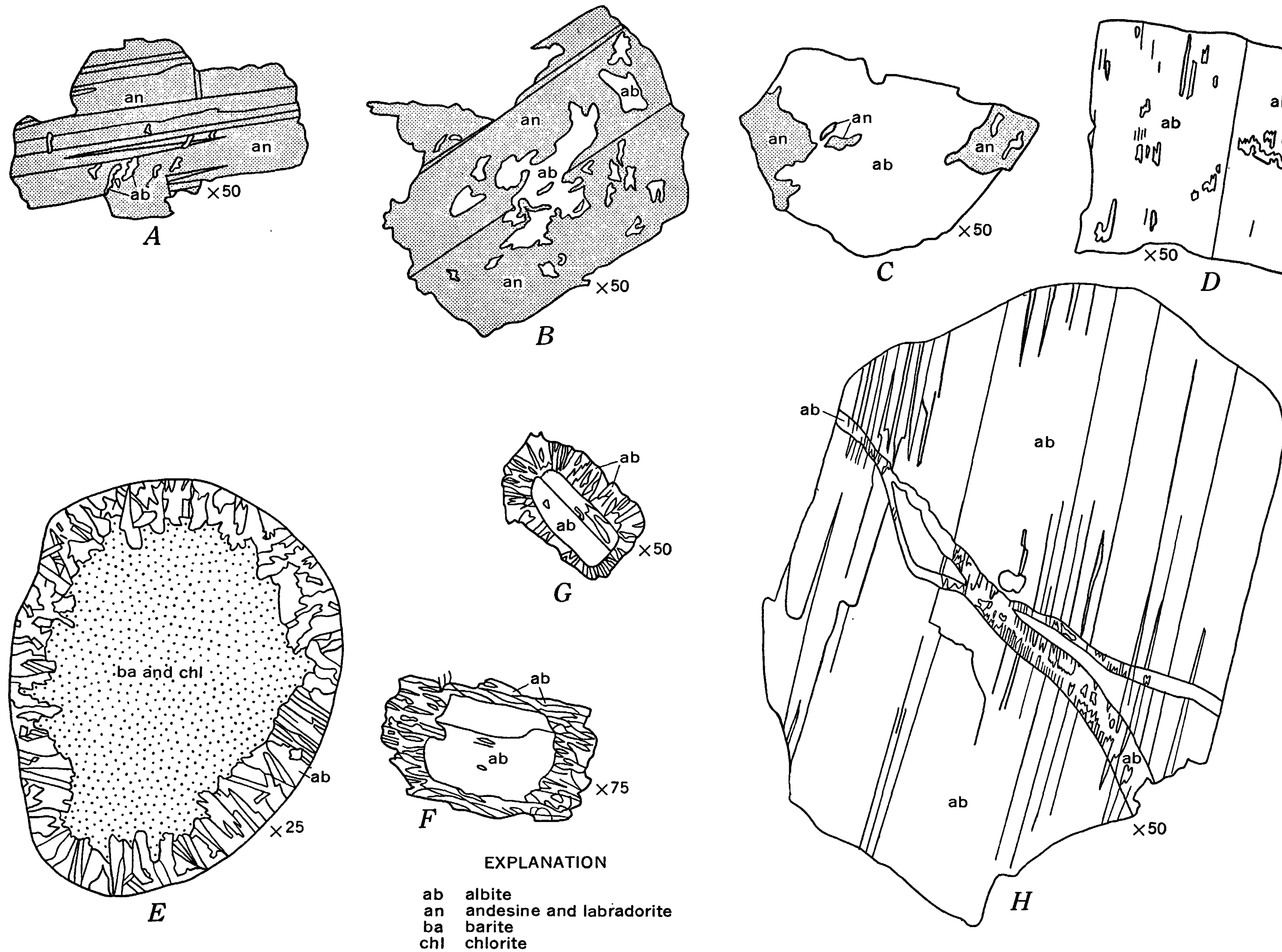

FIGURE 5.—Sketch showing kinds of secondary albite in thin sections of rocks from the East Shasta copper-zinc district (traced from photomicrographs). A, B, and C show progressive stages of replacement of plagioclase crystals of intermediate composition by albite; D, albite crystal interpreted as pseudomorph after plagioclase of intermediate composition (note the discontinuous twin lamellae); E, amygdule lined with secondary albite; F, albite host crystal with overgrowth of secondary albite crystals oriented approximately parallel to the host; G, albite host crystal with overgrowth of secondary albite crystals oriented about normal to the host; H, albite veinlet filling a fracture in albite host crystal; partly developed twin lamellae in the veinlet tend to be in optical continuity with lamellae adjacent to the veinlet.

In general, epidote, clinozoisite, calcite and other calcium-bearing minerals are rare as alteration products in the plagioclase as well as in the rocks as a whole. The scarcity of these minerals shows that the replacement of intermediate plagioclase by albite is not merely a saussuritic alteration involving the breakdown of the anorthite molecule to albite and a member of the epidote group or to calcite in response to low grade metamorphic conditions. Saussurite occurs in a few places but is rare.

From the above relations it seems that in the meta-andesites, metadacites, metabasalts, and metaquartz diorites albite has replaced a more calcic plagioclase on a volume for volume basis and that the transformation has added sodium and silicon to the rock, and simultaneously removed calcium and aluminum. Possibly the reaction proceeded according to the equation proposed by Turner and Verhoogen (1951, p. 208):

$$NaCaAl_3Si_5O_{16}+Na^{+}+Si^{+4}\rightarrow 2NaAlSi_3O_8+Ca^{+2}+Al^{+3}$$

Oxygen, which constitutes the framework of feldspars, is assumed to remain constant in this reaction. The reaction is virtually equivalent to the spilite reaction:

$$CaAl_2Si_2O_8+Na_2CO_3+4SiO_2\rightarrow 2NaAlSi_3O_8+CaCO_3$$

found experimentally by Eskola and others (1937, p. 61–68) to take place most effectively at about 300°C.

The keratophyres, quartz keratophyres, spilites, albite diabases, and albite granites are megascopically indistinguishable from the partly albitized rocks described above by lithology, texture, and structure, but the microscope reveals that the only feldspar present is albite. Chlorite or fine-grained white mica is generally present with the albite; other minerals that may be present include augite, quartz, calcite, sphene, leucoxene, celadonite, uralitic amphibole, and epidote. Volcanic rocks are commonly porphyritic; groundmass textures range from pilotaxitic and intersertal in the keratophyres and spilites to felty and microspherulitic in the quartz keratophyres. Pyroclastic facies of these rock types have clastic textures. Albite diabase commonly has an intergranular texture, and albite granite has hypidiomorphic granular texture.

Albite occurs mainly as phenocrysts and microlites in the lavas, as phenocrysts, clasts, and microlites in the pyroclastic rocks, and as subhedral crystals in the intrusive rocks. It occurs also in subordinate amounts as dilatation veinlets, as amygdule fillings, as nests of water-clear crystals apparently filling cavities in some pyroclastic rocks, and as porphyroblasts (fig. 5). Commonly the albite phenocrysts and clasts in the volcanic rocks, and the subhedral albite crystals in the intrusive rocks are clouded with chlorite, fine-grained white mica, celadonite, calcite, or one of the epidote group of minerals as alteration products. Some slides, however, show albite almost free of alteration products, and poorly twinned with checkerboard-type, discontinuous lamellae (fig. 5*D*), whereas in other slides (pl. 18*A*) the albite is well twinned, with broad, continuous lamellae. The composition ranges from An_0 to An_9, but albite more calcic than An_4 is rare.

Albite that occurs as veinlets, as amygdule fillings, and as nests of crystals apparently filling cavities is commonly free of alteration products. In most places it is either untwinned, or poorly twinned with ill-defined lamellae whose exact position of extinction is difficult to determine. The albite (*H*) in one veinlet (fig. 5) is untwinned except where the veinlet cuts through a twinned albite phenocryst. There the albite shows partly developed twinning, with composition planes and lamellae oriented parallel to composition planes and lamellae in the phenocryst. Some pyroclastic rocks contain nests of clear, poorly twinned albite crystals. In places groups of these crystals have apparently recrystallized to porphyroblasts showing sutured boundaries and sieve texture.

The secondary origin of albite, occurring as veinlets, as amygdule fillings, and as nests of crystals interstitial to lithic fragments in pyroclastic rocks seems beyond doubt. Likewise, the secondary origin of albite occurring as a replacement of intermediate plagioclase in meta-andesites and in other partly albitized rocks is clear.

The occurrence of demonstrably secondary albite in many places throughout the area (fig. 4) suggests that the albite that forms phenocrysts, clasts, microlites, and subhedral crystals in the albitic rocks is also secondary, and is a pseudomorphous replacement of an originally more calcic plagioclase. This origin would apply to all albite in the area. The keratophyres are thus albitized andesites, the quartz keratophyres albitized dacites, and spilites albitized basalts, and the albite granites albitized quartz diorites.

Differences in the intensity of albitization are apparently unrelated to the geologic age of the rocks. If a pulse of albitization had accompanied each epoch of volcanic activity the albitization would have been cumulative and Devonian rocks should be more completely albitized than Triassic rocks. But this hypothesis is not substantiated, nor is the degree of albitization related to the proximity of rocks to exposed intrusive bodies. Differences in albitization intensity seem, instead, to have been controlled at least in part by the relative permeability of the rocks and the consequent accessibility of albitizing fluids to them. Evidence for this conclusion lies mainly in the observation that lenses of pyroclastic rocks enclosed in impermeable shaly rocks of the Bragdon, Baird, Nosoni, and Pit formations commonly show only partly albitized clasts of intermediate plagioclase, whereas large masses of volcanic breccia and block lava such as are common in the Copley greenstone, Dekkas andesite, and Bully Hill rhyolite, commonly contain completely albitized plagioclase. Although exceptions to the above generalization can be found, (completely albitized plagioclase in pyroclastic lenses enclosed in shale, and partly albitized plagioclase in thick volcanic rock units) the exceptions seem sufficiently rare as to suggest a causal relation.

TIME OF ALBITIZATION

Rocks ranging in age from probable Devonian to Late Jurassic are albitized. The albitization postdates all the intrusive rocks in the East Shasta district, as well as the Mule Mountain stock in the West Shasta district, but apparently it predates the intrusion of the Shasta Bally batholith in the West Shasta district. This plutonic mass it not albitized and has formed around it a contact aureole consisting of gneissic rocks containing intermediate plagioclase. The Shasta Bally batholith is overlain nonconformably by rocks of Early Cretaceous (Valanginian and Hauterivian) age according to Hinds (1934, p. 190), and Hauterivian age according to Murphy (1956, p. 2098).

Except for the lack of albitization in the Shasta Bally batholith, the intensity or degree of albitization seems unrelated either to the age of the rocks or to the kind of rocks; intrusive rocks, as well as extrusive and sedimentary rocks are affected. In some places albite veinlets fill small fractures in the rocks. These observations suggest that albitization took place probably in Late Jurassic time contemporaneously with or slightly later than rock deformation and intrusion of all igneous rocks except the Shasta Bally batholith and its apophyses. Whether albitization also occurred one or more times before this could not be determined. Certainly the possibility of several episodes of albitization during the geologic history of the area cannot be dismissed, but the fact that intensity of albitization shows no cumulative effect and is apparently unrelated to the age of rocks suggests otherwise.

NATURE AND SOURCE OF THE ALBITIZING FLUIDS

Abundant chlorite, fine-grained white mica, and other hydrous secondary minerals are associated with and seem to be virtually contemporaneous with albite in the altered rocks. This evidence and the experimental finding of Eskola and others (1937, p. 68) that the spilite reaction takes place most effectively at about 300°C, suggest that the albitizing agents were hot aqueous fluids charged with Na^{+} and Si^{+4} ions, and capable of exchanging these ions for Ca^{+2} and Al^{+3} ions, probably according to the equation given on page 48. The same aqueous fluids may also have served as the vehicle of transport for Mg^{+2}, Fe^{+2}, $K+$, and CO_2—in the redistribution of these substances to form chlorite, fine-grained white mica, calcite, and other secondary minerals associated with albite.

As already noted on page 45, the distribution of completely albitized specimens shown on figure 4, indicates that the intensity of albitization is spatially unrelated to any exposed intrusive body. Alteration of shaly rocks to adinoles adjacent to intrusive bodies by addition of new albite has apparently not occurred in the area, and the degree of replacement of intermediate plagioclase by albite is in some places actually less complete near intrusive bodies than in places remote from them. Moreover, the plagioclase in the intrusive rocks themselves is so completely albitized in many places that autolytic albitization by fluids indigenous to altered parts of the intrusive rocks seems precluded. Such alteration would require far too much sodium and silicon retained in the residual magma fluids to account for all the albite present in albitized intrusive rock itself, disregarding the albite in surrounding rocks.

Other possible sources for the albitizing fluids include (a) sea water trapped in the pores or intergranular spaces of marine sedimentary rocks and in volcanic rocks that had been deposited in the sea; (b) a subjacent plutonic mass as yet largely unexposed by erosion; and (c) water that had been chemically bound in minerals in deeper zones, and which was set free during the metamorphism of these deeper zones.

Which of these possible sources is most probable is highly speculative; possibly all contributed. The area is part of a eugeosyncline in which wet sediments accumulated and were buried. No doubt the sea water trapped in the pores of these sediments contained an ample supply of sodium ion. Heating of this water by deep burial, by magmatism, or by radioactive means could have caused it to become resurgent and to react with minerals in the rocks through which it passed. But what of the other substances, especially chloride ion, which must have been as abundant as sodium in this resurgent sea water? None of the rocks in the area contain scapolite or other chlorine-bearing minerals. The absence of minerals containing chlorine is no proof that the fluids did not contain chloride ion, for it could have been taken up in rocks either already removed or not yet exposed by erosion; or, it may have been completely expelled either during volcanism or during alteration. Nevertheless, the complete absence of chlorine-bearing minerals is difficult to explain if the hypothesis is adhered to that resurgent sea water supplied the sodium in the albitizing process.

The possibility that a subjacent plutonic mass as yet largely unexposed may have been the source of the albitizing fluids is suggested by the distribution of three small, lithologically similar stocks—the Pit River stock in the area studied, the Mule Mountain stock in the West Shasta district (Kinkel, and others, 1956 [1957]), and a small body of coarse-grained intrusive rock exposed in secs. 5 and 6, T. 32 N., R. 1 W., about 5 miles southeast of the East Shasta area (Diller, 1906, geol. map). The rock forming these three stocks was originally hornblende quartz diorite and trondhjemite, now altered in places to albite granite. Because of the lithologic similarity of the three stocks it seems permissible to suppose that they are eminences rising above the general level of a subjacent mass that may underlie the entire area at depth. The albitization may be a result of a trondhjemitic differentiation in this subjacent mass, which is suggested by the low-potassium content in the volcanic and intrusive rocks of the area as well as by the presence of trondhjemite facies in the intrusive rocks. This type of differentiation, which was first described by Goldschmidt (1922, p. 7), and later subscribed to by Gilluly (1935, p. 336) to explain the albitization near Baker, Oreg., is supposed to be typical of geosynclinal belts (Barth, 1952, p. 232). This differentiation is thought to be conditioned by a high-water content in the magma, which results in the early and abundant crystallization of biotite. This crystallization of biotite causes a deficiency of potassium in the magma so that little or no potassic-feldspar is formed in the later stages of crystallization. The magma also becomes somewhat deficient in aluminum which causes sodic plagioclase to be favored over calcic plagioclase in the magmatic crystallization because there is insufficient alumina to meet the requirements of anorthite. The result is a rock consisting of quartz, oligoclase or sodic andesine, and biotite, or, if the biotite has been separated out, quartz and oligoclase or sodic andesine. Residual fluids from a hydrous magma such as this are apt to be abundant and rich in sodium and silicon. They are thus ideally suited for the role of albitizing the surrounding and overlying rocks.

If trondhjemitic differentiation has taken place in a subjacent magma chamber beneath the Shasta area it may actually have been going on from Middle Devonian to Late Jurassic or Early Cretaceous time, culminating in the emplacement of the Pit River and Mule Mountain stocks. This is suggested by the siliceous volcanic rocks markedly low in potassic feldspar at several places in the stratigraphic column. It seems possible that the Balaklala rhyolite and Bully Hill rhyolite are extrusive facies of this trondhjemitic magma.

The metamorphism of rocks at depth containing hydrous minerals such as chlorite, micas, and clay minerals to rocks containing less hydrous minerals as amphiboles and pyroxenes also represents a potential source for the albitizing fluids. Certainly a large quantity of chemically bound water would be set free in the conversion of rocks of the greenschist facies to those of a higher facies as the amphibolite or granulite facies. That sufficient sodium and silicon could also be derived from the metamorphism to effect extensive albitization of rocks elsewhere seems improbable unless accompanied perhaps by magnesium or calcium metasomatism. Under such circumstances, sodium and silicon might well be displaced along with water from the rocks undergoing the higher grade metamorphism and thus made available as albitizing agents.

CHLORITIZATION

Throughout the area intermediate and mafic volcanic rocks that are strongly albitized are also strongly chloritized. Chlorite occurs in these rocks as amygdule fillings, as a replacement of phenocrysts, and as a component of the groundmass. Chlorite is also a widespread but minor constituent in the more silicic rocks and locally it has extensively replaced such rocks. The Bully Hill rhyolite is so strongly chloritized locally in the southeastern part of the area that only the quartz phenocrysts remain as testimony of the original character of the rocks.

Chlorites, identified by optical properties and according to Winchell's (1951, p. 383) data, include delessite, diabantite, penninite(—), aphrosiderite, and clinochlore. The most common varieties in the albitized intermediate and mafic rocks are delessite and diabantite; these two minerals probably make up 75 percent of all chlorite in the rocks of the area. Other varieties are much less common. Clinochlore was seen only at Bully Hill and locally in the core of the Afterthought anticline (pl. 2) in the southeastern part of the area west of U.S. highway 299E. In both places clinochlore is a replacement of the Bully Hill rhyolite.

Thin sections show every stage of replacement of augite, actinolite, hornblende, and plagioclase phenocrysts by chlorite. In early stages of replacement the chlorite forms wisps along cleavage planes and zonal growth lines in the host crystal. In later stages it spreads out until in the extreme stage it forms a pseudomorphous replacement of the entire host crystal. In some chlorite pseudomorphs after augite and plagioclase the twinning of the host crystal is preserved and is conspicuously shown under crossed nicols by a marked difference in the orientation of chlorite plates in adjacent replaced twin lamellae.

The process of chloritization seems to have been contemporaneous with the albitization of intermediate and mafic rocks. Where such rocks are albitized they are also strongly chloritized. And, conversely, where they are not albitized or only slightly albitized, as is the mass of meta-andesite pyroclastic rock of the Baird formation between Goat Creek and Packers Gulch northwest of the Pit bridge, the mafic alteration mineral is acicular blue-green actinolitic amphibole instead of chlorite. In a few places the actinolite is in turn partly altered to chlorite, generally with the appearance of some albite in the rock. In the chloritization process the iron, magnesium, silicon, and oxygen may have been derived from ferromagnesian minerals in a mafic rock undergoing alteration, but unless aluminous amphibole is abundant, the source of the aluminum for the chlorite must come from elsewhere. A potential source within rocks undergoing alteration is the anorthite molecule of plagioclase in the process of being altibized. Marked parallelism in distribution of albitized and chloritized mafic rocks throughout the area suggests that this was the source of aluminum for the chlorite in the East Shasta area. If this is true, the processes of albitization and chloritization must have occurred contemporaneously.

HYDROUS MICA ALTERATION

Most of the silicic volcanic rocks in the area contain a very fine grained claylike white micaceous mineral. This material is most abundant along shear zones and in strongly schistose phases of the Bully Hill rhyolite. In places it forms as much as 15 percent of the rock. This micaceous mineral marks planes of parting in the schistose rocks and commonly forms an anastomosing network around lozenge-shaped fragments in the highly sheared rocks. In a few places feldspar phenocrysts are selectively replaced by a felted mass of this mineral whereas the groundmass contains virtually none.

Seven specimens of Bully Hill rhyolite containing this claylike micaceous mineral were collected from the Bully Hill and Little Cow Creek areas and submitted to the U.S. Geological Survey laboratories for examination. Robert L. Smith identified the material as hydrous mica by its indices of refraction (Robert L. Smith, written communication, 1953). The highest gamma index obtained was 1.58±0.003 and most of the material examined has gamma in the range of 1.570 to 1.575. The gamma index for muscovite, on the other hand, should range above 1.585. One specimen was checked under the electron microscope by Fred A. Hildebrand of the Geological Survey and its identity as hydrous mica confirmed. The physical and optical similarity of fine-grained white micaceous material from other parts of the area to hydrous mica in the seven specimens examined in the Survey laboratories suggests that most of the fine-grained white micaceous material in the silicic rocks is hydrous mica rather than sericite. However, the possibility that some may be sericite or paragonite cannot be ruled out. B. S. Butler (Graton, 1910, p. 88) inferred that some of the micaceous material at Bully Hill is paragonite.

The hydrous mica seems to bear the same relation to albitization in the silicic rocks as chlorite bears to albitization in the intermediate and mafic rocks. Hydrous mica is abundant in albitized silicic rocks but is sparse or absent in those that are not albitized. Paragenetic relations suggest that albitization either slightly preceded or was contemporaneous with hydrous mica alteration. Possibly the aluminum of the hydrous mica was derived from the anorthite molecule of plagioclase during the albitization process. This type of alteration seems to have no definite spatial relation to sulfide mineralization except that hydrous mica is generally most abundant in shear zones, as also are the sulfides.

SILICIFICATION

Rocks of many kinds throughout the area are silicified. Limestone of the Baird and McCloud formations is in places largely replaced by chert. Shale and mudstone in parts of the Kennett and Baird formations have a siliceous character, which thin sections show is due to a mosaic of microcrystalline quartz that has replaced original rock constituents. The Copley greenstone and Dekkas andesite locally contain abundant microscopic quartz veinlets. Moreover, as was shown on page 48, much silicon as well as sodium must have been added during albitization of the intermediate plagioclase that was originally in the Copley and Dekkas formations. Although this is not silicification in the sense that new quartz is formed, it nevertheless does show that these rocks were enriched in silicon.

Probably the most markedly silicified rock unit in the area is the Bully Hill rhyolite. At least 75 percent and possibly as much as 90 percent of this formation is silicified. But except where silicification is intense, as on the ridge above the Rising Star mine, silicified phases are difficult to recognize in the field because virtually all the rocks that make up the Bully Hill rhyolite were siliceous originally. Only by examining thin sections is it possible to ascertain to what extent a given specimen is silicified.

At least two degrees of silicification are discernible in thin section. In the least silicified types only the groundmass of quartz keratophyres is replaced by anhedral microcrystalline quartz. Feldspar phenocrysts and microphenocrysts are unsilicified. Quartz phenocrysts retain their original shape but commonly have narrow overgrowths of the microcrystalline groundmass quartz. These overgrowths give the phenocrysts a fuzzy border under crossed nicols, and the phenocrysts that have irregular, lobate outlines seem to be corroded and replaced by the groundmass quartz (pls. 18*B* and 20*A*). However, because in some sheared specimens angular clasts of quartz phenocrysts strung out in trains parallel to foliation also have narrow overgrowths of the groundmass quartz (pl. 21*A*). The angular clasts show no rounding of edges or reentrants that might be construed as resulting from corrosion.

In more intensely silicified phases of Bully Hill rhyolite not only the groundmass but feldspar phenocrysts as well are replaced by anhedral microcrystalline quartz. The identity of these rocks as altered quartz keratophyre depends largely on the presence of relict quartz phenocrysts, which are the only original mineral components that remain.

An unusual variety of secondary quartz in some specimens of pyritized quartz keratophyre is feather quartz that partly surrounds and radiates from pyrite cubes. Individual quartz feathers are elongate normal to the pyrite face with which they are in contact. Most are extended parallel to schistosity and occupy what Pabst (1931) has called pressure shadows. It seems that this feather quartz in large part represents quartz expelled and replaced by pyrite cubes.

Although silicification doubtless occurred several times during orogenesis the principal silicification is believed to have taken place at about the same time as albitization. The ultimate source of the silicon introduced is debatable and it may have come from several sources. It seems very improbable that it could have been "sweated out" of any rocks now exposed for they nearly all show enrichment rather than impoverishment in silicon. Therefore, a deeper seated source is probable. If, as seems likely, a subjacent mass of trondhjemite underlies much or all of the area, the silicon as well as the sodium that must have been introduced during alteration may have come from it.

During later cycles of silicification no new silicon need to have been introduced but silicon already present in the rocks was redistributed. One small-scale example of this is the feather quartz surrounding pyrite cubes, which generally replaces a mixture of microcrystalline quartz and white mica. The quartz set free during the growth of a pyrite cube seems to have moved the shortest possible distance before being redeposited. A larger scale example is the intensely silicified Bully Hill rhyolite over the Rising Star mine. Beneath this silicified zone are bodies of massive sulfide and also masses of anhydrite and gypsum that replaced the Bully Hill rhyolite. It seems highly probable that at least part of the silicon expelled by this replacement enriched the overlying rocks in silicon.

CALCITIZATION

In the southeastern part of the area beds of tuff belonging to the Pit formation are extensively replaced by calcite, forming masses of medium dark-gray rock locally known as lime rock. These masses of calcitized tuff, which are generally parallel to the bedding, are common in the synclinal belt of Pit formation north of the Afterthought mine (pls. 1 and 5) but are rare elsewhere. The largest masses in the Afterthought area are about 100 feet wide and at least 1,000 feet long. A few masses, too small to be shown on the geologic map, were seen near the end of the peninsula east of Baxters Gulch and on the south side of the Squaw Creek arm of Shasta Lake, across from Bully Hill. Although tuff is the rock most commonly replaced by calcite, quartz keratophyre belonging to the Bully Hill rhyolite is calcitized locally along the margins of sulfide bodies in the Afterthought mine. The amount of calcite is extremely variable; it forms from 10 to as much as 90 percent of the altered rock. Thin sections show that calcite occurs as subhedral crystals 1 to 5 mm in diameter. Commonly numerous grains adjoin each other and form a mass of calcite several centimeters across. The calcite thus replaces, on a volume for volume basis, all the mineral constituents of the host rock without regard for their composition and apparently does not follow any recognizable pattern of selectivity. The calcite is in turn cut locally by microscopic veinlets of quartz and white mica and is replaced by sulfide minerals.

Although paragenetic relations indicate that calcitization took place after albitization, silicification, and hydrous mica alteration, it may not have been much later. One possible source of the calcium could have been intermediate plagioclase that was undergoing albitization elsewhere. On the other hand, the calcium, as well as the carbon dioxide, with which the fluids responsible for calcitization must have been saturated, could also have come from: (a) a subjacent body of cooling magma that had assimilated a mass of limestone and whose residual fluids were rich in calcium and carbon dioxide or (b) a mass of limestone which lay somewhere beneath the calcitized rocks and which was being replaced by some other mineral or minerals. The Pit formation about a mile north of the area where calcitized rocks occur contains lenses of limestone that dip south toward the area of calcitization (pl. 1). Such limestone lenses could be present at not too great a depth in the Pit formation near the Afterthought mine where the calcitized rock is so abundant.

STRUCTURE

GENERAL FEATURES

The sedimentary and volcanic basement rocks are complexly deformed by many folds and faults. Two prominent structural trends, one north-northeast and the other northwest, are recognized. The oldest rocks occupy the core of a large northward-plunging anticline in the western part of the area, and successively younger rocks crop out toward the east in a sequence that in gross aspect is homoclinal (pl. 1). The trend of major rock units in the homocline ranges from nearly north in the O'Brien Mountain area to about N. 40° E. in the Town Mountain area. The homocline is disrupted east of the McCloud River arm by an irregular belt of mafic quartz diorite that virtually isolates the McCloud limestone from the underlying Baird formation and the overlying Nosoni formation. This quartz diorite probably in part occupies a fault zone between the McCloud and Nosoni formations. This structure is herein referred to for convenience as the McCloud fault. Many dikes, mostly of mafic quartz diorite, cut the McCloud limestone and other formations west of this fault zone but few if any are present to the east. Most of these dikes strike northwest and occupy normal tension faults and fractures.

In marked contrast to the north-northeast structural trend that dominates in the western part of the map area, a northwest trend dominates south and east of Town Mountain. This northwest trend is represented chiefly by a series of folds involving the Pit formation, Bully Hill rhyolite, and Dekkas andesite. Locally, in the eastern part of the area, the rocks have a secondary foliation that strikes northwest and generally parallels the axial planes of folds. This foliation ranges from a weak cleavage to a strong schistosity.

In the western part of the area the northwest structural trend is present but not prominent. It is marked by the nearly ubiquitous northwest strike of bedding in the McCloud limestone as well as locally in the Baird and Nosoni formations, and by a few poorly defined cross folds and warps.

AGE OF DEFORMATION

A complex structural history is indicated, not only by the two fold systems nearly at right angles to each other but also by many unconformities and an abundance of volcanic rocks and orogenic sediments throughout the stratigraphic column. The latter features show that the area was tectonically unstable from at least Middle Devonian well into Mesozoic time. Prior to Late Jurassic, however, deformation seems to have consisted mainly of recurrent uplift and tilting; it seems doubtful that much folding and faulting took place until the Late Jurassic orogeny. The basis for this conclusion is that all the stratified basement rocks within the area, plus the Bagley andesite, and the Modin and Potem formations, which crop out east of the area, have undergone about the same degree of deformation. Crickmay (1931, p. 88) assigned the Potem formation to the Ludwigian stage of Middle Jurassic, but more recent data by A. E. Sanborn [11] indicate that it is probably of Bajocian age. On the other hand, the oldest formation in the region that has not undergone orogenesis is the Paskenta formation of Early Cretaceous age. If allowance is made for time to unroof the Shasta Bally batholith which postdates deformation and which lies nonconformably beneath the Lower Cretaceous sedimentary rocks it seems likely that deformation took place in Late Jurassic rather than Early Cretaceous time.

FOLDS

Two prominent fold systems, a north-northeast system and a northwest system, are indicated on plate 2. Also present, although not conspicuous, are a few small folds in the O'Brien Mountain area that seem to trend nearly east-west. The homocline through Horse and Town Mountains is probably ultimately part of a large regional fold and is included in the northeast fold system.

As measured along section *B–B′* (pl. 1), which trends N. 84° W., folding has resulted in a crustal shortening of 15 to 20 percent. Along section *A–A′*, which trends N. 33° E., the crustal shortening is about 25 to 30 percent.

NORTHEASTWARD-TRENDING FOLDS

Folds that trend northeastward include, in addition to the homocline through Horse and Town Mountains: (a) the O'Brien Mountain anticline; (b) small folds in the Bragdon formation on the west side of O'Brien Mountain, in the McCloud limestone south of Curl Creek, in the Dekkas andesite on Horse Mountain, and in the Pit formation and Bully Hill rhyolite west of Baxters Gulch; and (c) possibly the large mass of Pit formation, lying chiefly between the Squaw Creek and Pit River arms of Shasta Lake and which in gross aspect seems synclinal.

O'BRIEN MOUNTAIN ANTICLINE

The largest complete fold in the area is an anticline that strikes N. 10° to 25° E. through O'Brien Mountain

[11] A. E. Sanborn, 1952, The geology of the Big Bend area, Shasta County, California: Unpublished thesis, Stanford Univ.

and plunges northeastward at a low angle. This fold is called the O'Brien Mountain anticline (pl. 2). The outline of the anticline is best shown by the outcrop pattern of the Kennett and Bragdon formations, which wrap around the nose and flanks of the structure, with the Copley greenstone and Balaklala rhyolite forming the core (pl. 1). Along the west flank of the anticline the Kennett formation dips steeply east in most places and is presumably overturned. Throughout most of sec. 17, T. 34 N., R. 4 W., it is also highly sheared and may be in fault contact with the Copley greenstone. In the east-central part to sec. 8, T. 34 N., R. 4 W, fine-grained conglomerate beds that dip southeast show inverted graded bedding, suggesting that the Bragdon formation as well as the Kennett is overturned at least locally along the west flank of the anticline. On the east flank of the anticline sedimentary beds dip mostly east at moderate angles. The overturned beds on the west limb show that the anticline is overturned slightly to the west and a steep east ward dip on its axial plane is inferred.

The scarceness of bedding or original layering[12] in the Copley greenstone and Balaklala rhyolite in the core of the O'Brien Mountain anticline, and the intertonguing of the two formations, prevents the precise location of the anticlinal crest. Bedding in pyroclastic rocks on the east side of the Waters Gulch arm dips 40 to 60° E., suggesting that the crest is farther west. Also, opposed bedding attitudes in the Bragdon formation on the nose of the anticline north of O'Brien Creek help to define the position of the crest in that locality. But elsewhere the only guide is the shape of the core of Copley greenstone and Balaklala rhyolite; the crest is assumed to almost bisect this core.

SMALL FOLDS THAT TREND NORTHEASTWARD

In addition to the O'Brien Mountain anticline small northeastward-trending folds are shown in the Bragdon formation on the west side of O'Brien Mountain, in the Baird formation on the peninsula in sec. 33, T. 34 N., R. 4 W., in the McCloud limestone south of Curl Creek, in the Dekkas andesite on Horse Mountain, and in the Bully Hill rhyolite and Pit formation southwest of Baxters Gulch (pls. 1 and 2). The wavelengths and amplitudes of these folds range from a few feet to a few hundred feet.

