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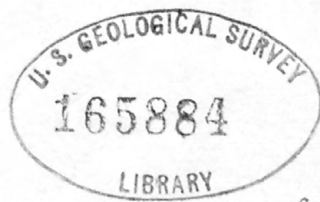
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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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

by

John P. Albers
U. S. Geological Survey
Menlo Park, California

October 1957

✓
U. S. Geological Survey
OPEN FILE REPORT

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UNITED STATES
DEPARTMENT OF THE INTERIOR
Geological Survey
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Geology and ore deposits of the East Shasta copper-zinc district, Shasta County, California

Abstract

The East Shasta copper-zinc district covers about 90 square miles in central Shasta County, California. It 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. A large part of Shasta Lake, formed by the impounding of the waters of the Sacramento, McCloud, and Pit Rivers, and of Squaw Creek behind Shasta Dam, is within the map boundaries. Maximum relief is about 3500 feet. The highest mountains rise to altitudes of over 4000 feet.

The map area is underlain by interbedded sedimentary and volcanic rocks that range in age from probable Middle Devonian to Upper Triassic. The formations, from oldest to youngest, include the Copley greenstone, Balaklala rhyolite, Kennett formation, Bragdon formation, Baird formation, McCloud limestone, Nosoni formation, Dekkas andesite, Bully Hill rhyolite, Pit formation, and Hosselkus limestone. 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. About 50 to 60 percent of the section consists of volcanic rocks. During probable late Jurassic 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 numerous dikes and sills of fine-grained mafic igneous rocks. These sedimentary, volcanic, and intrusive rocks constitute the basement rocks of the area. In the southeastern part of the area the basement rocks are overlain unconformably in places by the Tuscan formation, a poorly lithified tuff breccia and by basaltic lava of Pliocene age. Recent slope wash, talus, landslide debris, and alluvium obscure the bed-rock in much of the area.

The oldest rock unit exposed in the Copley greenstone of probable Middle Devonian age, consisting of at least 2000 feet of intermediate lavas (keratophyre) and pyroclastic rocks. The age of the Copley is not precisely known but it underlies rocks of Middle Devonian age with apparent conformity and is presumed to be of Devonian age.

The Balaklala rhyolite, about 1000 feet

thick, overlies and is interbedded with the Copley greenstone on the western side of O'Brien Mountain. It is a series of silicic lava flows and pyroclastic rocks altered to quartz keratophyre. The Balaklala, which is highly lenticular and of small areal extent, has a maximum thickness of about 1000 feet in the East Shasta area.

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

The Bragdon formation of probable Mississippian age and consisting of shale, mudstone, conglomerate, and minor tuff, overlies the Kennett formation with probable unconformity. The thickness of the Bragdon ranges from a thin film to about 3000 feet.

The Baird formation of Mississippian age and having a thickness of 3000-5000 feet lies next above the Bragdon formation. These two units are probably separated by a disconformity.

The Baird has a thickness of 3000-5000 feet. It consists of intermediate volcanic rocks and mudstone, minor limestone, and chert. The formation contains abundant fossils of Mississippian age.

The McCloud limestone consisting of gray limestone and some chert is next above the Baird formation but the two units are separated almost everywhere by intrusive rock. 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 hard to determine because the formation is not everywhere present and is separated into discrete blocks by faults filled by intrusive rock. The maximum thickness is probably about 2500 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 left-lateral fault along which mafic quartz diorite is intruded. Owing mainly to this fault the Nosoni is missing in some places. The Nosoni, which contains abundant fossils of Permian (Leonard or Word) age, consists chiefly of mudstone and fine grained tuffaceous rocks.

The maximum thickness of the Nosoni is about 2000 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 (Guadalupian) age. The upper part of the Dekkas, which consists chiefly of lava flows, may be of Triassic age. The thickness of the Dekkas ranges from 1000 to 3500 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 of the Bully Hill rhyolite type are locally interbedded with the Dekkas andesite, and mafic rocks of the Dekkas andesite type 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 2500 feet.

The Pit formation of Middle Triassic age conformably overlies the Bully Hill rhyolite. It consists principally of shale, mudstone, and pyroclastic rocks, with subordinate limestone and siltstone. The pyroclastic rocks are lithologically similar to those in the Bully Hill rhyolite, indicating that the volcanism that gives rise to the Bully Hill rhyolite continued sporadically after deposition of the Pit sediments began. The Pit formation contains fossils of Middle and Upper Triassic age. Its maximum thickness is about 5000 feet.

The Hosselkus limestone of Upper Triassic age conformably overlies the Pit formation. The Hosselkus forms the northeastern boundary of the map area and it was not studied in detail.

Intrusive into the above sequence of sedimentary and volcanic rocks is a small stock of granodioritic rock partly altered to albite granite, and numerous dikes of altered fine-grained mafic quartz diorite, metadiabase and dacite porphyry. Practically all the intrusives are in the western third of the map area. They were emplaced after the sedimentary and volcanic rocks were deformed and are of probable late Jurassic age.

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 greater or less extent but retain their original textures and structures. Only locally in the extreme southeastern part of the area and in the vicinity of Bully Hill do the rocks have a secondary foliation that has largely obliterated original textures and structures. Sedimentary rocks, because of their more stable mineral assemblages, have suffered less alteration than volcanic and intrusive rocks.

Alteration processes that have been operative in the area include dynamic metamorphism, igneous metamorphism, and hydrothermal metamorphism. The alteration of rocks with secondary foliation, mainly in the eastern part of the district was accompanied by shearing and is therefore 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 the McCloud limestone to marble in the vicinity of the Shasta iron mine. Bodies of skarn, consisting of calc-silicate minerals and magnetite, have formed

by contact metasomatism locally in rocks adjacent to the quartz diorite along the McCloud fault zone. Hydrothermal metamorphism was the most important alteration process in the area. It resulted in widespread albitization, chloritization and silicification, and in somewhat more restricted argillie alteration and calcitization. Sodium and silicon were the main substances added during alteration and calcium was the main substance removed.

The sedimentary and volcanic components of the basement rocks were deformed by folding and faulting. The oldest formations are exposed in the core of a large northeast-trending 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 in gross aspect 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 left lateral strike-slip fault between the McCloud and Nosoni formations along which mafic quartz diorite is intruded, disrupts the homocline in the western part of the area. In marked contrast to the north-

northeast structural trend shown by the pattern of major rock units, a northwest trend, defined by a series of northwest-trending folds and locally by a steeply dipping secondary foliation predominates in the eastern and southeastern part of the area. Lineations and observed plunges indicate that these northwest-trending folds plunge alternately northwest and southeast. Weakly developed northwest-trending cross folds are superimposed on the north-northeast-trending anticline and homocline in the western part of the area.

The basement rocks are also disrupted by high angle faults and shear zones. In the eastern and southeastern part of the area these high angle faults strike predominantly northwest, but from Bully Hill and vicinity westward faults that strike northeast are almost as common as those that strike northwest. The high angle faults are subdivided into strike faults and transverse faults. On most of the high angle faults the hanging wall is displaced downward with respect to the footwall. A few faults, however, chiefly the larger ones, show the hanging wall displaced upward. Because of the

lack of reliable reference beds, and the 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 largest faults have displacements of a few hundred to possibly a few thousand feet. In the central and extreme southeastern parts of the map 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 a mile long and 200 feet thick. Thin sections show that a good deal of distributed movement has taken place within the shear zones, but the contact between adjacent formations seem to be displaced hardly at all by the shear zones. It appears that these shear zones have mostly strike slip and reverse slip displacement.

Virtually all the folding and much of the faulting took place either before, or possibly contemporaneously with, the emplacement of intrusives was largely controlled by faults. Small faults cut some intrusive bodies. Mineralization postdated rock deformation, as shown by the fact that sulfide bodies are localized almost entirely along shear zones and faults.

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

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 lavas.

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 500 feet, but most weathering 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 map area lies mostly in the Klamath Mountain geomorphic province. The small part of the area south of the Pit River arm is in the Cascade Range province. Two of the five main streams, the Sacramento River and McCloud River, are more or less 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 formed, Little Cow Creek has incised itself 600 to 800 feet into the basement rocks, 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.

From 1900 through 1952 nearly 60 million pounds of copper, 50 million pounds of zinc, and small quantities of silver, gold, and lead were produced from the district. The total value of these metals is about \$16,000,000, 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 intermittent. The principal periods of activity

were 1900 to 1910 when copper was the principal metal produced, and 1922 to 1927 when the main interest was in zinc. The most recent production from the district was during the years 1949 to 1952, when copper-zinc ore was produced.

Three types of deposits present in the district are (1) massive sulfide replacement deposits, (2) contact metasomatic magnetite deposits, and (3) minor gold-bearing quartz veins. Virtually all the base and precious metal production has been from massive sulfide replacement deposits. These deposits are the main subject of the present report and the other two types of deposits are discussed only briefly.

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 formation. The sulfides replace either sheared and altered quartz keratophyre or shale. Sulfide lenses are commonly closely grouped along shear zones, but isolated lenses are by no means rare. Contacts between massive sulfide and host rock are in most places sharp but in a few places gradational. Typical ore is an intimate mixture of

fine-grained pyrite, sphalerite, and chalcop-
pyrite, and smaller amounts of galena, tetrahe-
drite-tennantite, and bornite. Gangue minerals,
which are intimately mixed with the ore miner-
als, include barite, quartz, clay minerals
(mainly hydromica), 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 to
2 percent lead, 5 ounces of silver, and .03 ounce
of gold. Although reversals are not uncommon,
the general paragenetic sequence among the prin-
cipal ore minerals is, from oldest to youngest:
pyrite, sphalerite-chalcoppyrite, 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 interme-
diate 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 near the sulfide deposits are in general more strongly silicified and altered to clay minerals, mainly hydrous mica, than elsewhere, but there is no distinctive alteration envelope around individual sulfide lenses.

The structural environment of sulfide lenses indicates that they 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 was beneath the intersection of a feeder channel and a fault that cuts the feeder channel at a considerable angle. The impermeable barrier thus formed apparently 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: 1) the presence of unsupported masses of host 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 horizons of host rock were not moved during mineralization; 2) banding in the sulfide at places parallels bedding or foliation in the host rock; the banding is nowhere crustified; 3) the presence, in some places, of a gradational contact between massive sulfide and host rock.

The deposits are believed to have formed from ascending hydrothermal fluids. Possible sources of these fluids and the substances they carried were: 1) a subjacent igneous mass of which the Pit River stock may be a cupola; 2) the volcanic and sedimentary rocks that lie beneath the Bully Hill rhyolite and the Pit formation, or 3) a combination of (1) and (2).

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 relationship 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, at least the H_2S required in the mineralization process, were derived from the postulated subjacent mass cannot be dismissed.

Quantitative spectrographic analyses show that the copper contained in samples of volcanic rocks from the Dekkas and Baird formations remote from mineralized areas is about .01 per cent, or about the average for the earth's crust. The zinc content of these rocks is about .030, which is about twice the average of .013 percent for the basic igneous rocks. No quantitative data are available for the Copley greenstone. Using the most conservative values for copper and zinc content, the Dekkas and Baird formations and possibly also the Copley as well, contain about 1,000,000 tons of copper and 2,500,000 tons of zinc per cubic mile. Thus it appears 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.

Whether the greenstones could also have supplied

the H_2S necessary seems doubtful. Possibly the H_2S was derived from the trondhjemitic magma while the metals came from the greenstones.

Assuming that the mafic volcanic rocks of the eugeosyncline were the source of at least the water and metallic constituents, two mineralization mechanisms seem possible. 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 possibly containing H_2S derived from a magmatic source, moved generally toward areas of relatively 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 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 or palingenesis of mafic volcanic rocks buried deep in the geosyncline. In the formation of a granitic rock by either of these processes the valuable elements of ore deposits theoretically should be concentrated in inverse ratio to the extent to which they are incorporated by isomorphous substitution in the common rock-forming minerals. Consequently, in the conversion 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. It is unlikely that exposed granitic rocks in the district formed by granitization. However, it is probable that a significant volume of Copley greenstone and other mafic rocks deep in the geosyncline were either assimilated by granitic magma or converted to granitic rocks by palingenesis. If so, the copper and zinc expelled would have been available for concentration in ore deposits in structurally favorable places higher in the crust.

The sulfide mineral assemblage is typically

mesothermal. The depth at which the sulfides formed was not greater than 11,650 feet, as this is the maximum stratigraphic cover that could have overlain the Bully Hill rhyolite. Inasmuch as deformation largely preceded sulfide mineralization it seems probable that a good deal of erosion of this stratigraphic cover took place before mineralization; thus the deposits may have formed at depths much less and 11,650 feet.

Five blocks of geologically favorable ground for prospecting are outlined. High grade sulfide lenses should be present in these areas. However, judged 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.

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

Introduction

Location and accessibility

The area described in this report includes approximately 90 square miles in west-central Shasta County, California (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 map is bounded on the west by the 122° 22½' W. meridian, and on the south mainly by the 40° 45' parallel, although the extreme southeastern part of the map extends about 3 miles south of that parallel.

U. S. highway no. 99, and the Southern Pacific railroad cross the western part of the map area, and U. S. highway no. 299 E. crosses the southeastern part. A large part of the Shasta Lake lies within the boundaries of the map area and much of the central part of the area including the Shasta Iron mine and most of the map area west of Horse Mountain, is accessible only

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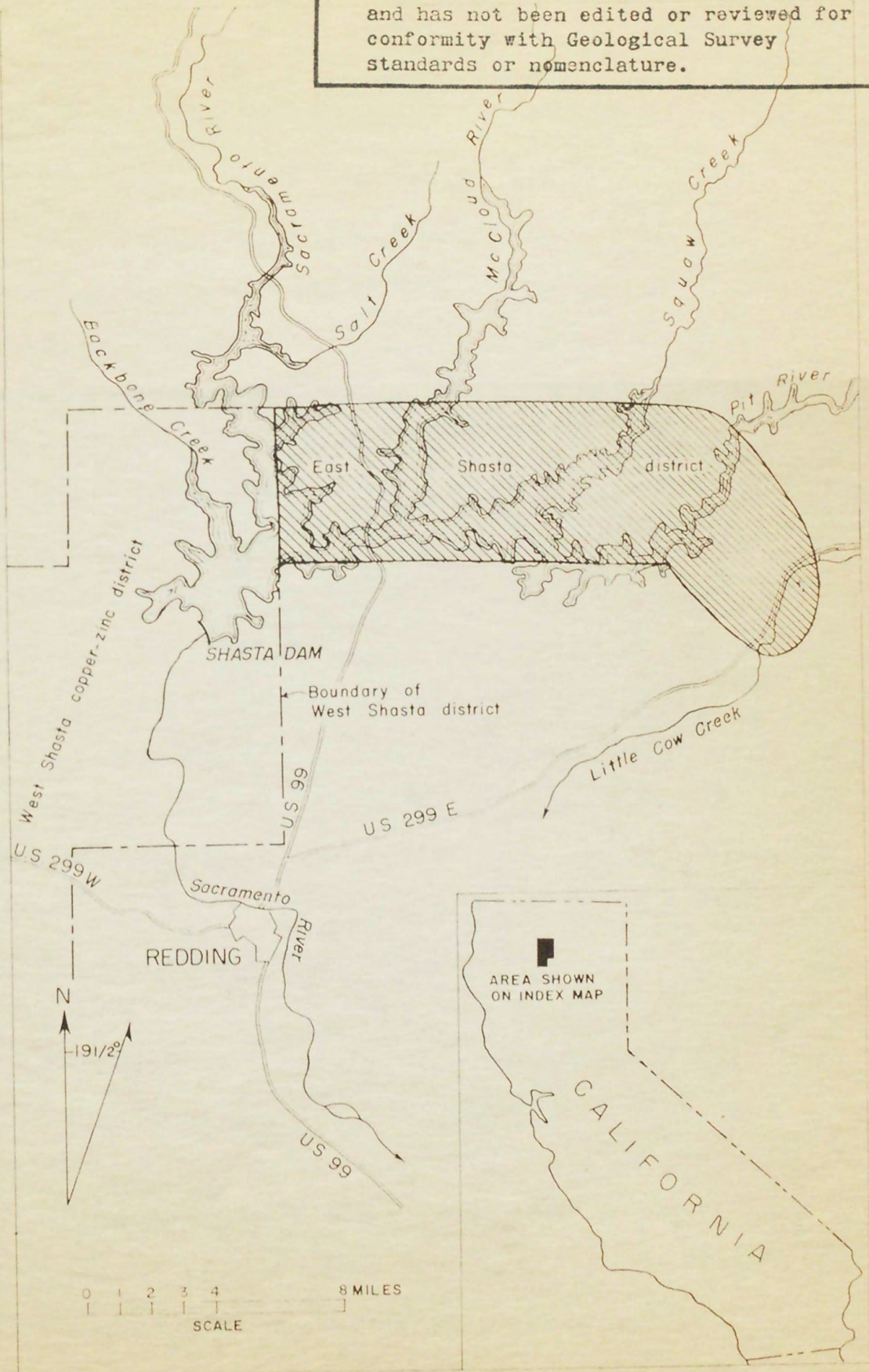


Figure 1. Map showing location of the East Shasta copper-zinc district

by boat. The Bully Hill mine is accessible by boat or via U. S. highway no. 299 E and a good dirt road.

Topography

The topography ranges from that of a partially dissected plain with a few hundred feet of relief in the southeastern part of the map area, to that of a rugged, maturely dissected surface with more than 3500 feet of relief in the north-central part. (See plate 1).

North of Backbone Ridge the canyons of the Pit River, Squaw Creek, the McCloud River, and the Sacramento River, now inundated by the waters of Shasta Lake, are the dominant topographic features. The highest peaks are O'Brien Mountain, altitude 2709 feet, on the divide between the Sacramento and McCloud arms of Shasta Lake, Horse Mountain, altitude 4025 feet, and Town Mountain, altitude 4325 feet, on the divide between the McCloud River and Squaw Creek arms, and Brock Mountain, altitude 2724 feet, on the divide between the Squaw Creek and Pit River arms. The waters of Shasta Lake have a maximum altitude of 1065 feet but generally stand at an altitude of 1000-1050 feet. The maximum depth is about 350 feet in the map area.

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 five 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. / The mean average

/ Weather data furnished by U. S. Bureau of Reclamation, written communication.

temperature during the coldest month, January, was 42.04° F for the five year period, with a minimum of 22° F recorded on January 25, 1950. The mean average temperature during July, the hottest month, was 80.86° F. for the five year period. The highest readings, 111° F, were recorded on September 2d and 3d, 1950.

Most hillslopes in the map area are brush-covered, with manzanita (Arctostaphylos sp.), and several species of scrub oak and chaparral being the most common types of brush. A single type of brush commonly predominates on a given hillside. At higher altitudes, especially on north hillslopes, groves of sugar pine

(Pinus lambertiana), and ponderosa pine (Pinus ponderosa) stand out in marked contrast to the surrounding brush-covered areas. At lower altitudes, especially in the southeastern part of the map area, digger pine (Pinus sabiniana), and oak (Quercus douglassi), and (Quercus wizlizenii) dot many of the low, grassy hills.

Previous work in the district

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

The earliest reference to the geology appears 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 between 1893 and 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 Fairbank's 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 formation of northwestern California, briefly mentions the rocks east of the Sacramento River in the present map area.

The general stratigraphy of the Klamath Mountains, and also the geology of the copper deposits in the Redding area, was reviewed by Diller in 1903; and in 1906 the Redding folio, also by Diller (1906), was published. The excellent geologic map and descriptive text in this folio has served as a firm 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 (1934) 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 (1957) on the geology and base metal deposits of the West Shasta copper-zinc district, which adjoins the map area on the west, is in press.

In addition to the literature mentioned above short references to the activity of mines 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: (1) to work out the stratigraphy and structure of the area in detail; (2) to determine the stratigraphic, structural, and alteration environment of the known sulfide deposits; (3) to locate geologically favorable areas to prospect for hidden sulfide deposits; and (4) to tie the geology of the East Shasta copper-zinc district to the geology of the West Shasta copper-zinc district.

Mapping south of Backbone Ridge was done on air photos 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 scale would allow. Age determinations of rock units are based on fossils and on stratigraphic relations.

The accessible workings of the Afterthought and Bully Hill mines were mapped on a scale of 1 inch to 40 feet. The surface geology of the Afterthought mine area and of the Bully Hill-Rising Star mine area was mapped by plane table methods on a scale of 1 inch to 100 feet.

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

Field work and acknowledgements

Field work was begun by the author in July, 1949, and completed in September, 1952. Jacques F. Robertson assisted with the field work from February, 1950 to 1952.

E. M. MacKevett and C. D. Rinehart assisted in the field mainly with plane table mapping for about one month each during 1949 and 1951, respectively. A total of about 30 man months were spent in the field.

Fossil collections were identified by R. C. Douglass, Helen Duncan, J. T. Dutro, Jr., L. C. Henbest, C. W. Merriam, S. W. Muller, J. B. Reeside, and J. S. Williams. C. W. Merriam and S. W. Muller also spent four days in the field 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 methods.

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 writer is indebted to Doctors C. O. Hutton, Adolph Knopf, Eleanor Bliss Knopf, Ben M. Page, and C. F. Park, Jr., of Stanford University, and to L. D. Clark, W. E. Hall, and A. R. Kinkel, Jr., of the Geological Survey for 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. Stanford University provided the writer with office space and the use of a microscope from 1952 to 1954.

Thanks are due officials of the Glidden Company, 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 Company, 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 pack horses and supplies across Shasta Lake.

General geology and geologic history

The East Shasta map area is underlain by sedimentary, volcanic, and intrusive rocks that range in age from probable Middle Devonian to Late Jurassic or 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, Balaklala rhyolite, and Kennett formation, all of probable Devonian age, are similar lithologically to the Dekkas andesite, Bully Hill rhyolite, and Pit formation of Permian to Triassic age. Basic and intermediate volcanic rocks make up the lower part of each of these two sequences; silicic volcanic rocks overlain by shales and tuffs 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, dike-like mass of mafic quartz diorite, and numerous 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 almost all units, to marked facies changes within short distances, to recurrent lithologic types, to structural complications, and to poor outcrop. Thicknesses shown in plate 2 are estimated mainly from map measurements. The total mean thickness of the basement rocks, computed from map measurements, is 19,000 feet, of which 12,400 feet are rocks of Paleozoic age and 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 cross 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 map area is the dominant and persistent role played by volcanism in the build-up of

the stratigraphic column. Volcanic rocks are present 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 map 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 ⁶ if rocks of Triassic and Jurassic age exposed east of the map area are included - coupled with the character of the rocks, indicates deposition in a eugeosynclinal trough. Based on the regional distribution of Paleozoic and Mesozoic rocks, the trough was probably elongate in a north-south direction. Within the trough there were probably volcanic islands and 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. However, folding and faulting, as well as igneous intrusion and hydrothermal metamorphism, occurred mainly during the Nevadan orogeny probably in Late Jurassic^{or} Early

Cretaceous time.

The basement rocks are overlain with marked unconformity in the southeastern part of the map 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 go to make up the Copley greenstone and the Balaklala rhyolite. The intertonguing of these two units in places shows that lavas and pyroclastics 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 during late Middle Devonian time is inferred 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. Somewhat later during the Mississippian at least part of the area began to subside rapidly and was covered with several thousand feet of mud and poorly sorted gravel comprising the Bragdon formation. This was derived partly from erosion of the Kennett formation.

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 greenstones and breccias, 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. This was followed by emergence, northward tilting, and partial erosion of the limestone.

Resubmergence and renewal of volcanic activity took place during the 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 de-

posited. 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 good share 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 NW $\frac{1}{4}$ sec. 4, T. 33 N., R. 2 W. and in the NE $\frac{1}{4}$ sec. 16, T. 34 N., R. 3 W. A possible vent for the Dekkas andesite was in the NW $\frac{1}{4}$ 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, with continued subsidence and contemporaneous erosion, 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 formation as well

as the Hosselkus limestone.

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

No record of sedimentation or volcanism exists within the immediate map 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 map area. The presence of these rocks shows 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 map 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 southeastern part of the area. The Tuscan formation was laid down 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 map 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. A skim of limonite at an altitude of about 1700 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 1000-1100 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 rocks

Copley greenstone

Distribution, stratigraphic relations, and thickness

The Copley greenstone (Kinkel and Albers, p. 4, 1951), 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 map 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 probable 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. Cross section B-B' through O'Brien Mountain (pl. 1) suggests a minimum thickness of at least 2000 feet.

Lithology and petrography

The Copley greenstone consists chiefly of fragmental

and non-fragmental 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, gradations between the various 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 non-amygdaloidal lava, and porphyritic lava grades into non-porphyritic lava.

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

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

Non-fragmental mafic lava:--The non-fragmental mafic lava is 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 amygdules as much as one cm across were seen. 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, pumellyite, epidote, zoisite (?), celadonite, fine-grained white mica, sphene, leucoxene, quartz, kaolinite, and limonite. The texture is commonly porphyritic, with phenocrysts of albite that are pseudomorphs after original more calcic plagioclase. Groundmass textures are pilotaxitic or felty. On the basis of 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 the basaltic composition.

Block lava:--As used here the term block lava applies to fragmental volcanic rocks of monomict composition. It is similar to aa, and according to MacDonald (1953, p. 182), is characteristic of lavas more calcic 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, with the majority ranging from 6 to 10 inches in diameter. The mineralogy and texture of the block lava are identical to the mineralogy and texture of the non-fragmental lava described above and contacts between the two types of rock are commonly gradational.

Pyroclastic rocks:-- The classification of pyroclastic rocks used herein is essentially that of Wentworth and Williams (1932), slightly modified. The fragmental rocks of presumed pyroclastic origin in the Copley greenstone are of more heterogeneous character than the block lavas, as shown mainly by the heterogeneity of composition and texture of the fragments. The chief size categories of pyroclastic rock in the Copley are volcanic breccia, tuff breccia, and tuff.

