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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF THE MAMMOTH MINE SHASTA COUNTY, CALIFORNIA

SPECIAL REPORT 28

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Geology of the massive sulfide deposits at Iron Mountain, Shasta County, California, by A. R. Kinkel, Jr. and J. P. Albers. Special Report 14, 19 pp., 6 pls., 6 figs., 1951. Price 75¢.

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Map of Shasta County showing mines and mineral resources. Scale 1″ = 3 mi., 1939. Price 25¢.

Outline geologic map of California showing locations of copper properties, by Olaf P. Jenkins. Scale 1 :1,000,000. Economic mineral map No. 6—Copper. Price $1.00.

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Iron resources of California. Bulletin 129, 304 pp., 25 pls., 68 figs., 1948. Price $2.50.

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DIVISION OF MINES
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GEOLOGY OF THE MAMMOTH MINE

SHASTA COUNTY, CALIFORNIA

By A. R. KINKEL JR. and WAYNE E. HALL

Prepared in cooperation with the
United States Geological Survey

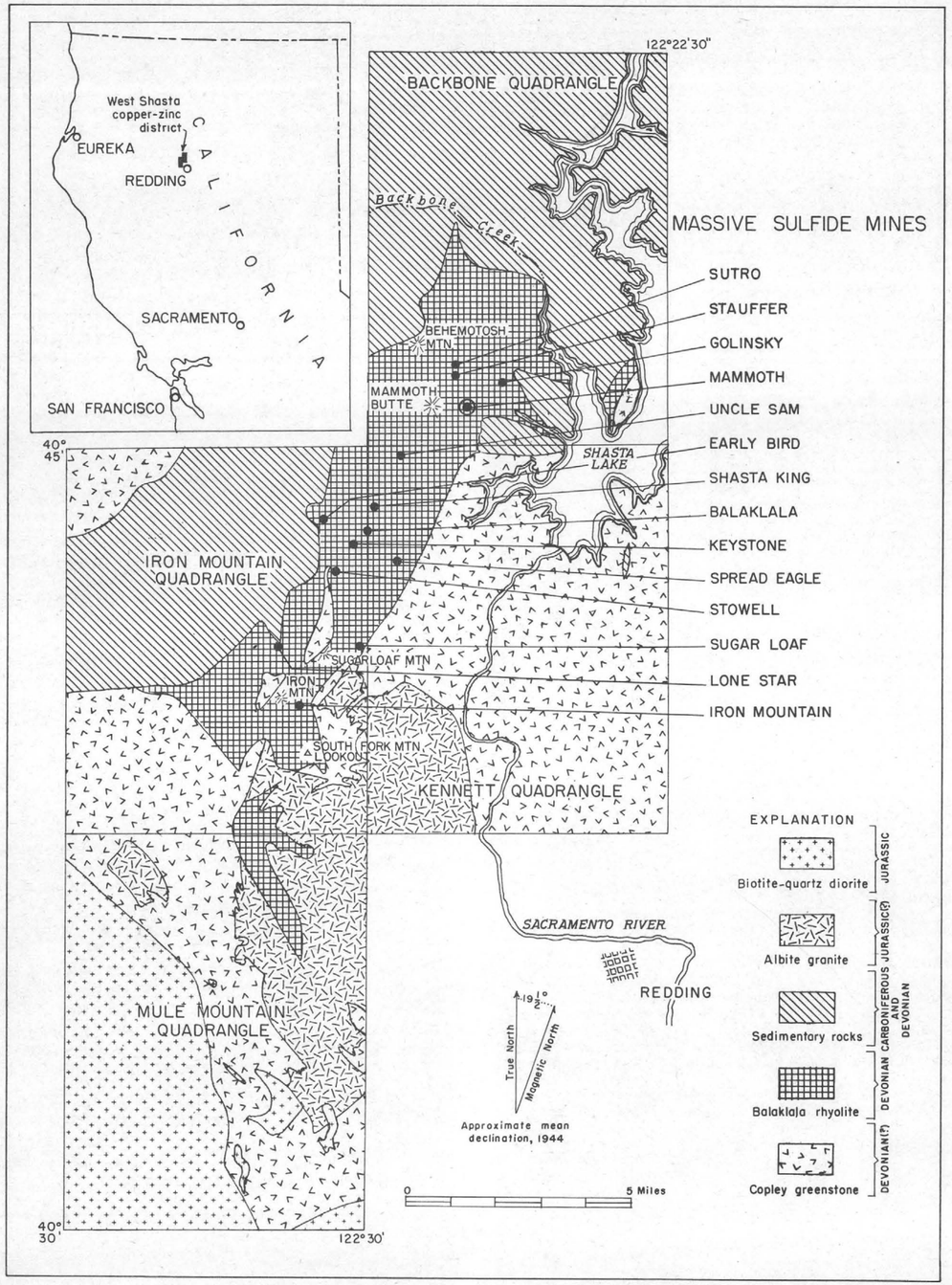

Figure 1. Index map showing location and geologic setting of the Mammoth mine, Shasta County, California.

the host rock here also. As far as is known, all base-metal ore deposits in the West Shasta district lie just below the base of the coarse-phenocryst rhyolite—or at the equivalent horizon, where the coarse-phenocryst rhyolite is absent—and throughout the district this horizon is the primary vertical control for ore deposits.

Foliation is not strongly developed in the Mammoth area, probably because the folds are broad, but the two types of foliation that are present have had a considerable effect on ground preparation prior to ore deposition. The first of these is a foliation parallel to bedding planes and is localized at flow contacts, particularly where there is much pyroclastic material between adjacent flows. Movement between beds during folding was controlled by the competence of the beds. The second type of foliation is a steeply dipping fracture cleavage across the bedding. It is most strongly developed in the axial-plane region of the folds. It ranges from a rude sheeting of the rocks without noticeable reorientation of minerals, through well-developed sheeting with sericite oriented along discrete planes, to a sericite schist in which only lenticules of unsheared rock remain.

The intersection of steep fracture cleavage with foliation parallel to the bedding plane is an important ore control at the Mammoth mine, because it formed a zone of fractured rock along the crest of an arch under a relatively impervious cover of unfractured rock (fig. 5).

Most of the ore bodies in the Mammoth mine lie along the culmination of an arch in the rhyolite. This is shown on the structure contour map (pl. 9) and on the level maps (pls. 4-8). In addition to the main arch extending from the outcrop to the Friday Lowden and Hanley ore bodies at the southwest end of the mine, several smaller arches that appear to localize individual ore bodies are present. Broad minor arches extend over the Clark ore body, over the northwestern extension of the Main ore body, and over the 437 and 313 ore bodies. The Copper Crest ore body appears to lie on the north-plunging nose of a major arch, the culmination of which has been eroded.

Faults or shear zones that act as feeder fissures are difficult to recognize with certainty. The criteria used by the authors in regarding certain faults as feeder channels were: (1) the location of several discrete ore bodies or heavily pyritized areas along the same fault or shear zone; (2) the presence of strongly altered rock along a fault, particularly claylike hydrothermally altered rock; and (3) ore minerals in a fault, either in the gouge or in bands in the locally sheared rock adjacent to a fault. It is recognized that these are questionable criteria, because solutions traveling through the rocks and encountering a premineral fault might deposit ore along the fault and cause hydrothermal alteration along it.

The faults along which claylike hydrothermally altered rock occurs are the California fault, the Schoolhouse fault, the Gossan fault (these last two are exposed on the surface for a short distance only), and the unnamed fault that lies about 200 feet south of the Copper Crest ore body. All these except the Gossan fault are steeply dipping, northeast-trending faults.

The California fault cuts the trend of the ore zone at a low angle, and at the southwest end of the known ore zone it lies 400 feet northwest of the ore bodies. This suggests that if the California fault is a feeder for the whole ore zone, ore solutions left the fault at a point below the Friday Lowden ore body and traveled upward along the main arch structure rather than along the fault itself. However, the presence of several small ore bodies on the 200-foot level (pl. 4) that are apparently alined along the California fault suggests either that some solutions continued up along the fault or that solutions traveling along the arch deposited ore against the fault where it cuts the arch.

The alinement of most of the zinc-rich ore bodies (473, 313, Graton, Yolo, and possibly the Copper Crest) along the 313 fault and its probable extension, the Yolo (313) fault, is conspicuous and suggests that the introduction of zinc into the ore was primarily along the 313 fault. This fault may have reopened slightly later than the main period of copper deposition.

The conjunction of the major ore controls is not merely by chance. Lenses of pyroclastic material initiated local folding because in contrast to massive flows, they form a less competent layer and because a change in dip, along the boundaries of a lens in this instance, is a favored locus for the initiation of folding. Movements along the bedding plane were strongest in folded areas, and fracture cleavage developed mainly in the axial regions of folds. The relationship, if any, between the location of feeder fissures and the other ore controls is not known.

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includes a little sphalerite mineralization; (3) sphalerite-chalcopyrite stage, which includes a little tetrahedrite and galena mineralization; (4) calcite stage; and (5) oxidation and enrichment stage.

Pyrite Stage. Pyrite was the first sulfide mineral introduced. Large bodies of fine-grained pyritic ore were formed by the nearly complete replacement of rhyolite. In most places a thin selvage of rock gangue was left as a network around pyrite grains. This network of gangue, before replacement by minerals later than pyrite, amounted to 25 or 30 percent by volume of the massive pyritic body.