POSSIBLE SYNCLINE MARKED BY OUTCROP PATTERN OF THE PIT FORMATION

The large mass of Pit formation that lies largely between the Squaw Creek and Pit River arms of Shasta Lake (pl. 1) may mark: (a) a topographic depression between volcanic highlands in which the sediments that form the Pit formation accumulated during Triassic time; (b) a shallow northeastward-trending synclinal trough; or (c) a combination of (a) and (b). The latter seems most probable. Evidence suggesting that it occupies a topographic depression lies in the distribution and different thickness of the underlying Bully Hill rhyolite along the margin of the mass, and in the probable presence of volcanic centers north of Bully Hill and south of Sugarpine Canyon. Evidence of a syncline is suggested by the fact that northeast of Bully Hill and also southwest of Baxters Gulch the Pit formation strikes northeast and dips southeast off the underlying rocks of the main homocline. Along the irregular southeast margin of the mass of Pit formation evidence of a northeast structural trend is lacking. If such a trend ever existed it has been obliterated by the system of northwest folds.

The Pit formation probably accumulated in a trough that at least within the area had a northeasterly trend. Deformation that produced the main homocline tilted the northwestern part of the trough toward the southeast. Therefore, the mass of Pit formation may be considered as a shallow synclinal warp associated with the northeast homocline and related to northeast folding.

NORTHWESTWARD-TRENDING FOLDS

The outstanding structures in the eastern part of the area are a series of northwestward-trending folds involving the Hosselkus limestone, Pit formation, Bully Hill rhyolite, and Dekkas andesite. These folds are well marked by bedding attitudes in the sedimentary rocks and by the outcrop pattern of lithologic units. The most continuous fold in this series includes the Afterthought mine on its north limb and is here called the Afterthought anticline (pl. 2). The strike of the folds ranges from approximately N. 70° W. in the Little Cow Creek area to about N. 25° W. in the Brock Mountain area. Just north of the Squaw Creek arm of Shasta Lake, near Bully Hill, many of the northwest folds define a cymoid curve by making a bend north-northeast for a few thousand feet before resuming their

[12] The intermediate and silicic volcanic rocks that make up such a large percentage of the stratigraphic column lack continuous marker beds and very likely were not laid down flat like marine sediments. Initial dips of 30° or more are common in many recent undeformed lavas of the type constituting the Copley greenstone, Dekkas andesite, Balaklala rhyolite, and Bully Hill rhyolite. Also, the volcanic rocks that make up each of these formations probably came from several different vents. Thus, the resulting volcanic pile for each of these units, consisting of interfingering flows and pyroclastic rocks, and with each lithologic unit possibly having a different initial dip, no doubt contained many unconformities and was structually complex even before orogenesis. For these reasons, in our interpretation of the structure and the amount of actual deformation, greater reliance is placed on structural features in sedimentary units than on those in volcanic units. Strikes and dips taken in laminated sedimentary rocks are regarded as a more reliable measure of deformation than strikes and dips taken on layering in lava flows or pyroclastic materials. Probably least reliable are strikes and dips on flow banding in silicic lavas.

northwest trends and eventually terminating on the flanks of Horse and Town Mountains. The wavelengths and amplitudes of the northwest folds range from a few hundred feet to about a mile. The consistently steep southwest dip of foliation as well as the attitude of drag folds a few feet across seen in many places on the flanks of larger structures suggests that most of the folds south of the Pit River arm are asymmetrical and have northeast limbs a few degrees steeper than southwest limbs. This is also true locally north of the Pit River arm but the majority of folds in the latter area are more nearly symmetrical.

As shown by the outcrop pattern of the Pit formation in relation to the underlying volcanic units, the dominant plunge of the folds is northwest south of the Pit River arm and southeast north of the Squaw Creek arm. Between the Squaw Creek and Pit River arms of Shasta Lake lineations (pl. 2) indicate that northwest and southeast plunges are about equally common. The folds in this part of the area are arranged en enchelon, and alternate folds plunge in opposite directions.

CROSS FOLDS

West of a line roughly joining Town Mountain and the Cove Creek arm of Shasta Lake (pl. 1) cross folds that trend northwestward are superimposed on the northeastward-trending homocline and on the O'Brien Mountain anticline. These cross folds are identified with the system of northwest folds in the eastern part of the area and include: (a) warps in the general northeasterly trend of lithologic units in the homocline; (b) warps on the O'Brien Mountain anticline; (c) small folds a few feet across that were seen in the field; and (d) folds indicated by opposed bedding attitudes.

The strike of the cross folds ranges overall from about north-south to about east-west. However, the majority strike in the range N. 20 to 40° W. All the small folds that were seen in the field as well as those indicated by opposed attitudes are shown on plates 1 and 2.

Warps and cross folds on the homocline are indicated by opposed bedding attitudes in mudstone beds near the summit of Town Mountain and by the sinuous form of mudstone beds between Town and Horse Mountains (pl. 1). Most prominent in this area is a synclinal warp that strikes about N. 30° W. from the summit of Horse Mountain.

Several cross warps on the O'Brien Mountain anticline are indicated by the shape of contacts between formations. The contact between the Bragdon and Baird formations in the southwestearn part of sec. 21, T. 34 N., R. 4 W. strongly suggests a synclinal warp plunging southeastward into the adjoining sec. 28. Just east of this synclinal warp, in the south-central part of sec. 21, the Bragdon and Baird contact is convex toward the southeast, indicating an anticlinal warp. This anticlinal warp is also suggested by opposed bedding attitudes in the Baird formation in sec. 28.

The form of the contact between the Copley greenstone and the Kennett and Bragdon formations suggests a synclinal cross warp extending from near the southwest corner of sec. 17, T. 34 N., R. 4 W. southeastward to about the southeast corner of sec. 20, T. 34 N., R. 4 W., where it is interrupted by a fault.

Convexities in the contact between the Copley greenstone and overlying formations suggest an anticlinal cross warp extending from the south-central part of sec. 8, T. 34 N., R. 4 W., about S. 35° E. to the south-central part of sec. 21, T. 34 N., R. 4 W.

In addition to the cross folds and warps noted above, the nearly ubiquitous northwest strike and northeast dip of bedding in the McCloud limestone and in parts of the Baird and Nosoni formations indicate tilting on a northwesterly axis. Although the present attitude of bedding in the McCloud limestone is probably in part the result of faulting, the similar attitude of bedding in so much of the Baird and Nosoni formation suggests that folding also played a part.

CLEAVAGE AND SCHISTOSITY

The basement rocks in many places in the eastern part of the area have a secondary planar structure that ranges from a weak cleavage to a prominent schistosity. This planar structure is especially conspicuous south of Backbone Ridge where it occurs in about 75 percent of the rocks. It strikes northwest or west-northwest and dips from vertical to 55° SW. (pl. 1). North of Backbone Ridge and between the Pit River and Squaw Creek arms of Shasta Lake it is less common and is generally restricted to crests and troughs of folds. The strike makes a gradual swing to a more northerly direction between Backbone Ridge and Squaw Creek as does also the strike of folds. Between Squaw Creek and Horse and Town Mountains cleavage and schistosity strikes mainly northwest but in places northeast; easterly dips are almost as common as westerly dips in this area. South and west of Horse Mountain cleavage and schistosity are virtually absent.

Rocks with cleavage have subparallel fractures or cleavage planes spaced a fraction of a millimeter to locally as much as a foot apart. In many places this cleavage approximately parallels the axial planes of drag folds in shaly rocks of the Pit formation. Thin sections cut normal to the cleavage show that the parting planes are commonly marked by thin layers of fine-grained platy minerals, chiefly chlorite in the mafic volcanic rocks, and fine-grained white mica in the siliceous volcanic rocks and shale beds. Individual platy minerals are mostly alined parallel to cleavage planes. However, the minerals between cleavage planes are chiefly feldspar, microcrystalline quartz, and other minerals of nontabular crystal habit, only rarely are fine-grained platy minerals present throughout the rock. The platy minerals along cleavages may have formed either contemporaneously with or later than the cleavage planes.

In several places near the Afterthought mine and in the Bully Hill-Baxters Gulch area rocks with cleavage, or, rarely, massive rocks contain lenses of strongly sheared rock as much as 200 feet thick and half a mile long. The rock within these lenses or zones is in some places soft and gougy and in other places strongly schistose, containing abundant platy minerals visible to the naked eye. Thin sections of the schistose rock cut normal to the schistosity show typical cataclastic structures. Augen of crushed rock are surrounded by braided or anastomosing stringers of fine-grained white mica (pl. 21*A*). Quartz and feldspar phenocrysts are commonly fragmented and the resulting clasts are strung out in trains parallel to schistosity, showing that marked displacement has occurred along the schistosity surfaces.

LINEATION

Two types of lineation in the area are the plunge of drag folds and the intersection of fracture cleavage and bedding. The first type is common in the Pit formation in the eastern part of the area and also in the Bragdon formation in the O'Brien Mountain area. The second type was seen only in the Pit formation in the eastern part of the area. All the lineations are plotted on plate 2.

Lineation in the Pit formation strikes northwest parallel to the axes of northwest folds. The plunge is either southeast or northwest and ranges from horizontal to about 70°; plunges of 10° to 25° are most common. Southeast of the Pit River arm of Shasta Lake most lineations plunge northwestward. Between the Squaw Creek and Pit River arms of the lake northwest and southeast plunges are about equally common. In the Bully Hill area lineations are variable; northwest and northeast plunges are about equally common and there are also a few southerly plunges. Northeast of Bully Hill the plunge of lineation is dominantly southeastward.

On the south and east sides of O'Brien Mountain minor folds plunge dominantly eastward and southeastward at low angles, whereas on the west side of the mountain they plunge mainly westward and northwestward. On the nose of the O'Brien Mountain anticline a few small folds plunge north-northeastward.

AGE RELATION OF NORTHEAST AND NORTHWEST FOLDING

Evidence on the relative age of northeast and northwest folds is not conclusive but the following relations strongly suggest that the northeast folds predate the northwest folds:

1. The large northeastward-trending homocline and the O'Brien Mountain anticline are warped along axes that trend northwestward.
2. The homocline through Horse and Town Mountains locally has a cleavage that strikes mostly northwestward (pl. 1), in approximate concordance with cleavage in the Pit formation and Bully Hill rhyolite in the Squaw Creek area, and also about parallel to the axes of northwestward-trending folds. If this cleavage had existed in the rocks at the time the strong northeast deformation (which locally produced dips as steep as 80°) occurred the cleavage most probably would not have escaped severe crumpling. However, no crumpling of cleavage was seen in this area. Moreover, if the cleavage and fold axes on Horse and Town Mountains had been present when the rocks there acquired their southeast dip they probably would have been pushed out of alinement with the cleavage and fold axes in the Squaw Creek area where the rocks have little if any component of dip as a result of northeast folding.
3. In many places northwest-bedding strikes prevail for several hundred feet within incompetent formations that in gross aspect strike northeast. An example of this is the Baird formation in the vicinity of Johns and Baileys Creeks. If the northeast folding were younger it seems unlikely that these incompetent rocks could have escaped being pushed into an orientation more compatible with the northwest-southeast compressive forces that would have been operative.

FAULTS

GENERAL FEATURES

A few moderately large faults and many small ones disrupt the basement rocks in the district. The largest fault, along the east side of the McCloud limestone, is interpreted as a left-lateral strike-slip fault (pl. 1). Most faults are high-angle faults, having dips greater than 45°. The majority of the larger faults and many of the smaller ones were formed before emplacement of hypabyssal igneous rocks and before sulfide mineralization. Some small faults, however, are of postintrusive age and a few occurred after sulfide mineralization.

DISTRIBUTION AND ORIENTATION

The accompanying geologic and tectonic maps (pls. 1 and 2) show four principal areas of faulting. They are (a) the general vicinity of the Afterthought mine; (b) an area extending from the peninsula in the west-central part of sec. 31, T. 34 N., R. 3 W. northeastward through Bully Hill to the eastern slopes of Town Mountain; (c) the area occupied by the McCloud limestone and mafic quartz diorite; and (d) the O'Brien Mountain area.

In the Afterthought mine area about 80 percent of the faults strike N. 50 N. 75° W.; northeastward-trending faults are rare. In the vicinity of Bully Hill northwestward- and northeastward-trending faults are about equally abundant but the northeast faults are larger. Also, the strike of northwestward-trending faults is more northerly, ranging from about N. 5° to N. 50° W. The northeastward-trending faults strike mostly N. 10° to 20° E. and N. 60° to 75° E. The McCloud limestone is apparently bounded on the east side by a strike-slip fault that trends about N. 30° E., but a series of northwestward-trending normal faults also disrupt the limestone. The strike of faults in the O'Brien Mountain area virtually boxes the compass but 3 principal directions, N. 60° W., N. 60° E., and N. 20° E., dominate. Easterly dips predominate over westerly dips.

Variations in the attitude of faults in different parts of the district are illustrated on the contour diagrams (figs. 6, 7, and 8).

TYPES OF FAULTS

Owing to poor exposure, to the parallelism of many faults to bedding or schistosity, and to the lack of reliable marker units, the direction and amount of displacement could be determined for only a few of the many faults in the area. For this reason, the classification adopted here is largely geometric rather than genetic. The following types of faults will be described: (a) Low-angle faults; (b) the McCloud fault; (c) high-angle strike faults; (d) high-angle transverse faults; and (e) shear zones.

LOW-ANGLE THRUST FAULTS

Faults that dip less than 45° are uncommon in the district and most of those recognized have displacements of only a few feet. Probably the largest low-angle fault is the Afterthought mine where a block of Bully Hill rhyolite between the 200 and 400 levels is thrust northeastward for about 150 feet on the Pit formation (pl. 5, section *A–A′*).

On the crest of the ridge leading north from Horse Mountain, at an altitude of about 3,400 feet are 2 faults marked by slickensided surfaces of quartz each about 50 feet square. These faults strike N. 75° E. and dip northwest at an angle of about 25°; the grooves on the slickensided surfaces plunge downdip. Displacement could not be determined but is probably only a few feet. A few low-angle faults, some showing reverse and others normal movement, were also seen in road cuts in the O'Brien Mountain area.

McCLOUD FAULT

The largest fault in the area is a preintrusive fault trending about N. 30° E. along the east side of the McCloud limestone. This fault is not exposed but its position is marked in most places by a continuous belt of intrusive rock (pls. 1 and 2). The following relations indicate the presence of this fault:

1. The McCloud limestone and the Nosoni formation are both missing for a strike length of about 1½ miles in the area of the Pit River arm (pl. 1); likewise, the Nosoni formation is missing for a mile or more between the upper part of Marble Creek and the upper part of Curl Creek; and the Dekkas andesite is partly cut out in the northeastern part of sec. 24, T. 34 N., R. 4 W. Inasmuch as fossil data shows the presence of time gaps between the Baird and McCloud, between the McCloud and Nosoni, and probably between the Nosoni and Dekkas, tilting and erosion during these intervals may be partly responsible for the absence of these formations in the places mentioned. However, if considered in conjunction with other evidence given below, it seems that faulting is probably the main cause.
2. The discordant attitude of bedding in the McCloud limestone with respect to the Nosoni and Dekkas formations is perhaps the strongest indication of a fault. In gross aspect, these 3 units strike about N. 20°–25° E. However, the strike of bedding in the McCloud limestone is northwest throughout most of the area (pls. 1 and 2). Thus, the limestone beds, if projected southeastward along their strike through the mafic quartz diorite, would either butt against or override the Nosoni and Dekkas formations. The strike of bedding in the Nosoni and Dekkas formations is also north or northwest in some places, particularly in sec. 24, T. 34 N., R. 4 W., indicating the same type of discordant relation.

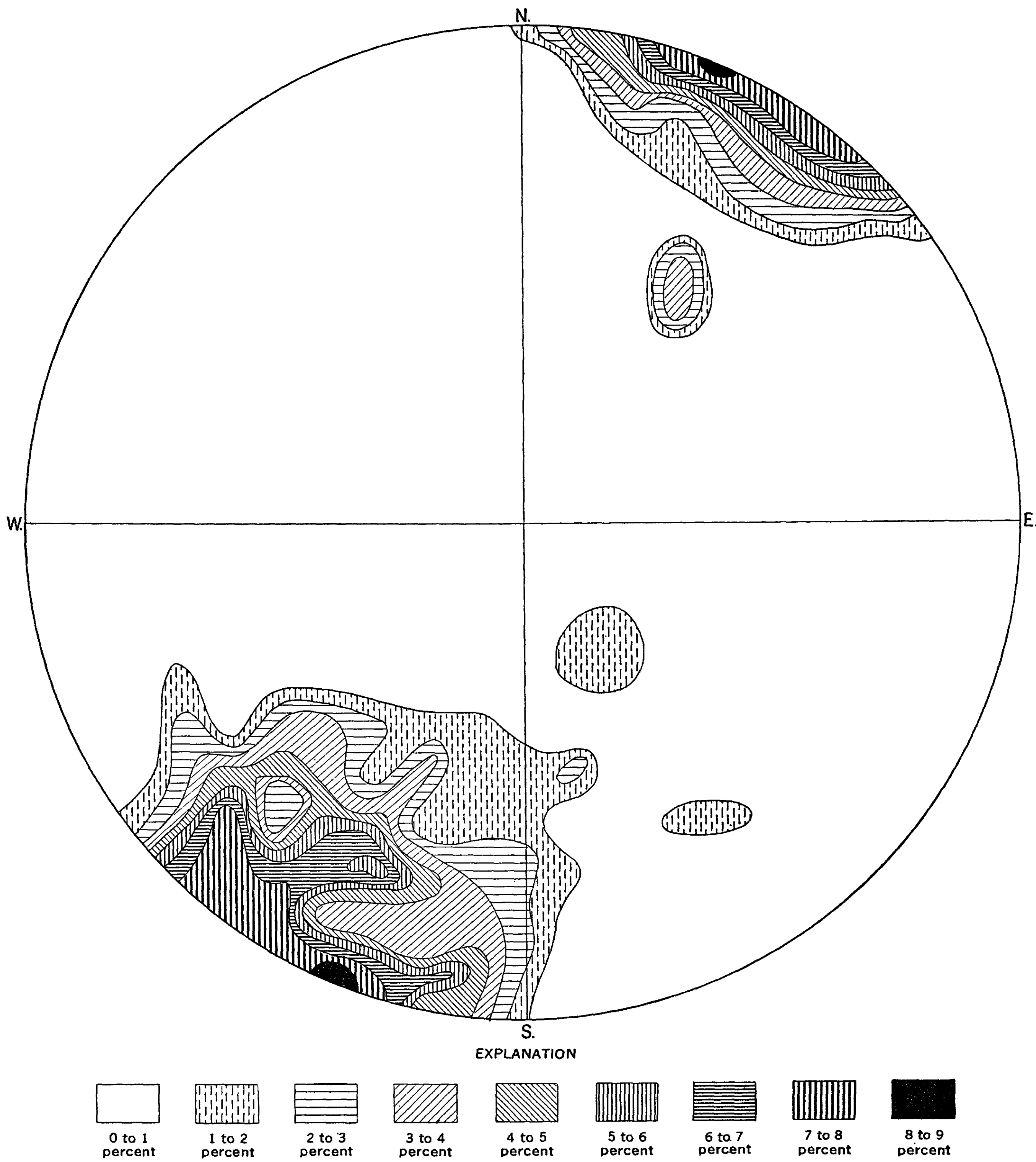

FIGURE 6.—Contour diagram of poles of 130 faults in the Afterthought mine. Plotted on upper hemisphere of a Schmidt equal-area net. The diagram shows that all but a few faults strike N. 50° to 75° W. and dip at high angles northeast or southwest.

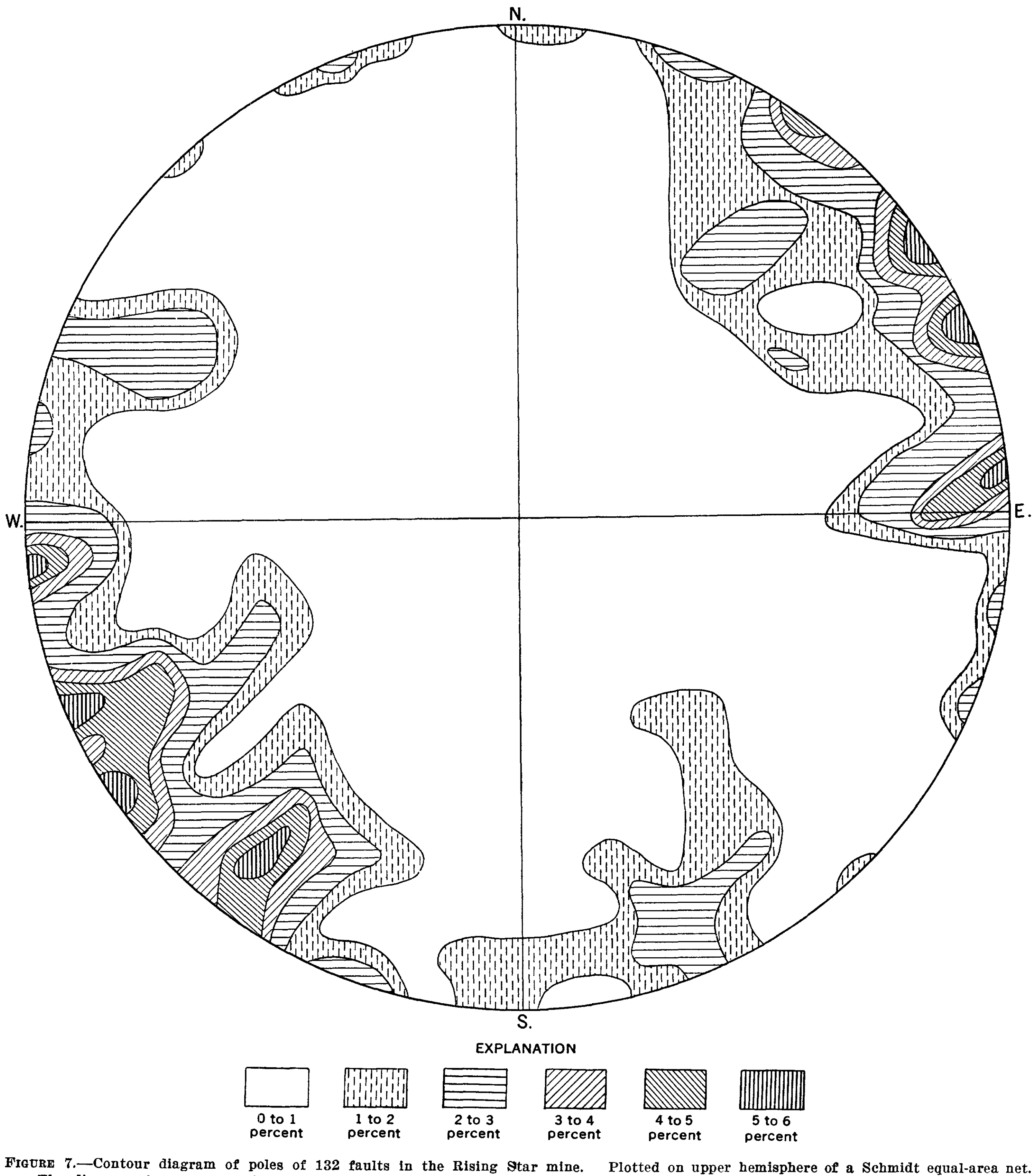

FIGURE 7.—Contour diagram of poles of 132 faults in the Rising Star mine. Plotted on upper hemisphere of a Schmidt equal-area net. The diagram shows that faults strike predominatly N. 5° E. to N. 50° W. and dip steeply either northeast or southwest. Another group of faults strikes N. 70° E. and dips mainly southeast at angles of 70° to 90°. Faults associated with the Bully Hill shear zone east of the Rising Star mine, which strike N. 10° to 30° E., are not shown.

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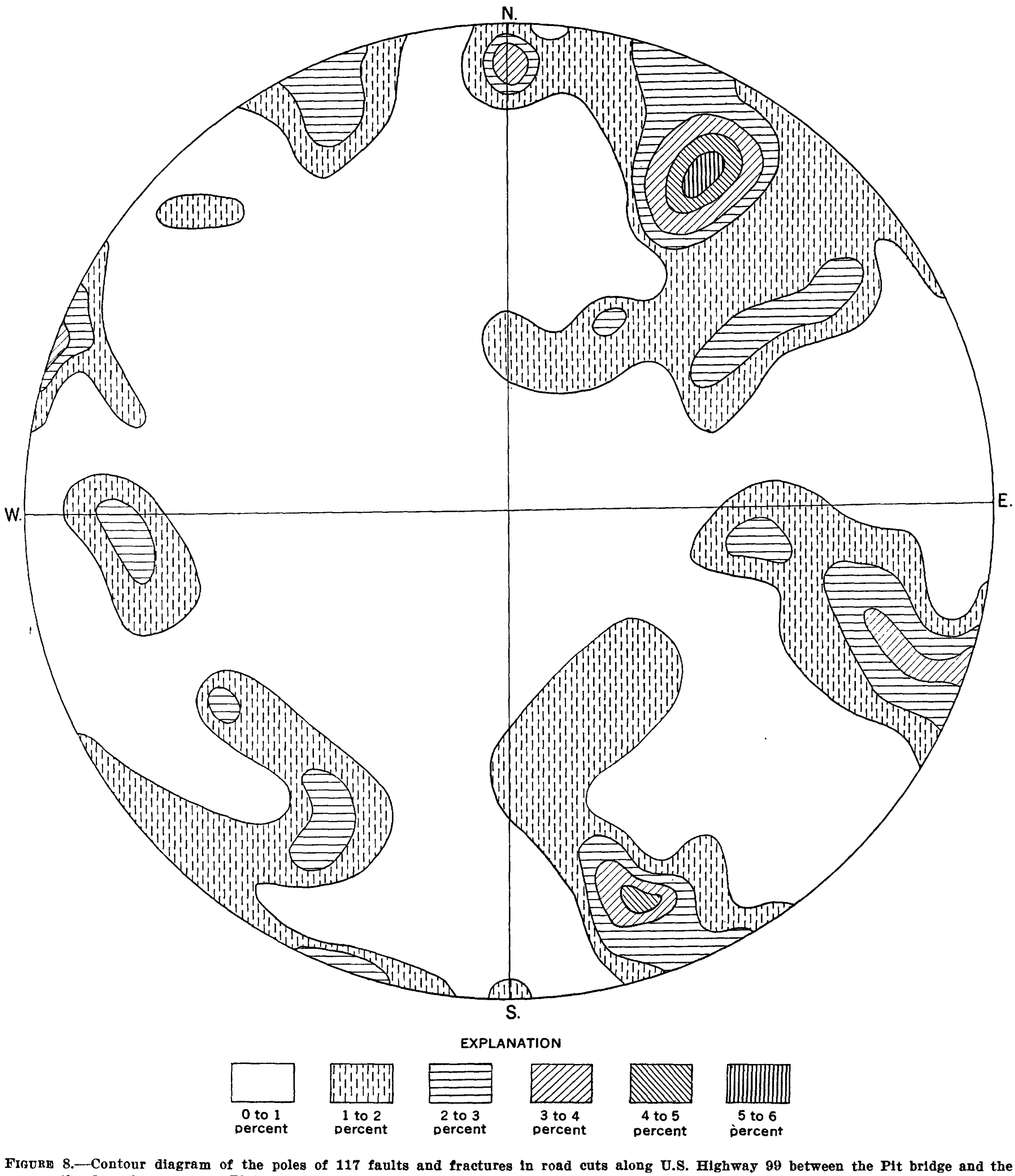


FIGURE 8.—Contour diagram of the poles of 117 faults and fractures in road cuts along U.S. Highway 99 between the Pit bridge and the north edge of map area. Plotted on upper hemisphere of a Schmidt equal-area net. The diagram shows that on the basis of attitude the faults along the highway fall into three main groups: a group that strikes N. 60° W. and dips 60° NE.; a group that strikes N. 60° E. and dips 65° SE.; and a group that strikes N. 20° E. and dips 60° to 90° SE.

3. North of Curl Creek the upper greenstone unit of the Baird formation lies directly opposite the Nosoni formation, separated by a few hundred feet of mafic quartz diorite; the McCloud limestone is on a small peak only a few hundred feet west of the greenstone outcrop but it strikes east-west and dips north, about at right angles to the younger Nosoni and Dekkas formations that lie to the east.

The McCloud fault apparently dips west at a moderately steep angle, but the precise dip is impossible to determine because the limestone west of the fault is disrupted by a series of northwestward-trending normal strike faults, most of which are preintrusive and occupied by dikes of mafic quartz diorite. The northwest strike of these faults, coupled with the dominant northwest strike of mafic quartz diorite dikes in the O'Brien Mountain area (pl. 1), and the anomalous northwest strike of bedding in the limestone, indicate left-lateral and reverse movement on the McCloud fault. The limestone was broken into discrete blocks that were rotated by the left-lateral motion into their present position of northwest strike. The regional outcrop pattern of the McCloud limestone and the dominant northwest strike of dioritic dike rocks shown on Diller's (1906) map of the Redding 30-minute quadrangle also strongly suggest left-lateral movement along this zone. The amount of movement is unknown but it may not exceed a few thousand feet.

HIGH-ANGLE STRIKE FAULTS

Most faults in the southeastern part of the area and many as far west as the McCloud River arm of Shasta Lake strike about parallel to adjacent rock units, and, with one notable exception, dip at high angles to these units. These faults are classed as strike faults. For purposes of description they are subdivided according to the three main areas in which they occur.

Afterthought area

As shown in figure 6, the vast majority of faults in the Afterthought mine strike N. 50°–75° W. and dip at steep angles, mostly southwest. The areal mapping shows, moreover, that this is the dominant attitude of faults throughout the southeastern part of the area. In the Afterthought mine the direction of movement on many of these strike faults is shown by the displacement of the contact between the Bully Hill rhyolite and the Pit formation. Most of the faults on which the displacement can be demonstrated dip steeply southwest and show the northeast side displaced downward with respect to the southwest side; the amount of apparent dip-slip displacement ranges from a few feet to as much as 250 feet (pl. 5). The strike-slip component is not known. Inasmuch as the hanging wall shows upward displacement with respect to the foot-wall, most of these faults would be reverse faults in a genetic classification. A few that show downward displacement on the southwest side have normal movement. At depth many of the strike faults in the Afterthought mine seem to branch out into shear zones.

The largest fault in the Afterthought mine is called the Main fault. It strikes northwest and dips northeast, about parallel in places to bedding in the Pit formation. It cuts all other faults in the mine. For reasons given on page 85 the northeast or hanging-wall side of Main fault probably moved upward about 450 feet relative to the footwall side. On the assumption that the strike faults in the Afterthought mine are representative of strike faults elsewhere in the southeastern part of the area, it is concluded that most of the strike faults in this part of the area have reverse movement.

CENTRAL PART OF THE AREA

The principal high-angle strike faults in what may be called the central part of the area are the Bully Hill Contact fault, which strikes about N. 45° E. through the central part of sec. 29, T. 34 N., R. 3 W., and a fault between the Dekkas andesite and Pit formation straddling the boundary between secs. 35 and 36, T. 34 N., R. 4 W. (pl. 1). All these faults dip west or northwest at angles ranging from 60° to 80°, have the older rocks on their hanging-wall side, and are probably reverse faults. The Bully Hill Contact fault at the surface dips 60° NW. but at a depth of 500 feet in the Bully Hill mine it joins the Bully Hill shear zone and at lower levels dips about 70° SE. (pl. 12).

Strike faults in the McCloud limestone

The McCloud limestone in the Marble Creek area is cut by at least three or more faults that strike northwest, about parallel to bedding, and dip about 70° SW. (pl. 2). Two of these faults are partly filled with mafic quartz diorite and from this it seems likely that several other mafic quartz diorite dikes that cut the limestone parallel to strike likewise mark faults. The displacement on the strike faults could not be determined owing to the homogeneous lithology of the limestone and to the fact that the faults, where not filled by quartz diorite, are largely healed by recrystallization of the limestone. Indirect evidence suggests that the southwest side on the faults may have moved down. A cross section drawn from near the mouth of Marble Creek northeastward across strike to Curl Creek shows an apparent thickness of 5,000 to 6,000 feet of limestone, disregarding the strike faults. However, if each of the three or four southwestward-dipping faults crossed by the line of section is assumed to have normal movement (southwest side dropped) the apparent thickness of the limestone would be reduced to a more reasonable figure. Reverse movement, on the other hand, would increase the limestone thickness. Mapping of fusulinid zones throughout the McCloud limestone as was done by Wheeler [13] in a small area is necessary to resolve the problem of thickness and faulting in the formation.

HIGH-ANGLE TRANSVERSE FAULTS

The principal high-angle transverse fault in the area is the Packers Gulch fault (pls. 1 and 2). Other noteworthy faults in the group include: (a) those that disrupt the nose and flanks of the O'Brien Mountain anticline; (b) a fault striking about east-west in the Pit formation between secs. 33 and 34, T. 34 N., R. 3 W.; and (c) a fault striking N. 10° E., lying largely in sec. 2, T. 33 N., R. 2 W., near the extreme east edge of the area. Most of these faults were not seen in the field but are inferred from the offset of rock units.

Packers Gulch fault

The Packers Gulch fault (pls. 1 and 2) extends from west of the mouth of Packers Gulch about N. 10° E. for three-quarters of a mile where it turns N. 60° E. and continues to Johns Creek. The presence of this fault is inferred from the fact that shale of the Bragdon formation exposed south of the fault is generally strongly sheared and dips north toward the Copley greenstone. Further evidence of a fault is inferred from the fact that the Kennett formation is missing for more than 1 mile between sec. 21 and 29, T. 34 N., R. 4 W., and the Bragdon formation, which is missing locally in sec. 21, leaving Copley greenstone in contact with the Baird formation. The distribution of stratigraphic units on either side of the Packers Gulch fault shows that the northwest side moved either upward or northeastward relative to the southeast side. However, the direction of movement on the fault is indeterminate because the direction of dip, although steep, is unknown.