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, with 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.

Volcanic breccia is especially 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 non-amygdaloidal lava, and flow-banded lava. In some places, especially where the Balaklala rhyolite is interlayered with the Copley greenstone, the volcanic breccia contains fragments of porphyritic and nonporphyritic quartz keratophyre. The quartz keratophyre / 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 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 important in

/ 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 calcic plagioclase. Some quartz keratophyre is porphyritic, and some is nonporphyritic. The groundmass is aphanitic.

that they commonly show bedding. The tuff and tuff breccia beds range from a few feet to about 100 feet thick. 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 places sparse fragments as much as 6 inches in diameter 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, 1957, p. 64) abundant pillow lava and tuffaceous mudstone in the Copley suggest that much of the formation was extruded into the sea. In view of the great areal extent of the Copley greenstone in northern California (Hinds, 1933, geologic map) it is probable 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 relationship to the overlying rocks. It is interbedded with rocks typical of the Balaklala rhyolite type and is overlain with apparent conformity by the Balaklala rhyolite in the West Shasta district. It is also overlain with apparent conformity by the Kennett formation in the O'Brien Mountain area of the East Shasta district. The Kennett formation and the Balaklala rhyolite are of Middle Devonian age (Kinkel and others, 1957, p. 16). Therefore the Copley greenstone is probably also of Middle Devonian or older.

Balaklala rhyolite

Distribution, stratigraphic relations, and thickness

About one 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 and petrographically similar to the Bully Hill rhyolite of Triassic age, which is the



chief host 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 especially common 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 intimately intermixed (Kinkel and others, 1957, p. 20). This relationship 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 appears from the above described relations that the Balaklala rhyolite is at least in part contemporaneous with the Copley greenstones.

The maximum thickness of the Balaklala rhyolite is about 1000 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 intimately 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 lithic 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 pre-

sence of 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.

Non-fragmental 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 with phenocrysts of quartz and feldspar, but in some places it is nonporphyritic. Phenocrysts in the porphyritic facies range from 0.5 mm to 6 mm in diameter. They are quantitatively subordinate to the groundmass. Quartz phenocrysts, although less numerous, are more conspicuous than the feldspar phenocrysts. Commonly individual flows contain phenocrysts that fall within a particular size range. Some flows are characterized by phenocrysts that range from 1 to 3 mm in diameter; others are characterized by phenocrysts as much as 6 mm in diameter; and still others 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 leucokene occur locally in very small amounts. The texture is commonly porphyritic, (fig. 3) and in some slides albite phenocrysts are grouped in clusters, giving a "glomerophytic" texture. Groundmass textures include felty, microgranular, and granophytic.

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 degrees. The optic sign is $(-\frac{+}{-})$, and the optic angle is large. Their properties correspond to plagioclase at least as sodic as An_5 . Albite of approximately the same composition forms lathes in the groundmass of the quartz keratophyre.

Quartz forms bipyramidal phenocrysts ranging from 0.5 mm 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 phenocrysts 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 refractive indices slightly

greater than 1.54. This material may be chalcedony.

Block lava:--Blocky lava is a common constituent of the Balaklala rhyolite though 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 blocky lava grades, in many places, into massive quartz keratophyre; in a few places it appears 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 an inch to about 15 inches in diameter. They greatly 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 relationship 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 sec. 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. 31-35), from a study of the mining district west of the Sacramento River believed the unit to be intrusive and renamed it alaskite porphyry. The character of the Balaklala rhyolite in the East Shasta map 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. (1957, p. 31-32.)

Age

No fossils were found in the Balaklala rhyolite in the present map area, but Kinkel and others have shown that in the West Shasta district the formation is overlain conformably by the Kennett formation of Middle Devonian age. Presumably the Balaklala rhyolite is of Middle Devonian age.

Kennett formation

General character and distribution

The Kennett formation is the oldest fossiliferous unit in the map area. The formation was named by Smith (1894, p. 591-593) from exposures between Squaw Creek

and Backbone Creek 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, 1957, p. 32).

In the East Shasta map area the Kennett formation forms a discontinuous belt as much as 1800 feet wide on the flanks of the O'Brien Mountain anticline. (see pl. 1). Dark gray siliceous shale, light brownish-gray fossiliferous shale, pyroclastic rocks, tuffaceous sandstone, and lenticular limestones are the chief lithic 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 minor faulting obscure the details of the relationship between the Kennett formation and the underlying formations. However, from relations seen in the West Shasta district (Kinkel and others, 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 maximum thickness of the Kennett formation is about 400 feet. A puzzling feature in view of the heterogeneous lithology and local absence of the formation is the uniform thickness of 300 to 400 feet that it maintains in most places where it is present.

Lithology

No well-defined stratigraphic sequence was recognized in the Kennett formation within the map 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 thick. The shale is bedded in layers ranging from 1 to 6 inches thick 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 much contorted and veined with milky quartz. This highly contorted siliceous shale may represent 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 a fraction of a mm 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 lens of agglomerate about 50 feet thick consisting of rounded porphyritic keratophyre fragments 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 an important horizon because it is the oldest rock in the East Shasta map area that has been dated by fossils. The best exposure is in the cut of an abandoned road in the NW $\frac{1}{4}$ 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. The limestone forms several discrete bodies ranging from 100 to 325 feet long and 40 to 50 feet thick on the east side of O'Brien Mountain. Locally, it contains minor chert. 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 it seems probable, as was first suggested by Diller and Schuchert (1894, p. 418), that it is at least in part a reef deposit. Kinkel, and others (1957, p. 35) from studies in the West Shasta district reached a similar conclusion.

Conditions of deposition

The presence of corals in sedimentary facies of the Kennett formation suggests 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 gave 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). Most age determinations have been based on 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 on lithologic grounds the limestone is assumed to overlie 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 this limestone is 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 writer making collections from some of the better fossiliferous localities. Collections were taken from the 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 is responsible for the following report on the age and correlation of Devonian rocks:

"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)"

" Fossils in the past identified as Devonian (Diller and Schuchert, 1894, Steuffer, 1930) occur in 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."

Bragdon formation

Distribution and general character

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 has an outcrop width of several miles, extending beyond the limits of the map, but on the east flank of the anticline the maximum outcrop width is about 3000 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 not present 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, with 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 in most places can be mapped with fair accuracy on the basis of lithology. The lower part of the Bragdon is very thin-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.

On the basis of regional mapping Diller (1906, p. 3, geologic map, and columnar section) concluded 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 a great deal of material derived from the Kennett, and that fossils indicate

a Mississippian age for the Bragdon, whereas the Kennett is of Middle Devonian age.

Kinkel and others (1957, p. 34-35) interpret the Bragdon and Kennett in the West Shasta copper-zinc map area to be essentially conformable. According to their 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 map area where erosion was taking place.

In the East Shasta map 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 relationship could not be definitely ascertained. An unconformity is suggested by the absence of the Kennett in some places (see pl. 1) and by the differing lithology of the Kennett immediately beneath the Bragdon. However, these features might also be explained by faulting. The fragments of limestone containing characteristic Kennett fossils in conglomerate beds in the Bragdon suggests an unconformity.

The thickness of the Bragdon formation ranges from a thin film near the mouth of Packers Gulch to at least 3000 feet in the extreme northwest part of the map. In the latter area the top of the formation is not exposed, and therefore the maximum thickness is undoubtedly greater than 3000 feet. Along the east side of O'Brien Mountain the maximum thickness is about 1600 feet, with an average thickness of about 1000 feet.

Lithology

The Bragdon formation is principally shale, mudstone, and conglomerate, with minor 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 thin-bedded to laminated, whereas the mudstone is flaggy, with beds several inches thick. In both the shale and the mudstone bedding is marked by slight color differences 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 five 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 is the most distinctive rock of the Bragdon formation and constitutes approximately 15 to 20 percent of its volume. It occurs as lenticular beds throughout the formation but is absent at the base. It forms hard, light gray or medium gray outcrops that stand out in marked contrast to the adjoining shale and mudstone. Conglomerate beds are common north and west of O'Brien Mountain but are sparse east of the mountain.

The conglomerate beds range from about 2 to 50 feet in thickness, but beds 10 to 20 feet thick are most common. Many 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 conglomerate beds lens out gradually along strike.

The conglomerate consists largely of chert fragments, with sparse fragments of limestone, greenstone, shale, white quartz, and sandstone. The fragments in most conglomerate beds range from grains a few millimeters in diameter 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 conglomerates 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 conglomerate 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 appreciably 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, mudstone-like matrix, crop out in the lower part of the Bregdon formation. One bed, about 50 feet above the base of the formation, crops out in sec. 18, T. 34 N., R. 4 W. on the east side of O'Brien Mountain. It averages about five 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 O'Brien 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 uncommon. 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 minor 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 the presence of 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 map. (pl. 1) This tuff bed, which lies about 3000 feet above the base of the Bragdon formation, is dark greenish-gray and massive. It contains feldspar crystals averaging about one mm in diameter, sparse, small crystals of ferromagnesian minerals, and sparse fragments of greenstone as much as half an inch in diameter. The matrix appears to be chiefly chlorite. Locally, this lithic crystal tuff grades into fine-grained silty tuff.

Tuff was also seen near the present mouth of Packer's Gulch, where at least two beds of tuff are inter-

bedded with the epiclastic rocks. One bed is about 100 feet above the base of the Bragdon formation and lies a few feet above a five 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 no. 92. 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 Packer's 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.

Thin section study reveals that the tuff in sec. 16 is lithic crystal tuff of two distinct petrographic types, one of andesitic or basaltic composition, with labradorite feldspar clasts, and the other of keratophyric composition, with clasts of albitized feldspar.

Conditions of deposition

Too small an area of Bragdon formation was mapped during the present study to permit speculation regarding source rocks and conditions of sedimentation but several features are suggestive of its source and mode of deposition. Most of the chert and all the limestone debris in the conglomerate were 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. That volcanoes were active intermittently is shown by the presence of pyroclastic rocks in the formation. One shore of the earliest Bragdon seas may have been near the now submerged mouth of Packers Gulch where shale of the Bragdon appears 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 being of Late Devonian or Early Mississippian age. Diller (1906, p. 3), on the basis of fossils found near Lamcine, a few miles north of the present map area, dates the Bragdon formation as early Carboniferous, and a Mississippian age is retained for this report.

Baird formation

Distribution and general character

The Baird formation crops out on both sides of the McCloud River arm of Shasta Reservoir and is assumed to be continuous beneath the submerged McCloud River valley. The outcrop width of the formation

ranges from about one mile to a little more than two miles and the general dip is 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 quartz diorite and is also much cut up by tabular bodies of mafic quartz diorite.

The Baird formation takes its name 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 shales, with subordinate beds of diabase and other eruptives 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 overlies 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 much minor faulting. The sparse conglomerate and comparatively small thickness 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 or 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 so cut up by small faults and by tabular intrusive bodies. A line of section drawn just north of Bailey Creek (see fig. 2) shows a maximum thickness of about 3000 feet, whereas a section drawn just north of the junction between the McCloud and Pit River arms of Shasta Reservoir shows a thickness of about 5000 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,

with minor 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 approximately 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 ferro-magnesian 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 phenocrysts and pyroxene crystals replaced pseudomorphously by uraltite in a groundmass of green amphibole, plagioclase, chlorite, stilpnomalene, epidote, magnetite, sphene, and leucoxene. Commonly the uraltite crystals contain small remnants of unreplaced augite. Most plagioclase phenocrysts are subhedral and range from .25 to 2.0 millimeters in diameter. They show normal oscillatory zoning, with cores slightly more calcic than 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 map 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 thick. It is poorly stratified and rarely shows bedding. The color

ranges from light greenish-gray through brownish-gray, to greenish-black. Lithic tuffs are more common than crystal tuffs but there are all gradations between.

Under the microscope the tuffs exhibit 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 celadonit^c_λ, 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 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, stilpnomelane, microcrystalline quartz, chlorite, epidote, sphene, leucoxene, fine-grained white mica, and pyrite. A striking feature 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 with commonly 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 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 two millimeters in diameter. These make up about 50 percent of the rock. Quartz clasts and lithic fragments are intimately mixed with the albite. Magnetite in layers averaging about one millimeter thick 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 it forms lenses interbedded with pyroclastic rocks, tuffaceous sandstone, and mafic lava in the lower part of the formation. 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 thick. Some beds contain abundant fossils. The tuffaceous mudstone commonly shows faint bedding and in a few places shows cross bedding.

In thin section the siliceous mudstone consists chiefly of microcrystalline quartz, with 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 .01 millimeter.

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 millimeter, but in some thin sections layers consisting of detrital grains of plagioclase as much as 0.5 millimeters in diameter were seen.

Limestone and chert:--Limestone partly replaced by chert crops out at an altitude of 1950 feet on a ridge at the north edge of sec. 3, T. 33 N., R. 4 W. This body of limestone has an outcrop width of about 200 feet on the crown of the ridge. It is about 25 feet thick. The limestone is light gray and contains abundant Lithostrotionoid corals and other fossils characteristic of the Baird.

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 rock and associated breccia that crops out along the east side of the McCloud River arm and in secs. 34 and 35, T. 34N., R. 4 W. are here considered as 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 separated in most places from the limestone by intrusive mafic quartz diorite.

Diller (1906, geologic map) apparently regarded these rocks as a facies of the quartz augite diorite intrusive mass. This interpretation cannot be positively 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 cross-cutting relations to adjacent rock units, and the local lenses of pyroclastic-like breccia suggest an extrusive origin.

The greenstone closely resembles the mafic flows of the Copley greenstone but differs from the latter 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 appears 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 constit-

uents of the greenstone apatite, amphibole, sphene, leucoxene, celadonite, leptochnorite, biotite, fine-grained white mica, pumpellyite, pyrite, and magnetite are minor constituents. Groundmass textures range from trachytic to hypidiomorphic microgranular.

The plagioclase forms phenocrysts ranging from 1 to 10 millimeters 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 some places. It replaces plagioclase and forms small grains and irregular clots in the groundmass. In some slides epidote is altered to chlorite, and the chlorite is in turn altered to leptochnorite. 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 some places it 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 some 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. Between was an interval dominated by marine sedimentation. As suggested by the intimate interbedding of 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 highland. The well sorted tuffaceous sandstone beds composed of slightly abraded feldspar grains and cleanly segregated layers of heavy minerals indicates that the water in which these sediments were deposited was probably shallow. The abundance of shallow water marine fossils including corals in the mudstone and limestone likewise shows 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 NW $\frac{1}{4}$, sec. 3, T. 33 N., R. 4 W. (field no. E 779), 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 E 779 from sec. 3 (U.S.G.S. locality 14983) in detail. Mr. Dutro examined the brachiopod-molluscan part of the assemblage, and Miss Duncan examined the bryozoans and corals. Mr. Dutro states (written communication):

"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 (deFrance)

Dictyoclostus cf. D. scabriculum Paeckelmann

"Productus" aff. "P." keokuk Hall

Echinoconchus aff. E. punctatus (Martin)

Spirifer cf. S. brazerianus Girty

Spirifer sp.

Torynifer? sp.

Parallelodon aff. P. reticulatus (McCoy)
Parallelodon aff. P. singulatus (McCoy)
Parallelodon aff. P. verneuillianus (deKoninck)
Parallelodon sp.
Schizodus sp.
Aviculipecten aff. A. fimbriatus (Phillips)
Aviculipecten aff. A. dissimilis (Fleming)
Aviculipecten sp.
Amusium? sp.
Pinna? sp.
Pteronites? sp.
Straparollus (Straparollus) sp.
bellerophonitid gastropod, genus indet.
pleurotomariid Gastropod, genus indet.
pseudozygopleurid gastropod, genus indet.
murchisonis (?) gastropod, genus indet.
Mooreoceras? sp.
ostrocodes, 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 Brazier 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 C₁st (Steshevskiy) horizon. These include:

Orbiculoidea aff. O. damanensis Sokolskaja
Isogramma cf. I. pachti (Dittmar)
"Cancerinella" cf. "C." undata (deFrance)
Echinoconchus aff. E. punctatus (Martin)
Dictyoelostus D. scabriculum 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 bryozoa and corals from the same locality (U.S.G.S. 14983) in sec. 3, T. 33 N., R. 4 W., (field no. E 779) Miss Duncan reports (1952, written communication):

"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 or-

dinarily 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 Lithostreton 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 (Visean) 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 (1953 oral communication) reports a fragment of a gigantoproductid brachiopod in this material. Gigantoproductus is a form characteristic of the Baird formation and is indicative of a Mississippian age.

McCloud limestone

General character and distribution

The McCloud limestone is the most prominently exposed formation in the map area. It consists mainly of light gray limestone that forms large cliffs along the east side of the McCloud River arm of Shasta Reservoir from the Shasta Iron mine in sec. 26, T. 34 N., R. 4 W. northeastward to the map 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 one 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, and pls. 1-2), Whitney (1865, p. 326-327), Fairbanks (1893, p. 35) 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) considered the McCloud limestone to be of Pennsylvanian (Upper Carboniferous) age. More recently Wheeler_, and Thompson, Wheeler, and Hazard (1946, p. 21-36) have contributed systematic studies of the fauna of the McCloud limestone, especially the fusilinids, 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 map area, the limestone is almost everywhere separated from these three formations by mafic quartz diorite. The quartz diorite is intruded partly 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

_/Wheeler, H. E., The fauna and correlation of the McCloud limestone of northern California; unpublished thesis, Stanford University, p. 1-166.

in the southeast part of sec. 12, in the central part of sec. 23, and in the southwest 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 trend 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 supported by 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 although it is probably separated from these two units by pre-intrusive 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 much broken by 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 2500 feet and possibly as much as 5000 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 fusilunid horizons as was done by Wheeler_/ 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 Creek and Potter Creek is about 2000 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

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.

_/Wheeler, H. E., 1934, op. cit.

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

Some limestone beds are richly fossiliferous. Limestone beds containing abundant fossils are commonly a fraction of an inch to several feet thick. Most of the fossils are fragmentary and are composed of fine-grained calcite, fine-grained quartz, or a mixture of calcite and quartz, depending on the degree of replacement by quartz. Beds with abundant fusulinids commonly have a mottled appearance, the fusulinids being 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 Creek and Potter Creek consists of ovoid bodies of calcite, ranging from a quarter of an inch to 2 inches in diameter. Wheeler_/ regards these ovoid masses as stromatoliths of inorganic origin.

_/Wheeler, H. E., 1934, op. cit.

In some places near mafic quartz diorite the limestone is coarsely crystalline or is altered to tactite. The most altered phases of the McCloud limestone are in the vicinity of the Shasta Iron mine in sec. 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 are 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.

Chert:--Chert of replacement origin, comprises about 5 percent of the McCloud limestone. It 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 two feet in diameter. Most chert lenses are approximately parallel to bedding in the limestone but some

cut across the bedding. The upper and lower edges of the chert lenses are commonly very irregular in detail. In some places chert nodules appear to coalesce into lenses along strike. Locally chert predominates over limestone through 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 cross-cut by the chert.

Conditions of deposition

The abundance of colonial corals and fusulinids, which are known to have 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 derived from calcareous sand. The absence of biohermal and biostromal structures indicates that it is not a reef limestone. The abundance of fusulinids shows that deposition may have taken place far from shore because, according to Moore and others

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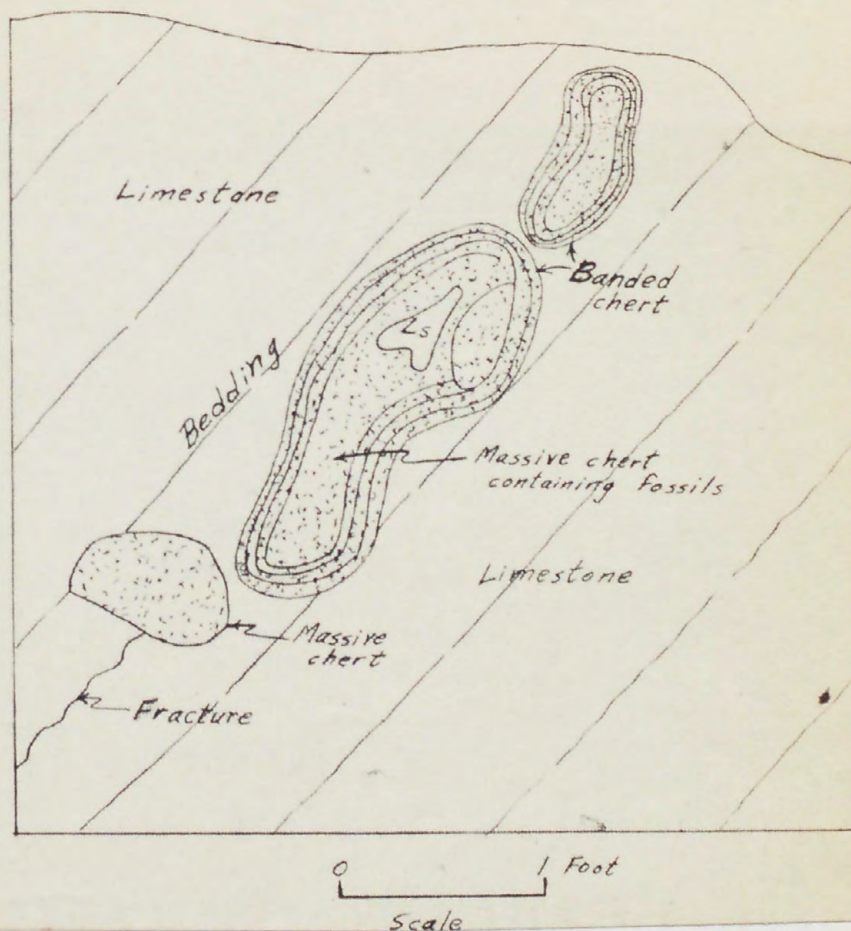


Figure 3--Sketch of chert bodies in the McCloud limestone on ridge between Marble Creek and Potter Creek. Note the concentric banding in the largest body of chert, and the remnant of unreplaced limestone in the central part of the kidney-shaped body.

(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 Creek and Potter Creek were identified by Lloyd G. Henbest and Raymond C. Douglass. Their findings are as follows (1952, written communication):

Field U.S.G.S. no. Collection no.	Stratigraphic posi- tion (approx.)	Fauna and age
31 f-9009	Upper 15-20 feet of exposed McCloud ls.	<u>Pseudofusulinella</u> aff. <u>P. occidentalis</u> (Thompson and Wheeler) <u>Schwagerina</u> sp. <u>Parafusulina</u> sp. Age: Hueco
28 f-9008	About 1500 feet above apparent base of the Mc- Cloud ls.	<u>Pseudoschwagerina</u> sp. Age: Hueco
25a f-9013	About 250 feet above apparent base of the Mc- Cloud ls.	<u>Bradyina</u> sp. <u>Schwagerina</u> sp. <u>Pseudoschwagerina</u> sp. Age: Hueco, poss- ibly Leonard

Two specimens of corals one a cup 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(1951 and 1956, written communications):

"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 the 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."

On the basis of the faunal data it seems highly probable that most of the McCloud limestone is of

Hueco (Wolfcamp) age although the anomalous F-2013 collection may be Leonard.

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 northwest 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 northwest part of sec. 18, T. 34 N., R. 3 W. northeastward to the edge of the map. 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 six miles north of the East Shasta map 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 field work has shown, however, that between Horse Mountain and Town Mountain (pl 1) lenses of tuffaceous rock containing Paleozoic fossils inter-finger 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, at a horizon where predominantly fine grained tuffaceous sedimentary rocks are overlain by generally coarser grained pyroclastic rocks and mafic lava such as characterize 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 map area the Nosoni formation and the McCloud limestone are everywhere separated by intrusive rock and by a pre-intrusive fault (pl 3) so that the stratigraphic relations between the two units are

obscure. That the Nosoni formation succeeds the McCloud limestone in the stratigraphic column is known from paleontologic data and from stratigraphic relations seen by Wheeler_/ outside the map area, where the two units are in contact.

The Nosoni is probably separated from the McCloud by a disconformity as is suggested by: (1) the absence of fossils of early Leonard age in rocks above the McCloud limestone; (2) 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 (3) 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 SW $\frac{1}{4}$ sec. 22, T. 33 N., R. 4 W." This locality is about four miles south of the East Shasta map area.

The maximum thickness of the Nosoni formation on the ridge between Marble Creek and Potter Creek, 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 Mountain and Town Mountain the thickness, assuming

/ Wheeler, H. E., 1934, op. cit., 1934

an average southeast dip of 30 degrees and no repetition of beds by faulting, is estimated to be about 2000 feet.

Lithology and petrography

The principal lithologic components of the Nosoni formation are mudstone, tuffaceous mudstone, tuffaceous sandstone, and tuff. The unit also includes minor conglomerate, mafic lava, and mafic tuff breccia. These various rock types are so intimately 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 intimately interbedded with each other and with tuffaceous sandstone and tuff. Many beds of mudstone and tuffaceous mudstone are fossiliferous. Fusilinids are common in some beds, whereas brachiopods, bryozoa, and other fossils are common in other beds. Fusilinids rarely are present 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 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 is present 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 clasts, 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 divide between Marble Creek and Potter Creek. 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. None of the fragments in the conglomerate appear to have been derived from the McCloud limestone. However, Wheeler 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 map area.

op. cit., 1934

Conditions of deposition

The interbedding of volcanic rocks with mudstone containing shallow water marine fossils indicates 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 and brachiopods suggests that the waters of the Nosoni seas were probably warm.

Age and fauna

Fossils were collected from the Nosoni formation at two localities. Field locality 58 is in sec. 24, T. 34 N., R. 4 W., on the ridge between Marble Creek and Potter Creek, 200 feet above the apparent base of the Nosoni formation. Field 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 (1952 and 1953, written communication) report that fusulinids in the collection taken from locality 58 (U.S. Geological Survey no. f-9010) include:

"?Parafusulina californica (Staff)

Parafusulina 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 (1953, written communication) 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 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 (1953 written communication) 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 (1953, written communication) 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 Dielasma 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 lava 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 three miles north of the present map area.