Chalcopyrite-Quartz Stage. Pyrite was completely deposited before the minerals of the chalcopyrite-quartz stage were introduced. The introduction of quartz, chalcopyrite, and some sphalerite was accompanied by little concomitant corrosion of pyrite. These minerals mainly replace the selvage network of gangue around the pyrite grains, although the mineral-depositing solutions did corrode the pyrite somewhat, destroying most of the crystal faces.

Quartz was the first mineral deposited in this stage. It filled fractures in pyrite and replaced the relict rock gangue around pyrite. Chalcopyrite and sphalerite are associated with quartz in the network veinlets, although they are both slightly later than quartz and contain corroded inclusions of quartz. They seem to have been deposited in the same period of deposition, as either mineral can be found corroding the other. Chalcopyrite predominates over sphalerite in this stage and deposition of chalcopyrite began first, as most of the sphalerite is introduced along chalcopyrite-pyrite boundaries.

Sphalerite-Chalcopyrite Stage. Sphalerite predominates over chalcopyrite in this stage and formed the ore bodies of high zinc content. The minerals introduced, listed in order of decreasing abundance, are sphalerite, chalcopyrite, tetrahedrite, and galena.

No sharp break exists between the chalcopyrite-quartz stage and the sphalerite-chalcopyrite stage. Sphalerite was introduced in small amounts near the end of the chalcopyrite-quartz stage, but it greatly predominated in the sphalerite-chalcopyrite stage, when it formed streaks, lenses, and veins cutting the pyritic ore bodies, and formed separate pods of high-grade zinc ore in rhyolite.

Sphalerite had an extremely corrosive effect upon pyrite in this stage. In the lenses and veins of sphalerite in highly pyritic ore, sphalerite contains less than 10 percent of tiny corroded pyrite relicts.

Chalcopyrite is present as tiny blebs in sphalerite and as irregular grains that have mutual borders with sphalerite. They apparently were deposited contemporaneously.

Tetrahedrite also appears to have been deposited contemporaneously with sphalerite. It occurs as tiny inclusions in sphalerite with mutual borders. Tetrahedrite and chalcopyrite were not in contact in any of the polished sections studied, so their relative age was not evident.

Galena is later than sphalerite, as it was introduced along sphalerite-gangue contacts and it has many apophyses extending into sphalerite.

Calcite Stage. Calcite is present in very small amounts in the massive sulfide ore. It is clearly later than all of the sulfide minerals, as it fills veinlets and vugs in the massive sulfides.

Oxidation and Enrichment Stage. No specimens of supergene enriched ore were available for study, so the mineralogy and paragenetic relationships are not known.

Hydrothermal Alteration

All gradations exist between unaltered porphyritic rhyolite and the same rock with quartz phenocrysts in a matrix of secondary minerals. The altered rocks have been formed by regional metamorphism, surface alteration, hydrothermal alteration, or a combination of these processes. The altered porphyritic rhyolite is white, pink, buff, or light green. A conspicuous white alteration of the rhyolite is known to be of hydrothermal origin because of its occurrence around ore bodies and along fractures in the ore zone. The intensely altered rock is composed of quartz and sericite, and crumbles apart in the hand.

The altered rhyolite of pink color is also localized close to ore deposits, but it is not certain whether the alteration to pink is in all places of hydrothermal origin. Similar pink altered rocks are present at Iron Mountain, at the Balaklala and Mammoth mines, and at a few other localities. In some places the whole rock is uniformly pink except for dark-red hematite in casts after pyrite. Under the microscope, the pink color is seen to result from minute flecks of hematite disseminated through the matrix, and from thin coatings of hematite along cracks that cut across foliation and across seams of sericite and hydromica. The hematite-filled pyrite casts have sharp contacts with the pink matrix, and there is no evidence that hematite migrated away from these casts with concomitant precipitation.

The pink altered rock is found in porphyritic rhyolite that has been strongly altered hydrothermally to sericite and hydromica. Pyrite casts are present in all the pink altered rock. The pink color seems to result from the adhesion of minute hematite specks to the sericite and hydromica. The association of pink altered rock with the ore deposits apparently indicates that the strong alteration to sericite and hydromica is associated with the deposition of the ore, and that hematite is deposited only on the sericite and hydromica.

Ore Controls

The four ore controls that are thought to be of major importance in localizing ore at the Mammoth mine are: (1) stratigraphic control, (2) structural control by foliation, (3) structural control by the main domelike flexure and minor flexures, and (4) location of feeder fissures.

The ore zone is restricted to the rocks that immediately underlie the coarse-phenocryst rhyolite, as shown in the cross sections (pl. 3). This is a zone that contains much bedded pyroclastic material, principally discontinuous tuff units and lenses of volcanic breccias, but it also contains flows of medium-phenocryst rhyolite. Mapping done at the Iron Mountain and Shasta King mines (Kinkel and Albers, 1951; Kinkel and Hall, 1951) showed that the massive sulfide ore preferentially replaced porphyritic rhyolite with 2- to 3-mm quartz phenocrysts. Although no direct evidence is available on the nature of the rock that was replaced by the ore bodies of the Mammoth mine, the presence of medium-phenocryst rhyolite in the ore zone at the Mammoth mine suggests that this may be

GEOLOGY OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA *

By A. R. Kinkel, Jr.,** and Wayne E. Hall **

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ABSTRACT

The Mammoth mine is in the West Shasta copper-zinc district 13 miles northwest of Redding, California, in the foothills of the Klamath Mountains of northern California. It is at an elevation of 3,000 feet. It is not accessible by road (1951) because the recent flooding of Shasta Lake has covered parts of the old access roads.

The ore produced from the Mammoth mine during its period of operation from 1905 to 1925 amounted to 3,395,145 tons. Of this, 3,311,145 tons was direct-smelting copper ore, and 84,000 tons was high-grade zinc ore. The average grade of the ore was 3.95 percent copper, 4.62 percent zinc, 0.039 ounce of gold, and 2.32 ounces of silver per ton.

The ore occurs as large, flat-lying tabular bodies of massive pyrite that contain copper and zinc, and minor amounts of gold and silver. The ore is a replacement of Balaklala rhyolite and formed near the contact between the upper two of the three units in the Balakala rhyolite. The upper unit is a thick, massive rhyolite with coarse phenocrysts of quartz and feldspar, and the middle unit consists of rhyolite flows and rhyolitic pyroclastics with much smaller phenocrysts. Some bedded tuff is present adjacent to the contact between the two units and immediately over the ore bodies. Individual ore bodies reach maximum horizontal dimensions of 900 feet by 500 feet and a maximum thickness of 110 feet. The ore zone has a known length of about 4,200 feet; it plunges 14 degrees to the southwest.

The geologic controls that localized the ore shoots are both stratigraphic and structural. The ore zone occurs along the crest of an elongated domelike arch at the base of the coarse-phenocryst rhyolite, the upper unit of the Balaklala rhyolite. In detail, ore is present where gently dipping bedding-plane foliation, which is localized by layers of pyroclastic material, is intersected by steep fracture cleavage. The solutions were introduced into this structure by premineral faults that apparently acted as feeder fissures.

* Publication authorized by the Director, U. S. Geological Survey; manuscript received for publication June 17, 1952.

** Geologist, U. S. Geological Survey.

INTRODUCTION

Previous Work. Geologic studies of the copper- and zinc-bearing areas of Shasta County have been carried on intermittently for many years; Diller's work in this district, beginning in 1884 and culminating in his report on the Redding quadrangle in 1906 [1] has been of inestimable help to the authors. More recent work on the base metal deposits includes that of Graton [2], Seager [3], Kinkel and Hall [4] and Kinkel and Albers [5]. This report is the first published description of the ore deposits of the Mammoth mine, which is one of the largest mines in the West Shasta copper-zinc district. The work is part of a cooperative program between the U. S. Geological Survey and the California Division of Mines for studying the ore deposits of the Shasta copper-zinc district; the field work was done during August and September, 1950.

The Mammoth mine is 13 miles northwest of Redding, Shasta County, California, in sec. 32, T. 34 N., R. 5 W., Mount Diablo base and meridian. The principal workings are at an elevation of about 3,000 feet in the rugged foothills of the Klamath Mountains (fig. 1). The mine is owned by the United States Smelting Refining and Mining Co. During mining operations from 1905 to 1925 the mine was accessible by road from Redding, but the flooding of Shasta Lake in 1944 submerged the lower part of the road. The road from the lake to the mine is 3 miles long and climbs 2,000 feet in elevation (fig. 1). In 1950 it was not passable for a car because of minor washouts. The mine plant was removed in 1925, when the mine was closed; an inclined tramway that carried the ore to a railroad spur on the North Fork of Backbone Creek has also been removed. Figure 3 is the view west from the road to the Mammoth mine, in 1950.