SHEAR ZONES

In the Bully Hill-Baxters Gulch area, and also in the area of the Afterthought mine, are zones of highly crushed and sheared rock as much as 200 feet thick. One shear zone was traced for about 1 mile and another for 3,000 feet along strike, but few extend for more than 1,000 feet. In the Afterthought mine area all the shear zones strike northwest and dip southwest about parallel to schistosity. These shear zones are: (a) the Afterthought; (b) those exposed mainly in the lower levels of the Afterthought mine (pl. 5); and (c) several exposed mainly northwest of the Afterthought mine (pl. 2). In the Bully Hill-Baxters Gulch area the Bully Hill shear zone and one in secs. 20 and 29, T. 34 N., R. 3 W., strike northeast, whereas others, including the Rising Star and the Middle shear zones, strike northwest. Although the crushing and stringing out of fragmented quartz phenocrysts (pl. 21*A*) shows that movement has taken place within the shear zones, the displacement of rock units seems to be small. At no place is a measureable offset of map units apparent, and the direction of movement on most of the shear zones is indeterminate.

The shear zones seem to be older that most of the high-angle faults and may have formed contemporaneously with folding. This is suggested by the fact that the shear zones are largely in siliceous, brittle rocks of the Bully Hill rhyolite. These siliceous rocks probably tended to rupture and shear out during stress rather than yield plastically as did the overlying shaly rocks of the Pit formation.

The shear zones are of economic importance because many of the known sulfide lenses in the district are localized along them.

SUMMARY OF DEFORMATION

The sedimentary and volcanic rocks in the East Shasta area were deformed and intruded by plutonic and hypabyssal rocks probably during Late Jurassic time. Although there was doubtless a good deal of overlap, the general sequence of events during the orogeny seems to have been about as follows:

1. Compression in an east-west or northwest-southeast direction resulted in the tilting of most of the rocks toward the east and formation of the O'Brien Mountain anticline and a few small northeastward trending folds.
2. The Pit River stock was probably emplaced at this stage although the evidence is not conclusive and its emplacement may have followed stage (3) of the orogeny. However, in the West Shasta district the Mule Mountain stock, which is probably the same age as the Pit River stock is much faulted and sheared, and a subsidiary stock of the same lithology in the aureole of the Shasta Bally batholith is strongly foliated. This foliation probably formed at the same time as the folds in stage (3) described below.
3. A right-lateral shear couple acting generally in a north-south direction resulted in the superposition of a series of northwestward-trending folds on the northeast fold system. These folds are

[13] Wheeler, H. E., 1934 The fauna and correlation of the McCloud limestone of northern California: Unpublished thesis, Stanford Univ., p. 1–166.

most prominent in the southeastern part of the area, and west of Bully Hill and Cove Creek they are represented only as poorly defined warps. With continuing stress, and possibly as a result of the resistance of massive limestone and greenstone to folding, a rupture, the McCloud fault, was ultimately formed along the east side of the McCloud limestone. The movement on this fault was left-lateral, and the block of Dekkas andesite and Nosoni formation east of the fault moved northward relative to the McCloud limestone. The limestone was rotated into its present position of northwest strike and northeast dip and torn apart into discrete blocks as a result of this left-lateral movement. The Baird formation and other units west of the McCloud limestone likewise were under tension at this time as shown by the multitude of dikes, most of which strike northwest, in the O'Brien Mountain area.

It seems likely that the Packers Gulch fault, the fault between the Dekkas and Pit formations on the boundary between secs. 35 and 36, T. 34 N., R. 4 W., the Bully Hill Contact fault, and the southwestward continuation of the Bully Hill Contact fault in the Baxters Gulch area, were formed in conjunction with the McCloud fault. All are probably reverse faults with the northwest side displaced upward and with possibly some left-lateral movement.

4. Probably nearly contemporaneous with the formation of the faults in stage (3) came the injection of mafic quartz diorite and related dikes along the faults, and, in places, along bedding. It is noteworthy that, with a few minor exceptions, these dikes are virtually restricted to the area west of the McCloud fault.
5. Hydrothermal activity, which resulted in widespread albitization, silicification, chloritization, and other types of alteration may have begun, culminating in sulfide mineralization, during stage (3) but continued after the intrusive rocks were emplaced, as indicated by the highly altered instrusive rocks. Normal faulting slightly preceded or accompanied mineralization.
6. The youngest structures in the area are minor high-angle faults that cut dike rocks and in a few places cut sulfide bodies. Whether these formed during the final stage of the orogeny or at some later date could not be ascertained.

POSTOROGENIC HISTORY

Postorogenic deposits in the area include the Tuscan formation of Pliocene age, basalt flows of Pliocene or Pleistocene age, and other unconsolidated deposits of Pleistocene and Recent age. No rocks of Cretaceous or early Tertiary age are exposed within the area, but marine sedimentary rocks of Late Cretaceous age crop out about a mile south of the boundary, and fluviatile conglomerate of Eocene age crops out just east of the area.

TUSCAN FORMATION

GENERAL CHARACTER AND DISTRIBUTION

The Tuscan formation was first described and named by Diller (1895, p. 1), and later renamed the Tuscan tuff by Turner (1896, p. 540–542). Diller (1906, p. 6) followed Turner's revised nomenclature in his description of the Redding quadrangle. Anderson (1933, p. 215–276), applied the name Tuscan formation because very little of the unit is tuff and the name Tuscan tuff is therefore misleading; the writers have followed Anderson's terminology.

In the East Shasta area, the Tuscan formation, consists entirely of soft, friable tuff breccia. It occurs chiefly southeast of the Pit River arm of Shasta Lake and underlies many of the low, rounded hills in the southeastern part of the area. Two outliers north of the Pit River arm in sec. 36, T. 34 N., R. 3 W., and in sec. 30, T. 34 N., R. 2 W., are the northernmost known occurrences of the Tuscan formation.

The undeformed Tuscan formation lies with marked unconformity on deformed basement rocks, including the Dekkas andesite, the Bully Hill rhyolite, and the Pit formation. The Tuscan lies on a surface of low relief.

The thickness of the Tuscan formation ranges from a few feet to a maximum of about 360 feet on a hill between secs. 34 and 35, T. 34 N., R. 2 W.

TOPOGRAPHIC EXPRESSION

The topographic surface on the Tuscan formation is characterized by broad, shallow valleys and rounded ridges that stand out in marked contrast to the commonly sharp ridges and V-shaped valleys carved in the basement rocks. The subdued topography apparently results from the permeable character of the tuff breccia that has a resulting high rate of infiltration. Surface runoff is thus at a minimum, and the formation of gullies in the tuff breccia is much slower than in the older rocks. Abundant small springs that issue from the base of the Tuscan during the spring and early summer further attest to the permeability of the Tuscan formation.

LITHOLOGY AND PETROGRAPHY

The Tuscan formation in the East Shasta copper-zinc district is composed of massive unbedded tuff breccia. It consists of blocks of several kinds of volcanic rocks erratically distributed in a light-gray to brownish-gray, friable, tuffaceous matrix. The blocks make up 10 to 50 percent of the tuff breccia. They are angular and range from a fraction of an inch to about 6 feet in diameter. Blocks or fragments ranging from 1 to 6 inches in diameter are most common. The blocks are composed of dacite porphyry, dark-brown and black obsidian, andesite, and several textural varieties of basalt. Thin sections show that the light-gray matrix of the tuff breccia in thin section consists of lithic fragments of andesite, basalt, and banded glass, and angular clasts of quartz, plagioclase, augite, hypersthene, and magnetite in a fine-grained mesostasis of crystal clasts and glass particles. Erosion tends to scour away the soft matrix leaving the blocks of the tuff breccia concentrated as residuals on the surface.

AGE

No fossils have been found in the Tuscan formation. However, Anderson (1933, p. 236), has shown that the Tuscan is the same age as the Tehama formation, which crops out on the west side of the Sacramento River valley south of Redding and contains vertebrate fossils of late Pliocene age.

PRE-TUSCAN TOPOGRAPHY

The surface on which the tuff breccia of the Tuscan formation was deposited was different south of Backbone Ridge than north of the ridge. South of Backbone Ridge the pre-Tuscan landscape was apparently a plain of low relief sloping gently westward, or southwestward, whereas north of the ridge the landscape was much more rugged.

The low relief south of Backbone Ridge is suggested by: (a) the present uplands on either side of Little Cow Creek are broad surfaces of low relief, including many of the highest ridges capped by the Tuscan formation; (b) the base of the Tuscan formation slopes gently southwestward, with the altitude of discrete outliers coinciding closely with a hypothetical sloping base throughout the area; and (c) the thickness of complete sections of the Tuscan formation beneath a basalt capping is fairly uniform south of Backbone Ridge.

The distribution of tuff breccia north of Backbone Ridge suggests that in places it was guided along valleys that nearly coincide with the present Sugarpine Canyon and Pit River (pl. 1). In sec. 22, T. 34 N., R. 2 W., near the head of present Sugarpine Canyon, the base of the tuff breccia is at an altitude of 2,275 feet, whereas 1½ mile farther south, in sec. 34, T. 34 N., R. 2 W., it is at an altitude of 1,600 feet. From this locality in sec. 34 the ancestral Sugarpine Canyon apparently turned westward, as shown by the series of tuff breccia outliers extending from sec. 34 along the north side of the canyon. Near the Pit River, in sec. 32, T. 34 N., R. 2 W., the base of the Tuscan formation is at an altitude of 1,200 feet (pl. 1). Within 3 to 4 miles, therefore, the altitude of the base of the formation decreases about 1,075 feet, and throughout the entire distance the tuff breccia outliers are flanked by higher ground underlain by basement rocks. This evidence suggests a valley in pre-Tuscan time in about the same location as the present Sugarpine Canyon.

Outliers of tuff breccia along the Pit River in the SW¼ sec. 36, T. 34 N., R. 3 W., and in the NE¼ sec. 32, T. 34 N., R. 2 W., shows that: (a) the Pit River, at least between secs. 36 and 32, was in about the same position when the Tuscan formation was deposited as it is today; and (b) that, inasmuch as the altitude of the present canyon floor beneath the lake is about 825 feet and the base of the tuff breccia in outliers along the canyon is 1,200 feet, the amount of downcutting of its canyon since deposition of the Tuscan is not less than 375 feet. If downcutting of the canyons is used as a measure, the amount of uplift since Tuscan time is at least 375 feet.

BASALT FLOWS

GENERAL CHARACTER AND DISTRIBUTION

Basalt crops out in the southeastern part of the area as small discontinuous bodies. The basalt in most places overlies the Tuscan formation but in a few places it lies on the basement rocks. Individual bodies of basalt range in size from a few hundred square feet to about a quarter of a square mile.

The basalt is differentiated into three general types on the map (pl. 1). One type exposed mainly north and east of Sugarloaf, is dark gray, fine-grained, and locally vesicular. Another type, which forms smaller bodies, is exposed north and south of Sugarloaf. It is medium gray and commonly porphyritic, and contains phenocrysts of plagioclase and pyroxene. A third type, which has a diabasic texture, is exposed in two small areas near the extreme east edge as shown on the map.

The basalt bodies seem to overlie the Tuscan formation with erosional unconformity. This relation is suggested in several places, for example in the northeastern part of sec. 35, T. 34 N., R. 2 W., where the contact between the dark-gray fine-grained basalt and the tuff breccia of the Tuscan is steeply inclined or vertical. Apparently the basalt filled steep-walled gullies in the tuff breccia.

The maximum thickness of the dark-gray fine-grained basalt is about 200 feet in the eastern part of sec. 35, T. 34 N., R. 2 W., and the greatest thickness of medium-gray, porphyritic basalt is about 125 feet near the head of Sugarpine Canyon.

PETROGRAPHY AND AGE

DARK-GRAY FINE-GRAINED BASALT

Thin sections show that the dark-gray fine-grained basalt is composed of plagioclase, augite, and glass in about equal proportions, and about 5 percent magnetite disseminated as very fine grains. The texture is microporphyritic, with a hyalopilitic groundmass. Plagioclase (An_{60-64}) occurs as sparse, strongly corroded microphenocrysts, and as microlites in the groundmass. Augite also occurs as partly corroded microphenocrysts, but the bulk of the augite is in the form of tiny grains in the groundmass. The pale-green glassy groundmass has an index of refraction slightly less than canada balsam.

Some vesicular facies of the dark-gray fine-grained basalt differ from the nonvesicular facies described above in that olivine occurs in amounts as great as 10 percent, and iddingsite and saponite occur as alteration products.

HYPERSTHENE-AUGITE BASALT

The hypersthene-augite basalt is medium gray, with a porphyritic, and locally a diktytaxitic, texture. Thin sections show that it consists of about 60 percent plagioclase (An_{61}), with hyperthene and augite in about equal proportions as varietal minerals, and oxyhornblende, apatite, and magnetite as accessory minerals. The groundmass texture is microgranular. Plagioclase forms microphenocrysts as much as 1 mm long and microlites in the groundmass. The microphenocrysts show marked oscillatory zoning with cores only slightly more calcic than the rims. Hypersthene and augite each make up about 10 to 15 percent of the rock. Both minerals occur as crystals 0.1 to 0.3 mm across. Augite also forms phenocrysts as much as 2 mm long. Magnetite and apatite each make up about 5 percent of the rock, and a few microphenocrysts of oxyhornblende with wide, nearly opaque borders are also present.

DIABASE

Small bodies of equigranular diabase are exposed in sec. 26, T. 34 N., R. 2 W., at the northwest end of a mass of dark-gray fine-grained basalt and in secs. 34 and 35, T. 34 N., R. 2 W., within a body of dark-gray fine-grained basalt. The diabase occurs mainly as a jumble of blocks mantling the surface and hence its relation to the basalt could not be determined. It weathers to a dark-brown soil.

A thin section shows that the diabase contains about 60 percent plagioclase (An_{72}) as laths, 25 percent augite enclosing plagioclase ophitically, and about 5 percent olivine, 5 percent magnetite, 3 percent apatite, and minor saponite as an alteration of olivine.

The diabase, which is younger than the Tuscan formation, may mark a fissure from which basalt was extruded, or it may be the more coarsely crystalline interior of a thick basalt flow.

The basaltic flows overlying the Tuscan formation are probably of late Pliocene or early Pleistocene age.

UNCONSOLIDATED DEPOSITS

Unconsolidated deposits of Quaternary age include colluvium, talus, landslide debris, alluvium, alluvial fan deposits, and terrace deposits.

Colluvium or slope wash forms a veneer on many hill slopes, but it was mapped only where it effectively obscures the bedrock. The main occurrences are east of the McCloud River arm, and on Town Mountain. Talus is not differentiated from colluvium. It occurs mainly beneath cliffs of McCloud limestone and is in part cemented by calcite.

Landslide deposits occur on the upper slopes of Town Mountain, on the west side of Horse Mountain, and on the southeast side of the canyon of Little Cow Creek just north of the Afterthought mine. These deposits are distinguished from colluvium by their hummocky topography and commonly by a scar on the uphill side. Most of the landslides on Town and Horse Mountains grade into colluvium on the downhill side.

Alluvial fan and terrace deposits occur mainly at low altitudes along Squaw Creek arm of Shasta Lake. The largest alluvial fan underlies the low ridge east of Bully Hill. It consists of subrounded rock fragments derived from the bedrock of Town Mountain in a silty matrix. The base of this deposit slopes south at an angle of about 6°; and the maximum thickness is about 20 feet. The upper end of the alluvial fan grades into colluvium and landslide debris. Terrace deposits occur mainly at altitudes of 1,000 and 1,250 feet. The base of the deposits is nearly horizontal. Rock fragments are of local origin, and the matrix shows about the same degree of lithification as the alluvial fan deposits.

An unusual type of deposit consisting of angular rock fragments in a matrix of limonite is exposed at altitudes of 1,650 to 1,700 feet in the upper part of First Creek. This material is in bodies too small to map but is traceable as discontinuous bodies for several thousand feet along the contour. It apparently marks a high-level terrace.

PHYSIOGRAPHY

The East Shasta area lies within two geomorphic provinces. That part of the area north of the Pit River arm of Shasta Lake is in the Klamath Mountain province (Diller, 1906, p. 1; Jenkins, 1938), whereas that part south of the Pit River arm is in the Cascade Range province (Jenkins, 1938). Diller (1906, p. 1) included the area south of the Pit River in a province called the Piedmont plain but this is no longer recognized.

The topography of the area is dominated by the canyons cut by five large streams, all of which flow southwestward. From west to east these streams are Sacramento and McCloud Rivers, Squaw Creek, Pit River, and Little Cow Creek. The first four streams join each other within the boundaries of the area (fig. 1 and pl. 1) and their canyons are partly flooded by Shasta Lake. Squaw Creek, Pit River, and Little Cow Creek are transverse to the structure of the basement rocks, whereas Sacramento and McCloud Rivers are almost parallel to the structure. In general, the topography north of the Pit River arm of Shasta Lake is in late youth, whereas south of the Pit River arm the topography is in early youth.

The divide formed by Backbone Ridge between Pit River and Little Cow Creek and the divide southeast of Little Cow Creek are remnants of a surface of low relief that slopes southwestward at about 140 feet per mile within the area. Sugarloaf, standing about 250 feet above the general level of Backbone Ridge (pl. 1), was probably a monadnock on this surface. The surface is incised by Little Cow Creek and its tributaries to depths of 600 to 800 feet. The tributaries of Little Cow Creek are closely spaced within ½ to 1 mile of the main stream, and are separated by fairly sharp ridges underlain by hard basement rocks. But farther from the main stream the divides between tributaries are broad and are commonly capped by 50 to 100 feet of soft tuff breccia of the Tuscan formation. In general, the tributaries where deeply incised into the older rocks adjacent to Little Cow Creek and Pit River have a crudely trellised pattern, whereas higher toward the main divides where the streams are not yet deeply incised the pattern is dendritic. The trellised pattern probably forms in response to the northwestward-trending secondary foliation in the older rocks.

The divide between Pit River and Squaw Creek is slightly higher than the Backbone Ridge divide. It is dominated by Brock Mountain (altitude 2,724 feet), and by Green Mountain (altitude 2,247 feet). Squaw Creek and Pit River are transverse to the structure of the basement rocks. The tributary canyons to Squaw Creek and Pit River are V-shaped, and the intervening ridges are sharp. The drainage has a crudely trellised pattern trending northwestward and reflecting a weak structural control by the northwestward-trending beds of the underlying Pit formation (pl. 1).

The divide between Squaw Creek and McCloud River is dominated by Town Mountain (altitude 4,325 feet) and Horse Mountain (altitude 4,025 feet), the highest peaks in the area. Another conspicuous physiographic feature in this sector of the area is the belt of McCloud limestone along the east side of McCloud River. In some places between Marble and Curl Creeks the limestone forms cliffs almost 2,000 feet high, which stand out in marked contrast to the less resistant formations adjacent to the limestone. West of Second Creek drainage basin on the Horse Mountain–Town Mountain divide, where the bedrocks are chiefly massive volcanic rocks, the drainage pattern is dendritic. But Second Creek and its tributaries and the small streams east of Second Creek have a trellised-pattern, reflecting control by the bedded shale and tuff of the underlying Pit formation.

The upper slopes of Town and Horse Mountains are scarred by landslides (pl. 1). These landslides are recognized by their steplike tops and by the jumble of boulders and loose rock debris that compose them. The absence of cracks in the landslides and the presence of evergreen trees as much as 3 feet in diameter indicate that the landslides have not moved much in recent times. Small permanent springs issue from near the toes of some landslides, reflecting their greater permeability and capacity for absorbing water as compared to the underlying bedrock.

North of Backbone Ridge traces of probable old valley levels are visible along the canyons of the four principal streams. These old valley levels are marked by small peaks and flat-topped spurs with common altitudes. Some levels, however, are marked in part by deposits of gravel, of the Tuscan formation, or of spongy transported limonite. The most conspicuous levels are at an altitude of about 1,025, 1,250 and 1,750 feet.

The 1,025-foot level appears most prominently along Squaw Creek where it is marked by benchlike deposits of gravelly material consisting of boulders and cobbles in a silty matrix. The 1,250-foot level is marked by flattopped spurs and small peaks along Pit River and Squaw Creek. Along Pit River it is also marked by outliers of Tuscan formation in the SW¼ sec. 36, T. 34 N., R. 3 W., and the NE¼, sec. 32, T. 34 N., R. 2 W. These two outliers of the Tuscan formation are especially significant in that they show that the amount of downcutting by the Pit River since Tuscan time is about 375 feet, inasmuch as the present canyon bottom is 825 feet. The level at 1,750 feet is marked on the divide between First and Second Creeks by a deposit of spongy transported limonite as much as 20 feet thick in some places. It crops out intermittently, forming a skim on the hillsides, and was traced for about 1½ miles.

The old levels apparently mark temporary base levels during which streams widen their valleys by lateral cutting. No levels of this type were observed along Little Cow Creek, suggesting that this stream came into being after the Tuscan formation had been deposited. Little Cow Creek has incised its canyon about 600 to 800 feet into the pre-Tuscan rocks while the Pit River has been cutting its canyon 375 feet into the pre-Tuscan rocks.

WEATHERING

The rocks of the district are weathered to depths ranging from a fraction of an inch to as much as 50 feet. Rarely, weathering has penetrated to depths as great as 100 feet along strong fractures. The most deeply weathered rocks are the feldspathic volcanic and intrusive rocks. The limestone, shale, and siliceous volcanic rocks contain mineral assemblages that are relatively stable under conditions of weathering and are therefore the least altered.

Weathering of the feldspathic rocks causes the feldspars to alter to clay minerals, chiefly kaolinite, and the ferromagnesian minerals to oxidize. This weathering process yields a rotten rock or saprolite that commonly has a red or buff coloration owing to the presence of iron oxide. The mafic and intermediate volcanic rocks weather to red or reddish brown, whereas the siliceous rocks commonly weather buff.

The agents of weathering generally penetrate downward from the surface along small faults and fractures. In areas where weathering is a few feet or more deep the rock adjacent to the fractures is altered first and, with time, weathering penetrates more and more deeply into the rock masses between fractures until the rocks are completely altered to saprolite. At the surface this saprolite gradually breaks down to colluvium and soil and is eroded away.

ORE DEPOSITS

GENERAL FEATURES

The East Shasta copper-zinc district has produced, in the approximate order of dollar value, copper, zinc, silver, gold, iron, and lead. The total value of these metals, excluding iron, is about $16 million, of which copper has accounted for slightly more than half. The value of iron produced is not known. The Bully Hill-Rising Star-Copper City area and the Afterthought-Donkey area (pl. 3) have produced all the base metals and most of the precious metals. The Shasta Iron mine in sec. 26, T. 34 N., R. 4 W. has produced iron ore.

Three types of ore deposits are in the district: (a) massive sulfide deposits, (b) contact metasomatic magnetite deposits, and (c) quartz veins. The massive sulfide deposits have produced virtually all the base metals. The remainder of this report is devoted chiefly to the description of these deposits. The other two types of deposits have produced much less and are discussed only briefly in the report.

During this investigation the only base-metal mines accessible were parts of the Afterthought mine and parts of the Bully Hill mine. Probably only 10 percent of the individual stopes and ore bodies in the district were seen. Hence we have necessarily had to rely on maps, records, and reports kindly made available by the Glidden Co. and by the Coronado Copper and Zinc Co. The history of the district and certain descriptive data, are taken largely from published sources. These sources of information, both published and unpublished, are in many ways incomplete and even contradictory. We have tried to be objective in assimilating this material with that derived from our own observations in order to give as complete a description of the sulfide deposits as possible. However, most of the detailed description and practically all of the interpretation is based on the few ore bodies that were accessible during the present study. For this reason, some features of the deposits may be overemphasized, and other features deserving of more attention may be underemphasized or even overlooked.

The sulfide deposits consist of isolated lenses or groups of lenses that replace chiefly the Bully Hill rhyolite and to a lesser extent the Pit formation. Most of the lenses are along shear zones in the Bully Hill rhyolite or along fault contacts between the Bully Hill and Pit formations. The lenses are mostly tabular and are steeply inclined from the horizontal, although a few are cigar shaped. They range from a few inches to as much as 400 feet in greatest dimension. In the Bully Hill mine about 15 discrete lenses, separated by only a few feet of country rock, are localized along a steeply dipping shear zone, and thus form a deposit that in gross aspect has the shape of a tabular lode (pls. 10 and 13). However, in the Afterthought and Rising Star mines discrete sulfide lenses occur along several faults and shear zones; some lenses in these mines are isolated from others by as much as several hundred feet of barren country rock.

The sulfide lenses are structurally controlled by steeply dipping shear zones and faults within the Bully Hill rhyolite and between the Bully Hill and Pit formations, and by a stratigraphic cover of shale of the Pit formation that acted as a barrier to the mineralizing fluids. The shear zones and faults served as feeder channels and the crushed siliceous rock within the shear zones, beneath the shale cover, was a favorable locale for the deposition of sulfide minerals. Locally the sulfide minerals replace shale.

The ore consists typically of a fine-grained mixture of pyrite, sphalerite, chalcopyrite, galena, and tetrahedrite-tennanite, as well as quartz, barite, and calcite. The proportions of these minerals vary greatly from place to place. The individual sulfide and gangue minerals commonly are segregated into discrete layers, so that much of the ore has a banded structure.

The overall assay of most of the ore mined is about 15 to 20 percent zinc, 3 percent copper, 0 to 2 percent lead, 5 ounces of silver, and 0.03 ounce gold. Iron commonly ranges from 10 to 25 percent and insoluble material from 25 to 40 percent. The ratio of copper to zinc varies greatly from one ore body to another and even within an individual ore body. As a result, some sulfide lenses have been mined principally for copper and others for zinc.

The last base metals produced from the district were from the Afterthought mine in 1952. From 1952 to 1956 two lenses of sulfide ore were discovered in the Bully Hill mine by the Glidden Co. under a contract with the Defense Minerals Exploration Administration. It seems likely that an intensive prospecting program in the district would reveal additional sulfide lenses. Geologically favorable areas most likely to contain such lenses are shown on plate 3.

HISTORY OF MINING

Mining in the East Shasta copper-zinc district first began in 1853, when placer gold was discovered in Town Creek east of Bully Hill. A gold rush ensued as a result of this discovery and many placer claims were located, most of which, according to Aubury (1902, p. 33) were of little value. The placer gold was derived in large part from the lode deposits on Bully Hill, and silver and copper were found with gold in the placers.

In 1862, about 10 years after the initial placer discovery, gold was found in the surface rock on the Excelsior claim near what was to become the mining town of Copper City, by two men named Jack Killinger and J. P. Williams. As a result of this discovery, Aubury (1902, p. 33) reports that: "* * * another rush into this district was begun for the location of the supposed rich veins of gold and silver. The hills were covered by locations for many miles." This activity resulted in the further discovery, in 1862, of the Bully Hill and Copper Hill (Afterthought) deposits. The Bully Hill–Copper City area was in what had been named the Pittsburg mining district during the 1850's and the Copper Hill (Afterthought) deposit was in what was known as the Cow Creek mining district.

The history of the district has been one of intermittent activity. Prior to 1900, repeated attempts were made to treat the base-metal ores but little success was attained. The main periods of activity were from 1900 to 1910, and from 1921 to 1927. A summary of activity in the district and a more detailed history are given in the description of individual mines.

Mining history is chronologically separable into about seven distinct phases as follows:

1853–61. Interest was entirely in placer mining, which was on a small scale and not very successful.

1862–99. Oxidized ores overlying the sulfide deposits were mined, mainly for their precious-metal content and to a lesser extent for copper. Probably some sulfide ore was mined from the Afterthought and Donkey deposits. A few ore shipments were made to Swansea, Wales and many attempts were made to treat the ore locally. These attempts were all economically unsuccessful although some metal was produced.

1900–10. The boom years. Copper ore was mined in quantity and smelted locally. The product was blister copper that was shipped elsewhere for refining. Gold and silver were produced in quantity as a by-product.

1911–20. Copper mining was largely dormant owing to smelter-smoke litigation and to depletion of copper-rich ore in Bully Hill mine. Much experimenting was done to devise ways to treat smelter fumes so as to make them harmless. Other experiments were conducted in an effort to find a method to recover zinc from the ore. Copper-rich sulfide ore, overlooked during the 1901–10 operations, was mined from Rising Star mine in 1917–18. Iron ore was produced on small scale from Shasta Iron mine.

1921–27. Zinc-rich sulfide ore was mined and treated mainly at Bully Hill smelter. The chief product was zinc oxide, which was in great demand. Operations ceased in August 1927. Iron ore was produced at a small but steady rate from the Shasta Iron mine.

1928–41. Virtually no mines were operating in the district owing to the low price of metals. A few small quartz veins were probably worked for gold but production was negligible.

1942–55. Magnetite was produced from the Shasta Iron mine from 1942 to 1944 as ballast for use in the U.S. Navy. The Afterthought mine was reopened and operated for 3 years from 1949 to 1952, and in 1953 the Bully Hill mine reopened and new ore bodies were discovered but no ore was produced. Diamond drilling was done at both the Afterthought and the Bully Hill mines.

PRODUCTION

Data on production of base and precious metals from the East Shasta district are sketchy and incomplete for the period before 1900 but are fairly complete since 1900. The Bully Hill, the Rising Star, and the Afterthought mines produced virtually all the ore. Production is summarized in table 4.

TABLE 4.—*Summary of sulfide ore produced from the East Shasta copper-zinc district, 1900–52*

Mine	Tons mined	Copper (pounds)	Zinc (pounds)	Lead (pounds)	Silver (ounces)	Gold (ounces)
Afterthought [1]	166, 424	10, 730, 580	23, 635, 840	1, 738, 300	923, 653	4, 992
Bully Hill-Rising Star [2]	579, 857	48, 788, 451	25, 113, 105	----------	2, 215, 270	38, 224
Copper City [2]	119	4, 600	23, 560	----------	----------	1
Donkey [3]	300	----------	----------	----------	----------	----------
Total	746, 700	59, 523, 631	48, 772, 505	1, 738, 300	3, 138, 923	44, 217

[1] Data furnished by the Coronado Copper and Zinc Co. Published with permission.
[2] Data furnished by the Glidden Co. Published with permission.
[3] Production prior to 1900; no data on grade of ore available.

The record shows that copper has been the most important metal produced, having accounted for about half the total value of base and precious metals. It should be borne in mind, however, that during the main period of mining, from 1900 to 1910, zinc was not recovered from the sulfide ores.

An accurate record of iron produced from the Shasta Iron mine is not available. According to Lamey (1948, p. 140) ore was mined for the Noble Electric Steel Co. between 1907 and 1926. How much of this period the mine was actually in operation is not known. Brown (1916, p. 805) reports that in 1913 the Shasta Iron mine produced 25 tons daily. In 1921 according to Tucker (1922, p. 732) the mine produced 12 to 15 cars per month averaging 65 percent iron. In 1925 the mine produced at the rate of 15 to 20 cars per month (Tucker, 1926, p. 192). February 1, 1942 through 1944 ore was mined for U.S. Navy ballast at the rate of 100,000 tons per year (Lamey, 1948, p. 140).

Production of gold from quartz veins has been very small but no quantitative data are available.

MASSIVE SULFIDE DEPOSITS

GENERAL FEATURES

The massive sulfide ore bodies occur as lenses that replace the Bully Hill rhyolite, the Pit formation, and metadiabase dikes that locally intrude the Bully Hill rhyolite. The three principal areas where sulfide lenses have been mined are: (a) the Bully Hill-Rising Star area; (b) the Copper City area, about a mile southwest of Bully Hill; and (c) the Afterthought-Donkey area in the extreme southeastern part of the district. These principal deposits, as well as other deposits of sulfide minerals and limonite, are shown on plate 3.

Most of the sulfide lenses are tabular and are steeply inclined. A few are cigar shaped. The lenses range from a few inches to as much as 400 feet in greatest dimension. Most tabular lenses are not markedly elongate but are nearly circular in a section drawn parallel to the greatest dimension of the lens. Few lenses have a well-defined rake. The largest lenses reach a maximum thickness of 35 to 40 feet.

In the Bully Hill mine the sulfide lenses are closely grouped along a steeply dipping shear zone. The lenses, as a group, rake steeply north, as shown in plate 13. In the Rising Star mine they are closely grouped (pls. 10 and 12) along or near a series of faults and shear zones. In the Afterthought mine the lenses are more widely dispersed along a series of faults and shear zones and are separated from each other by several tens of feet to as much as several hundred feet of barren rock (pl. 7). In the Donkey mine an isolated lens contains a few hundred tons of high-grade sulfide ore (pl. 16), and in the Copper City mine (pl. 14) several small lenses are grouped along a shear zone. Generally, owing to their small size, isolated lenses cannot be mined profitably, and the only successful mines are those in which several lenses are grouped closely together.

Virtually all the sulfide lenses parallel either schistosity or bedding in the enclosing host rock. The walls of most lenses are either frozen to the country rock or are separated from it by a layer of clayey gouge ranging from a thin film to a few inches thick. In most places the country rock adjoining a sulfide lens is barren, but a few lenses are enveloped by rock containing abundant disseminated sulfide minerals commonly arranged in stringers parallel to schistosity. The walls of most sulfide lenses are sharp and smooth but the edges, in contrast, are commonly irregular. Some lenses taper to a single knife edge. Others pinch out in many thin layers or sheets extending a few inches to a few feet into the host rock along bedding or schistosity planes. The edges of these individual sulfide layers may in turn pinch out to a knife edge or come to a blunt end. In section this gives either a saw tooth or an interfingering form, respectively (fig. 9 and pl. 21*B*).