Within the map area the Dekkas andesite is prominently exposed in a belt as much as two miles wide extending from the vicinity of Cove Creek in the southern part of the map northeastward through Horse Mountain and Town Mountain (pl 1). Mafic volcanic rocks correlated with the Dekkas andesite also crop out in the cores of anticlines in the southeastern part of the map area. Altogether, the Dekkas andesite is

exposed over an area of about 10 square miles with-
in 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 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 more or less 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) drew 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 Mountain and Town Mountain 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 pre-intrusive fault along the east side of the McCloud limestone (pls.1 and 3) 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 1000 feet to 3500 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 spilite rock correlated with the Dekkas andesite crops out in the northwest 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 map, where a weak foliation is present, 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 subordinate amount is spilite. These two petrographic types could not be differentiated in the field and can be distinguished from each other only with difficulty in thin section.

The spilites are dark greenish-gray, aphanitic rocks containing albite phenocrysts with an average diameter of about 2 mm and sparse amgdules 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 mag-

netite, 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 .5 mm in diameter. The texture is commonly porphyritic; in some places it is glomeroporphyritic (fig. 4). The groundmass texture in some specimens is pilotaxitic (fig. 5). In other specimens it is intersertal.

A chemical analysis of a spilite is given in table 1, 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, slightly amygdaloidal rocks that 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

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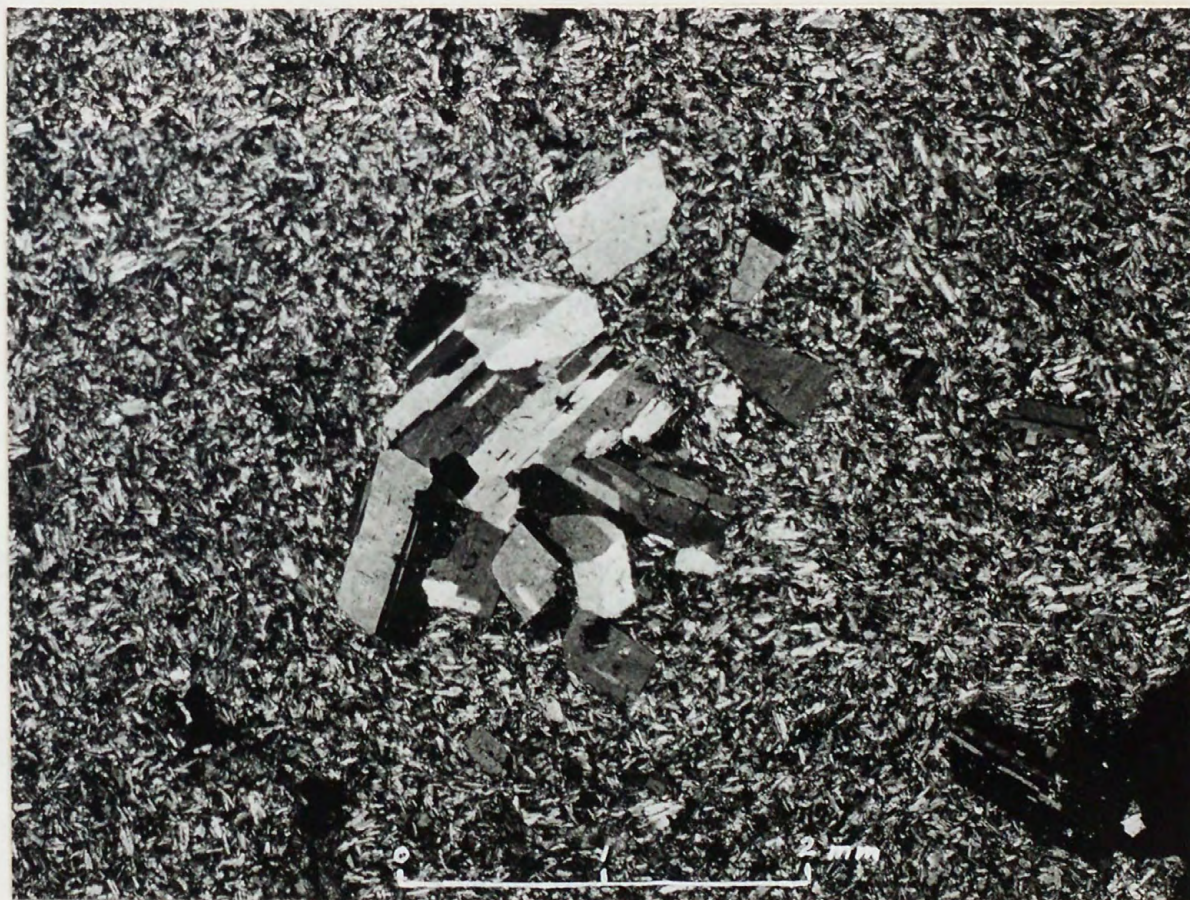


Figure 4--Photomicrograph of glomeroporphyritic keratophyre. Phenocrysts are nearly pure albite. Groundmass is albite laths with interstitial chlorite (X25).

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Figure 5--Photomicrograph of porphyritic amygdaloidal spilite with pilotaxitic groundmass. Principal minerals are albite (a) as microphenocrysts and groundmass lathes, chlorite (cl) as amygdule fillings and interstitial to albite in groundmass, pumpellyite (p) as amygdule fillings and interstitial to albite lathes, and quartz (q) which fills centers of some amygdules. Black grains are magnetite, which is disseminated throughout the rock. Some calcite is present (X 25).

Analyses of spilites and keratophyres

Bulk density	2.68	Not determined	2.65	Not determined
Powder density	2.72	Not determined	Not determined	Not determined

-94-

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 1, 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 irregular shaped masses.

Locations of analysed rocks listed in table 1

1. Spilite from upper Norton Gulch, southeast of Little Cow Creek, Shasta County, California. (Dekkas andesite). Harry Phillips, Joseph Dowd, and Katrine White, U. S. Geological Survey, analysts.
2. Average spilite, according to N. Sundius, Geol. Mag., vol. 67, p. 9, 1930.
3. Keratophyric lava from exposures near Horse Mountain trail in sec. 20, T. 34 N., R. 3 W., Shasta County, California. Harry M. Hyman, U. S. Geological Survey, analyst.
4. Keratophyre, Trevennen, Cornwall, (No. II, p. 209, Dewey and Flett, 1911). W. Pollard, analyst.

Amygdules are present in most of the spilites and keratophyres. In a few places amygdules are abundant and conspicuous but in most places they are sparse and erratically distributed. In general amygdules are more common in the spilites than in the keratophyres.

The amygdules range from a small fraction of a millimeter to more than an inch in maximum diameter; those less than five millimeters in maximum diameter are most common. The shape of the amygdules ranges from spherical to prolate; the smaller amygdules in general are nearly spherical, whereas larger ones have ratios of length to width as great as ten to one.

Chlorite is the most common mineral in the amygdules but quartz, calcite, pumpellyite, albite, barite, and celadonite are also present. Commonly two, or even three minerals, occur in separate layers of a single amygdale. Typical combinations of this sort include: 1) albite crystals oriented normal to and lining the wall of amygdules whose central part is filled with chlorite; 2) quartz linings with chlorite in the centers; 3) chlorite linings with an intermediate layer of a different type of chlorite, and pumpellyite in the center; 4) quartz lining with calcite in the center; and 5) chlorite linings with celadonite in the center. Several of the above combinations are present in some slides. A suggestion of possible feeders to the amygdules was found in one thin section. In this section

veinlets lined with microcrystalline quartz, with 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 northwest 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. That the mass is of intrusive origin is shown by its locally well-developed prismatic columns oriented normal to a steep unfaulted contact with gently dipping mudstone. 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 lath-like crystals of albite, having an average length of 0.5 millimeters, make up approximately 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 up to 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 degrees. 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. Most notable is its occurrence in a spilite flow that directly overlies the prominent mudstone layer extending between Horse Mountain and Town Mountain. This spilite flow is cut by the intrusive spilite described above. The close spatial relation of the augite-bearing intrusive spilite with an augite-bearing spilite flow of the same general character suggests that the intrusive body may mark the vent from whence came the flow.

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 it forms rosettes that show a deep anomalous blue interference color under crossed nicols. Its optic sign is negative and the mean refractive index is 1.605.

Sphene, with its alteration product leucoxene, occurs as cloudy patches and constitutes about two 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 map 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 is dense, siliceous, and dark-gray. It 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 keratophyres. Quartz, as highly corroded phenocrysts, forms about 5 percent, chlorite makes up 10 to 15 percent. Fine-grained white mica, calcite, epidote, leucoxene, and magnetite are present 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 are present 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 Mountain and Town Mountain, and locally in the extreme southeastern part of the map area. The breccia generally consists of fragments of various

textural types of keratophyre and spilite. In some places fragments of granitic rocks and quartz keratophyre are present 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 breccias grade into tuff breccias.

The tuff of the Dekkas andesite ranges from fine silty tuff to lapilli tuff. It forms beds ranging from 2 to 100 feet thick. The thinnest beds persist for less than 100 feet along strike but some of the thicker beds persist 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 color differences, or by differences 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 tuff are exposed in the upper part of Seaman Gulch and near the upper portion of Norton Gulch in the southeastern part of the map, and on the south slopes of Town Mountain and Horse Mountain. In most places the fine-grained tuffs are interbedded with coarser pyroclastic

rocks. Some lenses of tuff that crop out in the area between Horse Mountain and Town Mountain contain abundant fusilinids and other marine invertebrate fossils.

Mudstone:--Gray, siliceous mudstone is interbedded with the volcanic rocks of the Dekkas andesite on the upper slopes of Horse Mountain and Town Mountain. The most continuous mudstone bed was traced from the southwest side of Horse Mountain northeastward to the top of Town Mountain, a distance of about $3\frac{1}{2}$ miles (pl.1). The mudstone is olive-black on fresh surface but weathers to light brownish-gray. It 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 .05 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 the Dekkas andesite in the east-central part of sec. 8, T. 34 N., R. 3 W. (field locality D-207), and near the north edge of sec. 1, T. 33 N., R. 4 W. (field locality 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 (1906, geologic map), although according to his description of the Nosoni formation (1906, p. 4) he might have included them in the Nosoni had the fossils come to his attention.

Concerning the collection from locality D-207 (U.S. Geological Survey no. f-9010 b) L. C. Henbest

and R. C. Douglass of the U. S. Geological Survey state (1953, written communication) 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 examined the fossils other than fusulinids contained in the collection from locality D-207 and reports that (1953, written communication):

"It contains a specimen tentatively referred to Dietyoclostus 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 field collection F-142 from the northern part of sec. 1, T. 33 N., R. 4 W., and reports as follows: (1953, written communication)

"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 (1953, written communication) in collection F-142.

On the basis of fossil evidence it thus appears that the lower part of the Dekkas andesite is of late Permian (Capitan) 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 (1953, written communication), but

not significantly younger.

Diller (1906, p. 8) states that the Dekkas andesite is conformable with and interbedded with shales 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 writer to indicate that the upper part of the Dekkas is unconformable beneath the Pit formation and so 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 southeast parts of the map 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, with subordinate hypabyssal intrusive bodies. Much of the Bully Hill rhyolite is porphyritic, with 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 map area because most of the sulfide deposits occur as a replacement of its siliceous rocks.

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 as well as 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 volcanics are mapped with the Dekkas andesite. On the other hand, subordinate mafic lavas interbedded with silicic lavas in the upper part of Seaman Gulch 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, siliceous volcanic rocks are almost as abundant as shaly sedimentary rocks. Here some ambiguity exists as to the position of the Bully Hill-Pit contact.

The interbedding of volcanic rocks of the Bully Hill rhyolite type with the underlying Dekkas andesite and with the overlying Pit formation indicates that the Bully Hill rhyolite is essentially conformable with the enclosing formations.

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 2500 feet in the extreme southeast part of the map. (pl. 1 cross section A-A'). In the Bully Hill area the maximum thickness is estimated to be about 1500 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 map area shearing and alteration is locally so intense that the distinction between lava flows and pyroclastics is impossible. Therefore, some highly sheared and altered phases of the formation, shown as non-fragmental 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. Correlation of an individual lava flow or pyroclastic layer in a given locality with a rock of similar lithology elsewhere cannot be made with confidence 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 weak flow banding and sparse quartz phenocrysts 1 to 2 mm in diameter. This weakly flow banded quartz keratophyre is in turn overlain by quartz keratophyre with marked flow banding and with large quartz phenocrysts as much as six mm in diameter. Finally, on top, is volcanic breccia consisting chiefly of weakly porphyritic quartz keratophyre fragments of mixed sizes. This sequence was traced for about a half a 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 irregular-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 differs markedly among the various 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 with phenocrysts ranging from 1 to 3 mm in diameter is most common.

Feldspar phenocrysts are generally about the same size and 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 are present as phenocrysts and in the groundmass. The albite ranges in composition from Ab_{90} to nearly Ab_{100} . Most 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 specimens the groundmass is xenomorphic microcrystalline quartz and fine-grained white mica. The flakes of fine-grained white mica are arranged subparallel in schistose facies.

Albite phenocrysts are commonly idiomorphic 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 idiomorphic bipyramids to very irregular crystals with lobate outlines. Most commonly the quartz crystals are rounded and slightly embayed. The rounded and lobate shapes of some 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.

Locations of analysed rocks listed in table 2

1. Porphyritic quartz keratophyre (possibly intrusive) from lower Seaman Gulch in the southeast part of the East Shasta map area. Harry F. Phillips, Joseph Dowd, and Katrine White, U. S. Geological Survey, analysts.
2. Medium dark gray, porphyritic quartz keratophyre from northwest corner of sec. 15, T. 34 N., R. 3 W. Harry M. Hyman, U. S. Geological Survey, analyst.
3. 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. Harry M. Hyman, U.S. Geological Survey, analyst.
4. Quartz keratophyre from north central part of sec. 16, T. 34 N., R. 3 W., Shasta County, California. Harry M. Hyman, U. S. Geological Survey, analyst.

Table 2

Analyses of quartz keratophyres from the Bully Hill
rhyolite

	1*	2	3	4
SiO ₂	76.3	72.83	81.69	70.45
Al ₂ O ₃	12.4	12.77	10.66	14.47
Fe ₂ O ₃	1.1	2.55	1.74	1.25
FeO	1.9	1.15	0.09	2.07
MgO	0.69	1.45	0.59	1.38
CaO	0.74	2.07	0.06	0.85
Na ₂ O	6.0	4.38	0.14	5.99
K ₂ O	0.26	0.80	2.44	1.70
H ₂ O-	0.61	0.12	0.27	0.06
H ₂ O-		1.35	2.00	1.13
TiO ₂	0.20	0.35	0.11	0.36
CO ₂	0.39	0.18	0.00	0.22
P ₂ O ₅	0.02	0.10	0.04	0.10
MnO	0.06	0.04	0.01	0.05
Total	101	100.14	99.84	100.08
Bulk density	2.67	2.66	2.57	2.66
Powder density	2.67	Not determined	Not determined	Not determined

*Analysed by rapid methods

Non-porphyritic quartz keratophyre

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

In thin section the non-porphyritic quartz keratophyres are mineralogically and texturally similar to porphyritic facies with 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 of irregular distribution.

Fragmental quartz keratophyres

About half of the Bully Hill rhyolite is fragmental rock. Approximately 50 percent of the fragmental rock is blocky lava or flow breccia, and the remain-

ing 50 percent is pyroclastic rock, including volcanic breccia, tuff breccia, and tuff. A very minor amount of the fragmental rock appears to be of tectonic origin. On the geologic map (pl. 1) blocky lava is differentiated insofar as possible from pyroclastic rock.

The principal criterion used to distinguish blocky 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 blocky lava contains but a single variety. Generally a slight difference in color or texture enables one to distinguish fragments from matrix in both blocky lavas and pyroclastics. 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, i.e., whether holocrystalline, glassy, or clastic, cannot be determined.

Block lava:- Block lava, or flow breccia, (fig. 6) 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.

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Figure 6--Blocky, non-porphyrritic quartz keratophre on
ridge above the Copper City mine in the SW $\frac{1}{4}$ sec. 21,
T. 34 N., R. 3 W. The dark material (L), present
mainly in the upper part of the photograph is limonite
that replaces discrete blocks as well as part of the
breccia matrix.

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 non-porphyritic, massive non-porphyritic, and several facies of massive porphyritic. 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 essentially the same composition. Thin sections show that much of the matrix consists of nests of albite and quartz that appear to have been 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 on the one hand into

volcanic breccia, and on the other hand into tuff. It is not differentiated from tuff on the map (pl. 1).

The principal mass of tuff breccia is a sheet-like 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 a later page.

The tuff breccias have a poorly defined bedding structure that shows up 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 mm to 0.1 mm in diameter. Many of the 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 appear 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 albite phenocrysts by optically continuous quartz of presumed 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 (pl. 1) 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.

The tuff forms beds ranging from a few inches to about 50 feet thick and as much as half a mile long. It is most common in the southeastern part of the map area and in the vicinity of Bully Hill. Its color ranges from light brownish-gray to dark-gray. Some tuff is well bedded and some is poorly bedded.

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 cannot be distinguished from quartz keratophyre pyroclastics in the field and is not delineated on plate 1. Thin sections show that it is present mainly along the east and southeast sides of Bully Hill in a zone approximately parallel to the stratification. Metadacite pyroclastics may occur elsewhere in the Bully Hill rhyolite but have not been found.

The metadacite fragments in these pyroclastics are olive-gray to medium greenish-gray rocks. The microscope shows that they consist of quartz, albite,

plagioclase, ranging, in different specimens, from calcic oligoclase to calcic andesine An₂₇₋₄₉, chlorite, fine-grained white mica, sphene, and leucoxene. The texture is commonly porphyritic, with a xenomorphic micro-crystalline groundmass. Quartz and plagioclase form phenocrysts; some vermicular intergrowths of quartz and plagioclase resemble phenocrysts in hand specimen. The plagioclase commonly shows oscillatory zoning, with cores slightly more calcic than rims. In all slides veinlets and irregular masses of clear, un-twinned albite partly replace the plagioclase phenocrysts. The groundmass of the metadacite pyroclastics is commonly xenomorphic microcrystalline quartz.

Mafic lava and pyroclastic rock:--A few lenses of mafic lava and mafic 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 map between Little Cow Creek and Backbone Ridge. (pl. 1). It is indistinguishable petrographically from the mafic lavas 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 siliceous rocks in the upper part of Seaman Gulch, on the eastern

flank of Town Mountain and in the vicinity of Brushy Canyon. Fragments in these pyroclastics are chiefly keratophyre; a few light colored fragments are quartz keratophyre. The matrix of some mafic pyroclastics contains clasts of quartz.

Columnar structure

Columnar structure, consisting generally of four, five, and six-sided columns is developed locally in the porphyritic and non-porphyritic quartz keratophyres. It is best developed in non-porphyritic 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. In some places the 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 degrees 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. 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 in some places the markedly diverse orientation of neighboring groups of columns within short distances, may have resulted from slight movements in the lava when it was nearly consolidated. Or, if the Bully Hill rhyolite was extruded partly into the sea as appears probable, the diversely oriented columns may have resulted from many different cooling centers that would likely be set up in the extruded lava under submarine conditions. Slight fragmentation and brecciation of the columns in many places may also be in part attributable 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

A common feature in porphyritic facies of the

Bully Hill rhyolite are vermicular intergrowths of quartz and plagioclase that commonly have euhedral outlines. In thin section such intergrowths consist of discrete vermiform masses of quartz that extinguish simultaneously. 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. In metadacites it is oligoclase or andesine. Figures 7 and 8 show typical quartz-feldspar intergrowths.

That the vermicular quartz is a replacement of plagioclase rather than a eutectic intergrowth is suggested by the exceedingly irregular pattern of the quartz in the plagioclase and from the fact that different intergrowths contain vastly different proportions of quartz and plagioclase. (figs. 7, 8, and 9). Some intergrowths consist of only 20 to 25 percent quartz, whereas others are at least 90 percent quartz. Some plagioclase phenocrysts may be completely replaced by quartz.

A late magmatic rather than hydrothermal origin for the vermicular quartz is postulated because of its

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Figure 7--Photomicrograph of metadacite pyroclastic rock from southeast flank of Bully Hill. The phenocrysts are quartz (q), calcic oligoclase (O), and vermicular intergrowths of the two minerals. The vermicular quartz is interpreted as a replacement of plagioclase and is probably of late magmatic origin. The groundmass is chiefly xenomorphic microcrystalline quartz of hydrothermal origin; it locally replaces the plagioclase component of vermicular intergrowths, leaving vermiform quartz grains embedded in a groundmass of microcrystalline quartz that forms overgrowths on the vermiform quartz (X 50).

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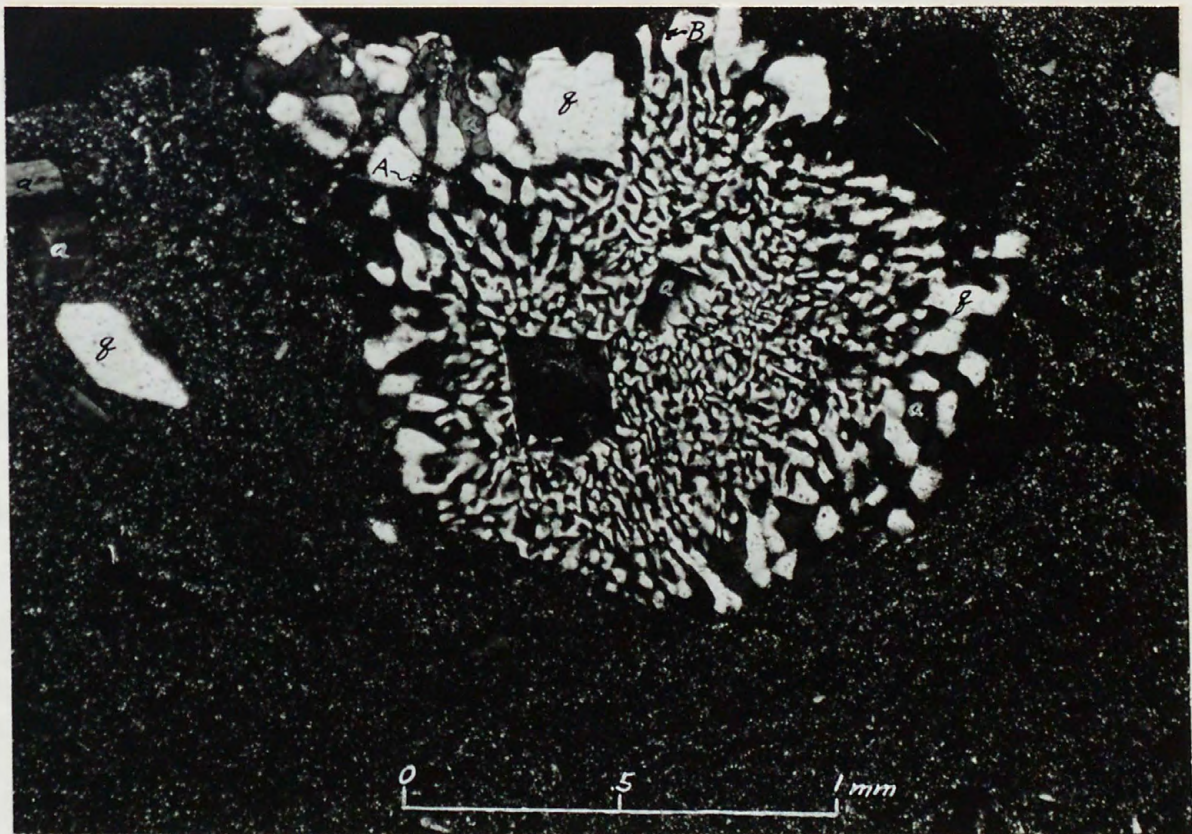


Figure 8--Vermicular relationship between quartz (q)
and albite (a) in quartz keratophyre. Near A and B
the microcrystalline groundmass quartz has partly re-
placed the albite of the intergrowth. Compare with
figs. 7 and 9 (X 50).

presence in rocks having either silicified or 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. (fig. 9).

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. That the microcrystalline quartz has actually replaced plagioclase is shown by a few key thin sections (fig. 7).