Acknowledgments. This report and the accompanying maps were prepared by combining the surface geologic mapping done by A. R. Kinkel, Jr. and Wayne E. Hall of the U. S. Geological Survey with the underground geologic information supplied by the United States Smelting Refining and Mining Co., owners of the Mammoth mine. Geologic maps of the mine workings and the production data were supplied by R. N. Hunt, Chief Geologist of the United States Smelting Refining and Mining Co., who also supplied records of the drilling and furnished information on the geology in the underground workings. In addition, Ralph Tuck, geologist for the United States Smelting Refining and Mining Co., spent 4 days in the field with the authors and contributed many

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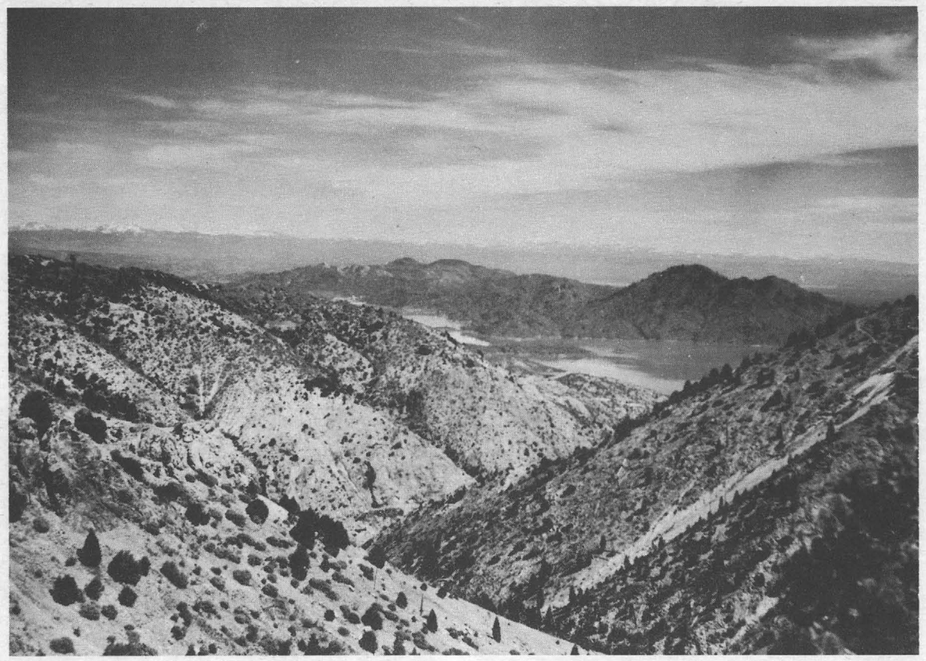

FIGURE 2. View east from the Mammoth mine.

useful suggestions. R. T. Walker, a geologist for the company during part of the mining operations, has contributed valuable information on the appearance and occurrence of the ore. As many of the workings in the vicinity of the ore bodies and all of the stopes were inaccessible at the time of the authors' study, no underground mapping was done by the authors.

HISTORY, PRODUCTION, AND GRADE

The date of discovery of the Mammoth mine is known only to have been after 1880 and probably before 1890. George Graves is reported to have discovered the ore body, and prior to 1900 a Mr. Nelson worked the property in a small way to recover the gold from the gossan. The United States Smelting Refining and Mining Co. acquired the property in 1904, and began large-scale mining operations in 1905. The mine was operated continuously from 1905 to 1919 but was closed from 1919 to late 1923. Operations were resumed late in 1923 but were again suspended in 1925. No ore has been mined since 1925, although some exploration work has been done. Plate 1 shows the extent of the mine workings.

The United States Smelting Refining and Mining Co. erected a smelter in 1905 on the Sacramento River, 1½ miles from Kennett. The smelter contained three blast furnaces, and two additional blast furnaces were built in 1907. The smelter was dismantled in 1925, and the smelter site now lies beneath Shasta Lake. Zinc was not recovered from the direct smelted ore or from the slag, and the sulfur dioxide in the fumes was not utilized.

Two kinds of ore have been mined from the Mammoth ore bodies. Most of the ore was mined only for its copper and minor gold content and was direct-smelted. Some bodies that contained high percentages of zinc, however, were mined as zinc ore during World War I, when the price of spelter was sufficiently high to justify shipping the ore to refineries in the Midwest.

Table 1 gives the production of copper and zinc ore from the Mammoth mine from 1905 to 1925. The gross value of the recovered gold, silver, and copper in the copper ore was $51,970,290, and the value of the zinc in the zinc ore was $4,525,870.

REGIONAL GEOLOGY

The oldest formation exposed in the West Shasta copper-zinc district is the Copley greenstone of probable Middle Devonian age (fig. 1). It is composed primarily of andesitic flows and pyroclastic rocks. The Balaklala rhyolite of Middle Devonian age overlies the Copley conformably. The rhyolites and associated tuffs and rhyolitic pyroclastics form a broad, elongate, complex volcanic pile, probably with many centers of volcanic activity. The Balaklala is conformably overlain by shale, tuff, and limestone of the Kennett formation of Middle Devonian age. The Kennett is overlain, with apparent conformity in the area mapped, by shale and conglomerate of the Bragdon formation of Mississippian age.

The Paleozoic rocks are intruded by a pluton of albite granite and another of biotite-quartz diorite. The albite granite is probably contemporaneous with a Late Jurassic

Sphalerite. Sphalerite in the Mammoth ore is a reddish-black variety that probably has a high iron content. It is predominantly massive, with a few recognizable cleavage faces as much as 1 mm in diameter.

The sphalerite is very unevenly distributed. In the ore mined for copper it was present in about equal quantities with chalcopyrite as irregular lenses and veins, and with chalcopyrite in the thin network veinlets around pyrite grains.

Some ore bodies—for example, the Yolo zinc lens, the 313 ore body, and the 472-raise ore body—are reported by R. T. Walker [9] to have contained mainly massive sphalerite with irregular lenses and streaks of chalcopyrite and pyrite. The zinc ore bodies also contained much quartz and corroded relicts of rock gangue. Unlike the copper ore bodies, the pyrite content of the zinc-rich ore is very low, and less than 10 percent of relict pyrite is present. The authors are not certain whether the zinc ore bodies have a low pyrite content because sphalerite had such an extremely corrosive effect upon pyrite that it removed the pyrite almost completely, or whether the sphalerite replaced rhyolite in preference to pyrite and formed isolated pods in rhyolite that contained only small amounts of pyrite. It seems likely that some of the sphalerite replaced rhyolite and had a different localizing structural control—the 313 fault—from the pyrite-chalcopyrite ore bodies, because the corroded relicts of quartz and rock gangue in sphalerite are larger than those in the pyritic ore and do not appear to be residual after the selective replacement of pyrite.

Greenockite (?). Cadmium was present in ore produced from the Mammoth mine, and it may have occurred as greenockite. Hamilton (1922, p. 241) reports that "Cadmium occurs [at the Mammoth mine] associated with the zinc sulfide, sphalerite, probably as the sulfide greenockite." Eakle (1923, p. 47) states that "Cadmium as greenockite occurs in the copper-zinc ores of this [Shasta] county and the Mammoth Copper Company recovers it in their electrolytic zinc plant." Murdoch and Webb (1948, p. 164) report that "Several thousand pounds of cadmium were produced [1917-18] at the Mammoth Copper Company plant, presumably from cadmium in the sphalerite. This may in part be as greenockite associated with the sphalerite."

Galena. Galena is present in minor quantities in the zinc-rich ore bodies. It occurs as irregular grains 0.1 to 0.2 mm in diameter in relict gangue in sphalerite at the contact between sphalerite and gangue, and as minute irregular grains in sphalerite.

Tetrahedrite. Tetrahedrite, associated with sphalerite and galena, is present in minor quantities in the zinc-rich ore bodies. It occurs in sphalerite as irregular grains 0.1 to 0.7 mm in diameter.

Gold and Silver. Appreciable quantities of gold and silver have been recovered from all the sulfide ore, but no gold or silver minerals have been recognized. The zinc ore is considerably richer in gold and silver than the copper ore. The copper ore that was smelted contained 0.038 of an ounce of gold and 2.24 ounces of silver per ton, but the sorted high-zinc ore that was shipped contained 0.111 of an ounce of gold and 9.51 ounces of silver per ton. Tetrahedrite may account partly for the higher silver content of the zinc ore. Little is known, however, about the relationship between the gold and silver content and the mineralogy of the ore.

[9] Oral communication.

Gangue. The principal gangue minerals are quartz, sericite, hydromica, chlorite, and calcite. Minor amounts of barite are reported by Graton (1909, p. 102) and by Seager. These gangue minerals make up about 15 percent of the massive sulfide ore.

Quartz is the predominant gangue mineral. It was introduced with chalcopyrite in a thin network of veinlets around pyrite grains. Most of these veinlets are too thin to be seen readily with the unaided eye but can be seen with a hand lens on a polished surface.

Sericite, hydromica, and chlorite are relict rock gangue left as a thin selvage between pyrite grains.

Calcite is present as a minor gangue mineral in lenses and thin veinlets cutting the massive sulfide ore.

Oxidation and Enrichment

The gossans at the outcrops of the ore bodies at the Mammoth mine are not large or impressive, considering the size and extent of the ore bodies. Gossans about 10 feet thick occur where the tips of the Main and Winslow ore bodies crop out, but most of the bodies of gossan are much thinner. Rock that contains disseminated pyrite is much more extensive at the surface than massive sulfide ore, and upon oxidation of the pyrite, forms considerable areas of rusty rhyolite (pl. 2).

Only a few small nodules of massive sulfide ore were found in the outcrop of the Main ore body, and R. N. Hunt and R. T. Walker [10] state that oxidation extended as much as 150 feet below the present erosion surface.