Much of the sulfide ore is banded. The banding results from the crude segregation of component minerals into more or less discrete layers a fraction of a millimeter to a few millimeters thick. In places, near the edges of lenses, banding in the sulfide parallels bedding or schistosity in the enclosing host rock (figs. 9 and 11). The perfect parallelism of this banding with schistosity or bedding indicates that the banding was inherited from the host rock and that the sulfide is of replacement origin.

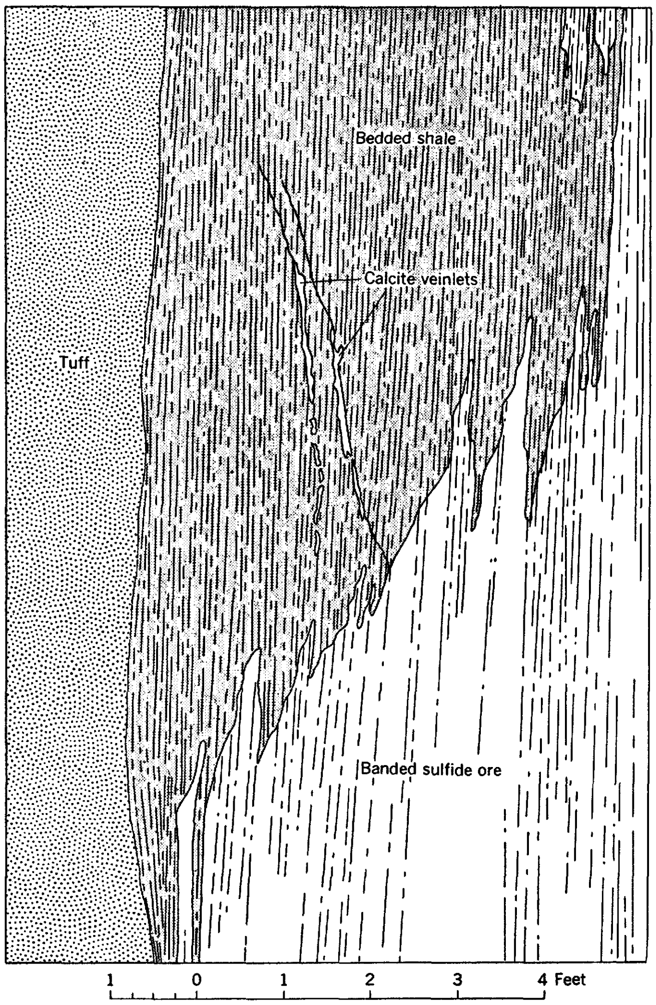


Figure 9.—Sketch showing saw-tooth relation between banded sulfide and shale at the northwest end of the 412 stope, Afterthought mine. Note the parallelism of sulfide banding to bedding in the host rock.

MINERALOGY AND GRADE OF ORE

Minerals associated with the massive sulfide deposits are listed in table 5. The main hypogene ore minerals are pyrite, sphalerite, chalcopyrite, galena, and tetrahedrite-tennantite. Other minerals of minor importance include bornite and luzonite. Quartz, barite, calcite, anhydrite, and gypsum are the principal gangue minerals; anhydrite and gypsum are found only in the Rising Star and Bully Hill mines. Typical sulfide ore is an exceedingly fine-grained mixture of the above minerals (pl. 22*A*). Some of the hypogene deposits, particularly those at Bully Hill, were capped by a rich layer of supergene minerals including chalcocite, covellite, cuprite, native copper, gold, and silver, azurite, and malachite. However, these deposits were mined out in the early 1900's and the workings are now inaccessible so that little information on supergene minerals was obtained during the present study.

Table 5.—*Minerals of the massive sulfide deposits, East Shasta copper-zinc district*

Mineral and composition	*Geologic occurrence*
Albite, $NaAlSi_3O_8$	Widespread hydrothermal replacement of more calcic feldspars.
Alunite, $KAl_3(SO_4)_2(OH)_6$	Minor gangue mineral in Bully Hill-Rising Star mines area. Identified in 2 thin sections.
Anhydrite, $CaSO_4$	Abundant as a replacement of the Bully Hill rhyolite in lower levels of the Bully Hill and Rising Star mines.
Azurite, $Ca_3(CO_3)_2(OH)_2$	Occurs in pits and shallow adits in the Afterthought mine area, and in oxidized zone just beneath the gossan at Bully Hill.
Barite, $BaSO_4$	One of the most abundant gangue minerals in the sulfide ores. Commonly forms the matrix in which sulfide minerals are embedded. Barite also present as replacement of country rock remote from known sulfide minerals.
Bornite, Cu_5FeS_4	A minor constituent of the massive sulfide ores. Sparsely present in most sulfide lenses.
Calcite, $CaCO_3$	A gangue mineral in the sulfide ore. Also abundant as a replacement of country rock along margins of some sulfide lenses in the Afterthought mine area. Also forms irregular masses in magnetite bodies.
Chalcocite, Cu_2S	Product of supergene enrichment. Occurs in all the mines but is not abundant. Was an important ore mineral in the upper part of the Bully Hill mine.
Chalcopyrite, $CuFeS_2$	The most important copper mineral. Common in all mines. It is generally mixed with pyrite, sphalerite, and other sulfide minerals but locally forms masses virtually free of other minerals.
Chlorite, complex hydrous silicate of Fe, Mg, and Al.	Common as an alteration product throughout the district. Variety clinochlore is locally present along shear zones in which sulfide lenses are localized.
Copper, Cu	Reportedly occurred in minor amounts along walls and joint planes in oxidized parts of ore bodies in Bully Hill mine. Also as disseminations in volcanic breccia in a prospect on Horse Mountain.
Covellite, CuS	A minor supergene mineral seen in some specimens from the Afterthought mine. Replaces chalcopyrite.
Cuprite, Cu_2O	Reportedly occurred in small amounts in the oxidized zone at Bully Hill.
Galena, PbS	Irregularly distributed in virtually all the sulfide deposits but more abundant in the Afterthought area. Commonly mixed with sphalerite and tetrahedrite-tennantite.
Gold, Au	Occurred in oxidized parts of sulfide bodies and in placers below outcroppings of oxidized ore. All the sulfide ore contains gold in recoverable quantities.
Gypsum, $CaSO_4{\cdot}2H_2O$	Abundant as a replacement of anhydrite in the Rising Star and Bully Hill mines.

TABLE 5.—*Minerals of the massive sulfide deposits, East Shasta copper-zinc district*—Continued

Mineral and composition	*Geologic occurrence*
Hematite, Fe_2O_3	Forms small lenses in sheared rocks near Baxter's Gulch northwest of Copper City mine area. Was not seen associated with sulfide deposits but seems to occur in similar structural environment.
Hydrous mica, $K_{<1}Al_2(AlSi_2O_3)O_{10}(OH)_{>2}$.	Commonly occurs as an alteration product in siliceous volcanic rocks throughout the district. Abundant in shear zones along which sulfide lenses occur but rarely as a gangue mineral in the sulfide deposits.
Kaolinite, $Al_2Si_2O_5(OH)_4$	Occurs in small amounts along shear zones in areas of the Bully Hill and Afterthought mines. Also is weathering product after feldspar throughout the district.
Limonite, $Fe_2O_3 \cdot nH_2O$	Occurs as gossan capping over massive sulfide, as pseudomorphs after pyrite, and as skims or isolated masses marking former high-water levels on hillsides in the vicinity of First and Second Creeks.
Luzonite, Cu_3AsS_4	A rare mineral seen in 2 specimens of sulfide ore.
Malachite, $Cu_2(Ca_3)(OH)_2$	A minor mineral in the zone of oxidation over sulfide deposits.
Pyrite, FeS_2	One of the three most abundant sulfide minerals in massive sulfide lenses. Also widespread as disseminations in the Bully Hill rhyolite.
Quartz, SiO_2	An abundant gangue mineral in sulfide ore. Quartz also has extensively replaced country rock in the vicinity of sulfide deposits.
Silver, Ag	Beautiful specimens are reported to have occurred in oxidized parts of sulfide lenses.
Sphalerite, ZnS	Fine-grained dark-gray sphalerite is the principal zinc mineral in all the massive sulfide lenses.
Tetrahedrite - tennantite, $(Cu, Fe)_{12}Sb_4S_{13}(Cu,Fe)_{12}As_4S_{13}$.	Present in practically all sulfide ore but is rarely abundant. Closely associated with galena.

The average overall grade of ore mined since 1900 has been about 15 to 20 percent zinc, 3 percent copper, 0 to 2 percent lead, 5 ounces of silver and 0.03 ounce gold. However, the proportion of the ore minerals differs greatly, not only from one sulfide lens to another but within single lenses. Consequently, some lenses or parts thereof were relatively rich in chalcopyrite and were selectively mined as copper ore, whereas others, consisting largely of sphalerite, were treated as zinc ore (pl. 22*A*, *B*). A few lenses were composed mainly of pyrite. During the early years of the district, when the ore was treated by direct smelting methods, zinc-rich ore bodies, as well as those consisting mainly of pyrite, were avoided as much as possible during mining operations.

Galena is irregularly distributed in virtually all the massive sulfide lenses; many of these contain appreciable amounts of this mineral. About 2 percent lead, all from galena, was recovered during the 1948–52 mining operations of the Afterthought mine. Ore rich in copper or zinc may contain galena but it is most abundant in zinc-rich ore. A mineral that etch tests indicate is intermediate in the tetrahedrite-tennantite isomorphous series is a common but not abundant mineral in the masive sulfide ore. Distribution of this mineral is closely related to that of galena. No silver minerals were seen in the hypogene ores and it seems that virtually all the silver is contained in the tetrahedrite-tennantite and galena. Ore rich in these minerals is also rich in silver. Ore produced from the Afterthought mine contained as much as 40 ounces of silver per ton, although the overall average from the district has been about 5 ounces. Gold is more evenly distributed throughout all types of ore and averages about 0.03 ounce per ton. No free gold was seen in the hypogene ore although oxidized parts of ore bodies yielded free gold during early mining in the district.

MINOR ELEMENTS IN THE SULFIDE ORES

Fourteen samples of sulfide ore from the Bully Hill, Rising Star, and Afterthought mines were analysed spectroscopically in the laboratories of the Geological Survey for five minor elements: germanium, cadmium, cobalt, nickel, and gallium. The results, given in table 6, show that cadmium is the only element present in significant amounts. Assuming an average zinc assay of 18 percent in the 11 samples classed as zinc ore (table 6), the ratio of cadmium to zinc is about 1:40. This is significantly greater than the

TABLE 6.—*Quantitative spectrographic analyses for germanium, cadmium, cobalt, nickel, and gallium in 14 ore samples, East Shasta copper-zinc district*

[Analyst, Harry Bastron]

Laboratory No.	Field No.	Locality and kind of ore	Percent				
			Germanium	Cadmium	Cobalt	Nickel	Gallium
		Bully Hill mine:					
53-1988 SW	BH-00	Copper-zinc	0	0.62	0.0011	0.006	0.0056
1989 SW	OD-9051	Copper	0	0	.012	.0014	.0015
1990 SW	9052	Copper-zinc	.003	.32	0	.0015	.0002
1991 SW	9053	Zinc	0	.74	0	.0024	0
1992 SW	9054	Copper	0	.22	0	.0009	.0012
		Rising Star mine (800 level):					
1993 SW	9062	Pyritic zinc	0	.56	0	0	.0027
1994 SW	9071	do	0	.36	0	0	.0004
		Rising Star mine (700 level):					
1995 SW	RS-00	Zinc	0	.32	0	.0007	0
		Rising Star mine (900 level):					
1996 SW	01	Zinc	.0022	.64	0	.0011	.0016
1997 SW	02	do	.0026	.64	0	.0018	.0007
		Afterthought mine (120 stope):					
1998 SW	OD 11158	Pyritic copper	0	.04	0	0	.0012
1999 SW	11161	Zinc	.011	.22	0	0	0
		Afterthought mine (220 stope):					
2000 SW	11165	Pyritic zinc	.010	.28	0	0	.0036
		Afterthought mine (420 stope):					
2001 SW	11171	Zinc	0	.22	0	0	.0037

average ratio of 1:200 for zinc ores given by Clarke and Steiger (1914, p. 61). Probably much of the cadmium substitutes for zinc in the sphalerite lattice, but in view of the high cadmium content it seems likely that the ores contain some greenockite. However, greenockite was not identified during the present study.

STRUCTURAL CONTROL

The massive sulfide lenses are chiefly localized along moderate to steeply dipping faults and shear zones within the Bully Hill rhyolite and along faults between the Bully Hill and Pit formations. It is probable that the shear zones and faults served as feeder channels for the mineralizing fluids and that the crushed siliceous rock within the shear zones was a favorable environment for deposition of sulfide minerals.

Unlike the sulfide bodies of the West Shasta district, which are localized within the middle unit of the Balaklala rhyolite (Kinkel and others, 1956 [1957]), the deposits of the East Shasta district, though largely restricted to the Bully Hill rhyolite, are not controlled by a particular lithologic unit or units within that formation. However, the Pit formation which consists largely of shale, probably overlay the Bully Hill rhyolite at the time of mineralization and it seems likely that this shale acted as an impermeable barrier which retarded the ascending ore-bearing fluids, thus resulting in the localization of sulfide largely in the more permeable Bully Hill rhyolite.

Although large-scale control of sulfide lenses along shear zones and faults is apparent from the localization of most lenses along these structures, the reason a given lens lies in a particular position along a fault or shear zone is not fully understood. Features that may have played a part in the detailed localization of lenses include: (a) transection of a feeder channel by a fault; (b) favorable dip of beds or schistosity adjacent to a feeder channel; and (c) drag folds in or adjacent to a feeder channel.

Detailed structural control by the transection of a feeder shear zone by a fault seems demonstrable in at least one place in the Afterthought mine (fig. 10 and pl. 5), and probably in one place between the 470 and 570 levels in the Bully Hill mine (pl. 12, section *B–B′*). Ore body 450 in the Afterthought mine was localized largely in a shear zone that dips steeply southwest in the Bully Hill rhyolite. Just above the 450 ore body this shear zone is transected by the Main fault, which dips 50° SE. Shale in the hanging wall of the Main fault near the 450 level also dips southeast about parallel to the fault and thus would have formed an impermeable barrier to fluids rising along the southwestward-dipping shear zone (fig. 10). The ascent of the fluids would presumably have been retarded beneath the juncture of the Main fault and the shear zone, thus giving the fluids additional time to react with and replace the crushed rock in the shear zone. This type of structural control is most clearly applicable to the 450 ore body but many also have been a factor in the localization of the 700a ore body (pl. 5, section *B–B′*).

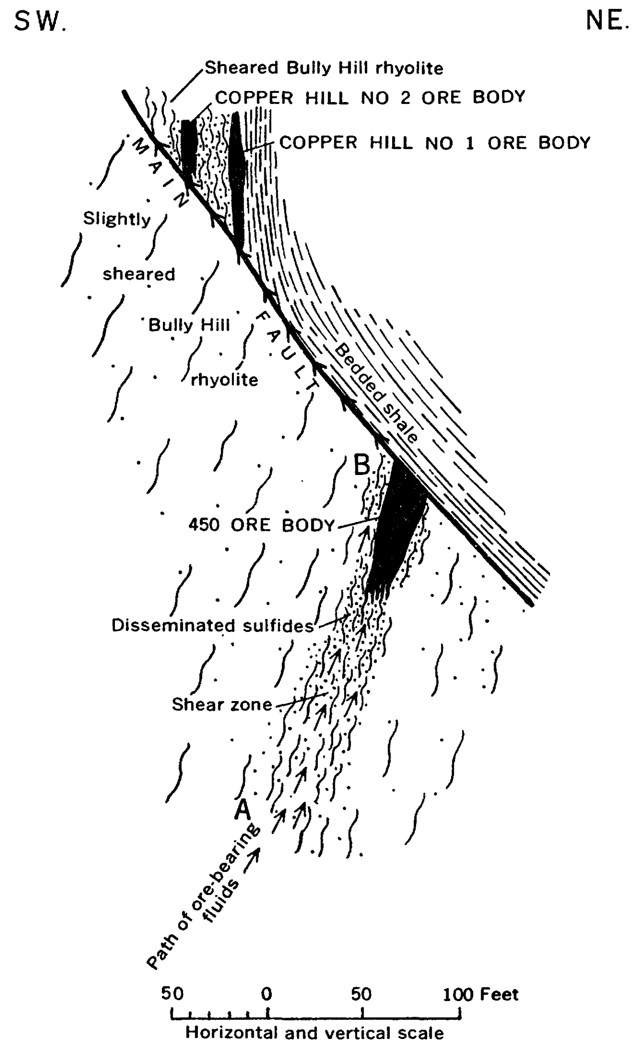


FIGURE 10.—Diagrammatic section of the Afterthought mine showing structural control of ore bodies and the path followed by ore-bearing fluids. Fluids from *A*, temporarily blocked at *B* by Main fault, deposited a concentration of ore. Then, following the Main fault, fluids were again diverted where shear zone and bedding in hanging wall dips toward Main fault. Here another concentration of ore formed.

As figure 10 illustrates, the Main fault apparently served as a channelway for the ore-bearing fluids, at least between the 400 and 200 levels in the Afterthought mine. Bedding in the shale in the hanging wall of the fault between these levels is about parallel to the fault, thus forming an impermeable barrier that would have prevented the fluids from access to the rock in the hanging wall. A short distance above the altitude of the 200 level, however, bedding in the Pit formation and schistosity in the Bully Hill rhyolite dip steeply toward and intersect the Main fault at an angle of about 45° (pl. 5). Here fluids ascending along the Main fault were able to penetrate shale beds along bedding and schistosity planes and thus replace the host rock. The Copper Hill ore bodies at the Afterthought mine seem to have formed in this type of structural environment. The 120 and 220 sulfide ore bodies in the Afterthought mine are similarly replacements of shale beds that dip toward feeder channels at a favorable angle (pl. 5).

Minor structural control by a drag fold having an amplitude of a few feet was seen near the north end of the 420 sulfide ore body in the Afterthought mine (fig. 11). This type of control seems to be of only minor importance.

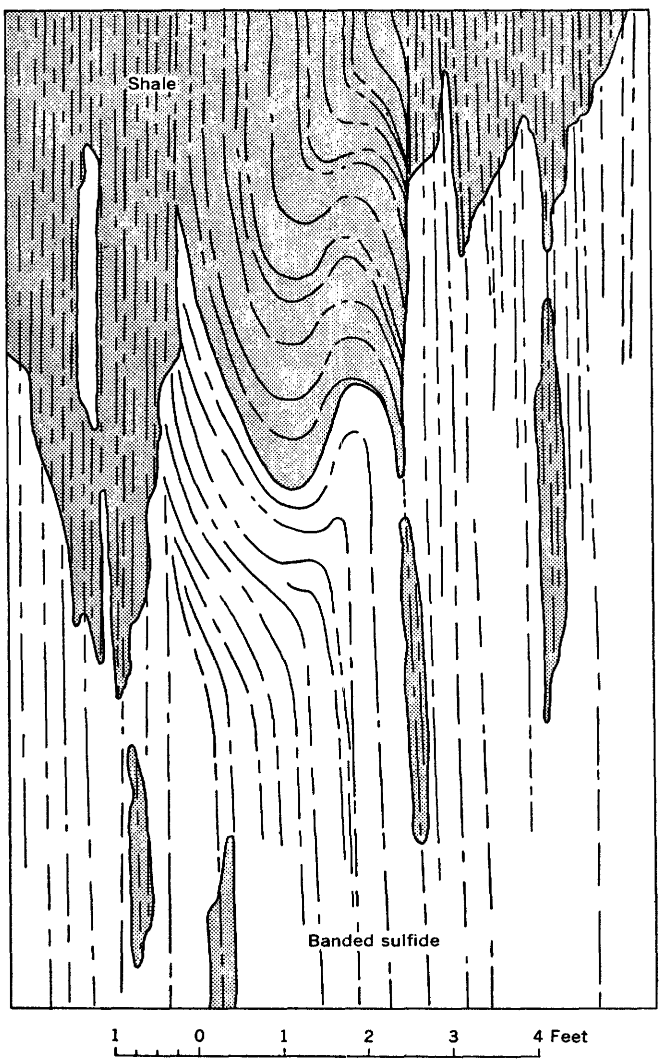


FIGURE 11.—Sketch showing preservation of a drag fold in banded sulfide ore near northwest end of the 420 ore body, Afterthought mine. Note the unreplaced remnants of shale in the sulfide.

ROCK ALTERATION AND PARAGENESIS

As described on pages 45–53, most rocks of the district have undergone extensive hydrothermal alteration. However, this alteration predates the deposition of sulfide minerals and is not restricted to the vicinity of known sulfide deposits. Nevertheless, certain types of alteration, notably silicification, pyritization, hydrous mica alteration, and calcitization, are locally more intense in areas of known deposits. Sulfatization seems largely restricted to the general vicinity of sulfide deposits. Anhydrite and gypsum occur only in the Bully Hill and Rising Star mines. Barite is a common gangue mineral in the sulfide ores and locally elsewhere.

The alteration that seems most clearly associated with sulfide deposits is at the Rising Star mine (pls. 8 and 12) where a group of sulfide lenses are overlain and largely surrounded by intensely silicified Bully Hill rhyolite and are underlain and partly surrounded by massive anhydrite and gypsum. The spatial relation between rock replaced by sulfates and sulfides and the intensely silicified rock suggests that as replacement of the siliceous Bully Hill rhyolite by sulfates and sulfides took place the silica that was liberated in the process moved upward where it replaced mainly feldspar and resulted in almost complete silicification of the Bully Hill rhyolite. As shown in plate 8, virtually all of this intensely silicified rock is on the hanging-wall side of the Rising Star shear zone, which presumably was one of the main feeder channels for mineralizing fluids in the Rising Star area. Silicification is also intense in places along the Bully Hill shear zone, above the Copper City mine workings, and locally in the Afterthought mine.

Anhydrite and gypsum, which extensively replace the Bully Hill rhyolite in the Rising Star mine, are closely related. The gypsum probably is formed by hydration of anhydrite in place. In the Bully Hill mine these minerals replace altered and sheared Bully Hill rhyolite and metadiabase along the Bully Hill shear zone on a much smaller scale than in the Rising Star mine, but locally they form fairly large pods and elongate lenses (pl. 11, 870 level). Although they occur in large amounts at depth, gypsum and anhydrite are less abundant at higher levels, and neither mineral crops out at the surface.

In the Bully Hill mine, the highest point at which gypsum has been reported is near the 300 level (Boyle, 1914, p. 100), about 350 feet below the surface. On the 770 and 870 levels of the Bully Hill mine gypsum and anhydrite were seen in lenses as much as 30 feet thick and 80 feet long, and as streaks and disseminations in the Bully Hill shear zone. They seem to have replaced sheared and altered porphyritic quartz keratophyre and metadiabase. Gypsum predominates in the Bully Hill mine; anhydrite occurs as small isolated masses within the gypsum.

The gypsum is brilliantly white, crystalline, and sugary grained. It has a banded appearance owing to preservation of schistosity from the replaced rock, and emphasized by discontinuous thin screens and remnants of schistose chloritic and sericitic country rock. Remnants of country rock range from a fraction of an inch to 2 inches or more in thickness. The masses of gypsum and anhydrite do not seem to have been much faulted or sheared, but in the Bully Hill mine they are limited to the main shear zone, except for minor amounts in veinlets and along fractures and shears in the adjacent wallrock.

Information concerning the occurrence of gypsum and anhydrite in the Rising Star workings, which were inaccessible at this writing, has been taken largely from Boyle (1914, p. 99–103) and from private reports kindly made available by the Glidden Co. As far as can be ascertained from existing records, gypsum has not been found above the 500 level of the Rising Star mine, where it is barely 100 feet below the surface (pl. 12, section *A–A'*). Below the 500 level gypsum and anhydrite become more abundant as a replacement of country rock; on the 900 level they constitute about 75 percent of the wallrock, and on the 1000 level nearly 100 percent. Gypsum is the predominant sulfate mineral on the 500 level; the amount of anhydrite relative to gypsum increases with depth below that level. Anhydrite is reportedly the predominant sulfate mineral on the 1000 level. The lateral extent or outline of the large masses of gypsum and anhydrite in the Rising Star mine is not known.

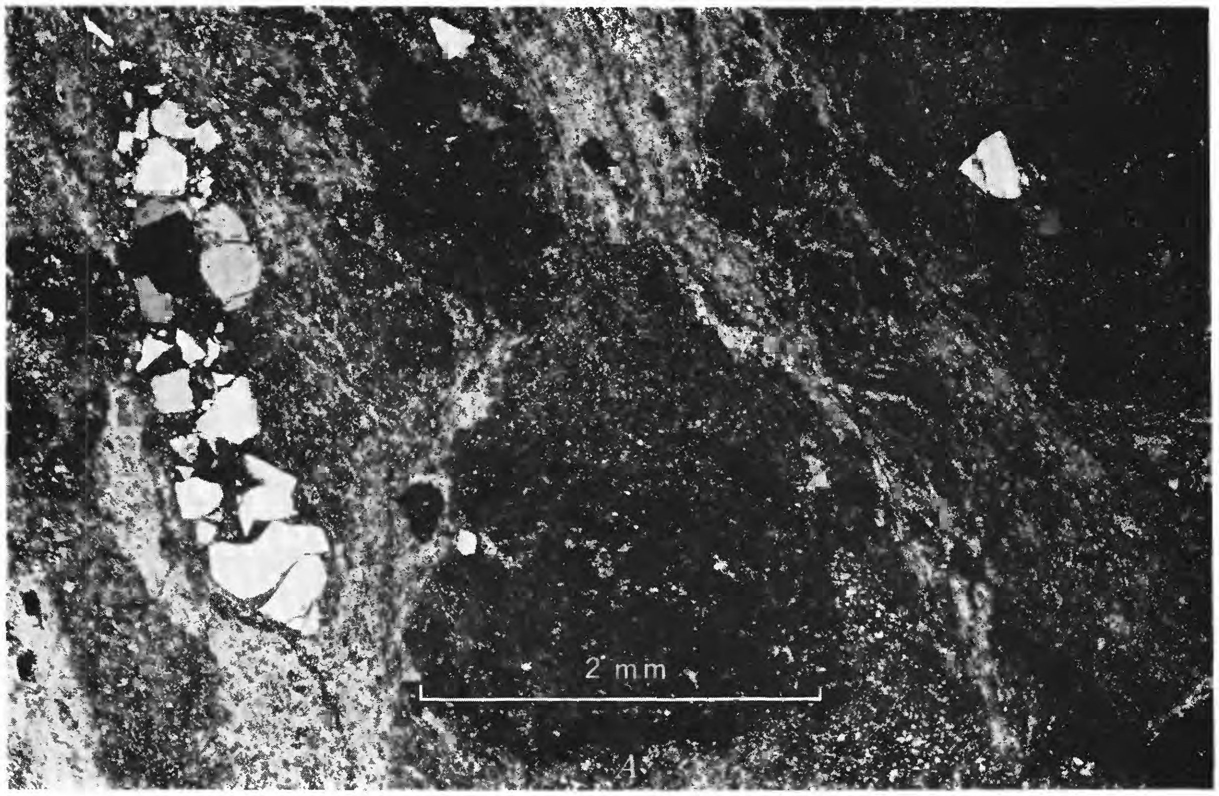
In places, the boundaries with country rock are reportedly irregular and gradational, but gypsum or anhydrite gradually feathers out as the proportion of country rock increases outward from the mass. Small lenses, veinlets, and fracture-fillings of gypsum or anhydrite locally extend into the country rock. At other places, however, the boundaries are sharp and deposition of gypsum and anhydrite seem to have been limited by gouge-filled faults and shear zones. Although banding preserves relict shear structures of the replaced rock in places, preexisting structures tend to be obliterated by the introduced anhydrite. In the lower levels of the Rising Star mine, traces of the main shear zones become obscure or lost entirely. Masses of porphyritic quartz keratophyre are enclosed by gypsum and anhydrite. Some of these masses of country rock contain ore bodies, as well as pods, streaks, and disseminations of the sulfide minerals, which also occur in the anhydrite.

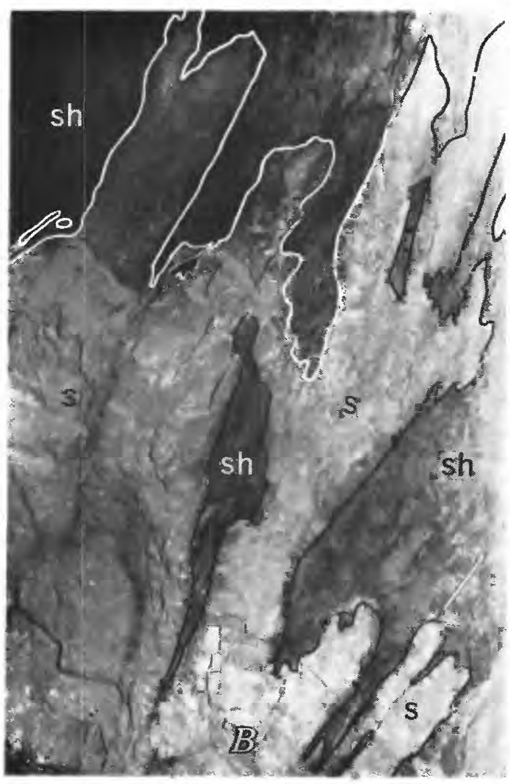
Thin sections show that the anhydrite has excellent rectangular cleavage, commonly lamellar twinning, and high birefringence. Gypsum commonly appears as an alteration of anhydrite in the form of a mat of fine-grained, randomly oriented, acicular crystals. In places the gypsum occurs as a fringe surrounding the anhydrite grains, showing that the replacement of anhydrite by gypsum proceeds from the grain boundaries inward. In areas where replacement is nearly complete, anhydrite crystals are isolated grains in a mass of fine-grained gypsum.

The origin of the large masses of anhydrite and gypsum at Bully Hill has been much discussed in the literature but is still speculative. Graton (1910, p. 103) believes that the anhydrite at Bully Hill is of hydrothermal origin, and that the gypsum is derived secondarily from anhydrite. This belief is shared by Rogers (1915, p. 133). Boyle (1914, p. 103) suggests that either anhydrite or gypsum was formed from hydrothermal solutions; if gypsum had been deposited first, he believes that it could have been transformed to anhydrite, then later reconverted to gypsum.

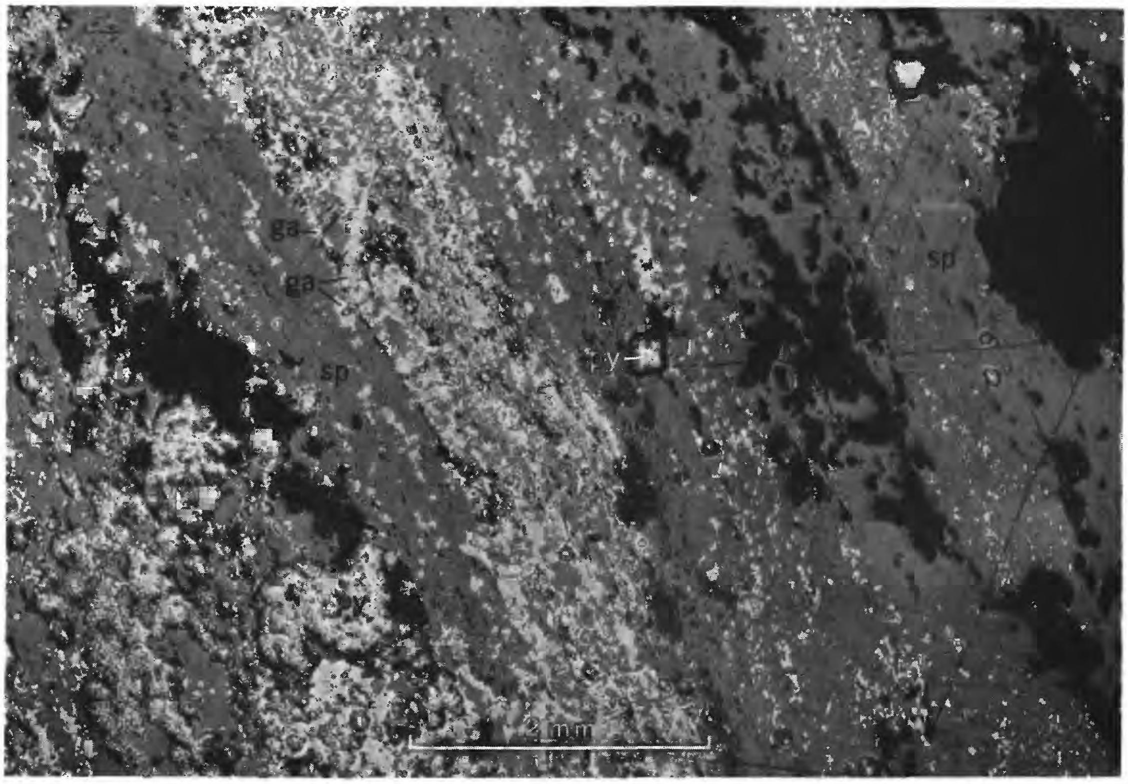
Petrographic evidence and general relations in the Bully Hill and Rising Star mines indicate that anhydrite was derived from ascending hydrothermal solutions, whereas gypsum seems to have been formed secondarily from anhydrite with the aid of supergene agencies. Anhydrite increases in amount with depth below the zone of oxidation, replacing vast quantities of siliceous country rock, whereas gypsum decreases in relative amount. Anhydrite occurs in the mines at depths attained by little or no ground water except through openings provided by mine workings. It is not accompanied by oxidized ore minerals, nor does it occur in the oxidized or enriched zones as might be expected if it were formed under supergene conditions. Instead, it is closely associated with the primary sulfide minerals to the deepest levels of the mines. Moreover, it is at least in part if not largely older than the sulfide minerals.