Origin

The origin of the Bully Hill rhyolite, like the origin of the Balaklala rhyolite, has been a matter of some 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 it 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

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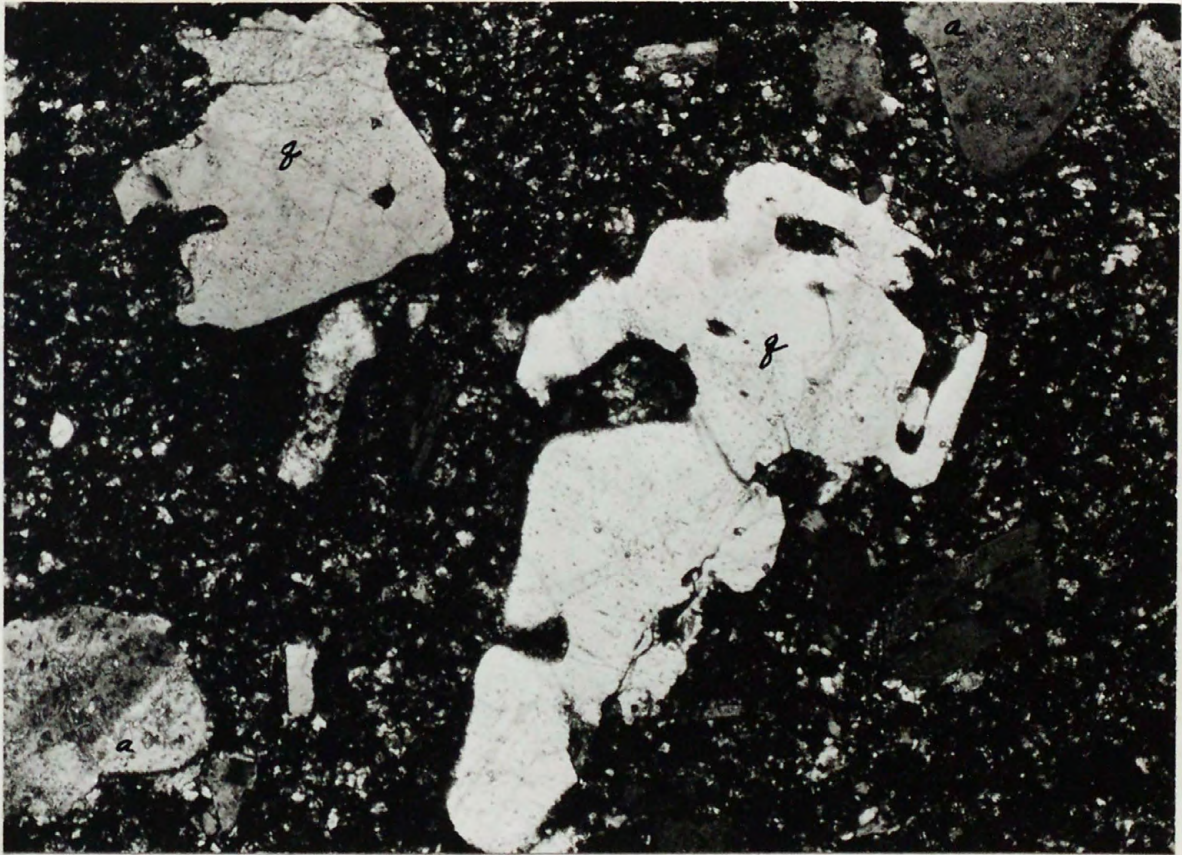


Figure 9--Vermiform quartz in quartz keratophyre tuff. The groundmass is secondary quartz and albite that partly replaces ragged albite crystals. The vermiform quartz (q) is interpreted to have been an intergrowth with (actually a replacement of) plagioclase (a). The plagioclase of the intergrowth has presumably been replaced by the secondary groundmass, leaving the highly irregular quartz. Compare with figures 7 and 8 (X 50).

and evidently he also considered 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, are intrusive into 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) have regarded the Bully Hill rhyolite and the Balaklala rhyolite as intrusive masses of similar age and character.

The writer concludes 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 aphanitic 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 intrusive 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 of the Bully Hill rhyolite type are interstratified with shale in the Pit formation. If the Bully

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

(3) The great lateral extent of the Bully Hill rhyolite and its small thickness compared to lateral extent. Including the portion 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 judged from Diller's regional map (1906, geologic map) it probably underlies a total of at least 100 square miles. The thickness, however, ranges from less than 100 feet to about 2,500 feet. A tabular intrusive body of this size and shape, and consisting of such exceedingly heterogeneous lithology, seems highly improbable. On the other hand, consideration of the Bully Hill rhyolite as a volcanic pile of silicic lavas and pyroclastics, 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 (1957, p. 31-32), after mapping the Balaklala rhyolite in the West Shasta copper-zinc district on a scale of 1:24,000 and studying its lithology and structural relations in commensurate detail, have also concluded that the Balaklala is largely of extrusive origin.

That the lavas and pyroclastics of the Bully Hill rhyolite were probably ejected from more than one vent is suggested by the differences in thickness and by the lithology. In the Bully Hill-Town Mountain area the volcanics may have come from a vent about a half a mile northeast of Bully Hill. This is suggested by (a) the heterogeneous lithology (fig. 2) (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 a great variety of rock types are present.

Age

The Bully Hill rhyolite overlies the Dekkas andesite 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 type was being erupted intermittently over a considerable interval of time. The Bully Hill rhyolite is

considered to be of Triassic age.

Pit formation

General character and distribution

The Pit formation, which consists principally of shale, mudstone, and pyroclastic rocks, with subordinate siltstone, limestone, and lava, underlies a roughly triangular area covering about 25 square miles in the northeast part of the map (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 the present report, except that three small bodies of limestone and one mass of lava near the east-central edge of the map, which Diller correlates with the Hosselkus limestone and 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 map 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. However, the pyroclastic rock in the cores of these anticlines consists mostly of coarse fragmental material more typical of pyroclastics in the Bully Hill rhyolite and therefore is correlated with that formation. The large mass

of metadacite and quartz keratophyre about a mile north-east of the Afterthought mine is mapped as a flow in the Pit formation but it may be part of the Bully Hill rhyolite.

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 map 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 rather closely folded almost everywhere in the map area and because of the intertonguing of the Bully Hill rhyolite with the Pit. However, a cross 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 5000 feet (see B-B', pl. 1). Diller (1906, p. 4) estimated the thickness to be "somewhat over 2000 feet".

Lithology

Shale, mudstone, and siltstone:--Approximately 60-70 percent of the Pit formation is shale, mudstone, and siltstone, undifferentiated on plate 1. These rocks are present 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 thick; 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 shales, mudstones, and siltstones ranges from medium gray to black on fresh surfaces; weathered exposures are commonly medium dark gray. Some shales 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 are present locally in fossil-bearing horizons.

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

Thin sections show that the shales and mudstones are composed principally of xenomorphic 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 is in the form of 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 shales and mudstones contain sparse, tiny clasts of quartz and feldspar. The clasts average about .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 here classed as siltstones. In some siltstones the feldspar clasts are albite, while 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 xenomorphic microcrystalline quartz.

Pyroclastic rocks:--Approximately 20 percent of the Pit formation is pyroclastic rock, including crystal tuff, lithic tuff, and tuff breccia. These volcanic rocks form beds ranging from a few inches to more than 100 feet thick. 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 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 along with sparse quartz crystal clasts and sparse 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. A few beds are graded. 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 of course cannot be differentiated in the field. A metadacite crystal tuff from the NW $\frac{1}{4}$ of sec. 22, T. 34 N., R. 2 W., which is fairly 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 An₃₀ to An₅₃. Many show normal oscillatory zoning; some 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 approximately 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 5-10 percent of the Pit formation exposed in the map 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 flows, not separable from pyroclastic rocks, are present in the lower part of the Pit formation south of Bully Hill and north of the Afterthought mine.

The mass of lava that is largely 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 through 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 .5 mm in diameter, in a felty groundmass of albite lathes, chlorite, sphene, and leucoxene. Minor amounts of calcite, prehnite, and pyrite replace other minerals in some slides.

About 1000 feet north of U. S. highway no. 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, 20-25 percent chlorite, 10-15 percent calcite, and minor sphene and leucoxene. Albite, chlorite, and calcite replace plagioclase phenocrysts; xenomorphic, 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 no. 299E, in the same body of lava, consist essentially of quartz and albite phenocrysts in a groundmass of xenomorphic, microcrystalline quartz

and chlorite.

Some of the quartz keratophyre lavas 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 very sparse, tiny quartz phenocrysts, and rounded feldspar crystals as much as 3 mm in diameter. Much of this lava has a close-spaced, platy parting that parallels the bedding in adjoining shales.

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

Limestone:--Several lenses of light-gray limestone containing abundant fossils are exposed in the extreme east-central part of the map area, north of U. S. highway no. 299E. The limestone lenses range from beds 1 foot thick and 10 feet long to beds 100 feet thick and at least 2000 feet long. Individual lenses are separated by shale. Some beds within the limestone lenses are composed chiefly of small brachiopods, ammonites, and belemnites as much as several feet long.

The limestone was correlated with the litholog-

ically similar Hosselkus limestone by Diller (1906, p. 4-5), but it is here considered as part of the Pit formation because: (1) the limestone is interbedded with shales and tuffs that are indistinguishable from those of the Pit formation; (2) the age of fauna in the limestone lenses is Middle Triassic, whereas the Hosselkus limestone according to Diller (1906, p. 5) is of Upper Triassic age.

Conditions of deposition

Deposition probably took place in the neritic depth zone, as is indicated by the presence of 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 suggests 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. 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 on by John B. Reeside of the U. S. Geological Survey as follows (1951, written communication):

"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 fig. 2.

		U.S. Geol.	
		Survey	
<u>Field</u>	<u>Number</u>	<u>Lithology</u>	<u>Fauna</u>
C-120	23313	Mudstone frag-	Juvenile ammonites, unde-
		ments in tuff	termined
C-213	23314	Limestone	Small rhynchonellid
			brachiopods, unnamed
			Eutomoceras ? sp.
			Arcestes (Proarcestes) sp.
			Ceratites? cf. C. occi-
			dentalis Smith
			Ceratites ? sp.
C-214	23315	Limestone	Ceratites (Paraceratites) sp. ?
			Arcestes (Pararcestes) sp. ?

<u>Field</u> <u>Number</u>	<u>U.S. Geol.</u> <u>Survey</u> <u>Number</u>	<u>Lithology</u>	<u>Fauna</u>
C-435	23316	Shale	Daonella sp.
C-856	23317	Shale	Arcestes (Proarcestes) sp. ?
D-273	23318	Shale	Indeterminable fragments of ammonites
D-572	23319	Shale	Eutomoceras sp. ?
D-646	23320	Shale	Undetermined impressions of ammonites
E-139	23321	Shale	Algae (?), undetermined Monotis ? sp. Arcestes (Proarcestes) sp. ? Tropigastrites sp. ?

Two additional collections from the SW $\frac{1}{4}$ sec. 36, T. 34 N., R. 4 W. (field localities E-434 and E-437) were examined by S. W. Muller of Stanford University, who reports the following fauna (1951, oral communication):

Halobia
Halobia sp.
Trachyceras
Trachyceras ?

Dr. Muller believes the evidence to be fairly substantial that this material is of Upper 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.

Hosselkus limestone

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

Intrusive rocks

Intrusive rocks in the East Shasta map area include, in addition to the minor intrusive phases of the Balaklala rhyolite, Bully Hill rhyolite, and Dekkas andesite already described; (1) a small stock of coarse-grained leucocratic rock called the Pit River stock; (2) an elongate, irregular mass of medium- and fine-grained quartz diorite that virtually surrounds the McCloud limestone; (3) numerous tabular bodies of quartz diorite, diorite, and metadiabase; and (4) a few tabular bodies of granodiorite and aplite. Most of the intrusive rocks are in the western part of the map area, 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 an intrusive body about 3 miles long and 1 mile wide, extending into the map area from the south. The northern part of the stock underlies about $1\frac{1}{2}$ square miles in the vicinity of the Pit bridge. The stock consists chiefly of coarse grained, leucocratic granodiorite and albite granite. In some places it contains abundant inclusions of mafic hybrid rocks with 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 intrusive body, the Mule Mountain stock (Hinds, 1933, p. 105) (Kinkel, and others, 1957, p 43-48) in the West Shasta copper-zinc district.

The stock intrudes 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, contact dips north. Small apophyses of the stock extend at least 50 feet into the Baird, and block-like bodies of mudstone and tuff protrude into the intrusive rock (fig. 10). In some places the intru-

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Figure 10--Crosscutting irregular contact between the
Pit River stock and the Baird formation. The bedding
in tuffaceous rocks of the Baird dips gently toward
the right. The railroad cut is about 30 feet high.

sive is slightly finer grained near the contact but more commonly 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 leucocratic, 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 leucocratic 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 an inch to as much as 50 feet in diameter. Most of the xenoliths are well rounded but a few are subangular. They exhibit marked variations in mineralogy, grain size, and fabric.

Most have the composition and texture of hornblende quartz diorite but some are stoped fragments of the Baird formation recrystallized to hornfels, and there are many intermediate types. All the xenoliths could have been derived from the Baird formation.

Sharp-walled aplite dikes, commonly a few inches to a foot thick, cut marginal parts of the stock and adjacent wall rocks.

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 is in the form of 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 albite is thought to be of either deuteric or hydrothermal origin.

Microperthite, consisting of orthoclase with tiny

Table 3.--Analysis of partly albitized granodiorite
from Pit River stock^{1/}

Lab. no.	52-1657
Field no.	B-76
SiO ₂	74.0
Al ₂ O ₃	13.4
Fe ₂ O ₃	1.3
FeO	1.2
MgO	0.62
CaO	3.0
Na ₂ O	3.8
K ₂ O	2.0
TiO ₂	0.30
P ₂ O ₅	0.01
MnO	0.04
Ignition ^{2/3/}	<u>0.69</u>
Total	100

Bulk density 2.61

Powder density 2.66

^{1/} Analysed by rapid methods in laboratories
of the U.S. Geological Survey

^{2/} Includes gain due to oxidation of FeO.

^{3/} Includes 0.06 percent CO₂.

Harry Phillips, Joseph Dowd, and
Katrine White, analysts.

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.

Quartz forms poikilitic masses as much as 1 cm across and exhibits a variety of relations to other minerals, especially feldspar. It is interstitial to, and encloses small euhedral crystals of plagioclase. Much of the quartz appears 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 overall 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 color 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 xenoliths in various stages of assimilation and recrystallization, and hence the

varietal name hornblende quartz diorite includes diverse textural and mineralogical types. Thin sections show most coarser grained xenoliths 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, with irregular-shaped quartz crystals as much as 1 cm across enclosing 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 $Z \approx 11^\circ$; optically (-); $2V=82^\circ$; 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 2-3 mm across and smaller crystals .3-.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

In places granodiorite grades into albite granite, a leucocratic rock similar in hand specimen to the granodiorite. Thin sections show the albite granite to consist 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 allotriomorphic 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 $X'c$ in the zone normal to (010) range from 15 to $16\frac{1}{2}$ degrees, and refractive indices 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 places it forms a pseudographic intergrowth with albite, and in other places it replaces albite along crystallographic directions. Locally, the quartz is simply interstitial to albite.

Biotite is in the form of 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 lithologic associations the albite granite here described is similar to the albite granite near Sparta, Oregon, 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 (i.e., whether late magmatic, or hydrothermal), are recognized in the Pit River stock. However, for reasons given in the section on albitization the albite granite is believed to have resulted from hydrothermal metamorphism.

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

Contact effects

The only metamorphism clearly related to intrusion 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 intrusive. 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 intrudes 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 Baird formation was folded before intrusion occurred. Other formations in the region, including those as young as the Potem formation, which according to Sanborn_, is of early

_/ Sanborn, Albert, 1952, The geology of the Big Bend area, Shasta County, California: unpublished thesis, Stanford University.

Middle Jurassic age, have undergone about the same degree of deformation as the Baird, suggesting that the time of deformation and subsequent intrusion did not take place earlier than late Middle Jurassic.

The Pit River stock is correlated on the basis of lithology with the Mule Mountain stock of the West Shasta district described by Kinkel and others (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)_. If allowance is made for the time required by 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.

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

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 mafic, finely granular to aphanitic, mafic quartz diorite, with 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 map 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, coupled with the structural discordance between the McCloud limestone and adjacent formations (pl. 1), suggests that the intrusive in part occupies faults along the limestone. A few dikes of quartz diorite in the limestone also are along pre-intrusive faults.

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, non-porphyrific, dark greenish-gray quartz diorite with a finely granular to aphanitic texture. Thin sections show that this rock consists principally of plagioclase, quartz, and augite. Apatite, magnetite, pyrite, sphene, leucoxene, and uraltic 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. Commonly 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 constitutes about 15 percent of one slide.

The mafic quartz diorite 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 an extremely altered dike in the McCloud limestone consists of about 90 percent of fine grained white mica and calcite, with remnants of unreplaced quartz and albite constituting 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, with a grain size ranging 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 uranalite, magnetite, ilmenite, leucosene, 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 six 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 (+); $2V=52^\circ$; extinction angle $ZAc=42^\circ$.

On the basis of optical properties this augite is a variety high in lime and iron and low in magnesia (Winchell, 1951, p. 408-410). It is partly altered to uraltic 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 suggests that it may be simply a coarser grained phase of the fine grained mafic quartz diorite.

Age

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

Dikes

Numerous dikes of quartz diorite, diorite, meta-diorite, and dacite porphyry, and a few dikes of granodiorite and aplite crop out in the western part of the map area, especially west of the intrusive mass enclosing the McCloud limestone. Most dikes are

steeply inclined or vertical; a few dip at low angles. Strikes range from northwest to northeast but the dominant strike is northwest (pls. 1 and 3). Most of the dikes occupy tension faults and joints. The most continuous dikes were traced for about a mile along strike. Thicknesses range from about 5 feet to about 500 feet.

Fine-grained quartz diorite, diorite, and metadiabase dikes:--Most of the dikes in the O'Brien Mountain area are fine-grained mafic quartz diorite. A few containing no quartz are classified as diorite, and fewer still, though altered, have an intergranular or diabasic texture and are classed as metadiabase. Except for the metadiabase dikes at Bully Hill these various dike rocks are not differentiated on plate 1 and are mapped simply 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 textures range from sugary to aphanitic. Thin sections show that plagioclase, augite, quartz, and chlorite are the most common minerals. Apatite, magnetite, leucoxene, epidote, calcite, uraninite, biotite, fine-grained white mica, and kaolinite are commonly present 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 was found to exhibit systematic changes in grain size, texture, and mineralogy from the center outward. In the center of the dike the feldspar crystals have an average size that measures 1.0 by 2.5 mm, whereas near the border their average size is about .1 mm by .025 mm. Granophyric textures and myrmekitic intergrowths of quartz and plagioclase (An₁₀₋₂₀) 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 from about 15 percent in the center to a trace near the margins. 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 urallite 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:--

Some dikes shown by the symbol in the western part of the map area (pl. 1) are holocrystalline gray to greenish-gray rocks with a grain size ranging 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 is in the form of subhedral, lath-shaped crystals some of which are strongly replaced by granophyric intergrowths of quartz and orthoclase. It shows maximum extinction angles of 8 degrees in the zone normal to 010, is optically (-), and has a large optic angle. Hornblende, with brown and green pleochroic colors, is in the form of euhedral crystals. It has the following optical properties: optic sign (-); $2V=85^\circ$; extinction angle $Z\wedge c=14^\circ$; and $n_x' 1.67\pm.002$. 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 of 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 anastomosing 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, other facies are nonporphyritic. The texture commonly ranges from porphyritic to nonporphyritic even within some dikes. Amygdules are common in some facies.

Locally the metadiabase grades into fragmental rock that looks like tuff.

Thin sections show the metadiabase to consist of albite, chlorite, sphene, leucoxene, magnetite, epidote, and calcite. The texture is intergranular or in places diabasic, with chlorite interstitial to divergently oriented albite lathes averaging .3 to .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 map area. (pl. 1). Most dikes are along faults. Strikes range from N. 75 W. to N. 25 E., and dips are nearly vertical.

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

Thin sections show that the dacite porphyry is composed of oscillatory zones plagioclase phenocrysts, sparse, round quartz phenocrysts, and a few hornblende phenocrysts in a groundmass of feldspar, quartz, apatite, and hornblende. The plagioclase ranges from An₄₅ to about An₁₁ 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 SW $\frac{1}{4}$ 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. In thin section the rock consists 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. Most of the volcanic rocks as well as the bulk of the intrusive rocks are mineralogically reconstituted to a greater or less extent although they retain their original 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 suffered less alteration than those of volcanic and intrusive origin.

Processes that have brought about alteration include: 1) dynamic metamorphism; 2) igneous metamorphism, including a) thermal metamorphism, b) contact metasomatism; 3) hydrothermal metamorphism that is spatially unrelated to any exposed intrusive mass; and 4) weathering. Of these, 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 foliation that ranges from a weak, discontinuous fracture cleavage to a well-developed 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 foliation. Some thin sections show strained and fragmented quartz and feldspar phenocrysts (fig. 4), 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 foliated rocks in the southeastern part of the map 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 Na, Si, Ca, and Al, attributed to hydrothermal activity, has taken place in the rocks of the East Shasta district. This transfer of materials has occurred in nonfoliated as well as in foliated rocks as shown by the similarity of the mineral assemblages and chemical composition of foliated and non-foliated rocks of like parentage. Therefore, although dynamic metamorphism effected rock alteration in some 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 wall rocks 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 map area are: (1) coarse grained marble formed by recrystallization of the McCloud limestone in the NE $\frac{1}{4}$ 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 (2) 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 have been altered by this process.

Contact metasomatism adjacent to intrusive bodies

Between Marble Creek and the south boundary of the map 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 having outcrop widths as great as 700 feet. The largest mass centers at the Shasta Iron mine in the NE $\frac{1}{4}$ sec. 26, T. 34 N., R. 4 W. This mass has a maximum outcrop width of about 700 feet and a strike length of approximately 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 are in different proportions in different masses and commonly are mixed with remnants of unreplaced host 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 and alkalis from the volcanic, sedimentary, and intrusive rocks.

Hydrothermal metamorphism

The principal alteration in the map area has resulted in the 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 here 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 nearly 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 kerstophyres, quartz keratophyres, spilites, albite diabbases, and albite granites, which collectively make up 40 to 50 percent of the basement, contain albite as the only feldspar. These rocks retain their igneous textures and are characterized chemically by a comparatively high content of soda and silica and by a low content of lime, alumina, and potassium. (Tables 1 and 3.) Another group of rocks containing albite includes the meta-andesites, metadacites, metabasalt, and most of the quartz diorites. The latter, strictly speaking, are meta-quartz diorites. These rocks, which make up 5 to 10 percent of the basement,

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 Scandinavian geologists, since Dewey and Flett (1911, p. 202-209 and 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 suite and the Pacific suite, 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. 225-232; 336-352).

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

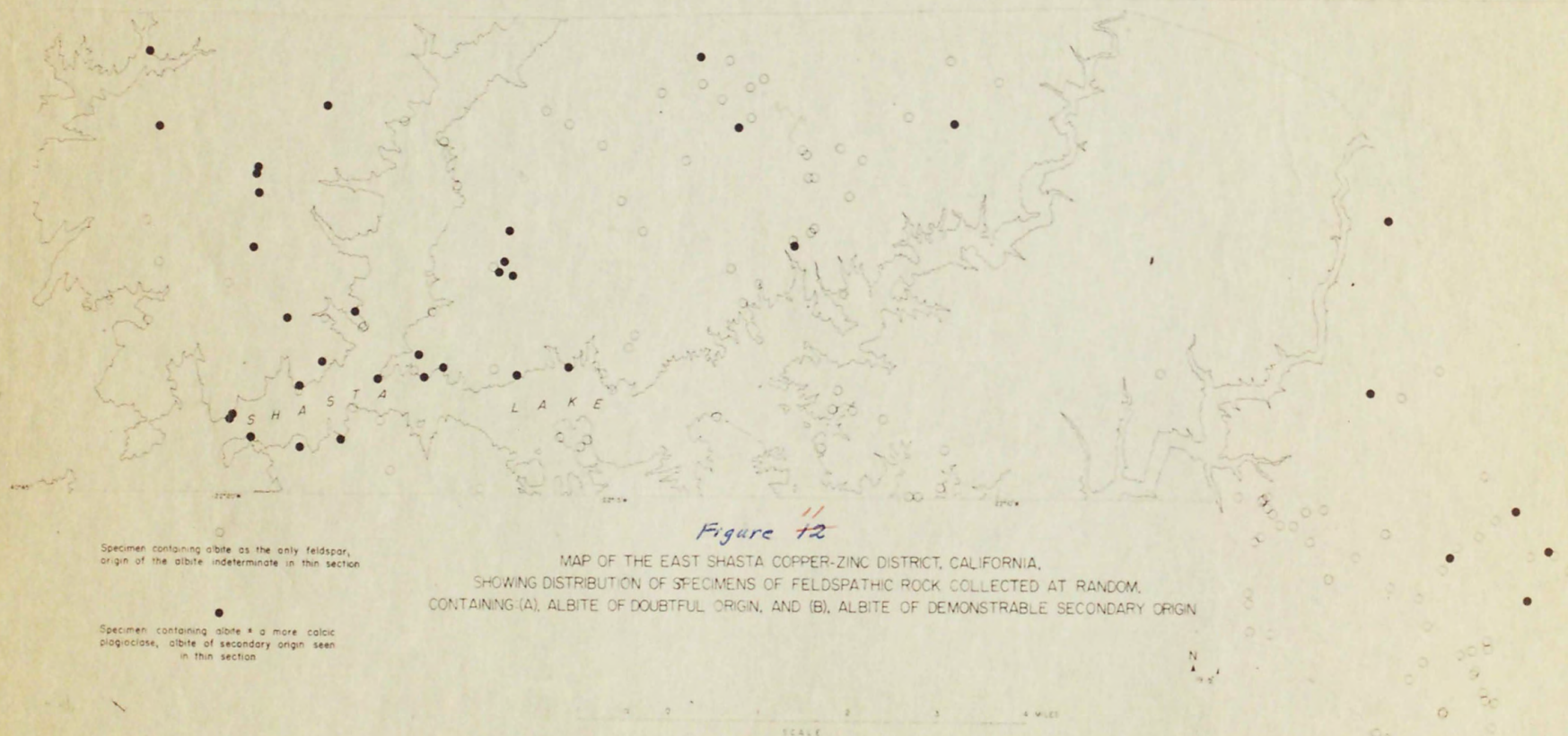
Field and petrographic relations of the albitic

rocks in the area indicate that practically all the albite is of metasomatic origin and that the soda-rich 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 rests largely on evidence furnished by the meta-andesites, metadacites, metabasalts, and meta-quartz 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. 11).