Supergene enrichment has not taken place on a large scale at the Mammoth mine, although some secondary enrichment has occurred as a result of oxidation of the ore near the outcrop. The Gossan, Main, and Winslow ore bodies were partly oxidized and enriched, but figures on the metal content of the oxidized and enriched ore are available only for the Gossan ore body. Specimens of enriched ore were not available to the authors, and the mineralogy of the enriched ore is not known. Seager reports that chalcocite and covellite are present in specimens of enriched ore from the Mammoth mine.

Ore production from the Gossan ore body.

	Ore (tons)	Gold (ounces)	Silver (ounces)	Copper (percent)
Gossan oxidized ore body	10,000	0.10	15.0	0.5
Gossan sulfide ore body	65,000	0.04	7.0	10.0

The enrichment of the Gossan ore body is about the same as that of the Old Mine ore body at the Iron Mountain mine. The gold content of the enriched oxidized ore body is about twice the gold content of the primary ore, owing to loss of weight in the formation of gossan from massive sulfide ore.

Paragenesis

Five stages are recognized in the formation of the ore bodies; the first four stages are hypogene, and resulted in the formation of the primary ore; the fifth stage is supergene. The stages of mineralization that are recognized are (1) pyrite stage; (2) chalcopyrite-quartz stage, which

[10] Oral communications.

sorted from the zinc ore was rock that contained some copper, gold, silver, zinc, and iron, but contained more rock material than massive sulfide ore (45.3 percent insoluble). The figures suggest that the discarded material consisted of rock containing stringers of the massive sulfide type of ore in essentially unmineralized rock, rather than that the discarded material contained disseminated minerals.

Little information is available to the authors on the appearance of the ore underground, or on the nature of the contact between ore and waste. The appearance of the specimens that the authors have collected from dumps and along the tramline, and the higher content of insoluble material in analyses of ore, show that although most of the ore was massive and pyritic, it contained more quartz and altered, unreplaced rock material than the ore of the Iron Mountain and Shasta King mines. However, observers who have seen the ore underground have noted that quartz is rarely visible megascopically in the Mammoth mine ore except where a few late veinlets cut both the ore and the wall rocks.

Frozen contacts between ore and wall rocks are reported to be rare; at most contacts, as in the other mines in the district, ore is separated from rhyolite by a clay selvage. R. N. Hunt [7] states that some ore bodies had sharp, smooth outlines. In these ore bodies the contacts between massive sulfide ore and wall rock were sharp; the ore was separated from the wall rock by a thin selvage of gouge at the ends of ore bodies, as well as along the top and bottom of the ore body, and the wall rock contained little or no pyrite. Contacts of this type are similar to those at Iron Mountain and at the Shasta King mine. R. T. Walker [8], however, reports that the material between some of the stopes was massive sulfide containing less copper than the ore that was mined. The ore zone was continuous between these stopes, and some stope outlines mark only the economic limit of mining. Thus, although many stopes were mined to a sharp waste wall at the ends of the ore bodies, at some places an individual stope does not represent the extent or continuity of a body of massive sulfide, which may be of considerably greater extent than is indicated by the outline of the stope.

The ore zone at the Mammoth mine extends S. 70° W. for 3,000 feet from the outcrop of the Main ore body to the deepest exploration southwest of the Friday Lowden ore body. The general trend of individual ore bodies—and of the ore zone as a whole, if the Gossan ore body is included—is more nearly S. 60° W. Part of the ore zone is eroded between the Gossan ore body and the Main ore body. Although the Gossan ore body lies at a lower stratigraphic horizon than the main part of the ore zone, it seems reasonable to assume that ore bodies were present along the eroded upper part of the ore zone and in the eroded extension of the ore zone northwest of the Gossan ore body. The ore zone must thus have been at least 4,200 feet long, and it may have been considerably longer.

The plunge of the ore zone ranges from horizontal to vertical, but from the outcrop of the Main ore body to the deepest known ore the plunge averages only 14° W.

A few large faults and many small faults cut the ore bodies. Small faults are marked in the ore by slickensided surfaces, and small offsets complicated stope layouts in some places. The larger faults appear to have offset ore bodies several hundred feet and the present distribution of ore bodies is due in part to postmineral faulting. The alinement of zinc-rich ore along the 313 fault and the Yolo (313) fault is discussed under *Ore Controls.*

[7] Oral communication.
[8] Oral communication.

Hypogene Minerals

The mineralogy of the primary ore from the Mammoth mine is comparatively simple. The ore consists mainly of pyrite, chalcopyrite, and sphalerite; minor galena and tetrahedrite are present, and the gangue consists of sericite, hydromica, chlorite, quartz, and calcite. Graton (1909, p. 102) reports finding also small particles of barite in the gossan and in the sulfide ore, but this mineral was not observed by the authors. The ore contains small quantities of gold and silver, but no gold or silver minerals have been recognized. Sulfide minerals constitute about 85 percent of the ore.

Pyrite. Pyrite is the most abundant mineral in the primary ore and constitutes about 70 percent of the ore by volume, except in the zinc-rich ore bodies. The range in pyrite content is from 85 percent in the low-grade copper or pyritic ore bodies to a few percent in the high-grade zinc ore bodies. In the low-grade pyritic ore, pyrite megascopically appears to form massive aggregates with a few disseminated 1- to 2-mm euhedral cubes and pyritohedrons. Under the microscope pyrite is seen most commonly as discrete subhedral grains that average 0.4 mm in diameter, separated by a network, 0.05 to 0.3 mm thick, of gangue and/or chalcopyrite and sphalerite, but in places the pyrite forms granular aggregates without the surrounding network.

Chalcopyrite. Chalcopyrite constitutes from 1 percent of the low-grade pyritic ore to more than 50 percent of the high-grade ore, and it averaged 12 percent in the ore that has been shipped. It is present as a network pattern around grains of pyrite, as thin veinlets cutting pyrite, as minute blebs and corroded relicts in sphalerite, and as bands and irregular masses associated with sphalerite.

Chalcopyrite, sphalerite, and quartz commonly form a network, generally less than 0.3 mm thick, around pyrite grains. The sulfide mineral grains are so small that to the unaided eye they appear to blend as massive sulfide with a metallic luster and a brassy yellow color between that of pyrite and chalcopyrite. Pyrite has a uniform distribution throughout the copper ore, indicating that the chalcopyrite network did not have a very corrosive effect upon pyrite. In only one of the polished sections studied had chalcopyrite corroded pyrite to such an extent that pyrite was almost entirely removed and a body of massive chalcopyrite was formed. Some chalcopyrite is present as thin veinlets cutting pyrite and filling fractures in pyrite.

Chalcopyrite is always present in the zinc-rich ore bodies; about 15 percent chalcopyrite is present in sphalerite as blebs and corroded relicts 0.02 to 0.03 mm in diameter.

Although massive chalcopyrite was not common in the specimens studied, specimens from the Grotefend collection on display at the California Division of Mines office in Redding contain banded chalcopyrite-sphalerite ore and irregular masses of chalcopyrite with minor relicts of pyrite.

FIGURE 3. Mammoth mine; view west from the road to the mine.

orogeny, but the biotite-quartz diorite, although it is also probably of Late Jurassic age, was emplaced after the orogeny.

A preliminary geologic column for the West Shasta copper-zinc district is given in table 2.

The Paleozoic rocks in the West Shasta copper-zinc district have been folded into a broad arch with an axis trending N. 15° E. that passes through Iron Mountain and Behemotosh Mountain. Dips on the flanks of the fold are mostly 10 to 20 degrees, but locally they may be vertical. The broad arch has a culmination in the central part of the mining district at the Uncle Sam mine, and plunges gently to the north in the northern part of the district, north of the Mammoth mine. The arch is broken by numerous faults. Two directions of faults are prominent; one set strikes about N. 30° W., and the other set strikes N. 60°-70° E. Both vertical and horizontal movements are recognized; in nearly all the faults the north block is the downthrown side.

GEOLOGY OF THE MINE AREA

Formations

Only the Kennett formation and the Balaklala rhyolite crop out in the vicinity of the Mammoth mine (pl. 2).

Balaklala Rhyolite. The Balaklala rhyolite consists of porphyritic and nonporphyritic rhyolite flows with intercalated coarse to fine rhyolite pyroclastics. Although the formation consists mainly of flows and pyroclastics, dikes and sills of rhyolite intrude the volcanic pile and the underlying Copley greenstone. Individual flows and pyroclastic beds are lenticular, and few can be traced for as much as 2,000 feet. The most notable exception is the broad, elongate mass of coarse-phenocryst flow rhyolite and associated tuffs, which forms the upper unit of the Balaklala and extends from the Stowell mine to the Golinsky mine, except where cut out by the major canyons—a distance of approximately 6 miles.

Although no flows or pyroclastics are continuous throughout the Balaklala rhyolite, and no horizon marker is present, a general stratigraphy is recognized in the volcanic pile. The Balaklala is divided into three main units as shown in table 3. The table contains a preliminary generalized stratigraphic section of the Balaklala that has been built up from studies of the district.

The lower unit of the Balaklala rhyolite is the most extensive and most continuous. It consists mostly of light-gray to light-green nonporphyritic rhyolite and rhyolite tuff and volcanic breccia, but locally it contains a few flows of porphyritic rhyolite and beds of pyroclastics. Much of the rhyolite is flow-banded, and amygdaloidal rhyolite is fairly common. It contains a few thin mafic flows near the base similar to the underlying Copley greenstone. This lower unit of the Balaklala is as much as 900 feet thick at some places, but its thickness has a wide range. Most of the lower unit of the Balaklala is present in the area of the Mammoth mine and is exposed in the deep canyon of Little Backbone Creek north of the mine.