Barite occurs as a gangue mineral in sulfide ore in the three principal mines of the district, and massive barite was seen as a replacement of a tuff bed in sec. 29, T. 34 N., R. 3 W. (pl. 3). Small masses of crystalline, light-gray to white barite 1 to 2 feet thick by several feet long are exposed along the Bully Hill shear zone in the vicinity of Bully Hill adit 0 (pl. 8). The gully below the adit contains many boulders of barite apparently dug out in mining or eroded from this zone. It is fine to medium grained, massive or

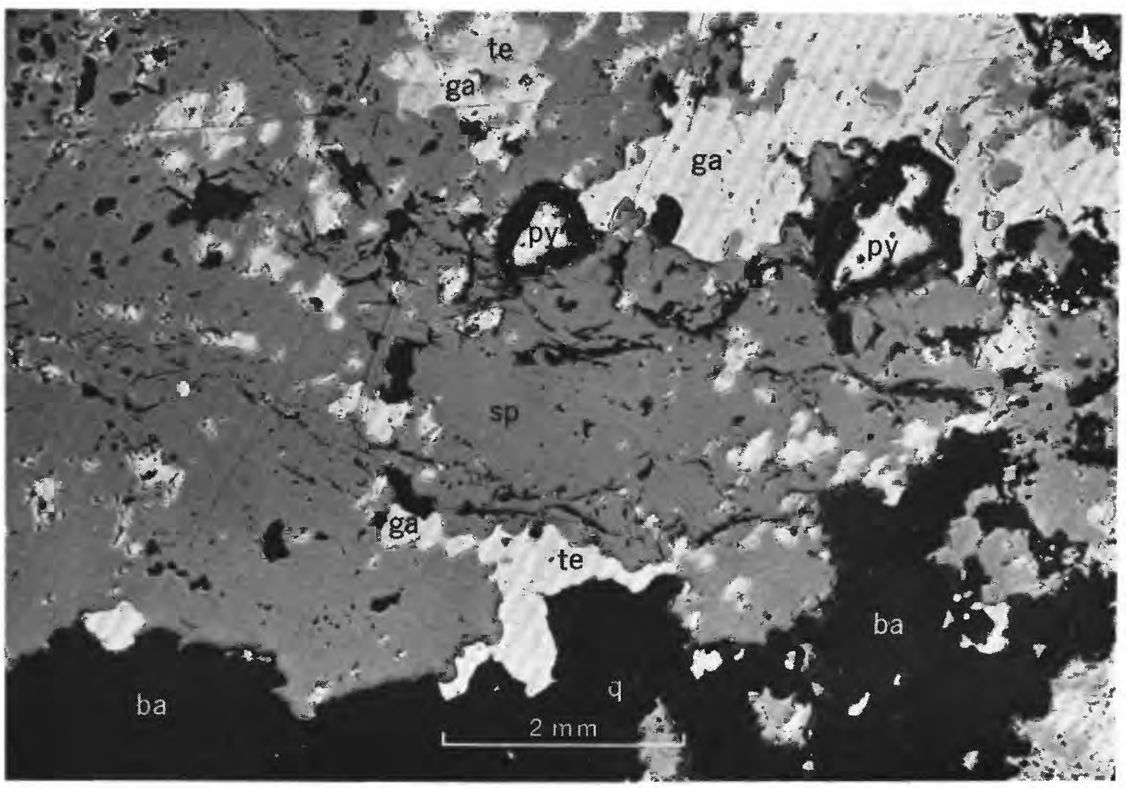




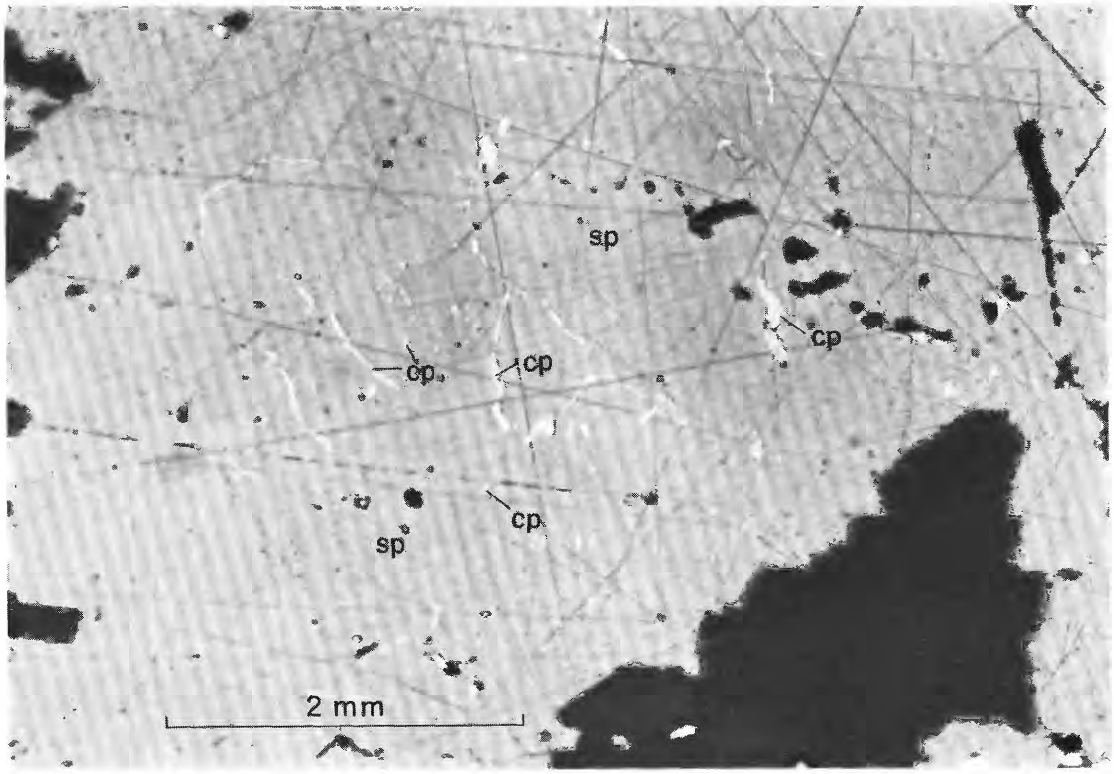
A. Photomicrograph of schistose quartz keratophyre showing cataclastic structure. A quartz phenocryst at left has been crushed and elongated parallel to schistosity. Groundmass is mainly microcrystalline quartz and fine-grained white mica. *B*. Photograph showing interfingering relation between sulfide and shale, 120 stope, Afterthought mine. Sulfide (*s*); shale (*sh*). Pencil at lower right is 6 inches long.



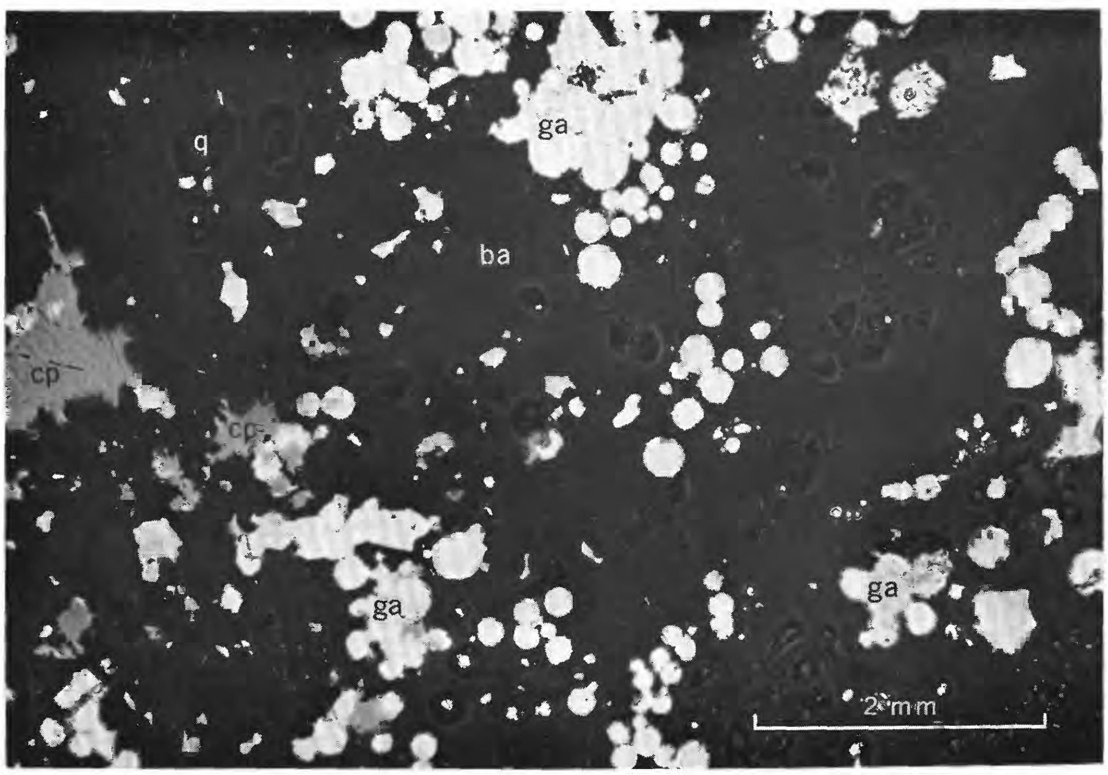
A. Typical zinc-rich banded sulfide ore from the Afterthought mine. Minerals are sphalerite (*sp*), galena (*ga*), and pyrite (*py*). Successful milling of this ore is difficult because of the extreme fineness of grain and intimate admixture of sphalerite and galena.



B. Photomicrograph of zinc-rich sulfide ore from 420 stope, Afterthough mine. Sphalerite (*sp*); galena (*ga*); pyrite (*py*); tetrahedrite-tennantite (*te*); barite (*ba*); quartz (*q*). Note the association of galena and tetrahedrite-tennantite.



A. Photomicrograph showing mottled texture produced by chalcopyrite blebs (*cp*) in sphalerite (*sp*). The geometric arrangement of the blebs suggests that they are in part along crystallographic directions in the sphalerite.



B. Photomicrograph of barite replacement by galena. Isolated blebs of galena (*ga*) in barite (*ba*) are probably an initial stage of replacement whereas coalesced masses may be an advanced stage. Other minerals present include chalcopyrite (*cp*) and quartz (*q*).

banded, and replaces sheared rock in a manner similar to the anhydrite. Barite is a common gangue mineral in the sulfide ores, mostly occurring in minor amounts; it also occurs in post sulfide veinlets with calcite and quartz.

Thin sections show that barite is in the form of anhedral to subhedral tabular crystals. Well-defined cleavage parallels the length of the crystals at right angles; cleavage is poorly defined. Barite commonly forms the matrix in which sulfide minerals are embedded and in most places is replaced by the sulfides.

Disseminated pyrite occurs in virtually all the principal mine areas (pl. 3) but is almost equally common in places remote from known lenses of massive sulfide. Some sulfide lenses are surrounded by country rock containing no disseminated pyrite.

Hydrous mica alteration is generally more intense along shear zones that contain sulfide lenses, but within the shear zones hydrous mica is no more abundant in proximity to lenses than remote from them.

Calcitized rock occurs along the margins and at the edges of some sulfide lenses in the Afterthought mine (pl. 6) but forms much larger masses remote from known sulfide bodies (pls. 1 and 5).

Textural relations as determined by a study of thin and polished sections indicate that, with a few local exceptions, rock alteration and the deposition of gangue minerals at least slightly preceded the deposition of sulfide minerals. The sequence of deposition of gangue minerals differs from place to place and only a general age sequence could be determined. Microcrystalline quartz is the oldest of these minerals, as shown by the fact that it is everywhere replaced by other gangue minerals. Calcite and anhydrite are in general the youngest, but they were not seen together in the same slide and therefore their age in relation to each other is not known. Clinochlore, hydrous mica, and barite in most places seem to be of intermediate age between microcrystalline quartz and calcite, or anhydrite. The age of clinochlore, hydrous mica, and barite in relation to each other seems to vary in different places and no general age sequence among these three minerals could be established.

In a few places deformed calcite crystals are cut by hydrous mica stringers, although in most places calcite replaces hydrous mica. This relation suggests either virtual contemporaneity of hydrous mica and calcite, or two generations of one or the other. Likewise, barite, quartz, anhydrite or gypsum, and calcite are commonly replaced by sulfide minerals. On the other hand, stringers of one or more of these minerals locally cut sulfide lenses, showing that they were deposited during at least two different stages. Feather quartz adjacent to pyrite crystals replaces all other gangue minerals and is virtually contemporaneous with pyrite.

Pyrite is the oldest sulfide mineral and generally replaces microcrystalline quartz rather than other gangue minerals. Where pyrite is enclosed in gangue minerals it is commonly in the form of euhedral or subhedral crystals; in a few places it forms tiny spherical blebs in gangue. But where it is enclosed in other sulfide minerals pyrite is commonly rounded or embayed and is evidently older than the enclosing sulfide minerals. Sphalerite, chalcopyrite, and bornite followed pyrite in the depositional cycle, and galena and tetrahedrite-tennantite seem to be the youngest of the ore minerals.

Sphalerite is probably older than chalcopyrite although it may be in part contemporaneous. Dark-gray sphalerite commonly forms the matrix of the massive sulfide ore and encloses masses of gangue as well as other sulfide minerals (pl. 22*A*, *B*). It corrodes and embays pyrite and is therefore younger. In places sphalerite shows mutual boundary relations with chalcopyrite, but locally small masses of chalcopyrite are along the boundary between sphalerite and either pyrite or gangue and seem to encroach on sphalerite, suggesting that the sphalerite is older. Sphalerite also contains tiny blebs of chalcopyrite, producing the well-known mottled texture (Bastin and others, 1931, p. 570; Edwards, 1947, p. 80). The chalcopyrite blebs are mostly elongate and irregular but some are spherical. In places the blebs are arranged in geometric patterns, suggesting that they formed along crystallographic directions in the sphalerite (pl. 23*A*). In other places the arrangement of blebs appears highly irregular. The amount of chalcopyrite as blebs visible in sphalerite differs markedly from place to place even within a single specimen. Visual estimates range from less than 1 to about 15 percent, of chalcopyrite blebs in sphalerite. Spherical blebs of galena in gangue (pl. 23*B*), blebs of chalcopyrite in gangue, blebs of pyrite in gangue, blebs of galena in sphalerite, and blebs of tetrahedrite-tennantite in sphalerite are also seen in sulfide ores from the district.

The significance of the chalcopyrite in sphalerite mottled texture is difficult to evaluate. Bastin and others (1931, p. 570) state that mottled textures commonly form by exsolution in metal alloys, but they also state that similar textures in ores probably in some places represent the beginning of replacement of sphalerite by chalcopyrite, and in still others may be the residuals of nearly complete replacement of chalcopyrite by sphalerite. Buerger (1934) has shown experimentally that chalcopyrite can exist in solid solution in sphalerite and that exsolution, or unmixing, producing a mottled texture, can take place under certain conditions on cooling.

Although the chalcopyrite blebs in sphalerite in the East Shasta ores can possibly be explained in part as a result of exsolution, the blebs of sulfide minerals in gangue, which are markedly similar in appearance to the blebs of chalcopyrite in sphalerite, cannot be explained by this process. They are, however, reasonably explained as the product of an early stage of replacement of gangue by sulfide minerals. The similarity of the mottled texture produced by chalcopyrite in sphalerite to that produced by other sulfide minerals in gangue, in conjunction with the apparent highly variable amounts of chalcopyrite in sphalerite (less than 1 to about 15 percent), suggests that the chalcopyrite blebs in sphalerite did not result entirely from exsolution. Instead they probably in part represent a very early stage in the replacement of sphalerite by chalcopyrite. If this interpretation is correct chalcopyrite is in the main younger than sphalerite in the paragenetic sequence, although there was doubtless some overlap in the deposition of the two minerals.

Bornite forms small veinlets and irregular masses in sphalerite but in most places shows mutual boundary relations to chalcopyrite. Locally, bornite seems to embay chalcopyrite, but in one specimen from the Afterthought mine veinlets of chalcopyrite cut bornite. The chalcopyrite in this slide may, however, be supergene as it is closely associated with and is partly replaced by covellite. Although the relations are ambiguous, available data indicate that hypogene chalcopyrite and hypogene bornite are virtually contemporaneous.

Galena and tetrahedrite-tennantite are closely related spatially and show mutual boundary relations in most specimens. Commonly mixtures of these two minerals are enclosed in sphalerite but locally tetrahedrite-tennantite occurs along irregular boundaries between sphalerite and galena. This relation suggests that tetrahedrite-tennantite formed in part after galena, but the two minerals may be virtually contemporaneous.

OXIDATION AND ENRICHMENT

The zone of oxidation and enrichment is highly irregular. In most places it extends to depths of only a few feet, but locally, along strong fractures, it extends to depths as great as 100 feet. The deepest oxidation of sulfide lenses was reportedly in the Bully Hill mine.

The principal product in the oxidation of sulfide lenses is limonite gossan. Gold and silver are not readily taken into solution and thus remained behind during oxidation causing the gossan to be enriched in precious metals. This feature led to the discovery of the district. Lead is also relatively insoluble and much of this metal remained in the gossan. Most of the zinc and copper were taken into solution and removed from the gossan. Virtually all the zinc was carried away in streams, probably owing to lack of lime in the surface waters which prevented its fixation as carbonate. A small amount of copper was redeposited in the zone of oxidation as azurite, malachite, cuprite, and native copper.

Most of the copper set free in the oxidation process moved downward and was precipitated as black sooty chalcocite directly beneath the gossan. This zone of secondary enrichment formed a highly irregular blanket as much as 10 feet thick at Bully Hill (Diller, 1903b, p. 129), but elsewhere in the district it was less conspicuous. According to Diller (1903b, p. 129) chalcocite was most abundant near the borders of pyritic ore, but minor nodules and stringers of chalcocite were found in the Bully Hill and Rising Star mines as deep as 500 feet. Diller (1903b, p. 129) reports that secondary bornite and secondary chalcopyrite were found associated with chalcocite in the zone of enrichment at Bully Hill. In the Afterthought mine secondary sulfides occur in minor amounts as deep as the 120 stope, about 250 feet below the surface.

ORIGIN

Evidence is compelling that the massive sulfide deposits are of replacement origin and that the Bully Hill rhyolite, the Pit formation, and metadiabase dikes that intrude the Bully Hill rhyolite, are the rock units replaced. The replacement origin has been recognized by practically all geologists who have worked in the district (Diller, 1906, p. 13; Graton, 1910, p. 91; Boyle, 1914, p. 97), and is shown by the following features: (a) Unsupported horses of country rock within sulfide lenses; planar structures in many of these horses are demonstrably concordant with those in the rock enclosing the sulfide lens, showing that the horses of country rock were not moved during mineralization; (b) banding in the sulfide in many places parallels bedding or schistosity in the adjacent country rock, strongly indicating, if not proving, replacement (figs. 9 and 11); nowhere is the banding symmetrically crustified as might be expected if the deposits were fissure fillings; (c) in a gradational contact between massive sulfide and host rock; massive sulfide grades outward into rock containing heavily disseminated sulfide and the latter, in turn, grades into barren country rock.

The deposits probably formed from ascending hydrothermal fluids. Evidence that these fluids were aqueous is shown by the abundance of hydrous mica and chlorite in the country rocks surrounding the sulfide deposits and throughout the district. Two possible sources of the fluids and the metals and other substances they carried were: (a) a subjacent igneous mass; and (b) the volcanic and sedimentary rocks that lie beneath the Bully Hill rhyolite and Pit formation.

Geologists have traditionally appealed to a magmatic source for mineralizing fluids, and, for reasons given on page 50, the presence of a subjacent igneous mass of trondhjemitic or quartz dioritic composition beneath the East Shasta district seems highly probable. The Pit River stock is probably one cupola of this mass, the Mule Mountain stock in the West Shasta district is another, and a small body of quartz diorite about 5 miles southeast of the Afterthought mine (Diller, 1906) is a third. Although no known massive sulfide deposits can be positively related to any of these three cupolas, Kinkel and others (1956 [1957], p. 100) point out that the location of the massive sulfide deposits of the West Shasta district near the north end of the Mule Mountain stock and pyritized rock near the south end of the stock suggest a genetic relation. No such spatial relation between massive sulfide deposits and exposed plutonic rocks can be demonstrated, however, in the East Shasta district (pl. 3), even though a subjacent igneous mass beneath the entire area seems highly probable. Granting the presence of this mass, and assuming that it was emplaced as a magma, it could have given rise to the necessary mineralizing fluids by magmatic differentiation processes.

An alternative source for the mineralizing fluids, as well as the metals they transported, is the great thickness of volcanic and sedimentary rocks that underlie the Bully Hill and Pit formations. Inasmuch as these rocks were deposited chiefly in a marine eugeosynclinal environment a large volume of sea water must certainly have been trapped in their pore spaces. The heating of this water, by whatever method—deep burial, radioactivity, or proximity to a magma—would cause it to become resurgent and thus a potential vehicle of transport.

The copper and zinc content of three samples of spilite and keratophyre from the Dekkas andesite and of one sample of meta-andesite from the Baird formation were determined by quantitative spectrographic methods. The results are given in table 7. The 3 samples from the Dekkas andesite are each about 1 mile from the closest known massive sulfide deposits, and the sample from the Baird formation is about 5 miles distant. Thin sections show slight alteration of plagioclase to albite in the meta-andesite sample and complete replacement by albite in the keratophyre and spilite samples. Ferromagnesian minerals are altered to chlorite and uralitic amphibole.

TABLE 7.—*Quantitative spectrographic analyses for copper and zinc in four rock samples from the East Shasta copper-zinc district, in percent*

[Analyst, Harry Bastron]

Laboratory No.	Field No.	Type of rock	Locality	Copper	Zinc
53-2003 SW	B114	Spilite	Sec. 11, T. 33 N., R. 2 W.	0.019	0.026
2004 SW	D149	Keratophyre	Sec. 20, T. 34 N., R. 3 W.	.008	.021
2005 SW	D237	Spilite	Sec. 9, T. 34 N., R. 4 W.	.008	.039
2006 SW	F223	Meta-andesite	Sec. 33, T. 34 N., R. 4 W.	.008	.034

The analyses show that the copper content of mafic rocks of the Dekkas and Baird formations is about the same as the average content of the earth's crust (0.007 to 0.01 percent) as recently compiled by Fleischer (1953, p. 4), and also about the same as the Keweenawan lavas of Michigan as given by Broderick (Sandell and Goldich, 1943, p. 175). On the other hand, the zinc content of mafic rocks of the Dekkas and Baird formations is 2 to 3 times as great as the average (0.013 percent) found by Sandell and Goldich (1943, p. 172) in 25 samples of basic igneous rocks. No samples of Copley greenstone were analysed, but because of its lithologic similarity in bulk composition to the Dekkas andesite it seems reasonable to assume that it contains about the same amounts of copper and zinc.

Using the most conservative values of 0.008 percent for copper, and 0.021 percent for zinc (table 7), the Dekkas andesite, as well as the greenstone in the Baird formation, contains about 1 million tons of metallic copper and 2½ million tons of metallic zinc per cubic mile. The Copley greenstone probably contains similar amounts. Inasmuch as the average thickness of the Dekkas andesite is about 2,000 feet, the thickness of the mafic lava and pyroclastic rock in the Baird is at least 1,000 feet, and the thickness of the Copley greenstone is not less than 2,000 feet, it would seem that these formations represent a source more than adequate to account for the 30,000 tons of copper and 25,000 tons of zinc that the district has so far produced.

Assuming that the mafic volcanic rocks of the eugeosyncline (the ensimatic geosyncline of Wells (1956), were the source of the mineralizing fluids, two mineralization mechanisms seem possible. One would require that, by an increase in temperature and (or) pressure during orogenesis, sea water held in pore spaces of the rocks was mobilized and thereby made a potential vehicle of transport for the mineralizing substances. As these hydrothermal fluids moved through the rocks in the geosyncline, particularly the mafic volcanic rocks, they took into solution a small percentage of the copper and zinc (and also sulfur, iron, precious metals, and lead) in these rocks. The direction of movement of the fluids was presumably toward areas of lower pressure such as faults, shear zones, and masses of fractured brecciated brittle rock like the Bully Hill rhyolite. These structures thus served as the collecting channels and, finally, as loci of deposition for the mineralizers. A noteworthy feature of this hypothesis is that the volume of potential source rock can be very large, thereby necessitating the subtraction of only a small fraction of the contained metals to account for all the known sulfide deposits of the district. On the other hand, the hypothesis requires the movement of fluids pervasively through the pore spaces of a large volume of rock. Regional albitization and chloritization in the district indicate that such pervasive movement of fluids is possible and has taken place.

An alternative mechanism of mineralization might result from the granitization of mafic volcanic rocks deep in the geosyncline. Sullivan (1948) relates ore deposits and granitization. He points out that owing to the laws governing the geochemical distribution of elements as set forth by Goldschmidt (1937) the formation of a granitic rock by replacement processes causes the valuable elements of ore deposits to be concentrated in inverse ratio to the extent to which they are incorporated by isomorphous substitution in the common rock-forming minerals. Copper, for example, because of its similar ionic radius, is believed to substitute for ferrous iron in ferromagnesian minerals, particularly augite (Rankama and Sahama, 1950, p. 697), and is thus more abundant in mafic igneous rocks than in granitic rocks. Zinc behaves similarly except that it is more abundant in biotite than in augite (Rankama and Sahama, 1950, p. 710). In the granitization of mafic rocks, therefore, the copper and zinc cannot all be incorporated into the granitic rock by isomorphous substitution and is expelled into the surrounding rocks.

There is evidence that exposed parts of the Pit River and Mule Mountain stocks formed at least in part by replacement processes. Therefore, the possibility exists that a significant volume of Copley greenstone and other rocks deep in the geosyncline were either replaced or assimilated by granitic rocks, or were converted to granitic or quartz dioritic rock by palingenesis. In the replacement of such mafic rocks as the Copley and Dekkas formations a relatively large percentage of the copper and zinc would be expelled and thus made available for concentration in ore deposits in structurally favorable places higher in the earth's crust.

Based on Diller's (1906) data for the thickness of preorgenic formations younger than the Pit, and on the writer's estimate of 5,000 feet for the Pit formation, the maximum thickness of stratigraphic cover that could have overlain the Bully Hill rhyolite at the time of orogeny is 11,650 feet. The depth at which the sulfide deposits were formed was certainly not greater than 11,650 feet. Moreover, inasmuch as folding and faulting almost entirely preceded sulfide mineralization, it seems likely that a good deal of erosion may have taken place before mineralization, and the sulfide deposits may therefore have formed at depths much less than 11,650 feet.

The assemblage of sulfide minerals is typically a mesothermal assemblage as given by Lindgren (1933, p. 530) and therefore supposedly formed at temperatures of 175° to 300° C. The similarity in texture and mineral composition of sulfide lenses throughout the district suggests that the same general temperature conditions prevailed throughout the district during the period of sulfide deposition.

SUGGESTIONS FOR PROSPECTING

All the sulfide ore bodies that crop out at the surface have probably been found but it seems likely that blind sulfide lenses within a few hundred feet of the surface still remain undiscovered. These lenses are likely to be high-grade ore but they will be small and unevenly distributed. Exploration costs will be high and unless several lenses are found close together mining will be unprofitable.

The areas regarded as geologically most favorable for prospecting are shown on plate 3. These areas are generalized and it is not meant to imply that they are all considered equally promising. They are outlined according to the following criteria:

1. All the areas are either in the Bully Hill rhyolite, or in the Pit formation close to the contact with the Bully Hill rhyolite. Known deposits are restricted to these two formations and it is improbable that deposits will be found in other rock units.
2. The rocks within the outlined areas are in many places highly sheared and contain abundant faults that could have served as feeder channels for the mineralizing fluids and as loci of deposition; some of these structures are contiguous with shear zones or faults along which known sulfide lenses occur.

3. The rocks within the areas outlined are in general strongly silicified and in places contain disseminated base-metal sulfides, barite, disseminated pyrite, or limonite.

The Bully Hill rhyolite is probably much more favorable for prospecting than the Pit formation and deserves the most attention. Past production has been mainly from the Bully Hill rhyolite and it appears that that formation was both physically and structurally a highly favorable host rock for the mineralizing fluids. The siliceous, brittle, locally brecciated and faulted character of the rock provided abundant fractures and small openings that allowed the fluids easy access and channeled them toward areas of lower pressure. The stratigraphic position of the Bully Hill rhyolite beneath the impermeable shale of the Pit formation was also a favorable environment for the deposition of sulfide minerals, as the rising fluids were probably retarded by the shale. Any prospecting in the Pit formation should be restricted to within a few hundred feet of its contact with the Bully Hill rhyolite, preferably to within a few hundred feet of fault contacts with the Bully Hill rhyolite.

The only direct surface indication of massive sulfide is structureless, cellular limonite gossan derived from the oxidation, in place, of a massive sulfide lens exposed by erosion. However, only about half a dozen of the 40 or more known sulfide lenses were thus exposed and therefore gossans are not particularly prominent.

Although gossans are not prominent, limonite and heavily iron stained rock is abundant, and in places it is difficult to distinguish between the true gossan derived from the oxidation of massive sulfide and limonite formed by other processes. A few masses of structureless, cellular limonite interpreted as residual limonite overlie small bodies of massive or heavily disseminated pyrite (pl. 3). Also, on the divide between First and Second Creeks (pl. 3), and locally in the Bully Hill area (pl. 8) are masses of dense to spongy limonite that are far removed from any known sulfide mass. This limonite commonly has a weakly defined layering, as opposed to the structureless and generally more cellular residual limonite gossan. Discrete masses of this limonite are commonly at about the same altitude on hillsides, indicating that the limonite was probably deposited along the margins of a body of water during late Tertiary or Pleistocene time. The highest masses of this transported limonite are at an altitude of about 1,750 feet.

Heavily iron stained rock, derived from rock containing much disseminated pyrite, occurs at many places in the district and locally marks shear zones in which massive sulfide lenses are localized, either at depth, or along strike. The Afterthought shear zone (pl. 5) is an example. However, some areas of heavily iron stained or pyritized rock have been explored extensively by diamond drilling without success. The Cowboy (Abe Lincoln) prospect in sec. 4, T. 33 N., R. 2 W. is an example (pl. 15). Massive sulfide lenses, if present in these areas, are evidently neither directly beneath nor directly downdip from the heavily iron stained rock at the surface. This heavily iron stained rock therefore may or may not indicate massive sulfide nearby.

Eighteen chip samples of limonite, collected from several exposures in the area, were submitted in 1951 to H. E. Hawkes for chemical analysis for copper, zinc, and lead content. The results are shown on plate 3. Sample 1J13 represents limonite gossan collected from a few inches to about 2 feet above a small lens of massive sulfide unusually rich in lead. Sample B686 represents gossan collected from a few inches to a few feet above a lens of low-grade disseminated sulfide minerals. Samples D922, D608, and D611 are of limonite that occurs as a skim along the contour of hillsides in the First Creek area and which has obviously been water deposited. The remaining samples shown on plate 3 seem to be mainly of limonite derived from the oxidation, in place, of heavily disseminated sulfide.

The results of the geochemical tests are not promising and it seems unlikely that further geochemical analysis of limonites for copper, zinc, and lead, at least, will be of much value in prospecting for hidden sulfide deposits. No geochemical tests on bedrock were made in the East Shasta district. However, systematic sampling of bedrock for copper in the Mammoth mine in the West Shasta district gave negative results. Conditions in this locality are similar to those in the East Shasta district. Possibly geochemical testing of bedrock for cadmium or other minor elements might prove worthwhile.

Silicified rock containing in relative abundance one or more of a group of minerals that includes barite, anhydrite, calcite, hydrous mica or sericite, and pyrite in close proximity to a shear zone or fault is regarded as a favorable indication of sulfide mineralization. Sulfide bodies at the Rising Star mine, and also in the Copper City area are not exposed at the surface but are largely overlain by intensely silicified rock that commonly contains sparse stringers and small irregular bodies of limonite. Veinlets and blebs of barite are present in a few places. Cutting this intensely altered rock locally are shear zones containing gougy material composed of clay minerals mixed with silici-

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fied rock. In the absence of limonite gossan, the combination of intensely altered rock cut by shear zones may be an indirect surface expression of sulfide bodies. It is, however, not as reliable an indication of sulfide ore as residual limonite gossan, and therefore must be used with caution in searching for hidden deposits.

In our opinion, any serious prospecting program should begin with the detailed mapping of shear zones, faults, and alteration features. This should be followed by a geophysical and possibly geochemical survey of the most promising localities in order to define as closely as possible potential targets for diamond-drill exploration.

CONTACT METASOMATIC MAGNETITE DEPOSITS

Virtually all the skarn masses that crop out between Marble Creek and the southern boundary of the area (pls. 1 and 3) contain magnetite in minor amounts. However, the only mass containing magnetite of minable grade is that which constitutes the Shasta Iron mine in sec. 26, T. 34 N., R. 4 W. This deposit was not mapped in detail during the present study, as an excellent paper on the geology of the deposit by Lamey (1948, p. 139–164), including detailed maps and sections, has been published by the California Division of Mines. The following summary description of the ore deposits is quoted from Lamey's paper (1948, p. 139–140), but the reader is referred to the original report, especially to the detailed geologic map and sections and to the magnetic map.