Thin sections show that the rocks classed as meta-andesite, metadacite, metabasalt, and quartz diorite or meta-quartz diorite contain plagioclase of intermediate composition in addition to nearly pure albite. Other minerals commonly present are augite, uraltic amphibole, quartz, chlorite, sphene, leucoxene, epidote, fine-grained white mica, magnetite, and stilpnomelane. Textures of the volcanic rocks are commonly



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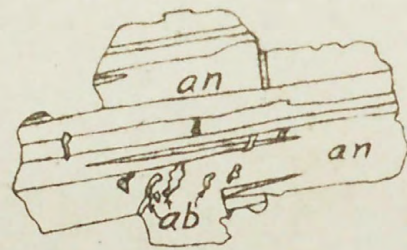
p 176

Fig 12 is p. 179

porphyritic. Groundmass textures include pilotaxitic, intersertal, and felty. The texture of the quartz diorite is commonly hypidiomorphic granular, with a marked tendency toward intergranular 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.

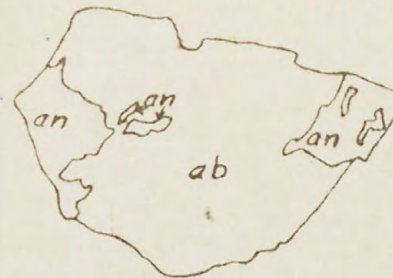
Albite in the meta-andesites, metadacites, metabasalts, and meta-quartz diorites occurs as a replacement of the intermediate plagioclase and as dilation veinlets. All the albite is at least as sodic as An_4 and much may be near An_0 . Most commonly it is untwinned, but some is poorly twinned. Every stage



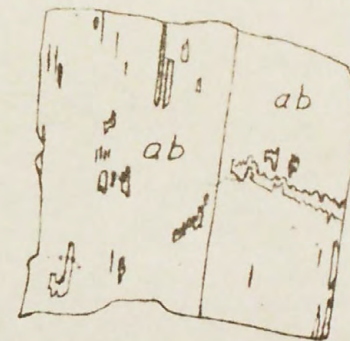
a. X50



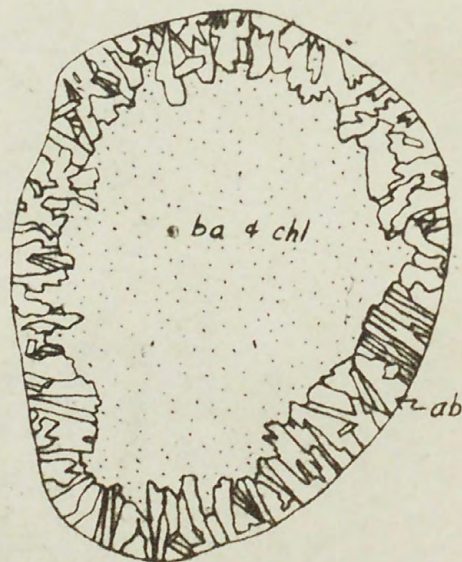
b. X50



c. X50



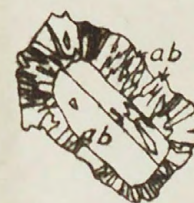
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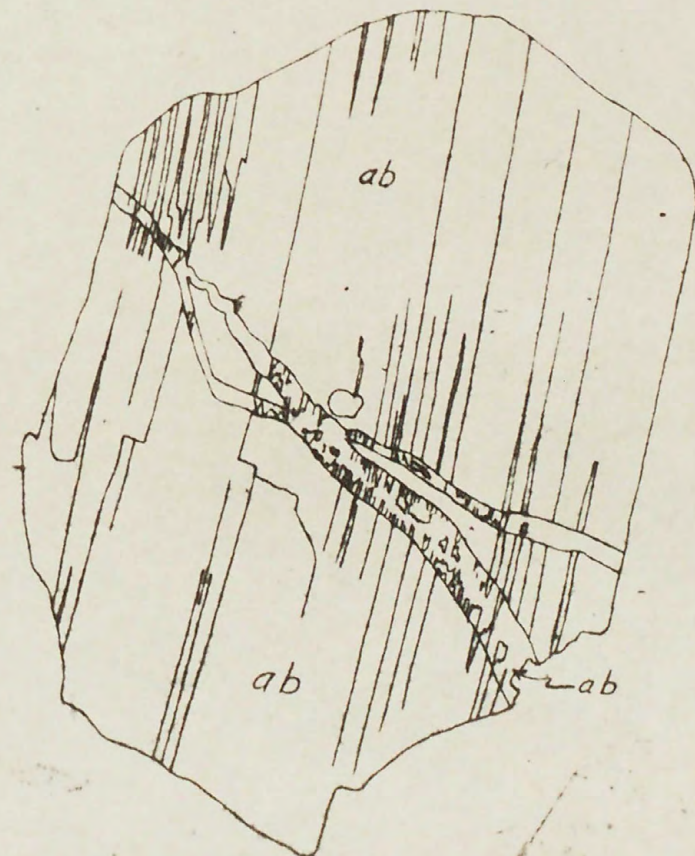
e. X25



f. X75



g. X50



h. X50

ab - albite
an - andesine and labradorite
ba - barite
chl - chlorite

Fig. 12. Sketch showing kinds of secondary albite seen 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 a 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 approximately 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.

transformation has involved an addition of sodium and silicon to the rock, with a simultaneous removal of calcium and aluminum. Possibly the reaction proceeded according to the equation proposed by Turner and Verhoogen (1951, p. 208):

$$\text{NaCaAl}_3\text{Si}_5\text{O}_{16} + \text{Na}^+ + \text{Si}^{4+} \longrightarrow 2\text{NaAlSi}_3\text{O}_8 + \text{Ca}^{2+} + \text{Al}^{3+}$$

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

$$\text{CaAl}_2\text{Si}_2\text{O}_8 + \text{Na}_2\text{CO}_3 + 4 \text{SiO}_2 \longrightarrow 2\text{NaAlSi}_3\text{O}_8 + \text{CaCO}_3$$

found experimentally by Eskola, et al (1937, p. 61-68) to take place most effectively at about 300° C.

The keratophyres, quartz keratophyres, spilites, albite diabases, and albite granites are indistinguishable from the partly albitized rocks described above on the basis of megascopic lithology, texture, and structure, but the microscope reveals that the only feldspar present is albite. Chlorite or fine-grained white mica are generally present with the albite; other minerals that may be present include augite, quartz, calcite, sphene, leucoxene, celadonite, uralitic amphibole, and epidote. The volcanic rocks are commonly porphyritic; groundmass fabrics 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.

The 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 of dilatation veinlets, as amygdule fillings, as nests of water-clear crystals apparently filling cavities in some pyroclastic rocks, and as porphyroblasts. (See fig. 12.)

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 essentially free of such alteration products. The albite is poorly twinned in some slides, with checkerboard-type, discontinuous lamellae (fig. 12d), whereas in other slides (fig. 4) it 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.

The 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. In one albite veinlet, (fig. 12h) the albite in the veinlet 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 amygdale 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. In view of the occurrence of demonstrably secondary albite in many places throughout the area (fig. 11) it is concluded that the albite which 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 the albite in the area. The keratophyres are thus albitized andesites, the quartz keratophyres albitized dacites, the 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 involved. If pulses 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 is not so. Nor is 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 rock enclosed in relatively impermeable shaly rocks of the Bragdon, Baird, Nosoni, and Pit formations commonly show only partially 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 al-

bitized plagioclase. Although exceptions to the above generalization can be found, (i. e., completely albitized plagioclase in pyroclastic lenses enclosed in shale, and partially albitized plagioclase in thick volcanic rock units) the exceptions appear sufficiently rare as to suggest a causal relationship.

Time of albitization

Rocks ranging in age from probable Devonian to Late Jurassic are albitized. The albitization post-dates 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 is unalbitized 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. 140), 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 appears 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

The abundance of chlorite, fine-grained white mica, and other hydrous secondary minerals, which are associated with and seem to be virtually contemporaneous with albite in the altered rocks, coupled with the experimental finding of Eskola and others (1937, p. 68) that the spilite reaction takes place most effectively at about 300° C, suggests 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 180. 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 an earlier page, the distribution of completely albitized specimens shown on Fig. 11, 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 portions of the intrusives seems precluded. Such alteration would require far too much soda and silica retained in the residual magma fluids to even account for the albite present in albitized intrusive rock itself, disregarding the albite in surrounding rocks.

In view of these circumstances it seems necessary to call upon some other source for the albitizing fluids. Possible sources include: 1) sea water

trapped in the pores or intergranular spaces of marine sedimentary rocks and in volcanic rocks that had been deposited in the sea; 2) a subjacent plutonic mass as yet largely unexposed by erosion, and 3) 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 likely 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, of course, 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 notion 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, 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 map area (Diller, 1906, geologic 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 intrusives. 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, Oregon, is supposed to be typical of geosynclinal belts (Barth, 1952, p. 232). It 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 leaves the magma deficient in potassium, so that little or no K-feldspar is formed in the later stages of crystallization. It also leaves the magma somewhat deficient in alumina, 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 in some way been separated out, quartz and oligoclase or sodic andesine. Residual fluids from a hydrous magma such as this are likely 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 time, culminating in the intrusion of

the Pit River and Mule Mountain stocks. This is suggested by the presence of siliceous volcanic rocks markedly low in K-feldspar at several places in the stratigraphic column. It seems at least reasonably probable 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 H_2O would be set free in the conversion of rocks of the greenschist facies to those representing a higher facies as the amphibolite or granulite facies. That sufficient Na and Si could also be derived from this metamorphism to effect extensive albitization of rocks elsewhere appears improbable unless accompanied perhaps by magnesium or calcium metasomatism. Under such circumstances, Na and Si might well be displaced along with H_2O from the rocks undergoing the higher grade metamorphism and thus made available as albitizing agents.

Chloritization

Throughout the map area intermediate and basic volcanic rocks that are strongly albitized are also strongly chloritized. Chlorite occurs in these rocks as amygdale 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 in some places in the southeastern part of the map area that only the quartz phenocrysts remain as testimony to the rock's original character.

Chlorites, identified on the basis of optical properties and according to Winchell's (1951, p. 383)

data, include delessite, diabantite, penninite (-), aphrosiderite, and clinochlore. By far the most common varieties in the albitized intermediate and basic rocks are delessite and diabantite, and these two chlorites 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. 3) in the southeastern part of the map west of U. S. highway 299E. In both places it 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 pseudomorph after 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 gone hand in hand with the albitization of intermediate and mafic rocks. Wherever such rocks are albitized they are also strongly chloritized. And, conversely,

where they are unalbitized 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 Fe, Mg, Si, and O may have been derived from ferromagnesian minerals in a mafic rock undergoing alteration, but unless aluminous amphibole is present in abundance, the Al that goes into the makeup of chlorite must come from elsewhere. A potential source within rocks undergoing alteration is the anorthite molecule of plagioclase in the process of being albitized. That this was the source of Al for the chlorite in the East Shasta area is suggested by the marked parallelism in distribution of albitized and chloritized mafic rocks throughout the area. If this is true, the processes of albitization and chloritization must have been simultaneously operative.

Hydrous mica alteration

Most of the silicic volcanic rocks in the area contain a very fine grained clay-like white micaceous

mineral. This material is most abundant along shear zones and in strongly foliated phases of the Bully Hill rhyolite. In places it forms as much as 15 percent of the rock. It marks planes of cleavage in the foliated 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 clay-like 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 on the basis of its indices of refraction (Robert L. Smith, 1953, written communication). The highest gamma index obtained was $1.578 \pm .003$ 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 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 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 relationship to albitization in the silicic rocks as chlorite bears to albitization in the intermediate and mafic rocks. It is common in albitized silicic rocks but is sparse or absent in those that are unalbitized. Paragenetic relations suggest that albitization either slightly preceded or was contemporaneous with hydrous mica alteration. Possibly the aluminum that goes into the makeup of the hydrous mica was derived from the anorthite molecule of plagioclase during the albitization process. Other than the fact that hydrous mica is generally most abundant in shear zones, as is sulfide ore, this type of alteration seems to have no definite spatial relation to sulfide mineralization.

Silicification

Rocks of many different kinds throughout the map area are more or less silicified. Limestone of the Baird and McCloud formations is in places largely re-

placed 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 180, 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 generally 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

phases only the groundmass of quartz keratophyres is replaced by xenomorphic microcrystalline quartz. Feldspar phenocrysts and microphenocrysts are unsilicified. Quartz phenocrysts retain their original shapes but commonly have narrow overgrowths of the microcrystalline groundmass quartz. These overgrowths give the phenocrysts a fuzzy border under crossed nicols, and those phenocrysts having irregular, lobate outlines appear to be eaten into and replaced by the groundmass quartz (figs. 8 and 9). That they have actually not been replaced, however, is shown by the fact that in some sheared specimens angular clasts of quartz phenocrysts strung out in trains parallel to foliation also have narrow overgrowths of the groundmass quartz (fig. 14).

The angular clasts show no rounding of edges or re-entrants 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 xenomorphic microcrystalline quartz. The identity of these rocks as altered quartz keratophyre rests 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 partially surrounds and radiates from pyrite cubes, (fig. 13). The individual quartz feathers are elongate normal to the pyrite face with which they are in contact. Most are extended parallel to foliation and occupy what Pabst (1931) has called pressure shadows. It appears that this feather quartz in large part represents quartz expelled and replaced by pyrite cubes.

Although silicification doubtless occurred at several different times during orogenesis it appears that the principal silicification took place at about the same time as albitization. The ultimate source of the silicon introduced is debatable and it may in fact have come from several different sources. It seems very improbable that it could have been "sweated out" of any rocks now exposed to view 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

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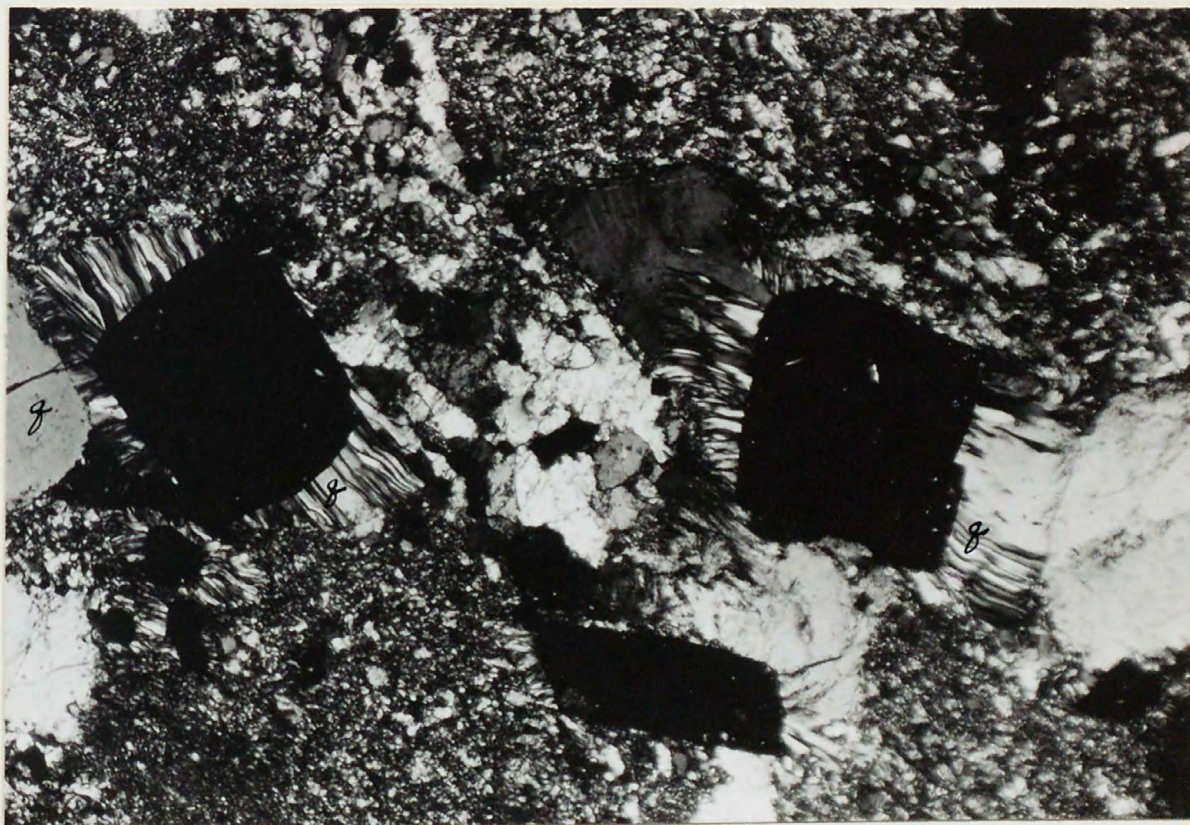


Figure 13--Photomicrograph of altered quartz keratophyre from the Afterthought mine showing feather quartz (q) radiating from pyrite grains (py). Most of the feather quartz is extended parallel to foliation and probably occupies what Pabst (1931) has called pressure shadows (X50).

pyrite cubes. The pyrite cubes in most cases replaced a mixture of microcrystalline quartz and white mica and 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 map 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 (plates 1 and 6) but are rare elsewhere. The largest masses in the Afterthought area are about 100 feet wide and at least 1000 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 as little as 10 percent to as much as 90 percent of the altered rock. Thin sections show that calcite is present as subhedral crystals 1 to 5 millimeters 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 in the main 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 CO_2 , 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 Ca^{++} and CO_2^- ions, or

b) a mass of limestone which lay somewhere beneath the calcitized rocks and which was itself 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 well 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 statement

The sedimentary and volcanic basement rocks are complexly deformed by numerous folds and faults and 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 (fig. 2). The trend of major rock units in the homo-

cline ranges from nearly north in the vicinity of O'Brien Mountain to about N 40 E in the vicinity of Town Mountain. 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 is believed in part to occupy a left-lateral fault between the McCloud and Nosoni formations. This structure is herein referred to for convenience as the McCloud fault. Numerous 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 map area the northwest structural trend is present but not prominent. It is marked by the northwest-trending dikes mentioned previously, by a 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 crossfolds and warps.

Structural features of the map area are shown on plate 3.

Age of deformation

A complex structural history is indicated, not only by the existence of two fold systems nearly at right angles to each other but also by the presence of numerous 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 appears 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 map area, plus the

Bagley andesite, the Modin formation, and the Potem formation, which crop out east of the map area, have undergone about the same degree of deformation. Crickmay (1931, p. 88) assigned the Potem formation to the Ludwician stage of Middle Jurassic, but more recent data by A. E. Sanborn_/ indicate that it is probably of Bajocian age. On the other hand, the oldest formation in the region that has not suffered orogenesis is the Paskenta formation of Early Cretaceous age. If allowance is made for time to unroof the Shasta Bally batholith which post-dates deformation and which lies nonconformably beneath the Early 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 present in the map area. Also present, though not conspicuous, are a few small folds in the O'Brien Mountain area that trend nearly east-west. The homocline through Horse

/ A. E. Sanborn, 1952, The geology of the Big Bend area, Shasta County, California: unpublished thesis, Stanford University.

The largest complete fold in the map area is an anticline that strikes north 10 to 15° E. through O'Brien Mountain and plunges northeast at a low angle. This fold is here called the O'Brien Mountain anticline (pl. 3). The outline of the anticline is best

O'Brien Mountain anticline synclinal. and Pit River arms and which in cross aspect appears Pit formation, lying chiefly between the Squaw Creek of Baxter's Gulch; and c) possibly the large mass of in the Pit formation and Bully Hill rhyolite west Creek, in the Dekkas andesite on Horse Mountain, and Mountain, in the McCloud limestone south of Curl in the Bragdon formation on the west side of O'Brien a) the O'Brien Mountain anticline; b) small folds to the homocline through Horse and Town Mountains: Folds that trend northeast include, in addition Northeast-trending folds

shortening is about 25 to 30 percent. section A-A', which trends N. 35° W., the crustal crustal shortening of 15 to 20 percent. Along which trends N. 84° W., folding has resulted in a As measured along cross section B-B' (pl. 1), northeast fold system.

a very large regional fold and is included in the and Town Mountains is probably ultimately part of

shown by the outcrop pattern of the Kennett and Bragdon formations, which wrap around the flanks and nose of the structure, with the Copley greenstone and Balaklala rhyolite forming the core (pl. 1). Along the western 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 of sec. 8, T. 34 N., R. 4 W., fine grained conglomerate beds that dip south-east 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 somewhat to the west and a steep eastward dip on its axial plane is inferred.

The scarceness of bedding or original layering/ in the Copley greenstone and Balaklala rhyolite in the core of the O'Brien Mountain anticline, coupled with 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 40-60° east, suggesting that

 / 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 degrees 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 pyroclastics, and with each lithologic unit quite possibly having a different initial dip, no doubt contained many unconformities and was structurally 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.

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 roughly bisect this core.

Small folds that trend northeast

In addition to the O'Brien Mountain anticline small northeast-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 3). The wave lengths 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 Pit sediments accumulated during Triassic time;

b) a shallow northeasterly trending synclinal trough; or c) a combination of (a) and (b). The last seems most probable. Evidence suggesting that it occupies a topographic depression lies in the distribution and differing 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 suggesting that it may be a syncline lies in 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.

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

Northwest-trending folds

The outstanding structures in the eastern part of the map area are a series of northwest-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 in places 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. 3). 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 northwest trends and eventually dying out 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 lineations (pl. 3) indicate that northwest and southeast plunges are about equally common. The folds in this part of the area are very likely arranged en echelon 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 northwest are superimposed on the northeast-trending homocline and on the O'Brien Mountain anticline. These cross folds, which are here identified with the system of northwest folds in the eastern part of the area, 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 approximately north-south to approximately east-west. However, the majority strike in the range N. 20-40° W. All the small folds seen in the field as well as those indicated by opposed attitudes are shown on pls. 1 and 3.

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). Especially 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 various formations. The contact between the Bragdon and Baird formations in the southwest part of sec. 21, T. 34 N., R. 4 W. is strongly suggestive of 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-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. so southeastward to approximately the southeast corner of sec. 20, T. 34 N., R. 4 W., where it is interrupted by a fault.

An anticlinal cross warp extending from the south central part of sec. 8, T. 34 N., R. 4 W., approximately S. 35 E. to the south central part of sec. 21, T. 34 N., R. 4 W. is suggested by convexities in the contact between the Copley greenstone and overlying formations.

In addition to the cross folds and warps noted above, the practically ubiquitous northwest strike and northeast dip of bedding in the McCloud limestone and in parts of the Baird and Nosoni formations indicate cross folding 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 formations suggests that folding also played a part.

Foliation

The basement rocks in many places in the eastern

part of the map area have a secondary foliation that ranges from a weak fracture cleavage to a prominent schistosity. This foliation is especially conspicuous south of Backbone Ridge where it is present in about 75 percent of the rocks. It strikes northwest or west-northwest and dips from vertical to 55 southwest (pl. 1). North of Backbone Ridge and between the Pit River and Squaw Creek arms of Shasta Lake, secondary foliation is less common and is present mostly near the crests and trough 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 foliation 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 secondary foliation is virtually absent.

The secondary foliation is divisible into two types: 1) cleavage; and 2) schistosity. These two foliations are essentially parallel and in places grade into each other.

Cleavage

Most foliation consists of 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 fine-grained white mica in the siliceous volcanic rocks and shales. Individual platy minerals are mostly aligned parallel to cleavage planes. However, the minerals between cleavage planes are chiefly feldspar, microcrystalline quartz, and other minerals of non-tabular crystal habit; only rarely are fine-grained platy minerals present more or less throughout the rock. The platy minerals along cleavages may have formed either contemporaneously with or later than the cleavage planes. In any event the distribution of platy minerals was probably controlled by the cleavage planes rather than vice versa.

Schistosity

In several places in the general vicinity of the Afterthought mine and in the Bully Hill-Baxters Gulch area rocks with cleavage, or, rarely, rocks with no foliation at all, contain lenses of strongly foliated rock as much as 200 feet thick and up to 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 (fig. 14). 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. Clearly this schistosity formed in response to shearing.

Lineation

Two types of lineation in the map area are:
1) plunge of drag folds; and 2) the intersection of 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 map area. All the lineations are plotted on plate 3.

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 degrees; plunges of 10 to 25

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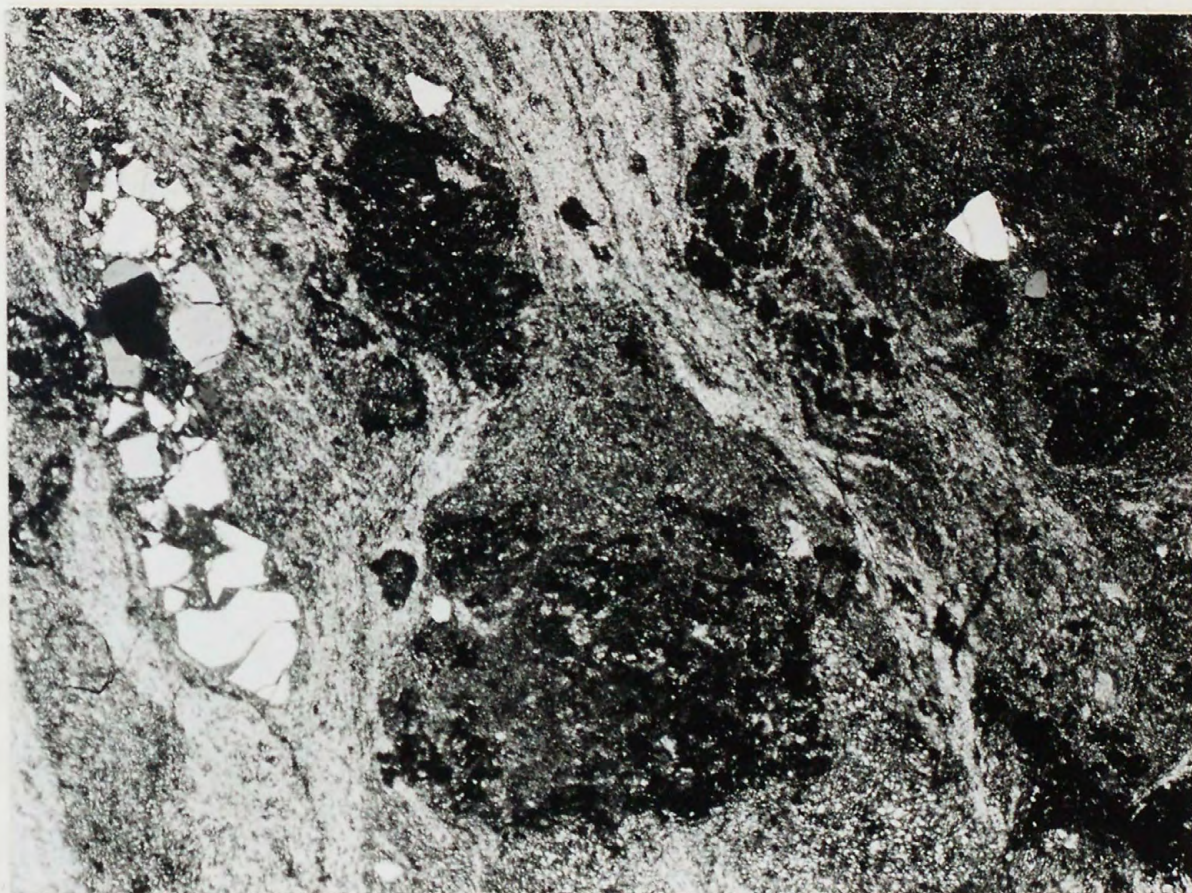


Figure 14--Photomicrograph of schistose quartz keratophyre showing cataclastic structure. At the left is a quartz phenocryst that has been crushed and strung out parallel to schistosity. Minerals in the groundmass are mainly microcrystalline quartz and fine grained white mica (X25).

degrees are most common. Southeast of the Pit River arm of Shasta Lake most lineations plunge northwest. Between the Squaw Creek and Pit River arms 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 lineations is dominantly southeast.