The middle unit of the Balaklala consists mainly of light-green to light-gray porphyritic rhyolite flows and pyroclastics with 1- to 4-mm phenocrysts of quartz and feldspar; it also contains a few flows of nonporphyritic

*Table 1. Annual production of ore from the Mammoth mine, 1905-25 **

Year	Ore (tons)	Gold (ounces)	Silver (ounces)	Copper (percent)	Zinc (percent)	Insoluble (percent)	Iron (percent)	Sulfur (percent)
			Copper ore					
1905	13,868	0.029	1.94	4.30	----	----	----	----
1906	181,733	0.048	2.12	3.95	3.30	9.5	39.0	42.2
1907	201,124	0.039	1.94	4.15	4.70	7.7	38.4	44.5
1908	311,997	0.033	1.90	4.03	4.70	12.6	35.6	41.9
1909	370,985	0.036	2.13	4.15	4.70	13.2	34.9	42.0
1910	315,189	0.038	2.38	3.83	4.40	15.1	34.2	40.7
1911	269,438	0.032	2.26	4.06	4.20	12.4	35.4	44.7
1912	273,555	0.034	2.24	3.47	4.20	12.6	34.0	40.9
1913	269,233	0.036	2.19	3.58	3.80	14.9	32.7	39.8
1914	227,459	0.043	2.28	3.96	4.10	12.5	33.9	40.3
1915	242,573	0.038	2.21	3.75	3.80	12.8	33.3	40.0
1916	223,458	0.042	2.74	4.77	4.20	13.8	32.6	37.6
1917	147,340	0.040	2.46	4.22	3.80	20.4	31.4	35.6
1918	76,079	0.040	2.29	3.91	4.30	14.2	32.4	37.6
1919	37,733	0.040	2.50	4.10	3.70	14.4	32.9	37.8
1923	9,221	0.050	2.85	4.42	5.00	16.6	33.2	36.9
1924	115,814	0.045	2.39	4.27	3.70	13.5	35.2	40.2
1925	34,346	0.037	2.17	4.34	4.30	11.0	36.6	41.4
Total and weighted averages	3,311,145	0.038	2.24	3.99	4.20	13.3	34.3	40.4
			Zinc ore					
1914-1915	84,000	0.078	5.79	2.40	21.10	----	----	----
Total and weighted averages	3,395,145	0.039	2.32	3.95	4.62	----	----	----

* Published by permission of the United States Smelting Refining and Mining Co.

Table 2. Preliminary geologic column of the West Shasta copper-zinc district, Shasta County, California.

Age	Formation	Thickness (feet)	Lithology
Recent	Alluvium	0-150	Alluvium, landslide deposits.
Pleistocene	Red Bluff formation*	0-100	Cemented sand and gravel.
Cretaceous	Chico formation*	0-200	Cemented mudstone, sand, and gravel.
Late Jurassic	Rocks of the Shasta Bally batholith		Biotite-quartz diorite.
Jurassic(?)	Rocks of the Mule Mountain stock		Albite granite.
Mississippian	Bragdon formation*	5,000-6,000(?)	Shale, sandstone, conglomerate.
Middle Devonian	Kennett formation*	0-865(?)	Limestone, dark-gray shale, black cherty shale, tuff.
Middle Devonian	Balaklala rhyolite	0-3,500	Soda rhyolite, quartz porphyry, pyroclastics.
Middle Devonian(?)	Copley greenstone	3,500	Greenstone flows and pyroclastics, diabase, andesite.

* These formations are largely eroded in the central part of the mining district.

quartz-sericite rock containing many anastomosing shear planes. Hydrothermally altered rock is not prominent in the exposures seen underground, although some sericite is present; but hydrothermally altered rock is recognized along the surface exposure of this fault, as weathering has emphasized the difference between altered and unaltered rock. The porphyritic rhyolite along the California fault at the surface is altered to white and pink clay minerals and sericite, but this alteration extends only 5 to 10 feet on either side of the fault.

The California fault is probably a premineral fault; reasons for this view are given under *Ore Controls*. That postmineral movement has also occurred on this fault is shown by offset ore bodies. The north block moved east and down, but the exact amount of movement is not known. The ore bodies plunge at a low angle to the southwest along the fault, so that the present position of offset segments of ore bodies could be due either to mainly dip-slip or mainly strike-slip movement. The 313 fault and the 12-drift fault on the 200-foot level (pl. 4) appear to be offset about 250 feet horizontally by the California fault, although neither the dips nor the accurate locations of these faults are known where they are cut by the California fault. If the Main and Winslow ore bodies were one ore body before being cut by the California fault, an apparently reasonable assumption, then the dip-slip movement on the fault would be less than the strike-slip movement. Along some parts of the California fault the lower contact of the coarse-phenocryst rhyolite has a very low dip, and measurements of the elevation of this contact on either side of the fault indicate a vertical displacement of 130 feet. From available data, the strike-slip displacement appears to be about twice the dip-slip displacement.

The 12-drift fault and the 313 fault, with its probable extension as the Yolo (313) fault, are shown on the maps of the mine levels, (pls. 4-8) and the cross sections (pl. 3). The vertical offset on each of these faults is approximately 40 feet, and the north side is down relative to the south side; but nothing is known about a possible horizontal offset on these faults. They are older than the California fault and are offset by it.

The Schoolhouse fault is exposed only on the 670-foot level (pl. 8) and for a short distance on the surface. The approximate vertical offset of the base of the coarse-phenocryst rhyolite at the surface is about 100 feet, and the north side is down relative to the south side; but exposures are poor where the fault cuts this contact. The offset on the Schoolhouse fault appears to be less in the east end of the mapped area than in the west end. The rhyolite along the Schoolhouse fault at the surface is pyritized and altered to clay minerals.

The Gossan fault is exposed on the 670-foot level (pl. 8) and for a short distance on the surface. The rocks on the east side of the fault are dropped relative to those on the west side; on the basis of a doubtful correlation of rock types, the vertical offset is judged to be about 50 feet. The rhyolite is pyritized and altered to clay along the outcrop of this fault.

Several north-dipping faults that strike N. 60°-80° W. are known in the vicinity of the Friday Lowden and Hanley ore bodies at the southwest end of the mine. The Friday fault is one of this group of faults that cut the Friday Lowden ore body and may offset it. The total offset on this group of faults may be considerable, but no data are available.

The Clark fault is a minor fault with a 10- to 20-foot offset. The north side has moved down relative to the south side (pl. 3, section D-E-F-G).

Ore Deposits

Character and Distribution

The ore bodies of the Mammoth mine are large, flat-lying, tabular bodies of copper- and zinc-bearing pyritic ore. The known ore bodies extend along a horizontal distance of 4,200 feet; but the northeast end of the ore zone has been eroded, and exploration has not delimited the southwesterly extension of the zone. The central part of the ore zone has a width of 1,000 feet. Minable ore bodies occur throughout the ore zone, but the entire zone is not ore. Individual stopes reach a maximum horizontal dimension of 900 feet by 500 feet and the maximum thickness of ore is 110 feet; ore bodies range from these maxima down to small stopes from which only a few hundreds of tons were mined. The ore zone lies along the crest of a broad arch in the rocks, and all known ore occurs at or a short distance below the contact between the coarse-phenocryst rhyolite and the underlying rhyolitic tuff and flows (pl. 3). The ore is formed by replacement of Balaklala rhyolite.

Table 4 gives the production and grade of stopes and other ore blocks; it also shows the uniformity of the gold, silver, and copper content of all the copper ore bodies, and the sharp distinction between copper-rich ore and zinc-rich ore. The pyritic ore that underlies the copper ore bodies contains a smaller quantity of copper than the massive sulfide that was mined for its copper content, but it is the same type of ore.

Table 5 gives information that is not available elsewhere on the distribution of metals in the zinc-rich parts of the ore bodies. The grade of the material sorted from the high-zinc part of the ore was calculated from the known assays. It is apparent, for instance, that the material

Table 5. Results of hand sorting of zinc ore from the Mammoth mine.

	(Tons)	Gold (ounces)	Silver (ounces)	Copper (percent)	Zinc (percent)	Iron (percent)	Insoluble (percent)
Crude ore produced*	84,000	0.078	5.79	2.40	21.10	12.6	35.5
Sorted ore shipped	28,800	0.111	9.51	2.4	39.6	8.9	16.8
Percent increase or decrease	—65.7	+42.3	+63.6	0.0	+87.5	—29.4	—52.6
Grade of discard (calculated)	55,200	0.061	3.82	2.4	11.42	14.5	45.3

* See table 4.