The deposits consist of very discontinuous and irregular lenses of magnetite intercalated between lenses composed chiefly of garnet, epidote, and pyroxene, accompanied by some serpentine, a mineral resembling anthophyllite, and small amounts of pyrite and chalcopyrite. In general the deposits lie between a late Jurassic or early Cretaceous quartz diorite and the Permian(?) McCloud limestone, and were formed by contact-metamorphic replacement and by fracture filling. In addition to iron, materials introduced by the mineralizing solutions include silica, some manganese and chromium, probably alumina, and perhaps magnesia.

The structure of the rocks is somewhat obscure, but two dominant structural trends are apparent, one of which is nearly northeast, the other nearly northwest. A magnetic map compiled from detailed dip-needle observations shows that the ore zone follows these two directions, especially the one trending northeast.

The total reserves, estimated by the Geological Survey from the magnetic map, mine pits, and five diamond drill holes put down by the Bureau of Mines, U.S. Department of the Interior (project No. 934), amount to 4,680,000 tons of ore having the following percentage composition: Fe, 37.82; SiO_2, 13.24; S, 0.173; P, 0.014; Mn, 0.273. If all material containing less than 25 percent iron is omitted from consideration, the reserves estimated by the Geological Survey amount to 3,893,000 tons containing 41.28 percent iron. About 40 percent of the ore analyzed contains more than 40 percent iron, about 21 percent of it more than 50 percent iron, and only 4 percent of it more than 60 percent iron.

QUARTZ VEINS

Quartz veins are common in two principal areas in the district. One is on the southeast slope of O'Brien Mountain in sec. 21, T. 34 N., R. 4 W.; the other is in the Backbone Ridge area in secs. 4 and 10, T. 33 N., R. 2 W. (pl. 3).

The veins on O'Brien Mountain are as much as 10 feet thick and one was traced for about 1,400 feet. These veins have been prospected by means of a few pits and short adits, but whether any gold or other metal has been produced could not be ascertained.

The veins in the Backbone Ridge area are smaller and less continuous than those on O'Brien Mountain but have been worked more extensively and reportedly contained pockets of rich ore. Included in this group are the Old Indian (F. J. Ward) prospect, and the Cook prospect (pl. 3). Most of the veins strike N. 45° W. to east-west and dip either northeast or southwest at moderate to steep angles. The veins range from 1 to 3 feet in thickness and continue for a few tens of feet to a few hundred feet along strike. Some veins contain numerous vugs lined with quartz crystals.

DESCRIPTIONS OF MINES AND PROSPECTS

AFTERTHOUGHT MINE

LOCATION AND OWNERSHIP

The Afterthought mine is near the east end of the East Shasta copper-zinc district in secs. 10 and 11, T. 33 N., R. 2 W. (pl. 3). The mine plant and main haulage level are about a third of a mile northeast of the village of Ingot on the east bank of Little Cow Creek, at an altitude of 1,125 feet. The mine is developed to a depth of 729 feet by 10 levels. It is owned by the Coronado Copper & Zinc Co.

HISTORY AND PRODUCTION

The history of the Afterthought mine dates back to 1862 when the Copper Hill claim was staked (Frank and Chappell, 1881, p. 23-25). During the first few years after discovery the oxidized ore near the surface was mined on a small scale for gold and silver. In 1873 C. M. Peck, who had erected the first ore mill in the Copper City area, purchased the property for a reported $6,000 and named it the Peck mine. During his first 2 years of ownership Peck and his men mined copper ore from shallow workings and carried it in sacks to the top of the hill east of the mine, where it was loaded on wagons and hauled to Stockton, Calif. At Stockton it was transferred to ships that transported it to Swansea, Wales.

According to Aubury (1908, p. 45), Peck, in 1875, built a reverberatory furnace, in which wood was to be used as a fuel in the reduction of the base ores beneath the oxidized surface ores. This furnace proved unsuccessful, and upon the advice of a Mr. Williams, a water-jacket furnace was built, in which charcoal was to be used. Owing to the refactory character of the ore, which caused repeated freezing and other difficulties that could not then be surmounted, this attempt to smelt the ore also ended in failure.

Later, according to Aubury (1908, p. 45), the property was acquired by Joseph Conland and associates, who built a small water-jacketed blast furnace of 25-ton capacity. Two attempts to treat the ore in this furnace were made but both were unsuccessful. In 1896, according to Aubury (1902, p. 66), 200 tons of ore were smelted. This yielded 32 tons of copper matte containing 37 percent copper, 45 ounces of silver, and $7 in gold per ton.

In 1903 The Great Western Gold Co. acquired the Afterthought property and built a 250-ton water-jacketed blast furnace (Tucker, 1924, p. 425). Ore was successfully reduced in this furnace for the first time in 1905 and the operation continued successfully until 1908. During this period the average yearly output is reported to have been $350,000 (Brown, 1916, p. 757–770). The copper matte produced in the blast furnace was shipped to a smelter in Salt Lake City where it was converted to blister copper (Aubury, 1908, p. 103). However, the high zinc content of the ore made it extremely refractory, necessitating a large coke charge and causing the furnace to freeze frequently.

In 1909 the property was acquired by the Afterthought Copper Co. but no further mining was done until 1919. A 300-ton oil-flotation mill and a 300-ton reverberatory furnace were completed in 1919, with the objective of treating the sulfide ore by the Harwood process. In this process the ore was first preroasted in the reverberatory furnace and then treated by flotation (Averill, 1939, p. 174). This operation continued from July 1919 to February 1920. The results were unsuccessful because the zinc and copper sulfides could not be cleanly separated.

Late in 1923 the Afterthought Copper Co. lost control of the property through foreclosure. Early in 1925 the California Zinc Co., owners of the Bully Hill-Rising Star property, began mining ore under lease and option. This ore was sent by aerial tram to Bully Hill for milling. The company operated successfully until 1927 when the mine closed owing to a drop in the price of metals. Zinc was the principal product during this period.

No further work was done at the Afterthought mine until 1945–46 when the mine was reopened by the Coronado Copper & Zinc Co. New ores bodies were found by exploratory drilling and the company purchased the property in 1947 for $110,000. A 100-ton flotation plant was built and mining was started in October 1948. In July 1949, the mine was closed, owing to a drop in the price of metals. It was reopened in July 1950 and operated continuously until August 1952, when it was again closed owing to the depletion of ore.

During the period of operation by the Coronado Copper & Zinc Co. the crude sulfide ore was ground to 94 percent minus 200 mesh and 2 concentrates were made by selective flotation. One, a copper-lead concentrate, was shipped to a smelter at Tooele, Utah; the other, a zinc concentrate, was shipped to a smelter at Great Falls, Mont. This method of treating the ore was reasonably successful, although a large amount of sphalerite was continuously lost in the copper-lead concentrate because of the fineness of grain and intimate admixture of sphalerite, chalcopyrite, and galena, and also because of marked variation in the character of ore from different stopes and even from the same stope. Smaller amounts of copper and lead minerals were lost in the zinc concentrate. These losses were kept within reasonable limits, thereby permitting profitable operation of the mine, owing to astute mine and mill management.

According to data furnished by the Coronado Copper & Zinc Co.[14] the gross production of the Afterthought mine since 1905 has been 166,424 tons of ore averaging about 16 percent zinc, 2.7 percent copper, 2 percent lead, 5 ounces of silver and 0.04 ounce of gold (table 8). Zinc was not recovered in the direct smelting methods of ore treatment before 1919. Production between 1862 and 1905 is unknown but was probably small.

TABLE 8.—*Summary of ore produced from the Afterthought mine, 1905–52* [1 2]

Year	Length of operation (months)	Tons mined	Copper (percent)	Zinc (percent)	Lead (percent)	Silver (ounces)	Gold (ounces)
1905–07	11½	52,150	4.30	NR	NR	7.44	0.03
1917–19	5	12,490	3.06	NR	NR	5.30	.02
1919–20	6	23,669	2.96	NR	NR	3.11	.01
1925	3	4,939	(3)	(3)	(3)	(3)	(3)
1926–27	20	33,123	2.71	16.01	NR	4.90	.02
1948–49	10	18,989	2.38	15.43	2.17	5.35	.04
1950–52	26	21,064	2.57	17.02	2.18	4.96	.04
Total	81½	166,424	[4] 3.23	[4] 16.15	2.17	[4] 5.55	.03

[1] Data furnished by Coronado Copper & Zinc Co. Published with permission.
[2] Mine was not in operation except during years listed.
[3] No assays available.
[4] Weighted assay.

NR Not recovered.

[14] Published with owners permission.

Workings.—The principal workings of the Afterthought mine include 10 levels and extend vertically for 729 feet (pl. 4). The 400 level, which is the main haulage level, extends 2,910 feet in an easterly direction from its portal on Little Cow Creek. At 1,450 feet from the portal a 329-foot vertical shaft called shaft 1 connects the 400 level with the surface. Two vertical underground shafts, one 300 feet deep and the other 400 feet deep, connect the 400 level with lower workings. The mine workings total about 19,400 linear feet, including 17,200 feet of drifts, crosscuts, and stopes and 2,200 feet of raises and shafts (pl. 4).

Sources of geologic data.—During the present study (1949–50) 9,790 feet of the mine workings were accessible and were mapped at a scale of 1 inch equals 40 feet. An additional 3,200 feet of workings, inaccessible at the time of this study, had been mapped in 1946 by F. W. Stewart, a consulting geologist retained by the Coronado Copper & Zinc Co., and his maps and report were made available to the writers through the courtesy of the company. The remaining 5,710 feet of workings were inaccessible in 1946 as well as at the time of the present study. Information on these workings is scanty and is taken largely from unpublished maps by C. O. Lindberg who examined the property in 1919. The areas where geologic data have been taken from maps by Stewart and Lindberg are shown on plate 6. However, the interpretation of these data, as presented on cross sections and in the text of the present report is entirely the authors' responsibility.

About 720 feet of new workings on the 500 and 600 levels were driven after completion of the present fieldwork. These workings are shown on the composite map of the mine (pl. 4) but the geology was not mapped.

GEOLOGY

The Afterthought mine lies astride the contact between the Bully Hill rhyolite and Pit formation on the northeast limb of the Afterthought anticline (pls. 1 and 3). The contact between the two formations strikes about N. 45° W. and in general dips northeast at moderately steep angles. Within the immediate mineralized area, however, the contact is disrupted by a series of steeply dipping strike faults, so that in section it has an irregular benchlike or steplike form. The benchlike form of the contact is shown by the accompanying sections (pl. 5) and in three-dimensional aspect by the block diagram (pl. 7).

BULLY HILL RHYOLITE

The Bully Hill rhyolite crops out in the western part of the Afterthought mine area as shown in plate 5 includes nonporphyritic and porphyritic quartz keratophyre flows and at least three kinds of quartz kerotophyre breccia of volcanic or tectonic origin. About 70 percent of the formation, including brecciated facies, is nonporphyritic; the remaining 30 percent is porphyritic. Quartz and albite phenocrysts in the porphyritic facies range from 1 to 4 mm in diameter. Contacts between nonporphyritic and porphyritic facies are sharp in some places but gradational in others. The two facies are not differentiated on underground maps. In some places both the nonporphyritic and porphyritic quartz keratophyre have columnar structure. This structure is most common in the upper part of the Bully Hill rhyolite within about 400 feet of the contact with the Pit formation (pl. 5). The columns are 4-, 5-, or 6-sided, commonly have a somewhat sinuous form, and in cross section average 1 to 2 inches in diameter. In most places they plunge northwestward or southwestward at moderate angles but in a few places they plunge southeastward.

Breccias.—Three main types of breccia were recognized in the Bully Hill rhyolite in the mine area. They are: volcanic breccia, monolithologic breccia (breccia composed of a single type of rock) and crackle breccia of probable tectonic origin, and shear breccia.

The volcanic breccia is a coarse breccia consisting of angular fragments of quartz keratophyre as much as a foot in diameter in a quartz kerotophyre matrix. The fragments are commonly closely packed and are of two types of rock: flow-banded quartz keratophyre and quartz keratophyre without flow structure. As shown on the surface map (pl. 5), this volcanic breccia crops out in the southwestern part of the Afterthought area, remote from the main area of mineralization.

At many places in the upper part of the Bully Hill rhyolite, within a few hundred feet of the contact with the Pit formation, quartz keratophyre with columnar structure grades into crackle breccia characterized by much fractured rock with but little disarrangement of the segments of columns, and thence into a monolithologic breccia consisting of closely packed angular fragments similar in size, cross-sectional outline, and composition to nearby columns. It seems evident that this breccia formed by the breaking up and dislocation of the small brittle columns, either by differential movements during late stages of consolidation of the lava, or, more probably, by tectonic movements during deformation.

Two types of breccia interpreted as shear breccia crop out in the mine area. One type, which crops out mainly north of the buildings, consists of sparse fragments of hard, unsheared quartz keratophyre in a matrix of softer sheared quartz keratophyre. The fragments are slightly elongate or lens shaped and most are a fraction of an inch in diameter. They are somewhat lighter in color than the sheared matrix and therefore stand out in sharp contrast to it. Contacts between this type of breccia and the unbrecciated rocks surrounding it are gradational.

A second type of tectonic breccia is referred to as puddinhead breccia by local miners. It consists of angular to subrounded quartz keratophyre fragments in a matrix of dark-gray to black, soft, commonly slickensided shaly material. Many fragments are similar in size and cross-sectional outline to prismatic columns in rocks with columnar structure and are evidently fragments of columns. A thin section of the shaly matrix of the puddinhead breccia shows that its dark color is due to carbonaceous material. Other constituents of the matrix are quartz and clay minerals. The matrix is probably sheared mudstone.

The distribution of the puddinhead breccia is irregular; it occurs near, but not everywhere adjacent to, shale of the Pit formation. Its contacts with the shale are commonly sharp and seem to be faults of small displacement. Observed contacts between puddinhead breccia and quartz keratophyre also are faults. Contacts with monolithologic quartz keratophyre breccia are commonly gradational. The largest exposed body of puddinhead breccia is on the 400 level a few feet northeast of the shaft 1. This body has an outcrop width of 40 feet and a strike length of 140 feet or more.

The puddinhead breccia is probably of tectonic origin although the shaly material that forms the matrix may originally have been mixed with columnar jointed volcanic rock by sedimentary processes.

PIT FORMATION

The shale and tuff that crop out in the northeastern part of the Afterthought area belong to the Pit formation. The shale is medium gray to black and is indistinctly bedded. At most places it has a prominent cleavage that locally parallels bedding but more commonly does not. Most of the shale effervesces slightly in dilute hydrochloric acid.

More than half of the Pit formation in the Afterthought area is tuff that forms beds interlayered with shale. Individual tuff beds commonly differ slightly in color, grain size, and composition but these differences are too slight and too variable to use in correlating the beds from one part of the area to another. Most of the tuff is light gray, poorly bedded, and consists mainly of fine chlorite, crystals and clasts of quartz and feldspar, and small lithic fragments, generally less than half an inch in diameter. Some tuff beds contain shale fragments as much as a foot long. Inasmuch as most of the tuff is about the same composition as the Bully Hill rhyolite, it is difficult to distinguish the two kinds of rock in places where they are poorly exposed and much sheared and altered.

ALTERATION

Five main kinds of alteration that have affected the rocks in the Afterthought area are albitization, silicification, hydrous mica alteration, calcitization, and pyritization. Although the effects of these alteration processes are not restricted to the mine area, all except albitization are, nevertheless, locally more conspicuous in the mine area than elsewhere. As shown by the secondary minerals, the effects of all 5 alteration processes can be seen in some places, whereas in others the effects of only 1 or 2 processes can be seen. The kind of alteration as well as the intensity seem to be dependent in part on the composition of the original rock and in part on local structural conditions at the time alteration occurred. In general, silicification, hydrous mica alteration, and pyritization are the most conspicuous alterations affecting the Bully Hill rhyolite, whereas calcitization is more conspicuous as an alteration of the Pit formation. The feldspar in all the rocks is albitized.

In many places along shear zones and faults in the mine the Bully Hill rhyolite, as seen in thin section, is intensely altered to a rock consisting of quartz, pyrite, hydrous mica, and calcite, in various porportions. Virtually none of the original mineral components except quartz remain; the quartz is largely recrystallized to a mosaic of microcrystalline grains, or to feather or ribbon quartz surrounding pyrite cubes. Pyrite, which forms euhedral and subhedral crystals, and hydrous mica, are concentrated in discrete layers parallel to schistosity. Rounded to irregular masses of calcite a few millimeters in diameter, characterized by wavy extinction, are present locally. These masses of intensely altered rock range from a few feet to several hundred feet in maximum dimension. They are localized largely along shear zones and faults and downdip and laterally from sulfide bodies. Below the 500 level this intensely altered rock is contiguous to and forms envelopes around sulfide lenses that replace Bully Hill rhyolite. In the upper part of the mine, the 120, 122, and 220 ore bodies (pl. 6) replace shale but the mineralizing fluids that formed them apparently traveled along faults that extend into the Bully Hill rhyolite downdip from the sulfide bodies. Along these faults the Bully Hill rhyolite is intensely silicified and moderately pyritized.

Elongate masses of calcitized tuff belonging to the Pit form conspicuous dark-gray, locally iron stained outcrops in the Afterthought area. The largest masses of calcitized tuff are several hundred feet long and as much as 100 feet wide. All are parallel to bedding. A few small masses of calcitized rock also occur locally underground along the margin of the 120, 220, and 420 ore bodies. These small masses replace the Bully Hill rhyolite. The calcitized rock, locally known as lime rock, consists of calcite crystals ranging from 1 to 5 mm in diameter that have partly to completely replaced the original constituents as well as earlier formed secondary constituents of the parent rock. Because the calcite replaces all other minerals except sulfides it seems that calcitization was the last alteration process, except sulfide mineralization, to be imprinted on the rocks in the area. Calcitized rock occurs along the margins of some ore bodies but its presence is not a reliable indication of sulfide mineralization because large masses of rock remote from known sulfide lenses are also calcitized.

STRUCTURE

Although the structural setting of the Afterthought mine, on the northeast limb of a large anticline and astride the contact between the Bully Hill rhyolite and Pit formation, is simple from a broad viewpoint, the detailed structural pattern of the immediate mineralized area is complex. The complexity results mainly from the many faults and shear zones that virtually surround the mineralized area and divide it into a group of fault blocks. Folds, though locally present, are of secondary importance in the shaping of the detailed structural pattern.

Interpretation of the detailed structural pattern is difficult owing in part to the lack of marker units in either the Bully Hill rhyolite or the Pit formation and in part to locally intense alteration that masks the original character of the rocks. The only marker that could generally be recognized with certainty is the contact between the two main rock units; but even this is subject to doubt in a few places because of the lithologic similarity between altered Bully Hill rhyolite and altered tuffaceous rocks of the Pit formation. On the other hand, interpretation of the structure has been greatly facilitated by the density of mine workings and by an abundance of diamond-drill core data. Without these data it would have been impossible to determine the shape of the highly irregular contact between the two formations.

Cleavage and schistosity.—Cleavage or schistosity, at an angle to bedding, is present in most rocks of the area as shown on the detailed geologic map (pl. 5). They are unequally developed and grade into each other locally; in a few places they are absent. Both cleavage and schistosity strike northwest and dip steeply southwest. They grade into each other in many places by a decrease in the distance of parting planes from several inches or a fraction of an inch apart in rocks with cleavage, down to a fraction of a millimeter in schistose rocks. The most strongly schistose rocks mark irregular zones of intense shearing that locally, at least, have controlled sulfide mineralization. In a few places where cleavage or schistosity is associated with small folds it parallels the axial planes.

Folds.—In the Pit formation 6 small folds having amplitudes and wavelengths of a few feet were seen underground and 9 slightly larger folds were mapped on the surface in the Afterthought area (pl. 5). Most of the folds are interpreted as drag folds on the northeast limb of the Afterthought anticline. The strike of all the small folds seen underground and of 7 of the 9 folds mapped on the surface ranges from N. 30° to 70° W. Fold axes plunge as much as 25°, either northwest or southeast, and axial planes dip steeply southwest, parallel to schistosity. Two folds on either side of coordinate E. 5,000 near the north edge of the surface map (pl. 5) strike nearly north and are at an angle to the main structural trend in the area. The divergence of these two folds may be due to faulting or to local buttressing during folding, caused by depositional irregularities in the contact between the competent Bully Hill rhyolite and the incompetent Pit formation.

In addition to the folds described above, a southeastward plunging troughlike structure occupied by the Pit formation and outlined by the contact between the Pit formation and the Bully Hill rhyolite is between the 400 and 600 levels in the mine (pls. 5 and 6). On its southwest side the trough is bounded by fault 420, which is nearly vertical. Northeast of the trough the southeastward-plunging nose of Bully Hill rhyolite is in part replaced by the 450 ore body and cut off on its northeast flank by the Main fault. This nose is exposed on the 400 level between the shafts 2 and 3. The overall shape of this combined trough and nose structure suggests a large drag fold plunging southeastward at an angle of about 30°. However, contacts between the 2 rock units that outline the structure, wherever they have been observed (on the 400, 450, and 500 levels), are faults, and if the structure is a drag fold it is certainly much modified by faulting. An alternative explanation to the drag fold hypothesis is that the "trough" of Pit formation is a depressed fault block bounded on the northeast as well as on the southwest side by structurally higher blocks. This is the preferred interpretation as it removes the necessity of drag folding the highly competent Bully Hill rhyolite and is in better accord with the fact that all observed contacts between the Pit formation and the Bully Hill rhyolite outlining the structure are faults.

Faults and shear zones.—The detailed structure of the Afterthought mine is largely determined by faults and shear zones. The immediate mineralized area, which is virtually surrounded by faults (pl. 5), is bounded by the Afterthought shear zone on the southwest side, by the Main fault and the fault to northeast of the glory hole on the northeast side, and by the Northeast fault on the southeast side. Faults and shear zones are also abundant in the underground workings. They can be subdivided into four main groups on the basis of their attitude and also roughly on the basis of age, as follows: (a) Low-angle thrust faults; (b) high-angle normal and strike-slip faults and shear zones that strike northwest; (c) moderately high-angle normal faults that strike northeast; and (d) the Main fault, a reverse fault that strikes northwest and dips 45° to 60° NE.

Low-angle thrust faults are the oldest. These faults, which were seen in only a few places on the 200, 300, and 400 levels, are scarce and data on them are scanty. Most of these faults dip south at angles ranging from 10° to 25°. They clearly cut cleavage but are offset by high-angle faults. The largest and principal thrust fault, is exposed on the 400 level about 65 feet southwest of shaft 1 (pls. 5 and 6, section *A–A′*). This fault, which strikes about east-west and dips 20° S., has Bully Hill rhyolite on the hanging wall and Pit formation on the footwall. The Bully Hill rhyolite on the hanging wall forms a block about 100 feet thick between the 200 and 400 levels, which is thrust northeastward over the Pit formation for about 150 feet (pl. 5, section *A–A′*). This block has been displaced and modified by younger high-angle faults and it is possible that the total horizontal displacement on the thrust fault is greater than the 150 feet shown on section *A–A′*.

The most abundant and probably the most important faults from an economic standpoint in the mine are high-angle faults that strike N 60° to 80° W., almost parallel to the general trend of the contact between the Bully Hill rhyolite and Pit formation, and dip vertically or steeply southwest. Locally, the dip is steeply northeast. These faults, which are largely responsible for the benchlike form of the contact between the two formations, will henceforth be called strike faults. Included in this group are faults 122, 220, 420, and 412, and many smaller unnamed faults.

Along faults 122, 220, 420, and probably No. 412 the northeast side is displaced downward relative to the southwest side but along at least three of the unnamed faults (pl. 5) the southwest side is displaced downward. Apparent dip-slip displacements range from a few feet to 250 feet or more. Strike-slip displacements are known but are probably small.

All except one of the strike faults, No. 122, intersect and are cut off underground by the Main fault and therefore do not crop out at the surface. Fault 122 (pl. 5, sections *A–A′*, *B–B′*, and *C–C′*) should reach the surface but is not exposed. At depth, where the strike faults are entirely within the Bully Hill rhyolite, they seem to branch or splay out into shear zones and thereby lose their identity as individual faults.

Zones of highly sheared Bully Hill rhyolite are common in the deeper parts of the Afterthought mine and locally elsewhere. The attitude of these shear zones is parallel to cleavage and also nearly parallel to the strike faults except that the dip is consistently southwest. The Afterthought, and other shear zones along which the 450, 700a, and 800 sulfide ore bodies are localized are typical (pls. 5 and 7). These zones of intensely sheared rock were probably formed in part at least during the same stage of deformation that produced the strike faults.

About 5 to 10 percent of the faults in the mine area are high-angle faults that strike northeast and dip either northwest or southeast at moderately steep angles. The Northeast, the principal fault in this group, is a normal fault with a dip-slip displacement of about 75 feet. Evidence on the relative age of the faults that strike northeast is scarce. They are younger than the low-angle thrusts and are older than the Main fault but their age relative to the strike faults is not known. Probably they are contemporaneous or slightly younger.

The Main fault, the largest and most continuous fault in the mine area, strikes N. 45° W., dips 45° to 60° NE., and cuts all other faults (pl. 5). In some places, as on the 200 level, the Main fault is a shear zone as much as 12 feet thick; in other places, as on the surface above adit 4, it is a shaly breccia zone a few inches thick bounded by slickensided surfaces. Grooves on the slickenside surfaces plunge directly downdip. Evidence regarding the direction of movement on the Main fault is scarce and inconclusive but it is intrepreted to have reverse movement with a dip-slip displacement of about 450 feet. This conclusion is based on the premise that the wedge-shaped segment of Bully Hill rhyolite in the hanging wall of the Main fault (pl. 5), is an upthrown segment of the nose of Bully Hill rhyolite that forms the footwall of the fault below the 400 level. Above the 400 level a block of sedimentary rock belonging to the Pit formation forms the footwall of the fault. This block gradually widens toward the surface (pl. 5) because the average northeast dip of the contact between the Bully Hill rhyolite and Pit formation is less than the dip of the Main fault. Under such circumstances, if the Main fault were a normal fault, there would be no source for the segment of Bully Hill rhyolite in the hanging wall.

It is possible that above the present erosion surface the contact between the Bully Hill rhyolite and Pit formation dipped at a steeper angle than the Main fault. Under these conditions, with normal movement on the fault, the wedge-shaped segment of Bully Hill rhyolite could be down-dropped. Owing to the known geometry of the contact this is here considered unlikely.

Virtually all the faults and shear zones, including the Main fault are of premineral age. This is shown by: (a) the presence of sulfide minerals as well as gangue minerals at many places along the faults and shear zones, especially along the strike faults (pl. 5); and (b) by the lack of brecciation or slickensiding of these secondary minerals. The premineral age of the Main fault, which is the youngest fault, is less well established than for the other faults, because many of the workings exposing this fault were inaccessible at the time the mine was mapped. The Main fault probably preceded mineralization because calcite-quartz veins, which are closely related in age to the sulfide minerals, were seen in the fault on the 200 and 300 levels and in adit 7 (pl. 6), and because sulfides in the hanging wall of the fault in adit 7 are not broken or slickensided and in part occur in the fault zone. Indirect evidence suggesting that the Main fault is premineral lies in the fact that the fault zone was explored at six different mine levels by hundreds of feet of workings, now largely inaccessible; although no geologic records for these exist it seems probable that at least small lenses of sulfide were found in places along the fault to encourage continued exploration.

Minor postmineral movement is postulated on the Main fault because locally the calcite-quartz veinlets in the fault zone are slightly crumpled.

Bench structure.—One of the most puzzling structural problems in the Afterthought mine is the irregular benchlike cross-sectional form of the contact between the Bully Hill rhyolite and the Pit formation (pl. 5). Five benches, ranging in width from 20 to about 200 feet, have been recognized. The benches, which slope gently southeastward occur through a vertical range of about 500 feet. In some places bedding in the Pit formation is conformable to the benches but locally, as in the 120 stope, it seems to be at an angle.

In an earlier report (Albers, 1953, p. 10) it was postulated that part of the Bully Hill rhyolite in the mine area was an intrusive body and that the bench structure resulted in part from intrusion of viscous magma into the Pit formation and in part from faulting. However, with additional data on the Bully Hill rhyolite now available from the areal study, it seems unlikely that any of the Bully Hill rhyolite in the mine area is intrusive. Also, a reexamination of all data, including new drill-core data not available at the time the earlier report was prepared, indicates that the bench structure in the mine area can be explained more reasonably by the combination of a local flattening of the dip between the Bully Hill rhyolite and Pit formation and high-angle faulting.

SULFIDE DEPOSITS

Mineralogy.—Primary sulfide minerals in the Afterthought mine are, in order of decreasing abundance, sphalerite, pyrite, chalcopyrite, galena, tetrahedrite-tennantite, bornite, and luzonite. Gangue minerals are calcite, quartz, and barite. The ore is a fine-grained mixture of these sulfide and gangue minerals and is commonly banded. Grain size ranges from less than 0.01 to 4 or 5 mm, and averages probably about 0.1 mm. Supergene minerals include covellite, chalcocite, chalcopyrite, azurite, malachite, and reddish-brown iron oxide.

Grade.—According to data furnished by the Coronado Copper & Zinc Co. (written communication, 1953), the average assay of sulfide mined from the Afterthought mine was about 16 percent zinc, 2.7 percent copper, 2 percent lead, 5.0 ounces of silver, and 0.04 ounce of gold. However, the grade of individual ore bodies may differ markedly from this overall average. Also, the grade within a given ore body is not uniform. Figure 12 is an assay map of the 220 stope. The grade of ore in this stope was somewhat higher than the average grade for the mine as a whole but was not as high as the grade of ore from the 450 stope. Most of the ore in the 220 stope replaced shale that overlay a bench of Bully Hill rhyolite.

Form and size.—Individual sulfide bodies are tabular to cigar-shaped lenses ranging from a few inches to about 400 feet in maximum dimension and from a few ounces to possibly 50,000 tons in mass. About 16 separate and discrete ore bodies have been mined. Some ore bodies were virtually massive sulfide but others consisted of many thin closely spaced layers of sulfide separated by septa of unreplaced country rock.

Practically all the lenslike sulfide ore bodies strike northwest parallel to the grain of the country rocks and dip vertically or steeply southwest. Some lenses plunge as much as 10° SE. but most are nearly horizontal, so that their maximum dimension or rake length is approximately in the horizontal plane. The thickness of the lenses, including those that consist of closely spaced layers of sulfide separated by bands of country rock, ranges from 0 to about 40 feet.

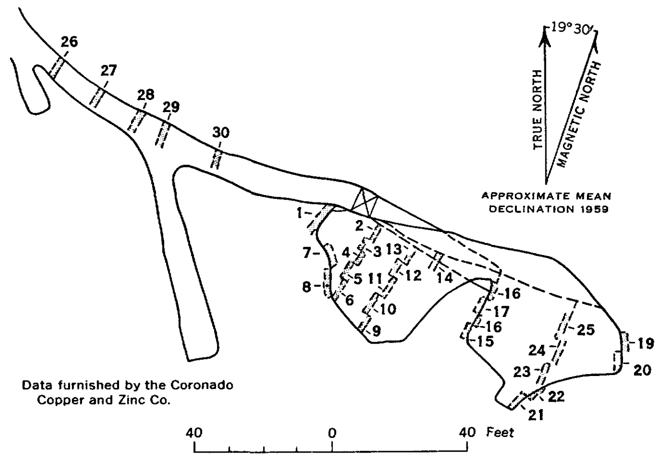

FIGURE 12.—Assay map of the 220 stope, Afterthought mine. Data are given in the following table.

Assay data of samples from the 220 stope, Afterthought mine

[Sample numbers are shown in figure 12. Data furnished by the Coronado Copper and Zinc Co.]

Sample	Horizontal width	Percent			Ounces	
		Zn	Cu	Pb	Au	Ag
1	9.6	14.0	1.68	1.1	0.05	4.0
2	4.6	28.0	3.50	3.8	.04	5.4
3	5.4	32.2	2.27	1.9	.04	7.0
4	3.7	19.6	1.55	3.0	.04	6.2
5	4.6	4.6	2.82	2.4	.04	5.2
6	6.0	1.6	2.54	.8	.02	7.6
7	8.1	1.8	1.11	.6	.01	.8
8	8.1	1.2	2.58	.3	.02	4.4
9	6.0	7.7	2.30	.2	.02	9.7
10	6.0	20.0	3.25	2.4	.04	7.7
11	6.0	3.5	6.72	4.0	.01	40.2
12	6.0	0.3	5.73	1.3	.03	12.4
13	7.0	20.5	5.80	2.2	.13	13.6
14	4.7	10.1	3.15	.7	.04	6.2
15	3.8	8.4	3.40	.5	.06	9.6
16	5.1	15.3	3.28	2.0	.08	6.6
17	6.4	35.1	1.10	5.8	.08	5.5
18	6.4	27.0	.95	4.9	.03	4.4
19	6.0	14.6	1.68	2.4	.08	5.6
20	6.1	22.7	2.46	1.1	.08	7.0
21	6.2	28.2	1.30	2.3	.05	5.5
22	6.7	19.2	5.60	1.5	.04	7.2
23	7.0	30.7	11.03	4.5	.06	11.9
24	7.0	31.2	3.58	5.0	.07	13.7
25	7.0	31.2	3.80	1.9	.08	13.9
26	2.7	10.0	.55	.6	.03	1.6
27	4.0	27.0	2.46	2.6	.06	7.4
28	3.0	25.3	3.30	6.6	.06	18.0
29	4.8	25.0	2.70	3.3	.06	19.8
30	6.8	22.5	2.05	4.3	.06	14.4
Total sample width	174.8					
Weighted averages		17.8	3.21	2.4	.05	9.3

For convenience in reference, the 16 ore bodies that have been mined are given a name or a number. The Afterthought, Copper Hill No. 2, AU 5, 450, 600, 700a, 700b, and 800 ore bodies are in the Bully Hill rhyolite, and the Copper Hill No. 1, 120, 122, AS 6, 220, 412, 420, and AU 40 ore bodies are in the Pit formation or along contacts between the Bully Hill rhyolite and Pit formation. Practically all the ore bodies mined are shown in plan and section on plates 6 and 7.