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

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 northeast-trending homocline and the O'Brien Mountain anticline are warped along axes that trend northwest.

- 2) The homocline in the Horse Mountain-Town Mountain area is locally cut by fracture cleavage that

strikes mostly northwest (pl. 1), in approximate concordance with cleavage in the Pit and Bully Hill formations in the vicinity of Squaw Creek, and also approximately parallel to the axes of northwest-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 degrees) occurred it seems almost certain that the cleavage would not have escaped being severely crumpled. 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 vicinity of Squaw Creek where the rocks must 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 Creek and Baileys Creek. 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 sensibly northwest-southeast compressive forces that would have been operative.

Faults

General statement

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

Distribution and orientation

The accompanying geologic and tectonic maps (pls. 1 and 3) show four principal areas of faulting. They are: 1) the general vicinity of the Afterthought mine; 2) 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; 3) the area in general occupied by the McCloud limestone and mafic quartz diorite; and 4) the O'Brien Mountain area.

In the Afterthought area about 80 percent of the

faults strike N. 50° to N. 75° W.; northeast-trending faults are rare. In the vicinity of Bully Hill northwest and northeast-trending faults are about equally abundant but the northeast faults are larger. Also, the strike of northwest-trending faults is more northerly, ranging from about N. 5° to N. 50° W. The northeast-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.; a series of northwest-trending normal faults also disrupt the limestone. The strike of faults in the O'Brien Mountain area virtually boxes the compass, but three principal directions, N. 60° W., N. 60° E., and N. 20° E., dominate. Easterly dips predominate over westerly dips in the O'Brien Mountain area.

Types of faults

Owing to poor exposure, to the parallelism of many faults to bedding or foliation, 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 considered: a) low angle faults; b) high

angle strike faults; c) high angle transverse faults; and d) shear zones.

Low angle faults

Faults with dips of 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 in 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.

On the crest of the ridge leading north from Horse Mountain, at an altitude of about 3400 feet are two faults marked by pavements of slickensided quartz each about 50 feet square. These faults strike $N 75^{\circ} E$ and dip northwest at an angle of about 25 degrees; the grooves on the slickensided surfaces plunge down dip. 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 pre-intrusive fault trending about $N. 30^{\circ} E.$ along the east side of the McCloud limestone. This fault

is nowhere exposed, but its position is marked in most places by a continuous belt of intrusive rock (pls. 1 and 3). 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 at least a mile and a half in the vicinity of the Pit River arm (pl. 1); likewise, the Nosoni formation is missing for at least a mile 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 and is perhaps the strongest indication of a fault. In gross aspect, these three units strike about N. 20° to 25° E. However, the

strike of bedding in the McCloud limestone is markedly northwest practically throughout the area (pl 1 and 3). 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 relationship.

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 present on a small peak only a few hundred feet west of the greenstone outcrop but it strikes E-W and dips north, about at right angles to the younger Nosoni and Dekkas formations, which 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 northwest-trending normal strike faults, most of which are pre-intrusive and occupied by dikes of mafic quartz diorite. The dominant strike of mafic

dikes that fill fractures in the O'Brien Mountain area is also northwest (fig. 2). 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 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 various dioritic dike rocks shown on Diller's (1906) map of the Redding 30 minute quadrangle also strongly suggests movement in the left-lateral sense along this zone. The amount of movement is unknown but it almost certainly does not exceed a few thousand feet.

High angle strike faults

Most faults in the southeastern part of the map area and a large percentage of faults as far west as the McCloud River arm of Shasta Lake strike approximately 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 below according to the three main areas in which they occur.

Afterthought area:--The vast majority of faults in the Afterthought mine strike N. 50 to 75 W. and dip at steep angles, mostly southwest. The areal mapping shows that this is the dominant attitude of faults throughout the southeastern part of the map 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 very 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. The strike-slip component is not known. Inasmuch as the hanging wall shows upward displacement with respect to the footwall, most of these faults would be reverse faults in a genetic classification. A few that show the southwest side down 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, approximately parallel in places to bedding in the Pit formation. It cuts all other faults in the mine. The northeast or hanging wall side of Main fault is thought to have moved upward about 450 feet with respect 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 map, it is concluded that most of the strike faults in this part of the area have reverse movement.

Central part of the map:--The principal high angle strike faults in what may loosely be called the central part of the map area are the Bully Hill Contact fault, a fault that 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° northwest 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° southeast.

Strike faults in the McCloud limestone.--The McCloud limestone in the vicinity of Marble Creek is cut by at least three faults that strike northwest, approximately parallel to bedding, and dip about 70° southwest (pl. 3). Two of these three 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 may 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 5000 to 6000 feet of limestone, disregarding the strike faults. However, if each of the three or four southwest-dipping faults crossed by the line of section is assumed to have normal movement (southwest side downdropped) 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 horizons throughout the McCloud

limestone as was done by Wheeler_ in a small area needs to be done to help 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 3). Other noteworthy faults in the group include: (a) those that disrupt the nose and limbs 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 eastern edge of the map. 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 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

_Wheeler, H. E., The fauna and correlation of the McCloud limestone of northern California: unpublished thesis, Stanford University, p. 1-166.

fact that shale of the Bragdon formation exposed south of the fault is in most places strongly sheared and dips north toward the Copley greenstone. Further evidence suggesting a fault is the fact that the Kennett formation is missing for more than a mile between secs. 21 and 20, T. 34 N., R. 4 W., and the Bragdon formation 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 up or northeast relative to the southeast side. However the direction of movement on the fault is indeterminate because the direction of dip, though certainly steep, is unknown.

Shear zones

In the Bully Hill-Baxters Gulch area, and also in the vicinity 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 a mile and another for 3000 feet along strike but few extend for more than 1000 feet. In the Afterthought area all the shear zones strike northwest and dip southwest approximately parallel to frac-

ture cleavage. Included are: (a) the Afterthought shear zone; (b) the shear zones exposed mainly in the lower levels of the Afterthought mine; and (c) several shear zones exposed mainly northwest of the Afterthought mine (pl. 3). 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 shear zone and the Middle shear zone, strike northwest. Although the crushing and stringing out of fragmented quartz phenocrysts (fig. 4) shows that movement has taken place within the shear zones, the displacement of rock units by the shear zones seems to be small. At no place does there appear to be a measureable offset of map units, and the movement sense on most of the shear zones is indeterminate.

The shear zones appear to be older than 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 great economic importance

because a large proportion 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 in the development of the O'Brien Mountain anticline and a few small northeast-trending folds.

(2) The Pit River stock was probably emplaced at this time 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 believed to be 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 Belly batholith is strongly foliated. This foliation is believed to have formed at the same time as the folds in

stage 3 described below.

(5) A right lateral shear couple acting generally in a north-south direction resulted in the superposition of a series of northwest-trending folds on the northeast fold system. These folds are most strongly developed in the southeastern part of the map area, and west of Bully Hill and Cove Creek they are represented only as poorly-defined warps. With continuing right-lateral 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 eastern side of the McCloud limestone. The movement sense 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.

In conjunction with the formation of the McCloud fault a group of right-lateral faults were formed

in the vicinity of Bully Hill, Copper City, and Baxters Gulch (pl. 3). These faults displaced the Dekkas andesite northward and also upward with respect to the Bully Hill and Pit formations. This movement sense is indicated by minor drag folds in shaly beds near the fault zone and by the northward bend of northwest-trending fold axes north of the Squaw Creek arm (pls. 1 and 3). Thus it appears that during stage 3 of the orogeny the block represented approximately by the belt of Dekkas andesite and Nosoni formation underlying Horse and Town Mountains moved relatively northward in relation to the rocks on either side.

(4) Probably nearly contemporaneous with the development 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 culminating in sulfide mineralization, may have begun during stage 3 but continued after the intrusive rocks were emplaced, as indicated by the fact that the intrusive rocks themselves are highly altered. Normal fault-

ing 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.

Post-orogenic history

Post-orogenic deposits in the map area include the Tuscan formation of Pliocene age, basalt flows of Pliocene or Pleistocene age, and various unconsolidated deposits of Pleistocene or Recent age. No rocks of Cretaceous or early Tertiary age are exposed within the map area, but marine sedimentary rocks of Late Cretaceous age crop out a mile or so south of the map boundary, and fluvial conglomerate of Eocene age crops out just east of the map area.

Tuscan formation

General character and distribution

The Tuscan formation was first described and named by Diller (1895, p. 1). It was 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 and the writer has 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 and underlies many of the low, rounded hills in the southeastern part of the map. 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 developed 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 with a resulting high rate of infiltration. Surface runoff is thus at a minimum, and the development of gullies in the tuff breccia is much slower than in the older rocks. Numerous, 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 haphazardly 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 obsidian, black obsidian, andesite, and several textural varieties of basalt. The light-gray matrix of the tuff breccia in thin section consists of lithic fragments of an-

desite, 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 west, or southwest, whereas north of the ridge it was much more rugged.

The low relief south of Backbone Ridge is suggested by: (1) the present uplands on either side of Little Cow Creek are broad surfaces of low relief, with many

of the highest ridges capped by the Tuscan formation; (2) the base of the Tuscan formation slopes gently southwest, with the altitude of discrete outliers coinciding closely with a hypothetical sloping base throughout the area; and (3) the thickness of complete sections of the Tuscan formation beneath a basalt capping is fairly uniform south of Backbone Ridge.

North of Backbone Ridge the pre-Tuscan landscape was more rugged. The distribution of tuff breccia suggests that in places it was guided along valleys that approximately coincide with the present Sugar-pine Canyon and Pit River (pl. 1). In sec. 22, T. 34 N., R. 2 W., near the head of present Sugar-pine Canyon, the base of the tuff breccia is at an altitude of 2275 feet, while $1\frac{1}{2}$ mile farther south, in sec. 34, T. 34 N., R. 2 W., it is at an altitude of 1600 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 Sugar-pine 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 1200 feet. (pl. 1.) Within a distance of 3 to 4 miles, therefore, the altitude of the base of the formation decreases approximately 1075 feet,

and throughout the entire distance the tuff breccia outliers are flanked by higher ground underlain by basement rocks. This suggests the presence of a valley in pre-Tuscan time in about the same location as the present Sugarpine Canyon.

The occurrence of outliers of tuff breccia along the Pit River in the SW $\frac{1}{4}$ sec. 36, T. 34 N., R. 3 W., and in the NE $\frac{1}{4}$ sec. 32, T. 34 N., R. 2 W., shows that: (1) the Pit River, at least between secs. 36 and 32, was in approximately the same position when the Tuscan formation was deposited as it is today; and (2) that, inasmuch as the altitude of the present canyon bottom beneath the lake is about 825 feet and the base of the tuff breccia in outliers along the canyon is 1200 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 map 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, aphanitic, and locally vesicular. Another type, which forms smaller bodies, is exposed both north and south of Sugarloaf. It is medium gray and commonly porphyritic, with phenocrysts of plagioclase and pyroxene. A third type, which has a diabasic texture, is exposed in two small areas near the extreme eastern edge of the map.

The basalts appear to overlie the Tuscan formation with erosional unconformity. This relation is suggested by the fact that in several places, as for example in the northeast part of sec. 35, T. 34 N., R. 2 W., the contact between the dark gray aphanitic 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 aphanitic basalt is approximately 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

Dark gray aphanitic basalt

Thin sections show that the dark gray aphanitic 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 a refractive index slightly less than Canada balsam.

Some vesicular facies of the dark gray aphanitic basalt differ from the non-vesicular facies described above in that olivine is present 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 hypersthene and augite in about equal proportions as varietal minerals, and oxyhornblende, apatite, and magnetite as accessories. 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 .1 to .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 aphanite basalt and in secs. 34 and 35, T. 34 N., R. 2 W., within a body of dark gray aphanitic basalt. The diabase occurs mainly as a jumble of blocks that mantle the surface and hence its relationship 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 lathes, 25 percent augite enclosing plagioclase ophitically, and about 5 percent olivine, 5 percent magnetite, 3 percent apatite, and minor bowlingite 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.

Age

The basalt 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 hillslopes, 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 the common presence of a scar on the uphill side. Most of the landslides on Town Mountain and Horse Mountain grade into colluvium on the downhill side.

Alluvial fan and terrace deposits occur mainly at low altitudes along the Squaw Creek arm. The largest alluvial fan underlies the low ridge east of Bully Hill. It consists of subrounded rock fragments derived from the bedrocks of Town Mountain in a silty matrix. The base of this deposit slopes south at an angle of about 6 degrees, and the maximum thickness is about 20 feet. The upper end of the fan grades into colluvium and landslide debris. Terrace deposits occur mainly at altitudes of 1000 and 1250 feet. The base of the deposits is approximately 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 1650-1700 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 map area lies within two geomorphic provinces. That portion of the area north of the Pit River arm is in the Klamath Mountain province (Diller, 1906, p. 1; Jenkins, 1938), whereas that portion 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 southwest. From west to east these streams are the Sacramento River, the McCloud River, Squaw Creek, the Pit River, and Little Cow Creek. The first four streams join each other within the boundaries of the map (fig. 1 and pl. 1) and their canyons are partly flooded by Shasta Lake. Squaw Creek, the Pit River, and Little Cow Creek are transverse to the structure of the basement rocks, whereas the Sacramento River and the McCloud River are more or less

parallel to the structure. In general, the topography north of the Pit River arm is in late youth, whereas south of the Pit River arm it is in early youth.

The divide formed by Backbone Ridge between the Pit River and Little Cow Creek and the divide southeast of Little Cow Creek are remnants of a surface of low relief that slopes southwest at the rate of about 140 feet per mile within the map 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. Within one half mile to a mile of the main stream the tributaries of Little Cow Creek are closely spaced, and separated by fairly sharp ridges underlain by hard basement rocks. But further 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 the Pit River have a crudely developed trellised pattern, whereas higher toward the main divides where the streams are not yet deeply incised the pattern is dendritic. The trellised pattern probably develops largely in response to the north-

west-trending secondary foliation in the older rocks.

The divide between the Pit River and Squaw Creek is slightly higher than the Backbone Ridge divide. It is dominated by Brock Mountain (altitude 2724 feet), and by Green Mountain (altitude 2247 feet). Squaw Creek and the Pit River are transverse to the structure of the basement rocks. The tributary canyons to Squaw Creek and the Pit River are V-shaped, and the intervening ridges are sharp. The drainage has a crude trellis pattern trending northwest and reflecting a weak structural control by the northwest trending beds of the underlying Pit formation (pl. 1).

The divide between Squaw Creek and the McCloud River is dominated by Town Mountain (altitude 4325 feet) and Horse Mountain (altitude 4025 feet) the highest peaks in the map area. Another conspicuous physiographic feature in this sector of the map area is the belt of McCloud limestone along the east side of the McCloud River. In some places between Marble Creek and Curl Creek the limestone forms cliffs almost 2000 feet high, which stand out in marked contrast to the less resistant formations adjacent to the limestone. West of the 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 trellis pattern, reflecting control by the bedded shale and tuff of the underlying Pit formation.

The upper slopes of Town Mountain and Horse Mountain are scarred by landslides (pl. 1). These slides are recognized by their step-like tops and by the jumble of boulders and loose rock debris that compose them. That the slides have not moved much in recent times is shown by the absence of cracks in the slides and by the presence of evergreen trees as much as three feet in diameter growing on the slides. 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 levels are marked by small peaks and flat-topped spurs with common altitudes. Some levels, however, are marked in part by deposits of gravel, deposits of the Tuscan formation, or deposits of spongy transported limonite. The most conspicuous levels are at about 1025 feet, 1250 feet, and 1750 feet.

The 1025 foot level appears most prominently along Squaw Creek where it is marked in some places by bench-like deposits of gravelly material consisting of boulders and cobbles in a silty matrix. The 1250 foot level is marked by flat-topped spurs and small peaks along the Pit River and Squaw Creek. Along the Pit River it is also marked by outliers of Tuscan formation in the SW $\frac{1}{4}$ sec. 36, T. 34 N., R. 3 W., and the NE $\frac{1}{4}$, sec. 32, T. 34 N., R. 2 W. These two outliers of Tuscan formation are especially significant in that they show that the amount of down-cutting by the Pit River since Tuscan time is about 375 feet inasmuch as the present canyon bottom is 825 feet. The level at 1750 feet is marked on the divide between First Creek and Second Creek 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 a mile and a half.

The old levels apparently mark temporary base levels during which streams widened 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 itself 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 mostly from a fraction of an inch to about 40 or 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 limestones, shales, 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 yields a rotten rock or saprolite that commonly has a red or buff coloration owing to the presence of more or less 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 they are completely altered to saprolite. At the surface this saprolite gradually breaks down to colluvium and soil, and is eroded away.

Ore deposits

General statement

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 \$16,000,000, of which copper has accounted for slightly more than half. The value of iron produced is not known. All the base metal production and practically all the precious metal production has come from the Bully Hill-Rising Star-Copper City area and from the Afterthought-Donkey area (pl. 4). Iron ore has been produced from the Shasta Iron mine in sec. 26, T. 34 N., R. 4 W.

Three types of ore deposits present in the district are: 1) massive sulfide deposits, 2) contact metasomatic magnetite deposits, and 3) quartz veins.

Virtually all the base metal production has been

from the massive sulfide deposits, and most of the remainder of this report is devoted to the description of these deposits. The other two types of deposits have been of much less importance as producers and are here treated only briefly.

During this investigation the only base metal mines accessible were parts of the Afterthought mine and parts of the Bully Hill mine. Probably no more than 10 percent of the individual stopes and ore bodies in the district were seen. Hence it has been necessary to rely heavily on maps, records, and reports kindly made available by ^{and published with the permission of} the Glidden Company and [by] the Coronado Copper and Zinc Company. The history of the district, as well as certain descriptive data, is taken largely from published sources. These various sources of information, both published and unpublished, are in many ways incomplete and even contradictory. The author has tried to be objective in assimilating this material with that derived from his own observations in order to give as complete a picture of the sulfide deposits as possible. However, it is only fair to say that 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 individual 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. A few lenses 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. In the Afterthought and Rising Star mines, on the other hand, discrete sulfide lenses occur along several different faults and shear zones; some lenses in these mines are isolated from their neighbors 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 is thought to have 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 sulfides replace shale.

The ore consists typically of a fine-grained mixture of pyrite, sphalerite, chalcopyrite, galena, and tetrahedrite-tennantite, along with quartz, barite, and calcite. The proportions of these minerals vary greatly from place to place. The individual sulfide and gangue minerals commonly are more or less 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 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 their copper content and others for their zinc content.

The last base metal production from the district was from the Afterthought mine in 1952. During the period 1952-1956 two lenses of sulfide ore were discovered in the Bully Hill mine by the Glidden Company under a contract with the Defense Minerals Exploration Administration. It appears likely that an intensive prospecting program in the district would reveal the presence of additional sulfide lenses. Geologically favorable areas most likely to contain such lenses are shown on figure 20.

History of mining

The history of mining in the East Shasta copper-zinc district dates back to 1853, when placer gold was discovered in Town Creek east of Bully Hill. The stampede that began as a result of this discovery resulted in the location of a large number of placer claims, 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 as well as copper were found to be present 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, during 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.

During the early 1860's mining was confined largely to the oxidized ores near the surface, which were rich in precious metals. As these ores were worked out attention was given to extracting the metals from the baser ores but most attempts were unsuccessful. A few shipments of ore were made from the Copper City mines to Swansea, Wales during the early 1860's, but, according to Aubury (1902, p. 34), only one realized a fair profit. This was a 250 ton shipment made in 1863 that is said to have assayed 8 percent copper, \$40.00 in gold, and \$20.00 in silver per ton (Aubury, 1908, p. 34).

Owing to the difficulty in treating the base ores, the bottom dropped out of the initial mining boom in 1865 but there was a revival of interest during the 1870's. A mill was built at Copper City in 1877 by the Extra Mining Company and an expensive tramway was built to convey ore from Bully Hill by gravity to this mill. Aubury (1902, p. 34) states that:

"During the few years (perhaps three or four) in which this company operated, it was said to have extracted as much as \$640,000 from these ores . . . The Extra Mining Company worked only the surface ores from these mines, having no successful process for the reduction of the baser ores, though an attempt was made at roasting".

The history of the Copper Hill (Afterthought) mine in the Cow Creek mining district was parallel in many respects to the history of Copper City and Bully Hill. C. M. Peck, who during the 1860's had built the first mill at Copper City, purchased the Copper Hill property in 1873 and it was renamed the Peck mine. Peck mined the oxidized ores and made small shipments to Swansea, but he was unable to reduce the sulfide ore in either of two reverberatory-type furnaces that he built around 1875 for

this purpose. Later a man named Joseph Conland acquired the property from Peck and tried unsuccessfully to reduce the sulfide ore in a small water-jacketed furnace of 25 tonw capacity. Aubury (1908, p. 45) reports that in addition to his work at the Afterthought mine Peck in 1876 discovered the Donkey mine, which he sold to A. J. Cook during the same year for \$1,100. Between 1876 and 1897 repeated attempts were made to extract the metals from the ores but little success was attained.

About 1897, James Sallee, who in 1879 had discovered that the great gossan at Iron Mountain in the West Shasta district contained valuable amounts of gold and silver, obtained the Bully Hill property. After driving several exploratory adits and developing considerable ore Sallee in 1899 sold the property to J. R. DeLa Mar for \$225,000 (Aubury, 1902, p. 75). DeLa Mar's acquisition of the property marked the beginning of the most active and productive years of the East Shasta district and the real beginning of copper mining. The Bully Hill Mining and Smelting Company was formed in 1901 and a smelter costing \$200,000, with a capacity of 400 tons per day, was installed. According to Aubury (1902, p. 80) the product of this smelter was blister copper, about

98 percent fine, which was shipped to a refinery built by DeLa Mar on Kill von Kull near New York City. In 1905 the Bully Hill property was acquired by the General Electric Company, which, in 1907, stopped mining operations in order to remodel the smelter and build a railroad to the mine (Tucker, 1924, p. 422). Mining began again in 1908 and according to Aubury (1908, p. 78), "bodies of unusually rich sulfides were opened during 1908 with remarkable consistency."

Between May 1901 and July 1910 the Bully Hill mine, and the Rising Star mine on the southwest flank of Bully Hill (pl. 4), produced more than 400,000 tons of gold-silver-copper ore valued at something like \$7,500,000. The ore also contained a high percentage of zinc that was not recovered in the direct smelting process.

While this activity was taking place at Bully Hill a good deal of prospecting and development work were going on elsewhere in the Pittsburgh mining district and the Peck (Afterthought) and Donkey mines in the Cow Creek district were also being worked. The Great Western Gold Company acquired the Peck property in 1903 and erected a 150 ton water jacketed blast furnace that was blown in 1905 (Tucker, 1924, p. 423). According to Brown (1916, p. 7), this smelter operated successfully until 1908 during

which period the average yearly output was \$350,000. This smelter produced a copper matte that was shipped to a furnace in Salt Lake City where it was converted to blister copper. In 1909 the mine passed into the hands of the Afterthought Copper Company.

What might be called the boom era in the history of mining in Shasta County ended in 1910 when most of the smelters, including that at Bully Hill, were forced to close down because smelter fumes were causing great damage to the countryside. According to an unpublished report on the Bully Hill property dated 1919, by S. H. Ball this shutdown approximately coincided with the depletion of copper ore at Bully Hill, though ore bodies rich in zinc remained unmined. During the next few years only development work was done in the mines of the East Shasta district, and a great deal of experimental work was done to devise ways to eliminate smelter fumes and to recover zinc from zinc-rich ore bodies that had been avoided in the mining for copper. A small experimental electric smelting plant was built, which for awhile in 1915 produced 300 to 400 pounds of metallic zinc per day (Tucker, 1924, p. 422).