Table 4. Production and grade of stopes and other ore blocks of the Mammoth mine †

Copper ore

Ore body	Tons	Gold (ounces)	Silver (ounces)	Copper (percent)	Zinc (percent)	Lead (percent)	Iron (percent)	Sulfur (percent)	Insoluble (percent)
Gossan (oxidized)	10,000	0.10	15.0	0.5					
Gossan (sulfide)	65,000	0.04	7.0	10.0					
Copper Crest	15,000	0.04	2.0	4.0					
Main	1,970,145	0.03	1.8	3.8					
Winslow	300,000	0.04	2.2	3.8					
Graton	2,000	0.03	2.0	3.0					
Sierra	100,000	0.04	2.2	3.8					
Smith Winze	2,000	0.03	2.0	3.0					
Clark	385,000	0.04	3.0	4.5					
Metcalf	200,000	0.04	3.0	4.5					
Starrow	100,000	0.04	3.0	4.5					
2784	2,000	0.03	2.0	3.5					
Friday Lowden	100,000	0.04	3.0	5.0					
Hanley	60,000	0.04	3.0	6.0					

Zinc ore

	Tons mined (before sorting)	Grade of sorted ore*							
		Gold (ounces)	Silver (ounces)	Copper (percent)	Zinc (percent)	Lead (percent)	Iron (percent)	Sulfur (percent)	Insoluble (percent)
Yolo	58,000	0.12	5.44	2.20	36.20	3.00	10.1	25.2	20.7
Copper Crest	Not available								
473	16,000	0.02	1.40	1.80	33.30	nil	9.2	24.7	19.8
313	5,000	0.13	6.50	1.00	27.70	1.00	9.5	23.5	31.8
Graton	2,500	0.40	4.90	0.72	36.35	1.40			
Metcalf	Not available								
		Grade of unsorted ore*							
Total*	84,000	0.078	5.79	2.40	21.10		12.6		35.5

* See table 5.

Pyritic ore underlying copper ore bodies

Main		0.04	1.0	2.0			42.0	45.0	10.0
Main } Separate blocks		0.03	0.4	0.5			38.0	40.0	18.0
Main		0.03	0.2	0.5			43.0	45.0	10.0
Shasta		0.01	0.6	0.5				35.0	
Clark		0.03	1.0	1.2				40.0	
Friday Lowden } Separate blocks		0.04	1.1	2.2				45.0	
Friday Lowden		0.01	0.3	0.5				40.0	
313, at 390-foot level		0.05	1.1	2.0				40.0	
Total		0.028	0.56	0.9				41.4	

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cleavage planes—developed in the non-porphyritic and medium-phenocryst rhyolite, particularly near the axes of folds. Movement along the bedding plane, with accompanying foliation parallel to the bedding plane, was concentrated in the layers of pyroclastics at the base of the coarse-phenocryst rhyolite (fig. 5). In the overlying massive coarse-phenocryst rhyolite, foliation is locally present but is rare because of the great thickness and competence of this rock.

Faults. Several large fault zones and many small faults are shown on the maps of the mine levels. They are of several ages, as shown by one fault cutting another; most are probably postmineral in age, but some appear to be premineral. The principal faults are the California fault, the 313 fault (and its probable extension, the Yolo (313) fault), the 12-drift fault, the Schoolhouse fault, the Gossan fault, the Friday fault, and the Clark fault. On all these faults, the north or east side has moved down relative to the south or west side. The horizontal component is not known except on the California fault, where it is about 250 feet.

Few of the faults can be located or traced for any distance on the surface. Their location on plate 2 is based largely on a projection of the faults from their known position underground. Except for short sections of the California, Schoolhouse, and Gossan faults, where these are exposed at the surface, information on the faults is derived from the underground maps of the United States Smelting Refining and Mining Co., from R. N Hunt [6] and R. T. Walker [6], and from the authors' brief visit underground, during which they examined the California fault.

The California fault zone is a group of subparallel and branching fault planes rather than a single plane, and, as seen underground, the zone does not have sharp boundaries at all localities. At some exposures the rock between the individual fault planes is massive and little altered; at others the fault consists of a zone of gouge and crushed

[6] Oral communications.

Table 3. Generalized stratigraphy of the Balaklala rhyolite.

Unit	Description	Thickness (feet)
Upper unit	Tuff with some quartz phenocrysts more than 4 mm in diameter, interbedded with thin shale beds. Transitional to Kennett formation.	0-300
	Coarse-phenocryst rhyolite with quartz and feldspar phenocrysts more than 4 mm in diameter.	0-1,200
	Sporadic tuff and volcanic breccia at the base of the unit.	0-150
Middle unit	Volcanic breccia and tuff, and medium-phenocryst rhyolite flows with quartz and feldspar phenocrysts 1 to 4 mm in diameter.	0-800(?)
	Medium-phenocryst rhyolite flows and minor pyroclastics. Minor flows of nonporphyritic rhyolite.	0-600(?) (except for one area of unusually large thickness)
Lower unit	Nonporphyritic rhyolite, much rhyolitic pyroclastics, and flow-banded and amygdaloidal rhyolite. Includes a few thin flows of medium-phenocryst rhyolite and a few thin mafic flows near the base.	0-900(?)
Transition zone to underlying Copley greenstone.	Mixed mafic and silicic pyroclastics.	0-150

rhyolite. The upper part of the middle unit of the Balaklala contains abundant, although discontinuous, coarse and fine pyroclastics interlayered with or overlying the medium-phenocryst rhyolite. The upper part of the middle unit is the ore horizon, and the ore deposits, as far as is known, occur as replacement bodies in medium-phenocryst rhyolite flows that lie under beds of pyroclastics. The middle unit does not extend as far laterally as the lower unit, but it is more extensive than the upper unit of the Balaklala rhyolite. It ranges from a few feet to 600 feet in thickness, but its thickness varies greatly in short distances because of the piling up or absence of individual flows. At the Mammoth mine, the thickness of this unit ranges from about 150 to about 300 feet, but the base of the unit is very irregular.

The upper unit of the Balaklala rhyolite consists of coarsely porphyritic rhyolite with quartz and feldspar phenocrysts that are more than 4 mm in diameter. It is about 1,200 feet thick at Mammoth Butte (fig. 1) but thins rapidly in all directions therefrom. A thin bed of tuff or volcanic breccia is present at many localities at the base of the coarse-phenocryst rhyolite. This pyroclastic bed is generally 10 to 50 feet thick, but where it is composed mainly of volcanic breccia it reaches 150 feet in thickness. Tuff beds are also present over the coarse-phenocryst rhyolite and are interbedded with thin shale beds of the overlying Kennett formation.

The origin of the coarse-phenocryst rhyolite is of interest, as this rock is the "cap rock" for ore bodies; that is, all known ore occurs at or a short distance below the lower contact of the coarse-phenocryst rhyolite.

Although some geologists have considered the coarse-phenocryst rhyolite to be a sill or gently domed laccolith, the present authors contend that the layers of pyroclastic material (interpreted by them as volcanic breccia and bedded tuffs containing fragments of coarse-phenocryst rhyolite, fig. 4) are evidence of surface origin; and that the coarse-phenocryst rhyolite was extruded as a surface flow, forming a broad, low domelike mass, the thickest part of which was at the principal vent at the Uncle Sam mine. In addition, the interbedding between the coarse-phenocryst rhyolite tuff and volcanic breccia at the top of the Balaklala rhyolite and the shaly tuff and shale at the base of the overlying Kennett formation is evidence of a sedimentary sequence.

Kennett Formation. A small area of the Kennett formation of Middle Devonian age is exposed in the southeast corner of the mapped area. It is an extensive formation to the east and northeast of the mine and probably once covered much of the mapped area. It lies conformably on the Balaklala rhyolite and dips gently to the east. The lower part of the Kennett consists of gray shale interbedded with water-laid rhyolitic tuff and arkose typical of the Balaklala.

Structure

The Mammoth mine lies along the crest of a broad arch or elongated domelike structure in the enclosing rocks. The rocks in the mine area are gently folded, and several small flexures are present in addition to the broad arch. Individual ore bodies are located in part along minor flexures on the major arch. Some of the rocks have been sheared and contain oriented mineral grains, which are commonly restricted to bands in the rock. The degree of foliation is dependent mainly on the competence of the various units. The folding and the foliation are interrelated elements in the geologic structure, and they are of equal importance in the localization of ore. The folds, which are revealed by the bedding of tuffs and volcanic breccia, are shown on the level maps (pls. 4-8) and on the structure contour map (pl. 9). The relationship between foliation and bedding is shown on plate 2 and figure 5. Several strong fault zones and many weak ones cut the rocks in the mine area. Most of these are probably postmineral in age, but a few that are premineral in age probably were feeder channels for mineral-depositing solutions.

Folds. The bedding in the mine area is delineated by the contact between the overlying coarse-phenocryst rhyolite and the underlying medium-phenocryst rhyolite and nonporphyritic rhyolite, and by bedded material between these two units of the Balaklala rhyolite.

The structure contour map (pl. 9) shows that a slightly elongate domelike structure trends N. 45° E. and has a culmination in the central part of the group of ore bodies. There are also numerous smaller arches or elongated contour "highs," the alinements of which appear to have no relation to the alinement of the main dome. Local dome and basin structures occur at the base of the coarse-phenocryst rhyolite throughout the district, and these range from small rolls a few tens of feet across to structures that are measured in thousands of feet.