Structural control.—Three structural features that have influenced the localization of ore bodies in the Afterthought mine are: (a) the strike faults and shear zones; (b) the Main fault; and (c) drag folds in the sedimentary rocks.

The Copper Hill No. 2, Afterthought, 450, 600, 700a, 700b, and 800 ore bodies were along shear zones that strike northwest and dip southwest in the Bully Hill rhyolite. All these shear zones except the first two are in the footwall of the Main fault and are truncated by the fault. Below the 200 level this fault has a shale hanging wall, and the bedding in the shale is nearly parallel to the fault plane. The 450 stope, which contained the highest grade ore in the mine, is in a shear zone that is cut off directly above the stope by the Main fault. As illustrated in figure 10, it seems likely that ore-bearing fluids rising along the shear zone were sufficiently retarded by the Main fault and the impermeable shale barrier to force a change in direction, thereby allowing time for reaction with, and replacement of, the host rock to take place. Other ore bodies in shear zones beneath the 450 ore body (pl. 5, section *B–B'*) may have formed in a similar manner but the evidence is less conclusive. The Copper Hill No. 2 ore body is in a shear zone in the wedge of Bully Hill rhyolite in the hanging wall of the Main fault. The shearing dips into the Main fault at an angle and, as illustrated in figure 10, this shear zone as well as the fault along which the Copper Hill No. 1 ore body was localized were structurally favorable for the reception of ore-bearing fluids rising along the Main fault.

The 120, AS 6, and possibly the AU 5 sulfide bodies replaced shale above benches of Bully Hill rhyolite. All these ore bodies were not immediately above the Bully Hill rhyolite but were separated from it by several feet of almost barren shale (pl. 5). Although no fault or shear zone is known to underlie these ore bodies it seems probable that such structures, with minor displacement, do exist. They probably served as feeders for the ore-bearing fluids in the same manner in which the strike faults and shear zones served as feeders along which other ore bodies in the mine were localized. What part, if any, the bench structure played in the localization of deposits, and why the bodies formed in shale above the Bully Hill rhyolite benches is not understood. Possibly the shale was chemically more receptive to replacement than the Bully Hill rhyolite.

The Copper Hill No. 1, 122, 220, 420, and AU 40 ore bodies were along strike faults between the Bully Hill rhyolite and Pit formation. The dip of these faults is not uniform but ranges from steep to the northeast, through vertical, to steep to the southwest. Where the dip is southwest the massive Bully Hill rhyolite steeply overhangs the Pit formation (pl. 5, sections *A–A′* and *B–B′*) and the sulfide lenses formed beneath these overhangs mainly as a replacement of shale. Elsewhere, mineralization along the faults is chiefly in the form of disseminated sulfide and quartz-calcite veins.

ASHER PROSPECT

The Asher prospect, located in the northeastern part of sec. 2, T. 33 N., R. 2 W., is along a fault in the Pit formation (pl. 3). The fault strikes about N. 10° E. and is almost vertical. The prospect is developed by an adit about 50 feet long that extends beneath U.S. Highway 299E and by a 60-foot inclined shaft. Rock containing heavily disseminated sphalerite is exposed for a width of about 2 feet in the adit, and the dump near the shaft has rock fragments containing sphalerite and galena. There is no record of ore having been produced from this prospect.

PROSPECTS IN THE BRUSHY CANYON AREA

The Brushy Canyon area embraces a group of adits and pits in the central and northern part of sec. 34, T. 34 N., R. 3 W. (pl. 3). It probably includes two prospects formerly known as the De Dallis and Brushy Canyon prospects (Brown, 1916, p. 763–764).

The area is underlain by shale and mudstone interbedded with quartz keratophyre flows and tuff of the Bully Hill rhyolite (pl. 1). These rocks strike generally northwest and dip northeast at moderate angles. They are strongly silicified and contain lenses of red and brown limonite as much as 10 feet thick and several hundred feet long. The limonite lenses seem to be derived from sulfide that has replaced quartz keratophyre breccia or tuff, and to be parallel to bedding in the enclosing silicified shale. Four samples of limonite, tested by geochemical methods for copper, zinc, and lead (pl. 3), showed a copper content ranging from 50 to 130 ppm, a zinc content ranging from 90 to 270 ppm, and no lead (H. E. Hawkes, written communication, 1952). Pyrite found on the dump of the northernmost adit in sec. 4 (pl. 3) was the only sulfide mineral seen in the area. This pyrite is heavily disseminated in a matrix of coarsely crystalline calcite.

The limonite lenses in the Brushy Canyon area are similar in their geologic environment to those at the Shasta May Blossom prospect (pl. 3). At both localities the limonite (and sulfide from which it was derived) replace beds of siliceous volcanic rocks that are either within or just beneath the Pit formation. The lenses seem to be unrelated to fractures or shear zones, at least in the sense that they do not occur along such structures, and also, the sulfide at both localities is mainly pyrite in a matrix of calcite.

Owing to the abundance of limonite and the intensely silicified rock, the area northwest of Brushy Canyon (pl. 3) must be regarded as at least moderately favorable ground for prospecting at depth. We do not endorse it as one of the most favorable areas, however, because of the low content of base metals in the four samples of limonite tested geochemically and in unoxidized sulfide minerals found on one mine dump.

BULLY HILL AND RISING STAR MINES

LOCATION AND OWNERSHIP

The Bully Hill and Rising Star mines are on the Squaw Creek arm of Shasta Lake in secs. 15, 16, 21, and 22, T. 34 N., R. 3 W.

The sulfide deposits occur close together in a local prominence known as Bully Hill, which has an altitude of 2,030 feet, and lies in the drainage basin between Horse and Town Mountains (pls. 1 and 3). The mines are owned by the Glidden Co.

HISTORY AND PRODUCTION

The first mining in the Bully Hill-Rising Star area produced placer gold on Squaw Creek and in the gullies around Bully Hill in the early 1850's. In 1862 gold and silver were discovered in surface rock between Baxters and Zinc Creeks, 1 mile southwest of Bully Hill. This deposit became the Copper City mine. A gold rush into the district ensued and mining claims were staked out over the entire area, including several on Bully Hill. Oxidized rock and gossan containing gold and silver were stripped from the surface and mined from shallow adits. Most of these operations were on a small scale. A notable exception was the Extra Mining Co., which built the first mill at Copper City in 1877, and in 3 or 4 years reportedly produced $640,000 in precious metals from surface ores at Bully Hill. When the copper- and zinc-rich parts of the deposits were reached a short distance below the surface the free-milling processes became useless. Several attempts were made to adapt milling processes to the reduction of base ores with no success, and interest in the district waned.

In 1895 interest in mining activity was aroused in the high-grade secondarily enriched copper ore below the gossan. Old adits were reopened and retimbered, and much development work was done in the following years. J. R. Delamar bought the Bully Hill properties in 1899 and began large-scale operations in the Bully Hill mine. In 1901 the mine was incorporated under the name Bully Hill Copper Mining and Smelting Co.; a copper smelter erected on the property began production of blister copper in May of the same year. Controlling interest in the company passed to the General Electric Co. in 1903.

Production of copper and associated gold and silver was high between 1900 and 1910, except in 1906 and 1907 when the smelter was extensively remodeled and enlarged. At the outset, enriched and oxidized ores from the upper levels constituted the main yield from the Bully Hill mine. A high content of chalcocite characterized these ores, but they were too low in iron for proper treatment in the smelter. For a time iron was added to the furnace from outside sources. When chalcopyrite ore bodies were developed lower in the mine, the problem of iron supply was ideally solved.

Large ore bodies of high-grade zinc were frequently found, but were bypassed by the company. No means of profitably separating zinc from mixed sulfides by milling had been devised, and it introduced several difficulties to the direct smelting of copper.

Oxidized and secondary ores were gradually depleted in the Bully Hill mine. To sustain smelter production at a high level, development of the adjacent Rising Star mine began about 1902. High-grade zinc ore was found in the Rising Star deposits and the copper content dropped from the high grade mined earlier, whereas the zinc content increased. Analysis of the combined ore from the Bully Hill and Rising Star mines, smelted during 1909 shows:

Copper	percent	3.61
Zinc	do	7.83
Iron	do	13.40
Silver	ounces per ton	7.15
Gold	do	.118

The smelter and mine were closed in 1910, presumably because of damage from smelter fumes. Although this may have been the deciding factor, the underlying cause probably was that the zinc-to-copper ratio in the ore mined increased to a point where direct smelting could no longer eliminate the zinc economically.

The General Electric Co. thereafter experimented in the treatment of zinc ore by roasting, leaching, and electrolytic deposition of zinc. A plant for the production of zinc by electrolysis of zinc sulfate was operated in 1915. This method of extraction proved impractical, and the property became idle.

Early in 1917 the Bully Hill Mines Co., Inc., took an option on the property, unwatered the Rising Star mine, and mined lenses of copper ore left by the General Electric Co. The Bully Hill mine was not reopened at this time. In the Rising Star mine a large tonnage of high-grade zinc ore was developed, and pioneer methods of extraction were investigated.

Tests were conducted to determine recovery and grade of concentrate obtainable by flotation in order to raise the grade of zinc ore for an electrolytic plant. In 1918 a flotation plant was built to treat 150 tons of ore per day, but operated for only 3 months. It produced a selective zinc concentrate assaying 48 percent zinc, and a zinc recovery of 80 percent.

In 1920 D. C. Jackling acquired the property under the name of Shasta Zinc and Copper Co., and determined to make a zinc oxide product by a fuming process and to recover copper from the matte. An experimental plant was completed in 1921 and preliminary tests were conducted. Assays of about 9,000 tons of ore, treated in this plant in 1922 averaged:

Zinc	percent	20.92
Copper	do	2.42
Silver	ounces per ton	1.19
Gold	do	.033

The plant operated from June to December 1922, during which period nearly 4 million pounds of zinc oxide were produced.

In August 1924 the Glidden Co. acquired the Bully Hill and Rising Star mines and adjacent properties, and operated the Rising Star mine, along with the Afterthought and Copper City mines, under the name of California Zinc Co. Considerable zinc oxide was produced in the fuming plant left by the previous operators, but this method of treatment was abandoned in late 1925 in favor of concentration by oil flotation. A bulk concentrate containing zinc, copper, gold, and silver was produced, and was shipped to Belgium for further treatment and smelting. During this period experimental work sought a suitable selective flotation process. Operations at the property were terminated in 1927, probably because concentrating and shipping costs could not compete with the steady decline of copper and zinc market prices.

No further interest in the mines was shown until 1952, when the Glidden Co. conducted a surface diamond-drilling program at Bully Hill, with financial assistance from the Defense Minerals Exploration Administration, to explore the northward extensions of the Bully Hill ore zone. In 1953 the company began operations to rehabilitate workings in the Bully Hill mine and to explore for new ore bodies.

Production from Bully Hill prior to 1900 is not recorded. Several reports relate that mining operations before 1900 were mainly for extraction of gold and silver from gossan and near-surface oxidized zones; evidence of this early activity is abundant. Serious development of Bully Hill copper ores began with the erection of a smelter on the property about 1900. From 1900 through 1927, in intermittent operations by several companies, the Bully Hill and Rising Star mines produced about 580,000 tons of ore containing nearly 49,000,000 pounds of copper, 2,200,000 ounces of silver, and 38,000 ounces of gold (table 9). Although mined only for copper and precious metals before 1913, the ores were rich in zinc. Before 1913 the zinc was lost in mine waste and in copper smelter slag and fumes, but from 1913 to 1927 zinc production, calculated for recoverable metal, amounted to about 25 million pounds.

GENERAL GEOLOGY

The area of Bully Hill is underlain by volcanic and sedimentary rocks of Triassic age. Tuffs and mudstones of the Pit formation occupy the east side of Bully Hill to an altitude of 1,700 feet, and volcanic flows and pyroclastic rocks of the Bully Hill rhyolite underlie the rest of the hill (pl. 8). The latter formation forms the core of a southward-plunging anticline.

Although the Bully Hill and Rising Star mines are close together and both lie in hydrothermally altered Bully Hill rhyolite, they have slightly different structural settings. Ore bodies in the Bully Hill mine occur in and near the prominent northward-striking Bully Hill shear zone, which is in the east limb of the steeply dipping, partly overturned anticline. Diabase has also been intruded along this shear zone. The Rising Star ore bodies, about 1,000 feet to the southwest, are closely related to northwestward-trending, steeply dipping shear zones near the crest of the anticline. The difference in the structural settings of the two mines is apparent in comparing the arrangement of underground workings on the composite level map (pls. 9 and 10) and in relating them to the structures shown on the geologic map of the mines area (pl. 8).

BULLY HILL RHYOLITE

In the mines area the Bully Hill rhyolite is differentiated into four mappable units (pl. 8). These units are: (a) porphyritic quartz keratophyre flows and breccia; (b) quartz keratophyre crystal-lithic tuff; (c) metadacite tuff and breccia; and (d) feldspathic quartz keratophyre.

All the Bully Hill rhyolite has undergone some hydrothermal alteration. Flow banding and bedding are widespread features that agree, in gross aspect, with bedding attitudes in the sedimentary rocks. Layering in the metadacite unit of the Bully Hill rhyolite is apparently conformable with bedding in the overlying sedimentary rocks, but in the porphyritic quartz keratophyre unit uniform flow layering passes into swirl patterns at many places. Volcanic and tectonic breccias are common, especially on the ridges of silicified porphyritic quartz keratophyre. Weakly defined cleavage occurs in places as on the anticlinal fold axis in the Rising Star mine area. Schistosity is well defined in large shear zones. Quartz keratophyre that is highly sheared disintegrates readily at the surface producing friable, clayey soil.

TABLE 9.—*Summary of ore produced from Bully Hill and Rising Star mines, 1900–50* [1]

Year	Dry tons		Recovered metal			
	Crude ore	Mine	Copper (pounds) net	Zinc (pounds) net	Gold (ounces)	Silver (ounces)
1900–1901	[2] 50,000	Bully Hill	[2] 11,200,000		3,513	439,227
1902	33,012	do	4,281,170		4,494	224,618
1903	27,727	Bully Hill & Rising Star	2,316,367		2,241	162,326
1904	52,748	do	4,410,365		4,064	257,564
1905	47,354	do	4,628,270		1,914	100,921
1906	10,000	do	735,405		677	32,522
1907	[3] NP					
1908	70,231	Bully Hill	4,150,228		5,660	227,562
1909	[4] 101,400	Bully Hill & Rising Star	6,577,059		8,135	347,777
1910	58,643	do	3,717,407		4,750	202,076
1911	[3] NP					
1912	[3] NP					
1913	129			93,914		
1914	25		6,782			12
1915	400		45,051	150,000	58	2,067
1916	265		30,000			
1917	4,692	Rising Star	623,516		108	13,651
1918	25,269	do	3,091,548		820	12,976
1919	[3] NP					
1920	88	Rising Star	9,238		1	246
1921	2,953	do	99,133	1,057,731	51	2,926
1922	13,968	do	613,482	2,954,250	529	15,390
1923	[3] NP					
1924	9,065	Rising Star	360,000	3,060,000	200	22,500
1925	29,118	do	}			
1926	[5] 29,471	Rising Star & Copper City	1,875,230	17,797,210	951	150,053
1927	[6] 13,418	do.[7]				
1928–50	([8])	([8])	18,200		58	856
	579,976		48,788,451	25,113,105	38,224	2,215,270

[1] Except where otherwise noted, these data are from records of the Mineral Resources and Economics Div., U.S. Bureau of Mines, and were compiled for the Glidden Co. in 1936. Published with permission of the Glidden Co.
[2] Data from Aubury (1908, p. 54).
[3] NP, no production.
[4] According to S. H. Ball (written communication, 1919), 46,761 tons of the 101,400 tons total were from the Rising Star mine.
[5] Includes 70 tons mined from Copper City mine.
[6] Includes 49 tons mined from Copper City mine.
[7] Data obtained from U.S. Bureau of Mines records by J. F. Robertson.
[8] Matte from furnace.

Porphyritic quartz keratophyre flows and breccia

This unit is the oldest exposed and consists of interlayered flows, flow and tuff breccias, and tuffs that are for the most part not differentiated on plate 8. Some of the larger tuff and tuff breccia beds are differentiated where they can be defined, however, and are mapped as quartz keratophyre crystal-lithic tuff (pl. 8). Sparse but ubiquitous quartz phenocrysts are the main features that distinguish the porphyritic quartz keratophyre unit as a whole from other units in the Bully Hill rhyolite. Rocks of this unit are exposed on bold, craggy ridges in rough, knobby outcrops produced as a result of differential weathering between tuff and breccia fragments and their matrices. Flow breccias are probably the most abundant type in the unit, but other varieties of the porphyritic quartz keratophyre, ranging from unbrecciated flows to tuff breccias and coarse crystal-lithic tuffs, are common. The various types occur in poorly defined beds or lentils that range in thickness from a few feet to more than 100 feet. Only a few beds were traced for as much as 200 feet and boundaries between types are mostly gradational.

Quartz phenocrysts, mostly 1 to 4 mm in diameter, generally are sparsely distributed (less than 10 to the square inch) in a layered or flow-banded, aphanitic groundmass. Locally quartz phenocrysts are abundant, and in places they are uniformly less than 1 mm across.

Feldspar phenocrysts are scarce, except in the tuffaceous rock, where they are abundant. Fresh rock ranges from a medium greenish gray to very light gray. Lighter parts commonly indicate concentrations of silica, but in places are caused by calcite or gypsum. Dark-green irregular patches scattered through the quartz keratophyre indicate concentrations of chlorite and epidote. Weathered rock is bleached to a very light gray or white. Brown iron oxides stain the rock surfaces and penetrate along fractures and bedding planes, but only locally have they invaded the rock matrix. Widespread brecciation and shearing have altered the original character of the rock in many places.

Banded flows are well exposed along the road near Rising Star adit 4, and above the upper road in the gully between the Rising Star and Bully Hill mines (pl. 8). The flow layers in these outcrops are fairly uniform and consistent, ranging in thickness from 10 inches to paper-thin partings, which are emphasized locally by differential weathering and by iron oxide stains. Contorted flow banding occurs in outcrops between Rising Star adit 5 (pl. 8) and the upper road, and in the saddle north of Bully Hill west of Town Creek.

The flow breccia, in general, consists of angular to subrounded fragments of porphyritic quartz keratophyre in a matrix of the same flow-banded rock. In addition, it contains a few fragments of other quartz keratophyric types. Fragments range from an inch to more than a foot in diameter, and commonly are deformed and elongated, many into rough ellipoids. Flow breccia is abundantly exposed in the craggy ridges above both mines.

Tuff breccias and crystal-lithic tuffs occur intercalated throughout the porphyritic quartz keratophyre flows and flow breccias. They are especially well displayed in cores from diamond-drill holes Al–3, 4, and 5 (pl. 8). Some tuff beds are differentiated on the map as quartz keratophyre crystal-lithic tuff where they form distinct mappable entities. The majority of the tuffs, however, are thin and lenticular, and so poorly exposed or discontinuous that they are mainly included in the porphyritic quartz keratophyre unit. Crystal-lithic tuff and tuff breccia make up about 20 percent of the porphyritic quartz keratophyre unit. In general, the tuff breccias contain angular to subrounded rock fragments as much as 4 inches in diameter of mostly porphyritic quartz keratophyres, plus fragments of andesitic and dacitic type rocks. The tuff breccia grades into coarse crystal-lithic tuff.

Quartz keratophyre crystal-lithic tuff

This unit occurs as lenticular beds interlayered with porphyritic quartz keratophyre flows and breccia, and is only partly differentiated from the latter unit. It forms lenticular beds that range from a few feet to as much as 100 feet in thickness. Most lenses are short and stubby. However, one bed, in the northern part of the area (pl. 8), was traced for 900 feet and probably continues 400 feet farther. The unit is composed of closely packed quartz and feldspar clasts and lithic fragments a fraction of an inch across in an aphanitic matrix. The quartz and feldspar clasts range from a fraction of a millimeter to a few millimeters in diameter. The crystal-lithic tuff is a key map unit in that it locally shows bedding and thereby helps greatly in delineating the structure.

Metadacite tuff and breccia

Metadacite tuff and breccia form a distinct unit of the Bully Hill rhyolite, lying stratigraphically between the porphyritic quartz keratophyre unit and the sedimentary rocks of the Pit formation. The unit shown on plate 8 is about 200 feet thick and includes about 10 percent of the area mapped. From the southwestern part of the area it extends northeastward along the east flank of Bully Hill. The metadacite tuff and breccia unit is separated from the porphyritic quartz keratophyre unit by faults and intrusive rocks throughout the area. Its stratigraphic position, therefore, is determined indirectly from structural data, from lithologic affinities, and from its conformable relation to the overlying basal tuff member of the Pit formation.

Exposures of the metadacite tuff and breccia in the southeastern part of the area, where weathering effects are least conspicuous, reveal what seems to be flow breccia that consists of medium greenish-gray, flow-banded, aphanitic fragments in a matrix of the same material. Included also are structureless light-gray to white, cherty fragments. These fragments are mostly lenticular, range from half an inch to more than a foot in length, and are generally oriented with their length parallel to the direction of the flow layering in the matrix. The layering is a distinctive character of this unit, being regular and continuous along strike, and parallel to bedding in the overlying sedimentary rocks. This feature is in marked contrast to the discontinuous and chaotic flow structures of the porphyritic quartz keratophyre unit.

This same unit where seen underground in the Bully Hill mine and in the drill cores of diamond-drill holes Al-1 and Al-2 near the north end of the Bully Hill mine area, contains few breccia fragments, is aphanitic, flow banded or massive, medium-dark to light-greenish gray, and may be hard and cherty or soft and clayey, depending on the degree and type of alteration.

The rock exposed at the southwest edge of the mines area (pl. 8) is similar to the rock described above except that it contains a few quartz and plagioclase phenocrysts 1 to 3 mm across that are sparsely distributed in the matrix and in some of the fragments. This rock occupies the same relative position stratigraphically as the aphanitic metadacite, and is probably a variety of it.

Feldspathic quartz keratophyre

Feldspathic quartz keratophyre forms a lenticular sill-like mass, about 300 feet thick in the thickest part, between the porphyritic quartz keratophyre unit and the metadacite unit in the south-central part of the mines area (pl. 8). Irregular masses of the same rock intrude mudstone and tuff beds of the Pit formation in the gully of Town Creek in the northeast sector of the mines area. It seems to be restricted to the basal part of the Pit formation and is regarded as a slightly later shallow intrusive phase of the volcanism that formed the Bully Hill rhyolite; it was probably emplaced at the same time that felsitic pyroclastic material from surface vents was being added to the Pit formation.

The feldspathic quartz keratophyre is characterized by abundant and conspicuous, white, euhedral plagioclase phenocrysts that range from 2 to 5 mm in diameter. Euhedral quartz phenocrysts, commonly of dipyramidal crystal form, are equally as abundant, but are generally smaller, 1 to 3 mm across, and are not as conspicuous. The crystals are in a flow-banded, aphanitic groundmass, which is cherty and hard in the fresh, dark-gray variety exposed in the gully of Town Creek (such as that near the portal of Bully Hill adit 3), but is somewhat softer and medium greenish gray from alteration in the sill in the south-central part of the mines area.

The feldspathic quartz keratophyre forms bold outcrops in Town Creek, where it has prominent joints that are especially well defined parallel to the regular flow layering which strikes northwest and dips northeast at a moderate angle. In the sill in the south-central part of the area, the rock, in large part, is an intrusive breccia, consisting of pebble to boulder-size fragments in a flow-banded matrix of the same rock. Flow banding has no consistent pattern, but is highly contorted. A coarse angular breccia along the western border of the mass probably is a tectonic feature formed by movement along the Bully Hill shear zone. It is silicified and otherwise altered, as shown by its generally white and bleached appearance.

Microscopic examination of the feldspathic quartz keratophyre reveals a microcrystalline groundmass that is somewhat felty from the formation of secondary micaceous minerals. In one of the thin sections studied the texture is spherulitic, consisting of closely packed, spherical aggregates of microlites that radiate outward from many centers. Locally the texture is decussate with spherules randomly oriented, but on the whole they are oriented along flow lines. The microgranular to aphanitic matrix and spherulitic texture suggest an originally glassy rock now devitrified.

Phenocrysts of plagioclase and quartz occur abundantly in clusters or singly. Plagioclase phenocrysts are mostly albite although some unablitized remnants of sodic oligoclase were seen.

PIT FORMATION

Only the lower 400 feet of the Pit formation is included on the Bully Hill-Rising Star mines map (pl. 8). In the Bully Hill area, meta-andesite tuff, which contains thin lenses of siltstone, makes up the lower unit of the formation. In most other parts of the East Shasta district this unit is absent. Above this basal unit, clastic quartz keratophyre and metadacite tuffs are interbedded with mudstone and siltstone in nearly equal amounts. Sulfide deposits have not been found in the Pit formation at Bully Hill, but the favorable contact area has not been prospected to any great extent.

Meta-andesite tuff

The meta-andesite tuff (pl. 8) is fairly well exposed in the gully at the southeast end of the mines area, on the placered slope above Bully Hill adit 1, and along the road north of Bully Hill adit 2 (pl. 8). It forms a bed that strikes slightly east of north along the east flank of the hill. It parallels layering in the underlying metadacite tuff and breccia unit of the Bully Hill rhyolite. It pinches and swells along strike, owing partly to primary differences in thickness and partly to the effects of folding and faulting. The thickness is estimated to range from 100 to 150 feet. A few thin layers of siltstone are interbedded in the meta-andesite tuff.

Unweathered meta-andesite tuff is medium- to light-greenish gray, but the rock is generally moderate olive brown in surface exposures. It is fine grained to coarse grained, and in places is silty. Commonly it contains lapilli that look like altered glass shards; their odd angular shapes, flattened parallel to bedding, give the rock a peculiar mottled appearance. Feldspar crystals and mafic minerals are abundant in some places, and locally quartz crystals are present.

Thin sections show that the meta-andesite tuff consists of abundant angular- and lenticular-shaped lapilli fragments in a clastic, fine-grained, xenomorphic groundmass of crystal fragments. The lapilli in plain light show faint flow structures. Some have a sort of bird's-eye structure produced by flow lines that bow around knots of crystalites. In contrast to the surrounding groundmass, most of the fragments stand out as colorless and textureless. Under crossed nicols the lapilli are nearly isotropic, but consist of a felty mass of very fine grained chlorite. A few subrounded to angular fragments of other volcanic rocks are also found in the meta-andesite tuff.

Metadacite and quartz keratophyre tuffs

As shown on the mines map (pl. 8) the metadacite and quartz keratophyre tuffs that are interbedded with the mudstone and siltstone seem to make up a small percentage of the Pit formation, but most of the rock represented as mudstone and siltstone contains thin interbeds of tuff that could not be differentiated at the scale of mapping. In general, these tuffs consist of lapilli in a medium- to coarse-grained matrix that includes silt, clay, and clasts of quartz and feldspar. Locally, it grades into tuff breccia containing fragments of volcanic rock of several compositions, and minor amounts of shaly material. Unweathered specimens are medium greenish gray to gray, but weathered rock is dark yellowish orange to light brown.

Mudstone and siltstone

Mudstone and siltstone, shown on the map (pl. 8) make up most of the Pit formation in the mines area. These beds are medium gray to black in fresh underground exposures, but on the surface they weather to medium- and light-grayish brown. Bedding is well shown by parting, and by slight differences in hardness and grain size. Fissility is developed only locally, so the term "mudstone" rather than shale is generally more applicable to this rock in the mines area. The mudstone is commonly siliceous; some layers in the diamond-drill cores are chertlike in texture and hardness. A few beds are slightly limy.

INTRUSIVE ROCKS

Two rocks of intrusive origin were mapped in the Bully Hill-Rising Star mines area—feldspathic quartz keratophyre and metadiabase. The feldspathic quartz keratophyre is described in the section on the Bully Hill rhyolite.

Metadiabase

The metadiabase intrudes all rocks in the mines area including the feldspathic quartz keratophyre. It is exposed discontinuously from the vicinity of the Rising Star main haulage tunnel 5, northeastward to the northern limit shown on the map. In the south-central part of the mines area (pl. 8), dikes of metadiabase, 2 to 20 feet thick, are exposed along the west margin of the sill-like mass of feldspathic quartz keratophyre and trend diagonally northeastward through the sill for nearly its whole length. North of the sill the metadiabase occurs as a large mass, displacing and engulfing parts of the metadacite unit of the Bully Hill rhyolite; it is limited on the west by the Contact fault. From coordinate 18,500 N. (pl. 8) the metadiabase follows the east side of the Contact fault northward. Underground, metadiabase is localized along the Bully Hill shear zone as well as along the Contact fault. So far as known, the metadiabase does not intrude the large mass of porphyritic quartz keratophyre that underlies the Rising Star mine area.

Fresh metadiabase is medium gray to dark greenish gray, but it weathers to dark yellowish brown. Hydrothermal alteration has colored it locally a pinkish to purplish gray, like that prominently exposed above Bully Hill adit 0. It is sugary grained to aphanitic and is commonly massive or amygdaloidal. Most amygdules are filled with calcite; a few are filled with quartz. They are as much as 2 centimeters in diameter. Vesicular metadiabase is common at the surface, but none was seen underground, which suggests that it is produced through weathering or leaching out of calcite amygdules. Rarely, the metadiabase is porphyritic with plagioclase phenocrysts 2 to 4 mm in diameter. The metadiabase is silicified at many places, locally to jasperoid.

STRUCTURE

FOLDS

The porphyritic quartz keratophyre that underlies Bully Hill forms the core of a broad anticline, the axis of which plunges at an angle of about 40° SE., and passes through the Rising Star mine area (pl. 1). East of the anticline is a southeastward-plunging syncline in the Pit formation. The trough of the syncline is about in the canyon of Town Creek. East of Bully Hill the limbs of syncline dip west and the structure is overturned to the east. Feldspathic quartz keratophyre locally intrudes the sedimentary rocks.

Beds that underlie the east slope of Bully Hill are on the east limb of the anticline and strike generally N. 10° E. At the southeast edge of the mines area (pl. 8) the beds dip 70°–80° E., but toward the north they are overturned and dips range from 50° W. to vertical. With increasing depth the dip of beds changes from overturned to vertical, then to steep east dips (pl. 12, section *C–C′*). Drag folds are abundant in the sedimentary rocks, and commonly are highly contorted, or tight and isoclinal. Many are asymmetrical or overturned; the axial planes dip steeply west and the axes plunge mostly north. On the surface map (pl. 8), minor drag folds are indicated between the larger folds. The contact between the sedimentary rocks of the Pit formation and the metadacite tuff and breccia unit of the Bully Hill rhyolite (pl. 8) seems to have the same attitude as bedding in the Pit formation.

Flow layering within the mass of porphyritic quartz keratophyre shows intricate fold patterns, but they probably result mostly from primary flowage in the molten lava. Minor drag folds undoubtedly have been superimposed, but the primary and secondary fold structures could not be separated.

SHEAR ZONES AND FAULTS

The most economically important structures in the mines area are shear zones along which the sulfide lenses are localized. The principal shear zones are the Bully Hill, Rising Star, Middle, and East shear zones (pl. 8). They consist of gouge and highly crushed and schistose rock, are as much as 40 to 50 feet thick and were traced for as much as 3,000 feet along strike. The shear zones are poorly exposed and are difficult to trace to the surface, but underground they are much more prominent and are easy to trace. In places individual shear zones branch and coalesce, forming an anastomosing pattern. The absence of a significant offset in rock units cut by shear zones is a unique feature common to all the shear zones. Nevertheless, the gouge, and crushed and schistose rock indicate that the zones mark belts of shear along which a large amount of differential movement occurred.

The Contact fault zone (pl. 8) is physically similar to the shear zones but differs from them in that rock units on opposite sides show a reverse dip-slip displacement of possibly 500 feet. The rocks in the mines area are cut by many smaller faults having displacements ranging from a few feet to a few tens of feet. These faults are generally younger than the shear zones and the Contact fault.

The metadacite unit, which dips steeply west, is truncated at an acute angle by the Contact fault. This fault is not exposed in any of the Bully Hill mine workings that were accessible to the writers, but is defined by the general relation of rock units (pl. 12, sections *B–B′* and *C–C′*. Total displacement on the Contact fault is not known, because it is cut off by the Bully Hill shear zone, but the porphyritic quartz keratophyre on the hanging wall seems to be displaced updip a minimum of 500 feet along the line of section *B–B′* (pl. 12). The position of the Contact fault is uncertain northeast of the collar of DDH Al–3 (pl. 8), but it probably continues on a northeasterly trend through the area underlain by metadiabase near DDH Al–4 and beyond.

The Contact fault coalesces with, and is cut off by, the Bully Hill shear zone near Bully Hill adit 0 at the surface. Here the Bully Hill shear zone is poorly exposed in the shallow opencut, between outcrops of altered and sheared metadiabase and porphyritic quartz keratophyre. From this point the Bully Hill shear zone trends southwestward at least as far as the Rising Star dump and may extend beyond. It forms the contact between porphyritic quartz keratophyre unit to the west and other rocks to the east, mainly the intrusive feldspathic quartz keratophyre. Although the fault plane is not exposed, the rocks on either side are brecciated, sheared, and altered, and the zone contains many metadiabase dikes. Particularly well exposed is the tectonic breccia in the feldspathic quartz keratophyre.