In October 1917 the W. Arnstein interests, known as the Bully Hill Mining Company, took over the Bully Hill-Rising Star properties. The Rising Star

shaft was repaired and in 1918 about 25,000 tons of silver-gold-copper ore from the lower levels of the Rising Star mine, which had been overlooked during earlier operations, was shipped to the United States Smelting Refining and Mining Company smelter located at Kennett in the West Shasta copper-zinc district. Arnstein operated the Bully Hill-Rising Star property until 1920, during which time he built a 150 ton differential flotation plant that was unsuccessful. According to Tucker (1924, p. 423), Arnstein in 1920 sold out to the Shasta Zinc & Copper Company, of which D. C. Jackling was president. A 150 ton reverberatory smelter and zinc oxide plant were constructed and were in production from June until December, 1922, when operations were stopped owing to a drop in the price of zinc oxide.

During the period 1909 to 1919 no ore was mined from the Afterthought mine but the Afterthought Copper Company constructed a 300 ton reverberatory furnace and a 300 ton oil flotation mill in an attempt to treat the ore by the Harwood process. In this process the sulfide was prerosted in the furnace and then treated by flotation (Averill, 1939, p. 174). The furnace was blown in 1919 and the operation continued until February 1920 when

it was stopped because the zinc and copper sulfide minerals could not be cleanly separated from each other. Further experiments were carried out but they were unsuccessful. Late in 1923 the Afterthought Copper Company, which according to Tucker (1926, p. 143) was a million dollars in debt, lost control of the property through foreclosure.

In 1924 the California Zinc Company was organized to take over the Bully Hill-Rising Star property from the Shasta Zinc & Copper Company (Tucker, 1926, p. 148). A new reverberatory furnace and flotation mill were built and mining of zinc-rich ore bodies in the Rising Star mine was started in September, 1924. Spurred by an insistent demand for zinc oxide for export the California Zinc Company in 1925 leased the Afterthought mine, constructed an $8\frac{1}{2}$ mile aerial tram, and trammed ore to their mill at Bully Hill for concentration (Tucker, 1926, p. 143). In August, 1927 the operations of the California Zinc Company were stopped owing to a drop in the price of zinc oxide, and sulfide mining in the district was dormant for about 20 years.

Mining activity during the early 1900's was not confined to the exploitation of base metal sulfide ores. From 1907 until 1926 (Lamey, 1948, p. 140) the Shasta iron mine, near the junction

of the Pit and McCloud rivers, was an intermittent producer of magnetite iron ore. This mine was owned by the Shasta Iron Company but was operated, under lease, by the Noble Electric Steel Company. Prior to about 1920 (Brown, 1916, p. 805), the ore was retorted in an electric smelter on the property, run into sand pig beds, and graded according to silicon content. In 1913 the daily production was about 25 tons of ore (Brown, 1916, p. 805). Some lime was manufactured as a byproduct of the operation. Starting about 1919 or 1920 and continuing until 1927 the magnetite ore mined was shipped to a furnace in the San Francisco Bay area at the rate of 12 to 20 carloads per month (Tucker, 1922, p. 732; Tucker, 1926, p. 192).

From 1927 until 1942 there was little mining activity of any kind though it is probable that a few quartz veins in the central and southeastern part of the district were worked on a small scale for gold.

Beginning in February 1942 and continuing through 1944 (Lamey, 1948, p. 140) magnetite was produced at the rate of 100,000 tons a year from the Shasta Iron mine for use by the U. S. Navy as ballast. These operations ceased in 1945 and no further mining has been done on the property since

(to January 1, 1956).

The year 1945 saw a resumption of interest in the copper-zinc deposits of the district. The Coronado Copper and Zinc Company took an option on the Afterthought mine, and after locating several ore bodies by diamond drilling, purchased the property in 1947. A mill was built and mining started in 1948. A drop in the price of metals caused a shutdown for a year during 1949-1950, after which operations were resumed. In August, 1952 the mine closed owing to the depletion of ore.

Early in 1952 the Glidden Company, owners of the Bully Hill-Rising Star property, obtained a DMEA loan to explore the long dormant Bully Hill mine. Diamond drilling resulted in the discovery of two lenses of massive sulfide ore in the northern part of the mine on the 870 level.

In summary, the mining history of the district is separable into about seven more or less distinct phases:

1853-1861: interest was entirely in placer mining, which was on a small scale and not very successful.

1862-1899: oxidized ores overlying the sulfide deposits were worked, mainly for their precious

metal values 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. All of these attempts were economically unsuccessful although some metal was produced.

1900-1910: The boom years. Copper ore mined in quantity and smelted locally. The product was blister copper that was shipped elsewhere for refining. Gold and silver produced in quantity as a byproduct.

1911-1920: Copper mining largely dormant owing to smelter smoke litigation and to depletion of copper-rich ore in Bully Hill mine. Much experimenting done to devise ways to treat smelter fumes so as to make them harmless. Other experiments conducted in an effort to find method to recover zinc from the ore. Copper-rich sulfide ore overlooked during the 1901-1910 operations was mined from Rising Star mine in 1917-1918. Iron ore produced on small scale from Shasta Iron mine.

1921-1927: Zinc-rich sulfide ore mined and treated mainly at Bully Hill smelter. Chief product was zinc oxide, which was in great demand.

Operations ceased in August, 1927. Iron ore produced at small but steady rate from Shasta Iron Mine.

1928-1941: Virtually no activity in district due to low price of metals. A few small quartz veins probably worked for gold but production negligible.

1942-1955: Magnetite produced from Shasta Iron mine 1942-1944 for use as Navy ballast. Afterthought mine reopened and worked for 3 years. Diamond drilling done at Afterthought and Bully Hill. Bully Hill mine reopened in 1953 and new ore bodies discovered.

Production

Data on production of base and precious metals from the East Shasta district are sketchy and incomplete for the period prior to 1900 but are fairly complete for the period since 1900. Virtually all the production has been from the Bully Hill, the Rising Star, and the Afterthought mines. Production is summarized in table 4.

The record shows that copper has been the most important metal produced, having accounted for roughly half the total value of base and precious metals. It should be borne in mind, however, that

Table 4. --Summary of production of sulfide ore from
the East Shasta copper-zinc district, 1900-1952

<u>Mine</u>	<u>Tons mined</u>	<u>Pounds copper</u>	<u>Pounds zinc</u>	<u>Pounds lead</u>	<u>Ounces silver</u>	<u>Ounces gold</u>
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	-----	-----	-----	-----	-----
	<u>746,700</u>	<u>59,523,631</u>	<u>48,772,505</u>	<u>1,738,300</u>	<u>3,138,923</u>	<u>44,217</u>

¹/ Data furnished by the Coronado Copper and Zinc Company. Published with permission.

²/ Data furnished by the Glidden Company. Published with permission.

³/ Production was prior to 1900; no data on grade of ore are available.

during the main period of mining, from 1900 to 1910, zinc was not recovered from the sulfide ores.

An accurate record of the production of iron from the Shasta iron mine is not available. According to Lamey (1948, p. 140) ore was mined for the Noble Electric Steel Company 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 daily production was 25 tons. In 1921, according to Tucker (1922, p. 732) production was at the rate of 12 to 15 cars per month averaging 65 percent iron. In 1925 production was at the rate of 15 to 20 cars per month (Tucker 1926, p. 192). During the period February 1, 1942 through 1944 ore was being mined for 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 are in the form of lenses that replace the Bully Hill rhyolite, the Pit formation, and metadiabase dikes that locally intrude the Bully Hill rhyolite. The three prin-

cipal localities where sulfide lenses have been mined are: 1) the Bully Hill-Rising Star area; 2) the Copper City area, about a mile southwest of Bully Hill; and 3) the Afterthought-Donkey area in the extreme southeastern part of the district. These principal deposits, as well as other occurrences of sulfide minerals, and occurrences of limonite, are shown on figure 20.

Most of the sulfide lenses are tabular and are steeply inclined from the horizontal. 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 roughly circular in a section drawn parallel to the greatest dimension of the lens. Few individual lenses have a well defined pitch. The maximum thickness of the largest lenses is 35 to 40 feet.

In the Bully Hill mine the sulfide lenses are mostly arranged close together in groups along a steeply dipping shear zone; the lenses, as a group, pitch steeply north (pl. 5). In the Rising Star mine the lenses are closely grouped along or near a series of faults and shear zones (pl. 5). 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. 6). The Donkey deposit was an isolated lens containing a few hundred tons of high grade sulfide ore, and the Copper City deposits apparently consisted of several small lenses along a shear zone. Generally, because of their small size, isolated lenses cannot be mined profitably, and the only successful mines have been those in which a number of lenses were grouped fairly close together.

Virtually all the sulfide lenses parallel either foliation 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 host rock adjoining a sulfide lens is barren, but a few lenses are enveloped by rock containing abundant disseminated sulfides commonly arranged in stringers parallel to foliation. The walls of most sulfide lenses are sharp and smooth but the edges, in contrast, are commonly irregular. Some lenses simply taper to a single knife edge. Others tail out in numerous thin layers or sheets extending a few inches to a few feet into the host along bedding or foliation

planes. The edges of these individual sulfide layers may in turn pinch out to a knife edge or come to a blunt end. In cross section this gives either a sawtooth or an interfingering form, respectively (fig. 15 and 16.).

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 foliation in the enclosing host rock (figs. 15 and 20). The perfect parallelism of this banding with foliation or bedding indicates that the banding was inherited from the host and that the sulfide is of replacement origin.

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. Others of minor importance include bornite and luzonite. Quartz, barite, calcite, anhydrite, and gypsum are the principal gangue minerals; anhydrite and gypsum are restricted to the Rising Star and Bully Hill mines. Typical sulfide ore is an exceedingly fine-

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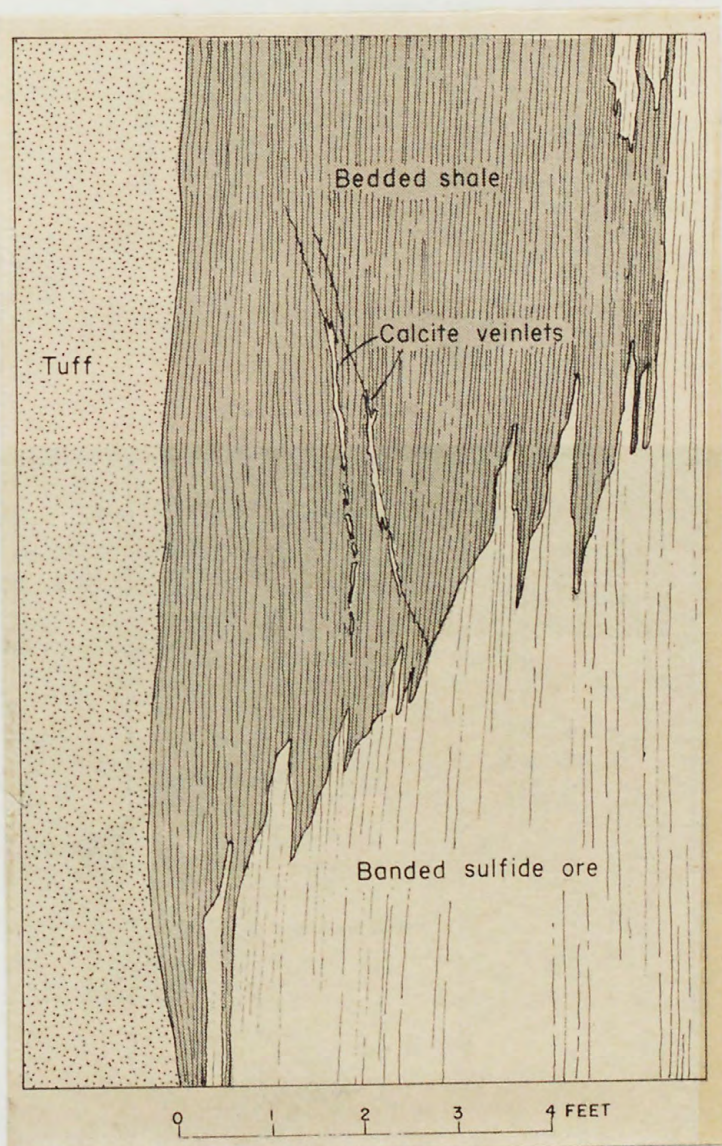


Figure 15--Sketch showing sawtooth relationship between banded sulfide and shale at the northwest end of the 412 stope, Afterthought mine. Note the parallelism of sulfide banding to bedding in the host rock.

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Figure 18--Photograph showing interfingering relation-
ship between sulfide and shale, 120 stope, Afterthought
mine. Sulfide (S); shale (sh). Pencil at lower right
is 6 inches long.

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

<u>Mineral and composition</u>	<u>Geologic occurrence</u>
Albite- $\text{NaAlSi}_3\text{O}_8$ -----	Widespread hydrothermal replacement of more calcic feldspars (see p. 193-208).
Alunite- $\text{KAl}_3(\text{SO}_4)_2(\text{OH})_6$	Minor gangue mineral in Bully Hill-Rising Star mines area. Identified in two 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 (see p. 322 to 326.)
Azurite- $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$	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 sulfides are embedded. Barite also present as replacement of country rock remote from known sulfides.

- Bornite- Cu_5FeS_4 -----A relatively 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 the mines. Is generally intimately mixed with pyrite, sphalerite, and other sulfides but locally forms bunches 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 portions
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-Cu₂O-----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 very intimately mixed
with sphalerite and tetra-
hedrite-tennantite.

Gold-Au-----Occurred in oxidized portions

of sulfide bodies and in
 placers below outcroppings of
 oxidized ore. All the sulfide
 ore contains gold in recover-
 able quantities.

Gypsum- $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ -----Abundant as a replacement of
 anhydrite in the Rising Star
 and Bully Hill mines.

Hematite- Fe_2O_3 -----Forms small lenses in sheared
 rocks near Baxter's Gulch
 northwest of Copper City area.
 Was not seen associated with
 sulfide deposits but seems
 to occur in similar structur-
 al environment.

Hydromica
 $\text{K}_1\text{Al}_2(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$ Very common as an alteration
 product in siliceous volcanic
 rocks throughout the district.
 Especially abundant in shear
 zones along which sulfide lenses
 occur but rarely is present as
 a gangue mineral in the sulfides.

Kaolinite- $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ -----Occurs in small amounts along
 shear zones in the Bully Hill
 and Afterthought areas. Also
 is weathering product after
 feldspar throughout the district.

Limonite- $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ -----Occurs as gossan capping over massive sulfide, as pseudomorphs after pyrite, and as skins 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 two specimens of sulfide ore.

Malachite- $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$ -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 portions of sulfide lenses.

Sphalerite-ZnS-----Fine grained dark gray sphal-
 erite is the principal zinc
 mineral in all the massive sul-
 fide lenses.

Tetrahedrite-tennantite-Present in practically all sul-
 fide ore but is rarely abundant.
 $(\text{Cu}_1\text{Fe}_1^{\text{As}})_{12}\text{Sb}_4\text{S}_{13}$
 $(\text{Cu}_1\text{Fe}_1^{\text{As}})_{12}\text{As}_4\text{S}_{13}$ Closely associated with galena.

grained mixture of the above minerals (fig. 17). 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 not inaccessible, so that little information on supergene minerals was obtained during the present study.

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 various ore minerals differs greatly, not only from one sulfide lens to another but within individual lenses. Consequently, some lenses or parts thereof were relatively rich in chalcocopyrite and were selectively mined as copper ore, whereas others, consisting largely of sphalerite, were treated as zinc ore (figs. 17 and 18). A few lenses were composed largely 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 main-

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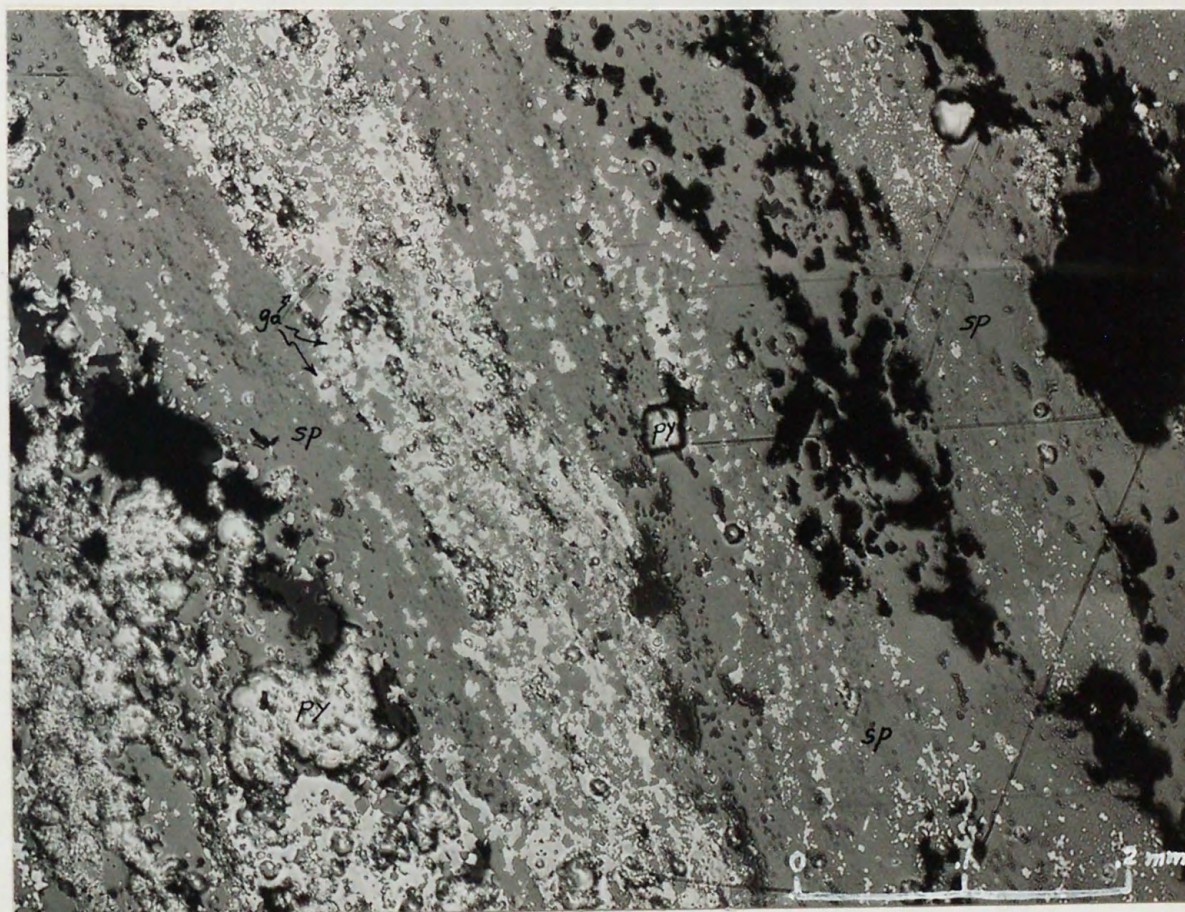


Figure 17--Typical zinc-rich banded sulfide ore from the Afterthought mine. Minerals are sphalerite (sp), galena (ga), and pyrite (py). Successful milling of this ore is difficult because of the extreme fineness of grain and intimate admixture of sphalerite and galena (X 195).

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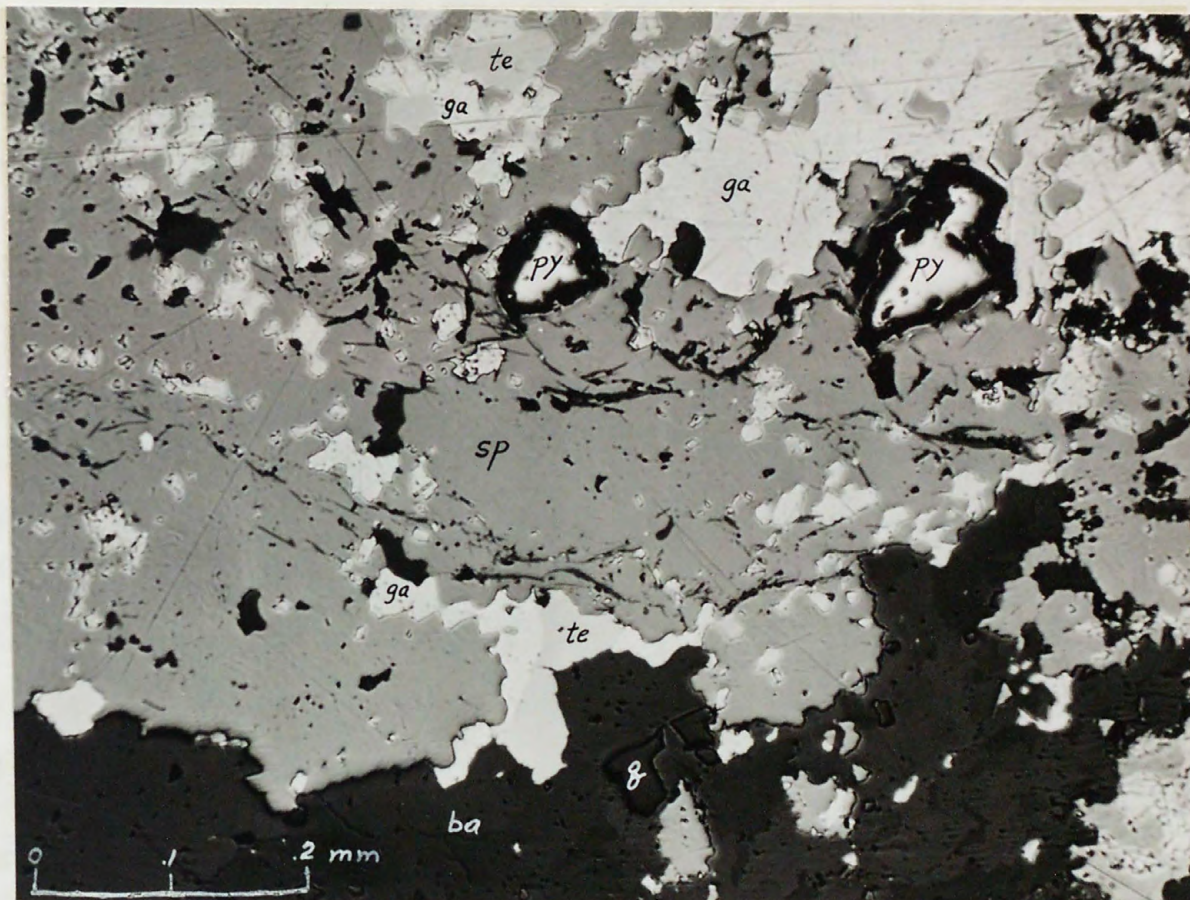


Figure 18--Photomicrograph of zinc-rich sulfide ore from the 420 stope, Afterthought mine. Sphalerite (sp); pyrite (py); galena (ga); tetrahedrite-tennantite (te); barite (ba); quartz (q). Note the association of galena and tetrahedrite-tennantite. Pyrite, where surrounded by other sulfides, is strongly corroded, but where it occurs in gangue it is in the form of euhedral crystals. (X 170).

ly of pyrite, were avoided as much as possible during mining operations.

Galena is irregularly distributed in virtually all the massive sulfide lenses; many lenses contain appreciable amounts of this mineral. About 2 percent lead, all from galena, was recovered during the 1948-1952 operations of the Afterthought mine. Either copper-rich or zinc-rich ore 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 massive sulfide ore. Its distribution is closely related to that of galena. No silver minerals were seen in the hypogene ores and it appears that virtually all the silver is contained in the tetrahedrite-tennantite and galena. Ore rich in these minerals is also relatively rich in silver. Some ore taken 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 rather 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 portions of ore bodies yielded free gold during the early days of 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 the only element present in significant amounts is cadmium. 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 average ratio of 1:200 for zinc ores given by Clarke and Steiger (1914, p. 61). Probably much of the Cd substitutes for Zn in the sphalerite lattice, but in view of the high cadmium content it appears likely that some greenockite is also present in the ores. 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.