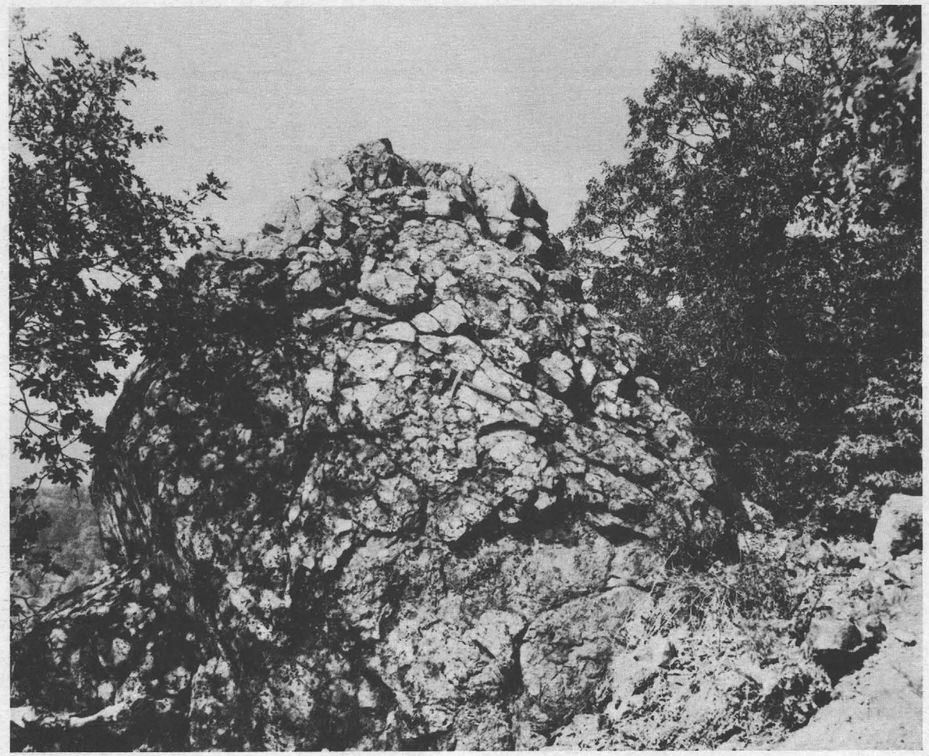


FIGURE 4. Volcanic breccia horizon in the coarse-phenocryst rhyolite.

The sedimentary material, where it is present at the base of the coarse-phenocryst rhyolite, is useful in delineating folded structures. This material was not seen underground by the authors, but on the basis of surface exposures it is thought to be a tuff. Dips and strikes in the bedded material underground, taken by company geologists, show that in most places the bedding is parallel to the contact of the coarse-phenocryst rhyolite (pls. 3, 5, 6, 7). Some random orientation of bedding has been observed, but such variations may be caused by close folding, faulting, or minor intrusions of coarse-phenocryst rhyolite.

If it were not for the presence of water-laid, bedded tuffs at the base of the coarse-phenocryst rhyolite, it might be argued that the present relief at the base of this formation was a result of the irregular topography of the old land surface at the time of extrusion of the formation, rather than of folding. The old surface probably had considerable relief, caused by the uneven distribution of the older volcanic flows and local eruptions of volcanic breccia. The distribution of the bedded tuff, however, would be more even and widespread than it is, even if tuff was erupted below water level, unless some of it was removed from higher parts of the surface by erosion and redeposited in local basins. The bedding in the tuff is conformable with the overlying flow contacts. Also, the greatest thickness of the bedded tuff at the base of the coarse-phenocryst rhyolite in the Mammoth mine occurs along the crests of the arches (300-, 470-, and 500-foot levels) and tuff is absent at most places along the flanks of the arches. Thus it seems certain that, although some relief in the surface of deposition can be assumed, the structures shown on the structure contour map are secondary features that have resulted chiefly from folding.

Flexural-slip folding, that is, folding in which movement along bedding planes is concentrated in the incompetent layers, and platy minerals in these layers are oriented parallel to bedding (Swanson, 1941, p. 1256; Knopf and Ingerson, 1938, pp. 157-161), is locally well developed in the West Shasta copper-zinc district. It occurs in conjunction with poorly developed fracture cleavage in the competent layers. At the Mammoth mine the degree and type of foliation that is developed depend on the competence of the rock units. The nonporphyritic rhyolite and the medium-phenocryst rhyolite are competent rocks. The beds of pyroclastics at the base of the coarse-phenocryst rhyolite form an incompetent layer that has a considerable areal extent; the coarse-phenocryst rhyolite is a thick, massive, very competent layer. During the folding in the mine area, steep fracture cleavage—with some recrystallization and alinement of minerals parallel to

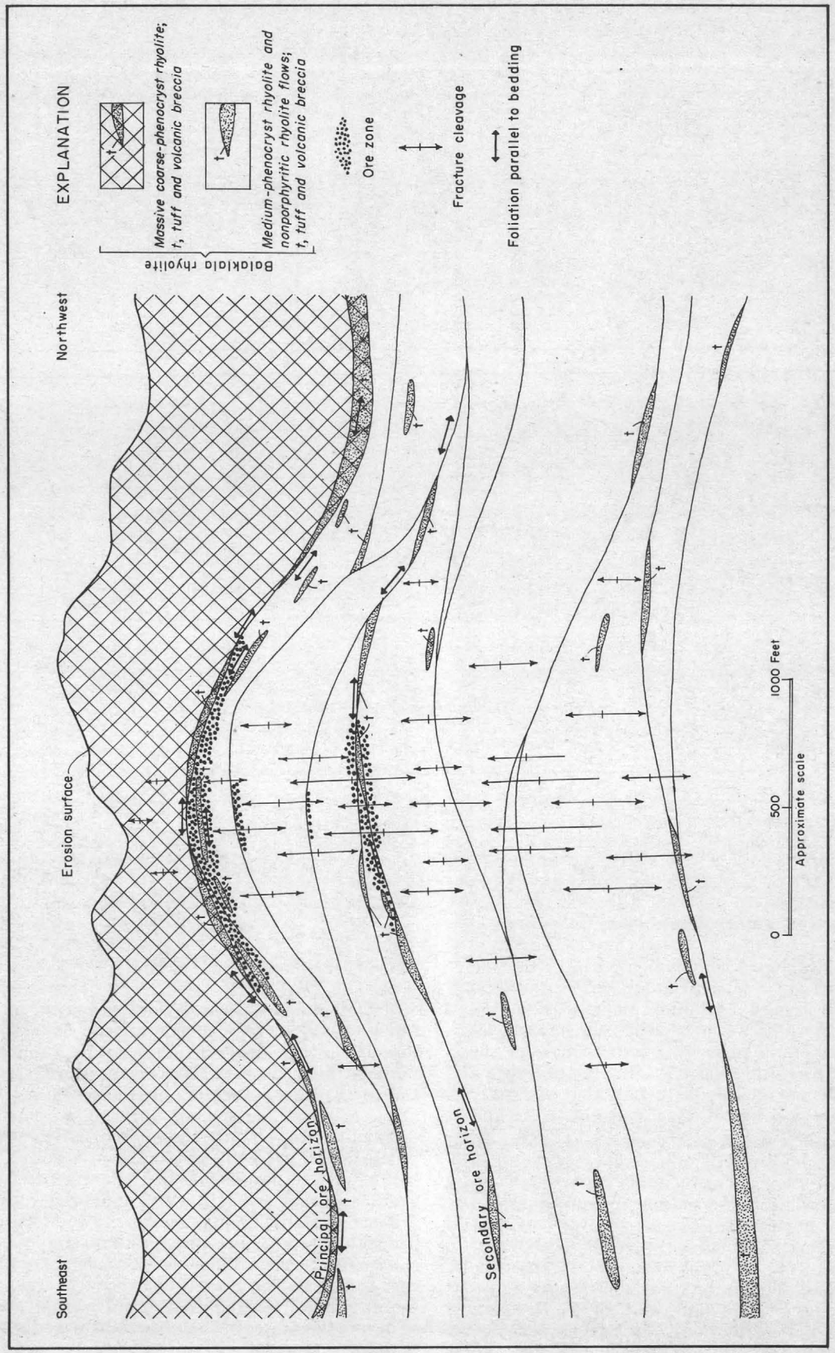
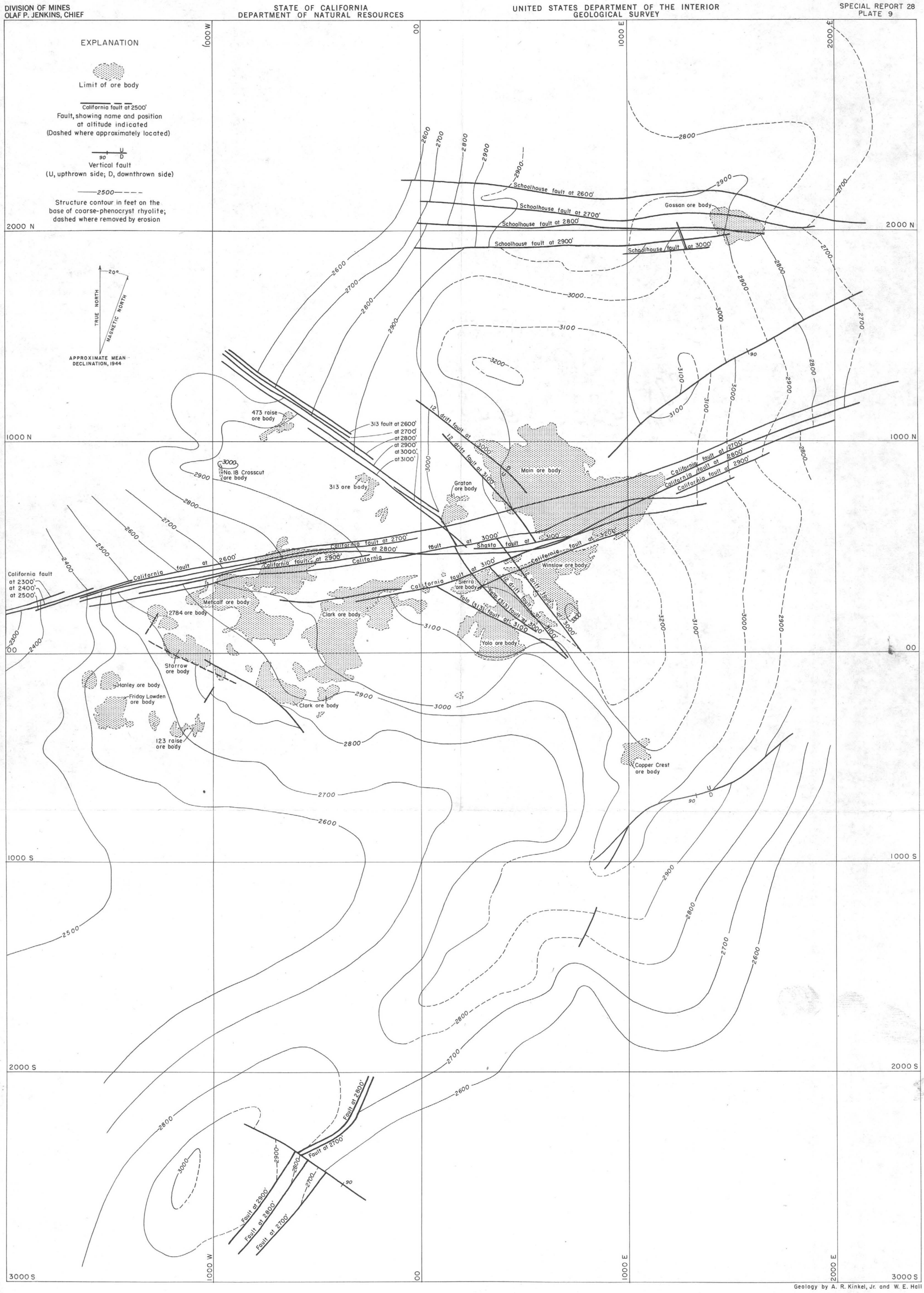