Bully Hill shear zone and Contact fault zone

The Bully Hill shear zone and the Contact fault (pl. 8) probably represent shear zones along which differential movement occurred. At the surface, the Contact fault forms the boundary between the porphyritic quartz keratophyre and metadacite units of the Bully Hill rhyolite. It is a reverse fault, with a dip that average 60° W., but which may flatten somewhat with depth. Metadiabase follows the Contact fault in many places indicating that the intrusion was guided by the shear zone. Sheared metadiabase indicates that locally some shearing also took place after intrusion. The zone of shearing is indicated by a wide zone lacking in outcrop, in which abundant fragments of highly altered and sheared metadacite, as well as metadiabase and gossan occur as float in a clayey, limonitic soil. Porphyritic quartz keratophyre in the hanging wall near the fault is brecciated and silicified.

North of Bully Hill adit 0 the location and trend of the Bully Hill shear zone on the surface is inferred from its prominent occurrence underground. It has a northerly strike and is entirely within the porphyritic quartz keratophyre unit. Sheared and brecciated rock, although poorly exposed, locally attests to its presence. Its northern extent is not known, but underground on the 870 level it extends 1,800 feet (pl. 11).

The Bully Hill shear zone is the main ore zone in the Bully Hill mine; it has been developed on nearly every level by long drifts, and by stopes between levels. Except for minor dislocations it is persistent downdip and along strike. From the surface to the 570 level it dips about 90° (pl. 12, section *B–B′*). From the 570 level to the 1100 level, which is the lowest, it dips about 60° E. with minor undulations along it. Between the 300 and 470 levels it seems to either cut off or merge with the Contact fault. Below the 470 level the shear zone is close to the contact between the porphyritic quartz keratophyre and metadacite units of the Bully Hill rhyolite. The east wall of the Bully Hill shear zone, as well as the shear zone itself, is intruded in many places by metadiabase. Shearing also occurred after the intrusion, as metadiabase in places is highly sheared and mylonitized though not so extensively as the quartz keratophyres. The shear zone is 5 to 40 feet thick and includes several segments. Tectonic breccia is present locally but is not common in the shear zone. Although differential movements in the Bully Hill shear zone were probably extensive it seems that net displacement was relatively small.

About 100 feet to the east in metadiabase a subsidiary fault or shear zone roughly parallels the Bully Hill shear zone on the 570 and 670 levels (pl. 12), and coalesces with it at the 1100 level. Above the 570 level this subsidiary fault seems to feather out or is cut off by a fault sympathetic with the Contact fault. It contains sulfide lenses of minable size.

The Contact fault and Bully Hill shear zone probably have formed as a result of shearing and bedding slippage along the contact between units of greatly different competencies, acting under stresses that compressed the weaker rocks to the east into a tight attenuated synclinal fold. The limbs of the syncline were highly deformed into drag folds, and were sheared out, whereas the competent Bully Hill rhyolite was more resistant to folding and moved upward and eastward as a block relative to the weaker beds. Continued application of stress caused the block of less competent rocks to the east at an acute angle to the bedding, thus forming the Contact fault.

Later, while the rocks were still under compression, and possibly in response to a right-lateral shear couple, the overthrust part of the block was broken along a plane extending vertically through the porphyritic quartz keratophyre on the west side of the Contact fault zone. This break in part coincided with the earlier formed zone of slippage between the Bully Hill and Pit formations and constitutes the Bully Hill shear zone (pl. 12, section *B–B′*). This shear zone either cuts off or merges with the Contact fault zone at depth and along strike (pls. 8 and 12, section *B–B′*). Diabase dikes intruded both zones, followed by continued shearing, at least in the Bully Hill shear zone and along parallel faults. Some of these later faults disrupted the Contact fault. Sulfide lenses formed locally along the shear zone after faulting had ceased.

Shear zones in the Rising Star mine area

Three main shear zones, the Rising Star, Middle, and East occur in the Rising Star mine. In common with the other shear zones at Bully Hill, they are poorly defined at the surface although fairly well defined underground, judging from maps made by mining company geologists underground during the period of the mines' operation (pl. 12). They diverge to the northwest from a point near Rising Star main adit 5, where they seem to be truncated by the Bully Hill shear zone (pl. 8). Other similar shears occur along and parallel to the northwestward-trending contact between the porphyritic quartz keratophyre unit and the metadacite unit in the southwestern part of the mines area. Lesser shear zones and faults occur as offshoots of the main shear zones named above. Almost all the larger subsidiary shear zones have a northwesterly trend also. They are restricted to the porphyritic quartz keratophyre unit and seem to have no great displacements, although differential shearing probably was extensive.

The Rising Star shear zone strikes N. 60° W. but curves to the north near the western limit of the area (pl. 8). It is nearly 40 feet thick in places, and thins gradually with depth in the mine. From the surface to the 700 level mining company maps indicate that the shear zone dips about 80° NE. Below the 700 level the dip flattens to about 60° and the zone is penetrated by massive anhydrite and gypsum, which so engulf and replace the shear zone that it has not been identified on the 900 level (pl. 12, section *A–A′*).

The Middle shear zone is irregular and not well defined, but in general strikes N. 30° W., and dips southwest from 85° on the 500 level to 70° on the 700 level. The shear zone is as much as 30 feet thick; it is also replaced at depth by anhydrite and gypsum and loses its identity.

The East shear zone is exposed in Rising Star adits 4 and 7, and on the 500 level (pl. 12), but is best known from surface features. The gully, in which the portal to Rising Star adit 4 is located, is developed in the East shear zone. Porphyritic quartz keratophyre exposed in the gully is highly altered and sheared; fine-grained white mica is abundant and the rock is schistose. Limonite gossan is present locally, and limonite and pyrite are generally distributed through the brecciated rock in and along the margins of the shear zone. Shear planes exposed along part of the zone dip vertically, and strike from N. 10° W. to N. 28° W., from south to north. The East shear zone is about 30 feet thick throughout a greater part of its exposed length. Postmineral faulting and shearing are not obvious, and probably were minor as in the Bully Hill mine.

There is little evidence from which to determine the direction and amount of displacements on the shears and faults in the Rising Star mine area. Ore shoots that terminate against the Rising Star shear zone, as shown in section *A–A′* (pl. 12), suggest that postmineral normal faulting. One explanation, however, is that as mineralizing fluids moved upward they were prevented from penetrating gouge of the shear zone, but were guided along it to more permeable zones and faults.

The shear zones in the Rising Star area were not intruded by the metadiabase, suggesting that most of them were not as strongly nor as deeply developed as the Bully Hill shear zone at the time of the diabase intrusion. Later hydrothermal fluids were guided by the shear zones, however, as the zones are mineralized. Anhydrite masses seem to have destroyed many of the shear zones at depth by wholesale replacement of large quantities of country rock.

ROCK ALTERATION

All the igneous rocks of the Bully Hill-Rising Star mines area are strongly altered, and new minerals have largely replaced the original country rock. The principal types of alteration are: albitization, silicification, chloritization, hydrous mica alteration, sulfatization, and pyritization. Albitization and chloritization are widespread throughout the district and have no apparent spatial relation to sulfide mineralization. Silicification is also widespread but the occurrence of intensely silicified rocks throughout the Rising Star mine and locally adjacent to the Bully Hill shear zone (pl. 8) suggests a genetic relation between this type of silicification and sulfide mineralization. Hydrous mica is generally abundant in the shear zones but is hardly more common at Bully Hill or near sulfide bodies than elsewhere in the Bully Hill rhyolite. Clay minerals other than hydrous mica include montmorillonite and kaolinite. They are not abundant, however. Disseminated pyrite or its alteration product limonite occurs throughout the mines area but is most abundant over the Rising Star mine and adjacent to the Bully Hill shear zone (pl. 8). The close spatial relation between barite, anhydrite, and gypsum, and sulfide lenses suggests a genetic relation between sulfatization and sulfide mineralization.

SILICIFICATION

The rocks in the mines area are for the most part silicified; in places, as above the Rising Star mine, adjacent to the Bully Hill shear zone, and locally elsewhere silicification is intense. Intensely silicified porphyritic quartz keratophyre crops out on the surface in bold ridges. Commonly the rock in these ridges is stained and veined with limonite and locally contains concentrations of pyrite. Generally, the silicified rock contains numerous small irregular cavities where the sulfides and other minerals have been leached out, leaving in places, a quartz-limonite boxwork.

Quartz makes up more than 90 percent of the most intensely silicified rock. Close examination shows that the introduced quartz, which is in white, finely crystalline masses, has permeated along fractures and flow lines, and has surrounded and infiltrated breccia and lapilli fragments. As seen under the microscope these masses are coarser grained areas of the groundmass that display xenomorphic-granular and sutured textures. Large quartz phenocrysts and clasts have coxcomb boundaries and ragged overgrowth. In places the quartz has replaced virtually all the other minerals, producing a coarsely crystalline, seriate-replacement texture. Feather or ribbon quartz is locally present around individual pyrite crystals. Fresh rock generally contains numerous quartz veinlets that transect the rock in all directions.

A dense, flintlike jasperoid rock that contains reddish-brown, cloudy masses of limonite and hematite was seen in the Bully Hill mine. One mass of this material is on the 870 level, exposed in the 2 short west crosscuts and in the drift north of the First ore body (pl. 11). Another mass is at the west edge of the east ore body on the 570 level. Here the jasperiod rock may be extensive. This siliceous rock seems to be in irregular masses within metadiabase, which suggests that it is a replacement of the metadiabase. However, inasmuch as the metadiabase intruded the metadacite (pl. 8) and displaced fairly large volumes of it, the jasperoid rock conceivably could be silicified inclusions of the metadacite.

In thin section the original character of the jasperiod rock is obscured by complete replacement of the primary rock-forming minerals by microcrystalline quartz. The crystal development and peculiar texture, however, may be a clue, because the quartz crystal grains are elongate and lath shaped and occur in a random arrangement; this feature suggests that the quartz may have replaced lath-shaped plagioclase and partly preserved the ophitic or felty texture of original diabase. The rock contains abundant very fine grained pyrite and in places other sulfides; it is veined by chalcopyrite. In the 570 east stope the jasperoid rock contains high concentrations of ore minerals. Its presence near prominent ore shoots seems to be an important indicator of mineralization within the metadiabase.

Veinlets of white quartz, with or without calcite, and rarely barite, irregularly transect all the country rocks and shear zones. They are thin, generally less than 1 foot thick, and commonly about 3 to 4 inches thick. Some contain chalcopyrite, but most are later than the sulfides. The quartz and calcite in these veinlets are virtually contemporaneous. They have no regular pattern of deposition, and only locally form clearly defined crystals in open spaces or vugs. The quartz and quartz-calcite veinlets seem to have been formed in the waning stages of hydrothermal activity.

PYRITIZATION

Pyrite occurs in practically all the rocks in the Bully Hill-Rising Star area. It is the oldest sulfide mineral but seems to be, in the main, younger than most of the gangue minerals.

Commonly the disseminated pyrite in the weakly silicified quartz keratophyres and metadacites has well-defined cubic or pyritohedral forms and is concentrated along schistosity planes, or, rarely, bedding. In highly silicified phases of these rocks the pyrite crystals are generally larger and seem to be concentrated along fractures as well as along schistosity planes. It forms replacement veinlets ranging from a fraction of a millimeter to about 6 inches in thickness. The veinlets generally have no great continuity and may pinch out abruptly or coalesce with other veinlets. Pyrite is also concentrated in bunches or occurs in a fine network of veinlets or seams. Rock between seams may contain abundant pyrite in disseminations. Some chalcopyrite is commonly associated with pyrite. Pyrite is abundant in the main shear zones and in fractures subsidiary to the shear zones in the adjacent wallrocks. In the shear zones the pyrite occurs as aggregates of fine-grained crystals, either massive or arranged in bands parallel to the schistosity, and commonly interlayered with screens of sericitic or chloritic rock. Other sulfide minerals extensively replace pyrite and its host rock in the shear zones, and form ragged boundaries with them, or contain the earlier pyrite as myriad tiny islands randomly dispersed or alined in chains.

The metadiabase contains, throughout, clusters or blebs of fine pyrite crystals 1 mm in diameter or smaller.

HYDROUS MICA ALTERATION

Hydrous mica is a common mineral in virtually all the rocks in the mines area, and is most abundant in the strongly schistose rocks of the shear zones. These rocks generally are poorly exposed and produce soft, clayey, friable soils. Where wet, rocks consisting largely of this fine-grained white mica produce a soft white sticky clay.

SULFATIZATION

The sulfate minerals barite, anhydrite, and gypsum are important gangue minerals in the Bully Hill and Rising Star mines. Barite is mostly in minor amounts but locally it is abundant. Barite and quartz, commonly form a matrix for the sulfide minerals in the massive sulfide lenses. Barite is also found admixed with quartz and calcite in veinlets in and near these lenses. Anhydrite and gypsum are closely related and extensively replace the Bully Hill rhyolite in the Rising Star mine. Elongate lenses of the same two minerals also occur as a replacement of sheared Bully Hill rhyolite and metadiabase in the Bully Hill mine.

Anhydrite and gypsum do not crop out at the surface. The highest point at which gypsum has been reported in the Bully Hill mine is near the 300 level (Boyle, 1914, p. 100), about 350 feet below the surface. Some gypsum may occur at higher levels but presumably most of the gypsum has been dissolved from rocks at altitudes above the present water table. On the 770 and 870 levels of the Bully Hill mine gypsum and anhydrite lenses as much as 30 feet thick and 80 feet long were observed. Streaks and disseminations of these minerals were also observed in the Bully Hill shear zone. They seem to have replaced porphyritic quartz keratophyre and metadiabase. Gypsum predominates over anhydrite; the latter mineral occurs commonly as small isolated masses within the gypsum.

The gypsum is white and sugary grained. Commonly it is banded owing to the preservation of foliation inherited from the replaced rock and locally to the preservation of thin screens and remnants of chloritic and micaceous host rock.

So far as can be determined from existing mining company maps and records gypsum did not occur in the Rising Star mine above the 500 level, or about 100 feet below the surface. Below the 500 level anhydrite and gypsum become increasingly abundant with depth; on the 900 level they constitute about 75 percent of the wallrock and on the 1000 level nearly 100 percent. Gypsum predominates on the 500 level; but anhydrite increases proportionately and predominates on the 1000 level in the Rising Star mine.

Light-gray anhydrite and gypsum replace both sheared and unsheared Bully Hill rhyolite, forming large irregular masses hundreds of feet thick. The lateral extent of this gypsum and anhydrite in many places is not known. Locally, boundaries between the sulfate minerals and country rock are irregular and gradational; in other places, where deposition of gypsum and anhydrite seems to have been limited by gouge-filled faults and shear zones, the contacts with country rock are sharp.

ORE DEPOSITS

GENERAL FEATURES

The sulfide bodies are lenticular masses that range from nodules a few inches in maximum dimension to masses up to 300 feet in length and height, by as much as 40 feet thick. Their distribution is controlled by major shear zones and subsidiary faults in the Bully Hill rhyolite and locally in the metadiabase dikes. The ores consist of a mixture of dense, fine-grained hypogene sulfides—pyrite, sphalerite, chalcopyrite, galena, tetrahedrite-tennantite, and bornite, listed in order of decreasing abundance. Secondary minerals—native copper, bornite, chalcocite, covellite, cuprite, malachite, azurite, and limonite—derived by alteration of the primary sulfide minerals, occur only in minor amounts below a depth of 300 feet in the mines. In the early days of mining at Bully Hill the supergene ore minerals near the surface constituted, along with free gold and silver, an enriched copper ore. Neither gold nor silver has been found in the free state in the primary ores. Silver occurs in fairly large amounts, and is chiefly contained in galena and tetrahedrite-tennantite; gold occurs uniformly throughout the primary ores in minor amounts.

Reports of former mine operators ascribe dominantly zinc ore to the Rising Star mine and copper ore to the Bully Hill mine. This idea may have been fostered by the more enriched secondary copper ore that was mined from the upper workings of the Bully Hill mine in the early days, and later by meager information available on the primary ores of Bully Hill mine during most of the period that ore bodies were actively worked in the Rising Star mine. Observations made subsequent to reopening of the Bully Hill mine in 1954 and 1955, however, indicate that primary ores in the two mines are similar mineralogically and in relative abundance of primary ore minerals.

Although they have many mineralogic features in common, ore bodies in the Bully Hill and Rising Star mines have somewhat different structural settings and show differences in wallrock and gangue-mineral associations. Ore bodies in the Bully Hill mine are oriented principally along one major shear zone, near and parallel to the edge of the porphyritic quartz keratophyre (pl. 8), whereas Rising Star ore bodies are distributed along several divergent shear zones within the porphyritic quartz keratophyre unit. The Rising Star ore bodies also spread out and away from the main shear zones and extend along subsidiary faults and shears. The difference between the two mines in the distribution of ore bodies is reflected in the development of mine workings, as shown by plates 9 and 10. Ore in the Bully Hill mine is partly in metadiabase, whereas no metadiabase has been found in the Rising Star mine. Great mases of anhydrite and gypsum occur with the ores in the Rising Star mine, but in the Bully Hill mine gypsum and anhydrite are local and minor gangue minerals. Because of such differences, ore deposits of the two mines are discussed under separate headings, but generalizations that apply to both are first considered.

The ore is separable into three main types. One type is represented by sphalerite in concentrations containing as much as 20 percent or more of zinc, with less pyrite, and some chalcopyrite. The chalcopyrite generally yields 2 percent copper, but ranges from a trace to 5 percent. The second type of ore consists mostly of pyrite, with small amounts of chalcopyrite and sphalerite. The third type consists mostly of chalcopyrite with pyrite and a minor amount of sphalerite. Galena, tetrahedrite-tennantite, chalcocite, bornite, and luzonite are also present and locally may occur in important quantities in the first and third types. Each of the three main types of ore is found in isolated deposits, and also closely associated within ore shoots as alternating bands or as pockets of one in another. The boundary between the types of ore may be sharply defined or may be gradational.

The boundary between ore and gangue is sharp and well defined, generally, with little suggestion of sulfide zoning. Ore bodies may be directly in contact with quartz keratophyre, metadiabase, or anhydrite, but commonly clay selvage or gouge, from a thin film to several feet thick, intervenes between ore and wallrock. Pyrite is nearly ubiquitous, and locally it is heavily disseminated and forms a halo around lenses of massive sulfide.

Deposits in the Bully Hill mine

Sulfide lenses in the Bully Hill mine are mostly in the Bully Hill shear zone, which strikes slightly east of north and dips steeply, closely following the contact between porphyritic quartz keratophyre and metadiabase and approximately paralleling the layering in volcanic and sedimentary rocks on the east flank of the Bully Hill anticline. The sulfide lenses are scattered along the shear zone for about 1,500 feet and occur as a replacement of sheared and altered quartz keratophyre and metadiabase. A few sulfide lenses of minable size occur along smaller faults that parallel or diverge from the main Bully Hill shear zone.

The sulfide lenses reach their greatest dimensions in the plane of the Bully Hill shear zone. They range from a few inches to more than 300 feet in length and about the same in height. The thickness is about $\frac{1}{8}$ to $\frac{1}{10}$ the length. Isolated lenses have no marked rake but the pattern of stope development shown on plate 13 indicates that as a group they rake about 70° N.

That the Bully Hill shear zone provided the main control for the deposition of ore minerals is apparent from the location of most of the mine workings along this structure (pl. 11 and 12). The underground workings consist mainly of drifts that follow the shear zone for a little more than 1,500 feet. Twelve levels extending vertically one above the other for 1,100 feet follow approximately the same pattern of development. The deepest level, the 1100, has an altitude of 607 feet.

Structural features that may have governed the detailed distribution of sulfide lenses within the Bully Hill shear zone are obscure. The only noticeable variations in the character of the shear zone near sulfide lenses is slightly greater shearing and fracturing and possibly a slightly greater intensity of rock alteration. However, these variations do not apply to all the lenses and it is therefore difficult to evaluate their importance. The greater permeability provided locally by more intense shearing and fracturing may, nevertheless, account for the localization of some lenses.

Although the sulfide lenses are mostly in Bully Hill rhyolite and in general are bounded on the east by metadiabase, a few massive sulfide lenses are in the metadiabase. One such lens, which is the easternmost on the 570 level (pl. 11), is in a shear zone that is parallel to but lies about 100 feet east of the Bully Hill shear zone. Ore was mined from a stope measuring about 120 feet long, 60 feet wide, and 70 feet high, but the shear zone is mineralized along a developed length of 440 feet. The ore is a replacement in part of jasperoid, a highly silicified metadiabase, and in part of metadacite that is engulfed in the metadiabase.

This easternmost sulfide body on the 570 level (pl. 11) is apparently overlain by a fault that dips west at an angle of 45° and thus truncates the shear zone. Possibly the gouge along this fault served as an impermeable barrier that retarded the rising ore-bearing fluids and thus caused them to deposit their valuable metals. The structural environment of this sulfide body is similar to that of the 450 sulfide lens in the Afterthought mine (fig. 11) although no shale immediately overlies it.

A sulfide lens on the 870 level cut by Defense Minerals Exploration Administration diamond-drill hole A1–2 (pl. 11) is likewise beneath a fault that dips west at an angle of 55° to 65°. Here also the ascent of the mineralizing fluids may have been sufficiently retarded to cause deposition of the sulfides.

Inasmuch as the mineralized Bully Hill shear zone is on the east flank of an anticline (pl. 1) and was probably overlain by shaly rocks of the Pit formation at the time of mineralization it seems likely that the shale served as an impermeable barrier which caused the rising ore-bearing fluids to be retarded beneath the shale. The sheared and fractured siliceous rock in the shear zone might thus have been generally favorable ground for mineralization, and the most highly sheared and fractured areas within the shear zone may have been the specifically most favorable locales for ore deposition.

Deposits in the Rising Star mine

The Rising Star mine was inaccessible at the time of the present study and all information on the ore bodies in this deposit is taken from maps and private reports prepared during the period of the mine's operation and kindly made available to the writers by the Glidden Co. These data have been extremely useful and are gratefully acknowledged. They are, nevertheless, not a satisfactory substitute for information gained from firsthand observations, and for this reason our discussion of the Rising Star ore bodies must necessarily be brief.

The Rising Star mine is developed by 6 principal levels extending vertically for 644 feet (pl. 12). The altitude of the lowest or 1000 level is 743 feet. As may be inferred from inspection of the map showing the map of mine workings and stopes (pl. 9), the sulfide lenses in the Rising Star are more widely dispersed and do not make as simple a pattern as do those in the Bully Hill mine. In general, the lenses are scattered along three main northwestward-trending shear zones—the Rising Star, Middle, and East shear zones (pl. 12, section *A–A′*)—and along several smaller faults. However, the relation between the larger sulfide lenses and shear zones is obscure. The trend of one of the largest lenses in the mine is nearly parallel to the Rising Star shear zone but its dip is opposed to that of the shear zone (pl. 12, section *A–A'*); the shear zone dips northeast at an angle of 60° to 70°, whereas the sulfide lens dips southwest at an angle of about 60°. No offset of the ore shoot is discernible on opposite sides of the shear zone, but instead mineralization seems to have spread out along the shear zone. Judging from the environment of other sulfide lenses in the district a southwestward-dipping structure seems necessary to account for this lens but apparently no such structure was recognized and if one existed it probably has been obscured or obliterated by alteration.

Notwithstanding the above exception, a spatial relation to the three main northwestward-trending shear zones in the Rising Star mine is apparent. Also, unlike in the Bully Hill mine, sulfide lenses along cross faults and faults divergent from the shear zones are common. Many northeastward-trending faults as well as northwestward-trending faults probably were present in the Bully Hill rhyolite in the Rising Star area at the time of mineralization. The sulfide lenses were localized along both the northeast and the northwest structures, although the mineralizing fluids probably ascended along the stronger northwestward-trending shear zones.

The Rising Star area is slightly west of the crest of the Bully Hill anticline and it seems valid to assume that relatively impermeable shaly rocks of the Pit formation overlay the area at the time of mineralization. As elsewhere in the district this impermeable shale cover was probably a factor in the localization of the sulfide deposits in the underlying sheared and fractured Bully Hill rhyolite.

COOK PROSPECT

A prospect locally known as the Cook prospect (pl. 3), in the north-central part of sec. 10, T. 33 N., R. 2 W., consists of 2 quartz veins explored by 2 short adits and 2 pits. The principal quartz vein is 12 to 15 inches thick, strikes N. 15° W., and dips 25° SW. The size and shape of the workings suggest that some ore has been produced, but the amount could not be ascertained.

COPPER CITY MINE AREA

The Copper City mine area is between Zinc Creek and Baxters Gulch, about 1 mile southwest of Bully Hill (pl. 3). The discovery of native gold and silver in oxidized outcrops of ore by Jack Killinger and J. P. Williams in 1862 resulted in the first mining boom in the East Shasta district and led shortly thereafter to the discovery of the Bully Hill and Afterthought mines.

Exploration of the small but spectacular surface showings was done in the Copper City mine area during the early years. The principal work consisted of drifting, at 3 principal levels (altitude 815, 936, and 1,060 feet), along the Copper City shear zone (pls. 2 and 14). In addition, many short adits were driven to explore small gossan outcrops at several places around the hill (pl. 3). Despite the fairly extensive amount of work, the only known production from the Copper City mine area was 250 tons of ore assaying 8 percent copper, $40 per ton in gold, and $20 per ton in silver, shipped in 1863 to Swansea, Wales (Aubury, 1908, p. 34), and 119 tons of sulfide ore mined in 1926 and 1927 and smelted at Bully Hill (table 9).

The geologic environment of the Copper City mine area is almost identical to that of Bully Hill. The sulfide deposits are in the Bully Hill rhyolite on the east flank of a southward plunging anticline (pl. 1). Much of the country rock is strongly silicified, blocky quartz keratophyre of the type illustrated in plate 17*B*. The Copper City shear zone, which strikes about N. 20° E. and dips nearly vertical, cuts the Bully Hill rhyolite along the east limb of the anticline. Smaller fractures cut the Bully Hill rhyolite on the west limb of the anticline.

One small massive sulfide lens is partly exposed near the portal of tunnel 10 of the Copper City mine (pl. 14) at an altitude of 1,060 feet. The workings are inaccessible but judging from the stopes shown on the mine map (pl. 14), at least 3 or 4 additional sulfide lenses were found underground along the Copper City shear zone.

From a geologic standpoint, the Copper City mine area, particularly the part between Zinc Creek and Baxters Gulch, is one of the more favorable localities in the district for prospecting. The structural and lithologic environment is favorable, and there is abundant evidence of mineralization in the form of sulfide minerals, limonite, and intensely silicified rock. Moreover, despite the fairly large amount of work done in the early days, there still remains large areas of untested ground between the level of Shasta Lake and the top of the ridge (altitude 1,450 feet). Work below an altitude of 1,065 feet may not be possible because of the ingress of water from the lake.

COWBOY (ABE LINCOLN) PROSPECT

The Cowboy prospect, which in 1954 was owned by the Lyon Street Trust Co. of San Francisco, is on

Backbone Ridge in sec. 4, T. 33 N., R. 2 W. (pl. 3). The country rock is Bully Hill rhyolite which is strongly iron stained and in places largely replaced by limonite (pl. 15). The prospect lies near the axis of the Afterthought anticline. The rocks locally are weakly schistose and strike northwest and dip steeply southwest. Part of the mineralized area projects beneath the Tuscan formation (pls. 3 and 15). The prospect is explored by four short adits and several pits. According to Aubury (1908, p. 108), the adits have an aggregate length of 200 feet. Heavily disseminated pyrite and in places minor chalcopyrite in a siliceous matrix are on the dumps.

Four samples of limonite were analysed by geochemical methods for copper, zinc, and lead (pl. 3). The copper content ranged from 50 to 1,350 ppm, zinc from 70 to 230 ppm, and lead from 0 to 40 ppm (H. E. Hawkes, written communication, 1951).

In 1950–51 the Coronado Copper and Zinc Co. drilled six holes on the prospect, designed to explore the most favorable limonite exposures at depth down the dip of schistosity. The location of these holes and the mineralized rock found are shown on plate 15. Hole CS–4 cut through 13 feet of mineralized rock containing 1.2 to 11.9 percent zinc. The other five holes were mostly in rock containing disseminated pyrite but the only base-metal sulfide found was minor chalcopyrite.

DONKEY MINE

The Donkey mine is in sec. 11, T. 33 N., R. 2 W. about half a mile southeast of the Afterthought mine (pl. 3). According to Brown (1916, p. 765) the property was discovered in 1876 by A. J. Cook, and was believed to be an extension of the Afterthought lead. Prior to 1900 about 300 tons of high-grade sulfide ore was mined and shipped to a reduction plant at South San Francisco. The property is presently owned by the Coronado Copper and Zinc Co. Workings consist of pits, 2 short adits, a 200-foot shaft, and about 550 feet of drifts extending from the shaft (pl. 16).

A small amount of sulfide exposed in the surface workings is localized along a narrow fault zone in the Bully Hill rhyolite about 300 feet south of its contact with the Pit formation. The fault zone strikes about east-west and dips 75° S. (pl. 16). Presumably the sulfide at depth was along the same fault zone.

In 1951 the Coronado Copper and Zince Co. drilled three holes in the Donkey area. The first hole was designed to explore the shear zone at depth beneath the stoped sulfide lens. The second hole was designed for testing the shear zone a few hundred feet east of the known sulfide mineralization. The third was designed to test the contact between the Bully Hill and Pit formations. As shown on plate 16, sparsely disseminated sulfides were found in some places in these drill holes but no massive sulfide was found.

OLD INDIAN (F. J. WARD) PROSPECT

The Old Indian prospect, in sec. 4, T. 33 N., R. 2 W., was owned in 1950 by F. J. Ward. It includes three principal quartz veins along which several pits and short adits have been dug. Veinlets and blebs of galena, chalcopyrite, sphalerite, and pyrite are visible in the veins and on the dumps. According to F. J. Ward (F. J. Ward, oral communication, 1950), 1 of the 3 veins contained a small but very rich pocket that yielded $47,000 in gold.

SHASTA MAY BLOSSOM PROSPECT

The Shasta May Blossom prospect is on a prominent hill in the west-central part of sec. 14, T. 34 N., R. 3 W. (pl. 3). The prospect is developed by seven adits, and many pits and trenches.

The country rock is highly silicified shale and quartz keratophyre belonging to the Pit formation and the Bully Hill rhyolite, respectively. Interlayered with the silicified country rock are lenses of dense limonite gossan as much as 20 feet thick. The limonite layers dip southeast parallel to bedding in mudstone of the Pit formation.

The principal workings are on the southeast side of the hill. Many dumps of these workings contain heavily mineralized rock consisting of much pyrite and minor chalcopyrite in a matrix that is mainly calcite. The adits were not mapped during the present study and the following information is taken from Tucker (1923, p. 91).

The main tunnel is on the east slope of the hill at an altitude of 1,250 feet. It trends N. 50° W. for 720 feet and thence due north for 26 feet. At 320 feet from the portal a drift trends S. 70° W. for 120 feet. In this drift is an 18-foot winze in which a small lens of ore rich in gold and silver is reported to have been found. In 1921 a diamond-drill hole 170 feet long was sunk from the surface and connected with the drift.

Tucker (1923, p. 91) describes a second tunnel north of the main tunnel at an altitude of 1,350 feet, called the Porter tunnel, as trending due west for 600 feet. At 250 feet from the portal a 100-foot raise connects with the surface. An ore shoot about 40 feet long and 4 to 6 feet wide, containing 6 percent copper and $8 in gold and silver, is reported to have been developed in this raise.

A third tunnel described by Tucker (1923, p. 91) is 80 feet long and cuts a sulfide lens 50 feet long and 8 feet wide. The lens strikes N. 30° E. and dips 30° SE. (probably parallel to bedding). The sulfide minerals are chiefly pyrite and a little chalcopyrite.

No ore has been produced from the Shasta May Blossom prospect, but because of the strong showing of sulfide minerals, intense silicification, and favorable host rocks it is regarded as a moderately favorable prospecting area. The one feature that seems to be missing is a strong shear zone, and for this reason we do not regard the Shasta May Blossom prospect as favorable an area for prospecting as other areas outlined on plate 3.

SUGARLOAF PROSPECT

The Sugarloaf prospect, in the northeastern part of sec. 4, T. 33 N., R. 2 W., is on the contact between the Bully Hill rhyolite and the Pit formation. A quartz vein 1 to 2 feet thick strikes about east-west and dips about 50° N. (pl. 3). In places the quartz contains pyrite, galena, and sphalerite. In other places sulfide minerals occur as a replacement of the wallrock. According to Averill (1939, p. 162) the prospect is explored through a vertical range of about 160 feet by a 25-foot shaft and 2 adits, an upper adit 250 feet long, and a lower one about 800 feet long. The last 50 feet of the upper adit is a drift along the contact between the Bully Hill and Pit formations and sulfide minerals are exposed at several places. The last 400 feet of the lower adit, which is 120 feet lower than the upper one, also follows the Bully Hill and Pit contact. Averill (1939, p. 162) states that sulfide minerals occur in the last 25 to 30 feet of the lower adit, and that the face, which is in the Bully Hill rhyolite, shows 2 feet of ore containing pyrite, sphalerite, and galena. Apparently this sulfide ore is a replacement of the Bully Hill rhyolite.

So far as could be determined no ore has been produced from the Sugarloaf prospect. However, the showing here and at the Old Indian (F. J. Ward) prospect nearby is sufficiently promising to make this locality one of the more favorable prospecting areas.

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