Table 6. --Quantitative spectrographic analyses for Ge, Cd, Co, Ni, and Ga in 14 ore samples, East Shasta copper-zinc district. Harry Bastrom, U. S. Geological Survey, Analyst

<u>Laboratory No.</u>	<u>Field No.</u>	<u>Description and Locality</u>	<u>Ge</u>	<u>Cd</u>	<u>Co</u>	<u>Ni</u>	<u>Ga</u>
53-1988 SW	BH 00	Copper-zinc ore, Bully Hill mine	0	.62	.0011	.006	.0056
53-1989 SW	OD 9051	Copper ore, Bully Hill mine	0	0	.012	.0014	.0015
53-1990 SW	OD 9052	Copper-zinc ore, Bully Hill mine	.003	.32	0	.0015	.0002
53-1991 SW	OD 9053	Zinc ore, Bully Hill mine	0	.74	0	.0024	0
53-1992 SW	OD 9054	Copper ore, Bully Hill mine	0	.22	0	.0009	.0012
53-1993 SW	OD 9062	Pyritic Zn ore, Rising Star mine (800 level)	0	.56	0	0	.0027
53-1994 SW	OD 9071	Pyritic Zn ore, Rising Star mine (800 level)	0	.36	0	0	.0004
53-1995 SW	RS 00	Zn ore, Rising Star mine (700 level)	0	.32	0	.0007	0
53-1996 SW	RS 01	Zn ore, Rising Star mine (900 level)	.0022	.64	0	.0011	.0016
53-1997 SW	RS 02	Zn ore, Rising Star mine (900 level)	.0026	.64	0	.0018	.0007
53-1998 SW	OD 11158	Pyritic copper ore, Afterthought mine (120 stope)	0	.04	0	0	.0012
53-1999 SW	OD 11161	Zinc ore, Afterthought mine (120 stope)	.011	.22	0	0	0
53-2000 SW	OD 11165	Pyritic zinc ore, Afterthought mine (220 stope)	.010	.28	0	0	.0036
53-2001 SW	OD 11171	Zinc ore, Afterthought mine (420 stope)	0	.22	0	0	.0037

It appears 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 the 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, in press,), 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 a relatively 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 foliation 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. 19), and probably in one place between the 470 and 570 levels in the Bully Hill mine. The 450 ore body 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 southeast. The shale in the hanging wall of the Main fault in the vicinity of the 450 level also dips southeast, approximately parallel to the fault and thus would have formed an impermeable barrier to fluids rising along the southwest-dipping shear zone (fig. 19). The ascent of the fluids would presumably have been retarded beneath the juncture of the Main fault and the shear zone, thus giving them 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 sulfide lens

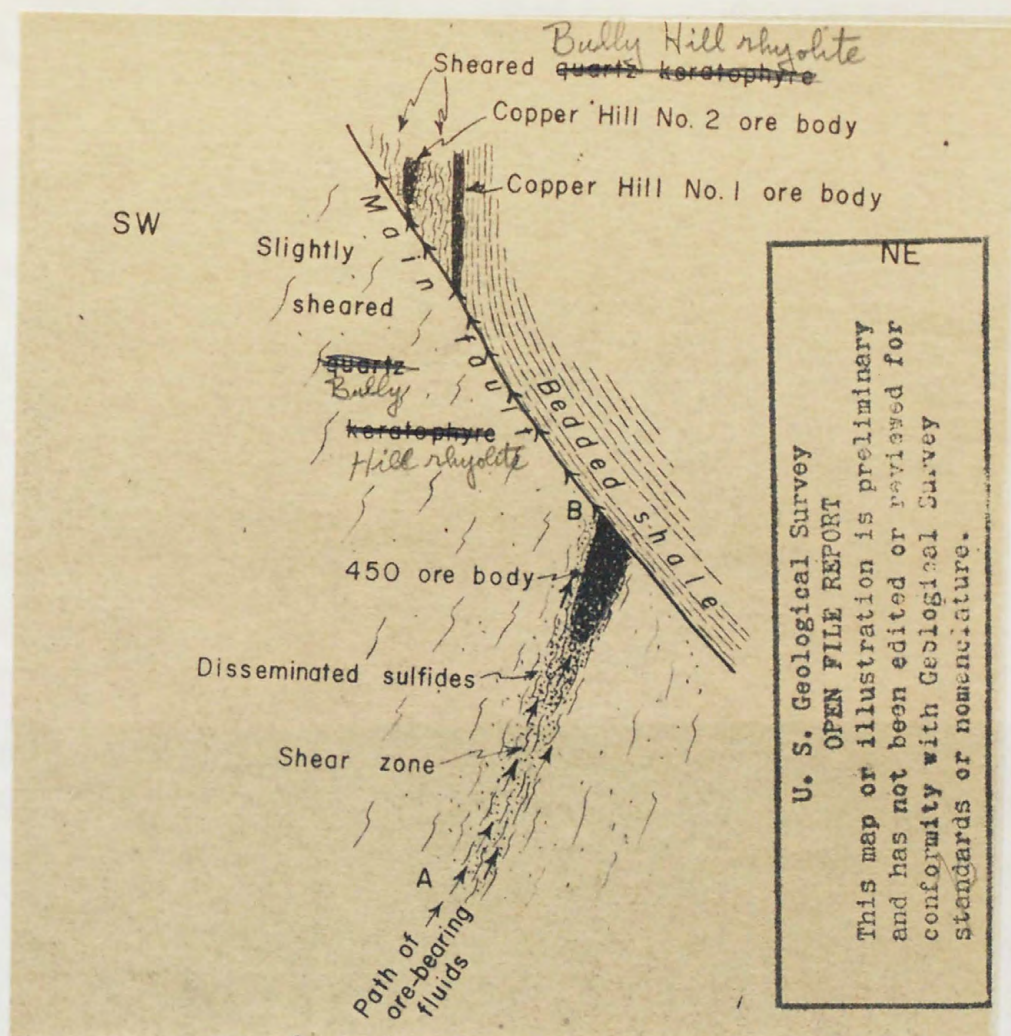


Figure 19--Sketch (section) of part of the Afterthought mine showing structural control of ore bodies and probable path of ore-bearing fluids. Fluids rose from unknown source along shear zone A in the Bully Hill rhyolite. At B the fluids were retarded and forced to change direction by the Main fault and by impermeable shale bedded parallel to the Main fault. This retardation and favorable structural environment resulted in the formation of the 450 ore body. Fluids continued ascent along the Main fault, and where bedding and foliation in hanging wall rock diverge from Main fault the Copper Hill ore bodies were formed. Path of ore fluids is shown by arrows.

but may also have been a factor in the localization of the 700a sulfide lens.

As figure 19 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 approximately parallel to the fault, thus forming a relatively 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 foliation in the Bully Hill rhyolite dip steeply toward and intersect the Main fault at an angle of about 45 degrees. Here the fluids ascending along the Main fault were able to penetrate along bedding and foliation 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 bodies in the Afterthought mine are similarly replacements of shale beds that dip toward feeder channels at a favorable angle.

Minor structural control by a drag fold having an amplitude of a few feet was seen near the north end of the 420 sulfide lens in the Afterthought

mine (fig. 20). This type of control appears to be of only minor importance.

Rock alteration and paragenesis

As described on pages 172-201, most rocks of the district have undergone extensive hydrothermal alteration. Most of this alteration, however, 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 is largely restricted to the general vicinity of sulfide deposits. Anhydrite and gypsum occur only in the lower parts of Bully Hill and Rising Star mines. Barite is a common gangue mineral in the sulfide ores and locally elsewhere near the Copper City and Bully Hill ore bodies.

The alteration that seems most cleanly associated with sulfide deposits is at the Rising Star mine 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 the intensely silicified rock and rock replaced by sulfates and sulfides

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Figure 20--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.

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. 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 relatively intense in places along the Bully Hill shear zone, above the Copper City mine workings, and locally in the Afterthought mine.

Anhydrite and gypsum are intimately related, the gypsum probably being formed by hydration of anhydrite in place. Anhydrite and gypsum extensively replace the Bully Hill rhyolite in the Rising Star mine. In the Bully Hill mine they 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. Although they occur in large amounts at depth, gypsum and anhydrite are less abundant at higher levels, and neither mineral has been found to crop 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), roughly 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 appear to have replaced sheared and altered porphyritic quartz keratophyre and meta-diorite. 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 foliation from the replaced rock, and emphasized by discontinuous thin screens and remnants of foliated chloritic and sericitic host rock. The remnants of host rock range from a fraction of an inch to 2 inches or so thick. The masses of gypsum and anhydrite do not appear to have been faulted or sheared. Masses of gypsum and anhydrite in the Bully Hill mine are rather limited to the main shear zone, though minor amounts occur in the adjacent wall rock in veinlets and along fractures and shears.

Information concerning the occurrence of gypsum and anhydrite in the Rising Star workings, which are inaccessible at this writing, has been taken largely from Boyle (1914, p. 99-103), and from private reports kindly made available by the Glidden Company. As far as can be ascertained from existing records the closest to the surface that gypsum has been found is on the 500 level of the Rising Star mine, where it is barely 100 feet below the surface. Below the 500 level gypsum and anhydrite become more and more abundant as a replacement of country rock; on the 900 level they constitute about 75 percent of the wall rock, and on the 1000 level nearly 100 percent. Gypsum is the predominant sulfate on the 500 level; the amount of anhydrite, relative to gypsum increases with depth below that level. Anhydrite is reportedly the predominant sulfate 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, with gypsum or anhydrite gradually feathering out as the proportion of country rock increases outward from the mass. Small lenses, veinlets, and frac-

ture-fillings of gypsum or anhydrite locally extend into the country rock. At other places, however, the boundaries are quite sharp and deposition of gypsum and anhydrite appears to have been limited by gouge-filled faults and shear zones. Although banding preserves relict shear structures of the replaced rock in places, pre-existing 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. Disseminated sulfide also occurs in the anhydrite.

Thin sections show that the anhydrite has excellent rectangular cleavage, lamellar twinning as a rule, and high birefringence. Where anhydrite grains are partially altered to gypsum, the gypsum commonly appears as a mat of fine-grained, randomly oriented, acicular crystals. In places the gypsum occurs as a fringe bounding the anhydrite grains, showing that the replacement of anhydrite by gypsum proceeds from the grain boundaries inward. In areas where replacement is nearly com-

plete, anhydrite crystals are isolated grains in a field 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 largely speculative. Graton (1910, p. 103) believes that the anhydrite at Bully Hill is of hydrothermal origin, and that the gypsum is derived from anhydrite secondarily. This view 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 supposes that it could have been transformed to anhydrite, then later reconverted to gypsum.

From petrographic evidence and general relationships in the Bully Hill and Rising Star mines, anhydrite is most reasonably explained as derived from ascending hydrothermal solutions, whereas gypsum appears 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 exists 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 intimately associated with the primary sulfides down to the deepest levels of the mines. Moreover, it is at least in part if not largely older than the sulfides.

Barite is 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. 4). Small masses of crystalline, light gray to white barite measuring a foot or two thick by several feet long are exposed along the Bully Hill shear zone in the vicinity of Bully Hill adit No. 0. 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 banded, and replaces sheared rock in a manner similar to the anhydrite. Barite is a common gangue in the sulfide ores, mostly in minor amounts, and it also occurs in post-ore veinlets with calcite and quartz.

Thin sections show that barite is in the form of anhedral to subhedral tabular crystals with excellent cleavage parallel to the length of the

crystals but relatively poor at right angles. It commonly forms the matrix in which sulfide minerals are embedded and in most places is replaced by the sulfides.

Disseminated pyrite is common in virtually all the principal mine areas (pl. 4) 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 close to lenses than remote from them.

Calcitized rock occurs along the margins and at the edges of some sulfide lenses in the Afterthought mine but forms much larger masses remote from known sulfide bodies (fig. 2).

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 somewhat from place to place and only a

very general age sequence could be determined. Microcrystalline quartz is the oldest gangue mineral, as shown by the fact that it is everywhere replaced by other gangue minerals. Calcite and anhydrite are in general the youngest of the gangue minerals, but they were not seen together in the same slide and therefore their age relative to each other is not known. Clinocllore, hydrous mica, and barite in most places seem to be of intermediate age between microcrystalline quartz and calcite, or anhydrite. The age of clinocllore, hydrous mica, and barite in relation to each other differs 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 essential 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 sulfides, but the fact that stringers of one or more of these minerals locally cut sulfides shows that they were deposited during at least two different stages. Feather quartz (fig. 3) adjacent to pyrite crystals replaces all other gangue minerals and is essentially contemporaneous with pyrite.

Pyrite is the oldest sulfide mineral and seems to have shown a marked preference to replace micro-crystalline quartz rather than other gangue minerals. Where pyrite is enclosed in gangue minerals it is commonly euhedral or subhedral; 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 appear to be the youngest of the ore minerals.

Sphalerite is believed to be 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 (figs. 17 and 18). 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, et al., 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 host (fig. 21). 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 percent to about 15 percent of chalcopyrite blebs in sphalerite. Spherical blebs of galena in gangue (fig. 22), blebs of chalcopyrite in gangue, blebs of pyrite in gangue, blebs of galena in sphalerite, and blebs of tetrahedrite-tennantite in sphalerite are also not uncommon 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 point out that similar textures in ores probably in some cases represent the beginning of replacement of sphalerite by chalcopyrite, and in still others may be the residuals of nearly

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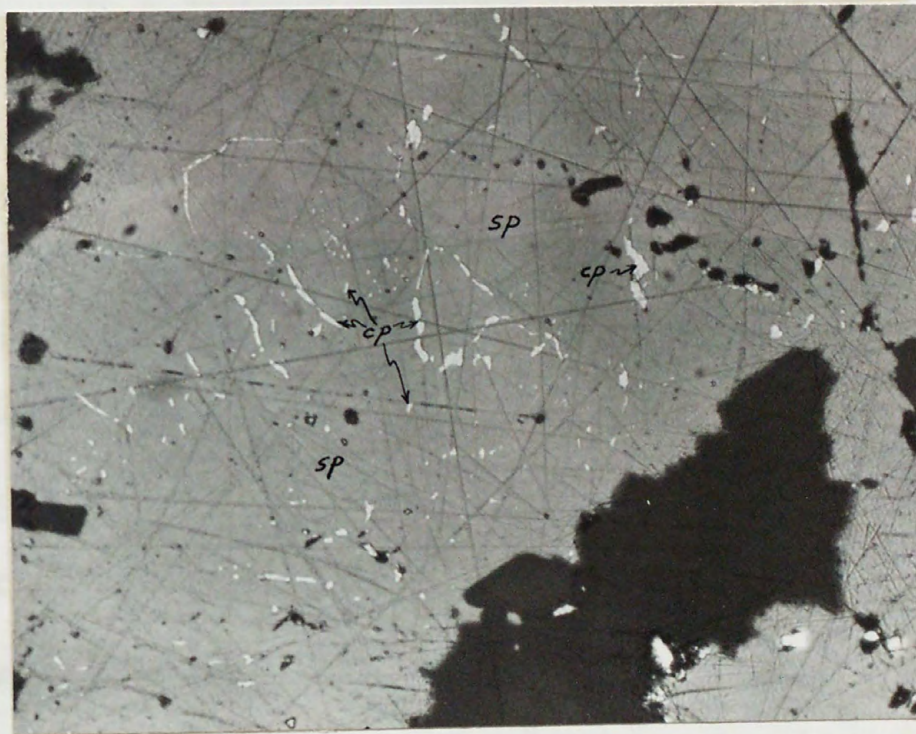


Figure 21--Photomicrograph showing mottled texture
produced by chalcopyrite blebs (cp) in sphalerite (sp).
The geometrical arrangement of the blebs suggests that
they are in part along crystallographic directions
in the sphalerite (X 170).

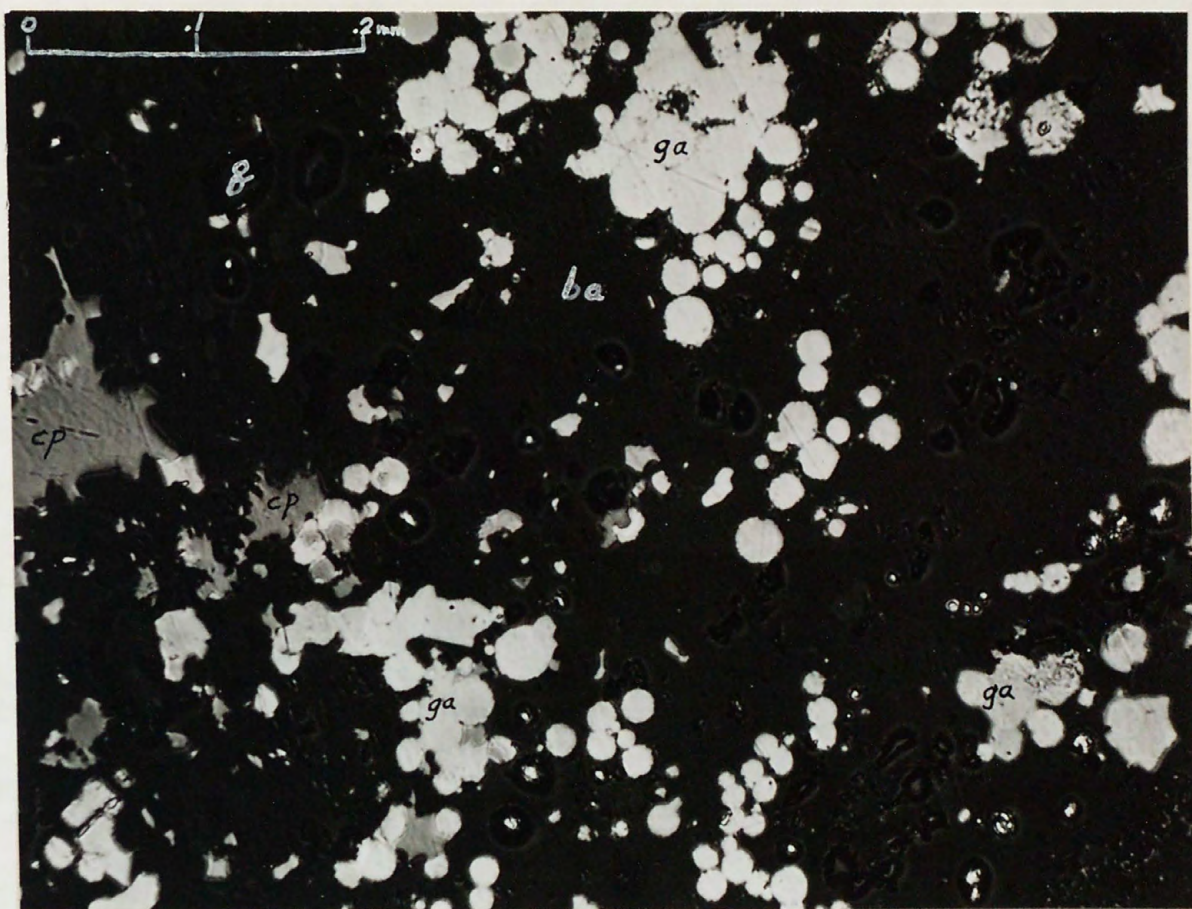


Figure 22--Photomicrograph showing mottled texture formed by galena (ga) in barite (ba). Pyrite in gangue and chalcopyrite in gangue form similar mottled textures in other specimens. Pellets or blebs are interpreted as very early stage of replacement of barite by galena. In more advanced stages of replacement the pellets coalesce into larger masses as those near top and bottom of photo.

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complete replacement of chalcopyrite by sphalerite. Buerger (1934) has shown experimentally that some 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 sulfides 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 various sulfide minerals in gangue, in conjunction with the apparent highly variable amounts of chalcopyrite in sphalerite (less than 1 to about 15 percent) suggest that the chalcopyrite blebs in sphalerite did not result entirely from exsolution. Instead they probably represent in part 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, it 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 essential contemporaneity between the hypogene chalcopyrite and hypogene bornite.

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 relationship suggest 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. It was this feature that 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 little 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 much less conspicuous. According to Diller (1903b, p. 129), chalcocite was most abundant near the borders of pyritic ore. Minor nodules and stringers of chalcocite were found in the Bully Hill and Rising Star mines to depths as great as 500 feet. Diller (1903b, p. 129) reports that secondary bornite and secondary chalcopryite were found associated with chalcocite in the zone of enrichment at Bully Hill. In the Afterthought mine secondary sulfides are present as deep as the 120 stope, about 250 feet below the surface, but are in very minor amounts.

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:

- (1) The presence of unsupported masses 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; (2) banding in the sulfide in places parallels bedding or foliation in the adjacent country rock, strongly indicating, if not proving replacement (figs. 15, 20); nowhere is the banding crustified as might be expected if the deposits were fissure fillings; (3) the presence, in some places, of 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 are believed to have formed from ascending hydrothermal fluids. That these fluids were probably aqueous is shown by the abundance of hydromica 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: (1) a subjacent igneous mass, and (2) the volcanic and sedimentary rocks that lie beneath the Bully Hill rhyolite and Pit formations.

Geologists have traditionally appealed to a magmatic source for mineralizers, and for reasons given on page 188 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 (1957) point out that the location of the massive sulfide deposits of the West Shasta district around the north end of the Mule Mountain stock and the presence of pyritized rock near the south end of the stock suggest a genetic relationship. No such spatial relationship between massive sulfide deposits and exposed plutonic rocks can be demonstrated, however, in the East Shasta district (pl. 4), even though the presence of a subjacent igneous mass beneath the entire map area seems highly probable. Granting the presence of this mass and assuming, as available evidence seems to indicate, that it was

emplaced as a magma, it could well 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 largely 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 three samples from the Dekkas andesite are each about a mile from the closest known massive sulfide deposits, and the sample from the Baird formation is about 5 miles from the closest deposit. Thin sections show slight alteration of plagioclase to albite in the meta-andesite sample and

Table 7. --Quantitative spectrographic analyses for Cu and Zn in four rock samples from the East Shasta copper-zinc district./

<u>Lab. No.</u>	<u>Field No.</u>	<u>Type of rock and locality</u>		
53-2003 SW	B114	Spilite - Sec. 11, T. 33 N. R. 2 W.	.019	.026
53-2004 SW	D149	Keratophyre - Sec. 20, T. 34 N. R. 3 W.	.008	.021
53-2005 SW	D237	Spilite - Sec. 9, T. 34 N. R. 3 W.	.008	.039
53-2006 SW	F223	Meta-andesite - Sec. 33, T. 34 N. R. 4 W.	.008	.034

/ Harry Bastrom, U. S. Geological Survey, Analyst

complete replacement by albite in the keratophyre and spilite samples. Ferromagnesian minerals are altered to chlorite and uralitic amphibole.

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 from various sources by Fleischer (1953, p. 4), and also about the same as the Keweenaw 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 two to three 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 similarity in bulk composition to the Dekkas andesite it seems reasonable to assume that it contains about the same amounts of copper and zinc.

If one uses even the most conservative values of 0.008 percent for Cu, and 0.021 percent for Zn (table 7), it works out that the Dekkas andesite, as well as the greenstone in the Baird formation, contains about 1,000,000 tons of metallic copper

and 2,500,000 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 2000 feet, the thickness of the mafic lava and pyroclastic rock in the Baird is at least 1000 feet, and the thickness of the Copley greenstone is a minimum of 2000 feet, it would seem that these formations represent a source more than adequate to account for the approximately 30,000 tons of copper and 25,000 tons of zinc that the district has so far produced.

If it be assumed 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 very small percentage of the copper and zinc (and probably also sulfur, iron, precious metals, and lead) present in these

rocks. The direction of movement of the fluids was presumably toward areas of relatively 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. An attractive feature of this hypothesis is that the volume of potential source rock can be very large, thereby necessitating the subtraction of only a very 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. That such pervasive movement of fluids is possible, and has taken place, is indicated by the regional albitization and chloritization in the district.

An alternative mechanism of mineralization might result from the granitization of mafic volcanic rocks deep in the geosyncline. In a recent interesting paper, Sullivan (1948) makes a good case in relating 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 little evidence that the exposed granitic rocks in either the East Shasta or the West Shasta districts have been formed by replacement of rocks in the geosynclinal prism. Nevertheless, the possibility that a significant volume of Copley greenstone and other rocks deep in the geosyncline were either replaced or assimilated by

granitic rocks cannot be lightly dismissed. In the replacement of such mafic rocks as the Copley and Dekkas formations a relatively large percentage of the copper and zinc present would be expelled and thus made available for concentration in ore deposits in structurally favorable places higher in the crust.

Based on Diller's (1906) data for the thickness of pre-orogenic formations younger than the Pit, and on the writer's estimate of 5000 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. Therefore, the depth at which the sulfide deposits were formed was almost certainly not greater than 11,650 feet. Moreover, inasmuch as deformation 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 considerably less than 11,650 feet.

The assemblage of sulfide minerals is a typically 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 and probably throughout 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 but they will be small and erratically distributed. The cost of finding them will be high, and unless several lenses are found close to each other it is unlikely that mining can be accomplished at a profit.

The areas regarded as geologically most favorable for prospecting are shown on figure 20. These areas are somewhat generalized and it is not meant to imply that they are all considered equally promising. They are outlined on the basis of the following criteria: 1) All the areas are either in the Bully Hill rhyolite, or in the Pit formation close to the Bully Hill rhyolite contact. 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 considered to be much more promising than the Pit formation and deserves the most attention. Past production has been mainly from the Bully Hill and it appears that that formation was both physically and structurally a highly favorable host for the mineralizing fluids. Its siliceous, brittle, locally brecciated and faulted character provided abundant fractures and small openings that allowed the fluids easy access and caused them to be entrained toward these areas of lower pressure. The stratigraphic position of the Bully Hill rhyolite beneath the relatively 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 the Bully Hill rhyolite contact, 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 situ, of a massive sulfide lens exposed by the accidents of erosion. However, only about half a dozen of some 40 known sulfide lenses were so 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. 4). Also, on the divide between First and Second Creeks (pl. 4), and locally in the Bully Hill area are masses of dense to spongy limonite that are far removed from any known sulfide mass.

This limonite commonly has a very 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 elevation 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 1750 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 is an example. However, some areas of heavily iron stained or pyritized rock have been explored rather extensively by diamond drilling without success. The Cowboy (Abe Lincoln) prospect in sec. 4, T. 33 N., R. 2 W. is an example. Massive sulfide lenses, if present in these areas, are evidently neither directly beneath nor directly down dip from the heavily iron stained rock at the surface. Heavily iron stained rock therefore may or may not be indicative of massive sulfide nearby.

Eighteen chip samples of limonite, collected from various exposures in the area, were submitted to H. E. Hawkes, who in 1951 was in charge of the U. S. Geological Survey's Geochemical Prospecting Unit, for chemical analysis for copper, zinc, and lead content. The results are shown on figure 20. Sample 1J13 represents limonite gossan collected from only 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 massive sulfide. Sample E47B is from a few feet above a lens of low grade disseminated sulfides. 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 limonite samples on figure 20 appear to be mainly of limonite derived from the oxidation, in situ, of heavily disseminated sulfide.

The results of the geochemical tests are erratic and it appears 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 geochem-

ical tests on bedrock were made in the East Shasta district. However, systematic sampling of bedrock for copper over the Mammoth mine in the West Shasta district for copper 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.

In the absence of gossan derived from massive sulfide the presence of 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. The 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. In a few places veinlets and blebs of barite are present. Cutting this intensely altered rock locally are shear zones containing gougy material composed of clay minerals mixed with silicified 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 my 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 a 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 map area (figs. 2 and 20) contain magnetite in minor amount. 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 work 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 interested 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 N. 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 3,983,000 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. 4).

The veins on O'Brien Mountain are as much as 10 feet thick and one was traced for about 1400 feet. These veins have been prospected by means of a few pits and short adits, but whether there

has been any production of gold or other metal 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 rich pockets. Included in this group are the Old Indian (F. J. Ward) prospect, and the Cook prospect (pl. 4). Most of the veins strike in the range between N. 45 W. to EW 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.

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