FIGURE 5. Diagrammatic drawing showing the relationship between bedding-plane foliation, fracture cleavage, and ore zones at the Mammoth mine, Shasta Co., Calif.



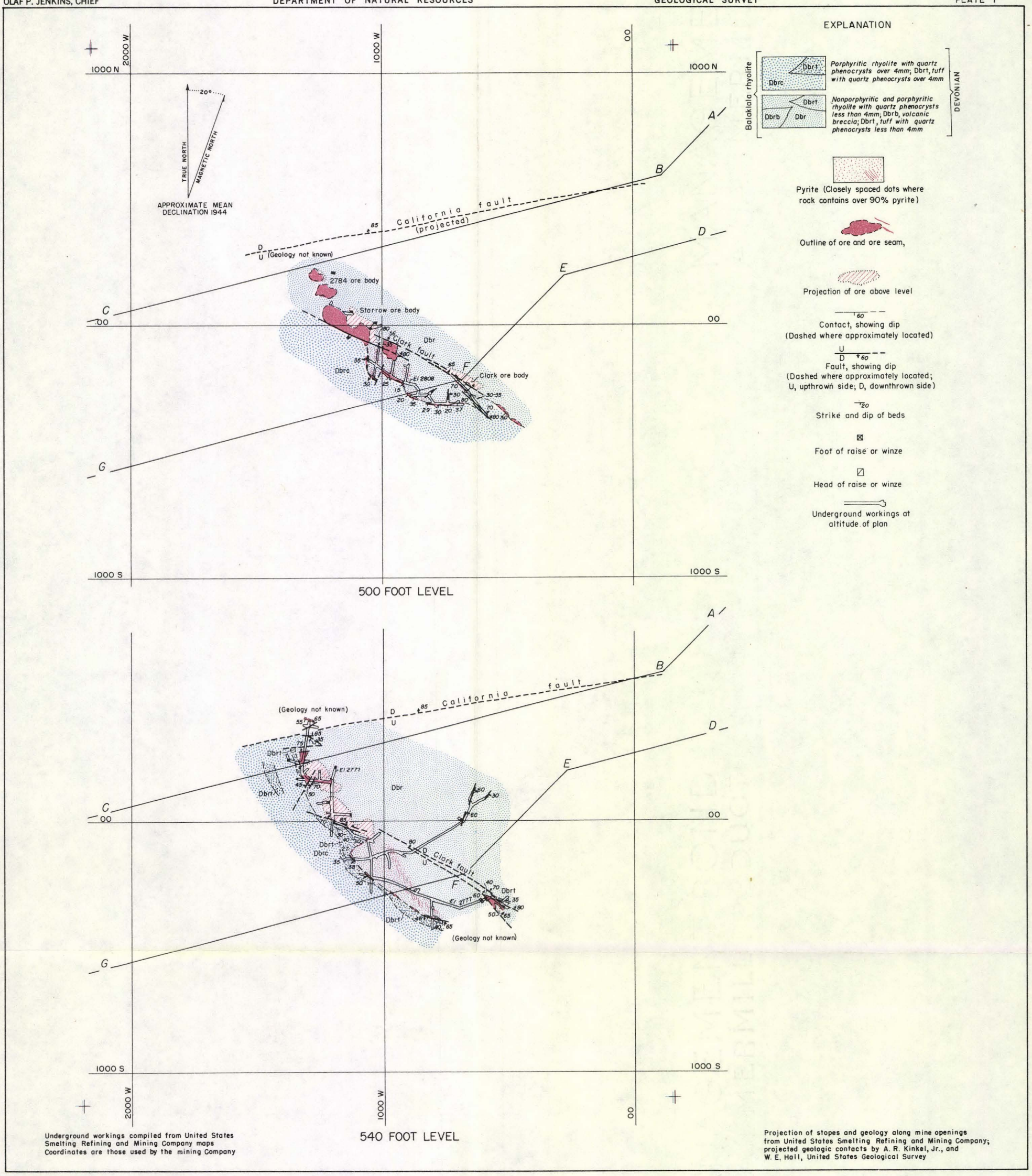
Geology by A. R. Kinkel, Jr. and W. E. Hall

STRUCTURE CONTOUR MAP ON THE BASE OF THE COARSE-PHENOCRYST RHYOLITE

MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

400 0 400 800 Feet

Contour interval 100 feet
Datum is mean sea level



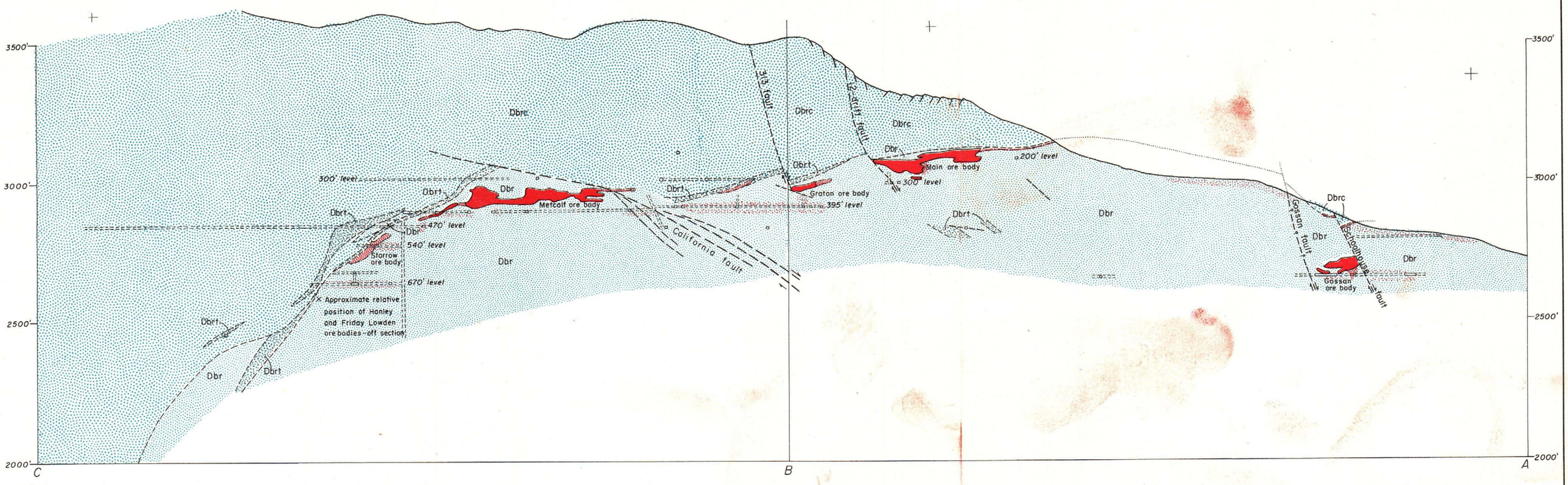
Underground workings compiled from United States Smelting Refining and Mining Company maps
Coordinates are those used by the mining Company

Projection of stopes and geology along mine openings from United States Smelting Refining and Mining Company; projected geologic contacts by A. R. Kinkel, Jr., and W. E. Hall, United States Geological Survey

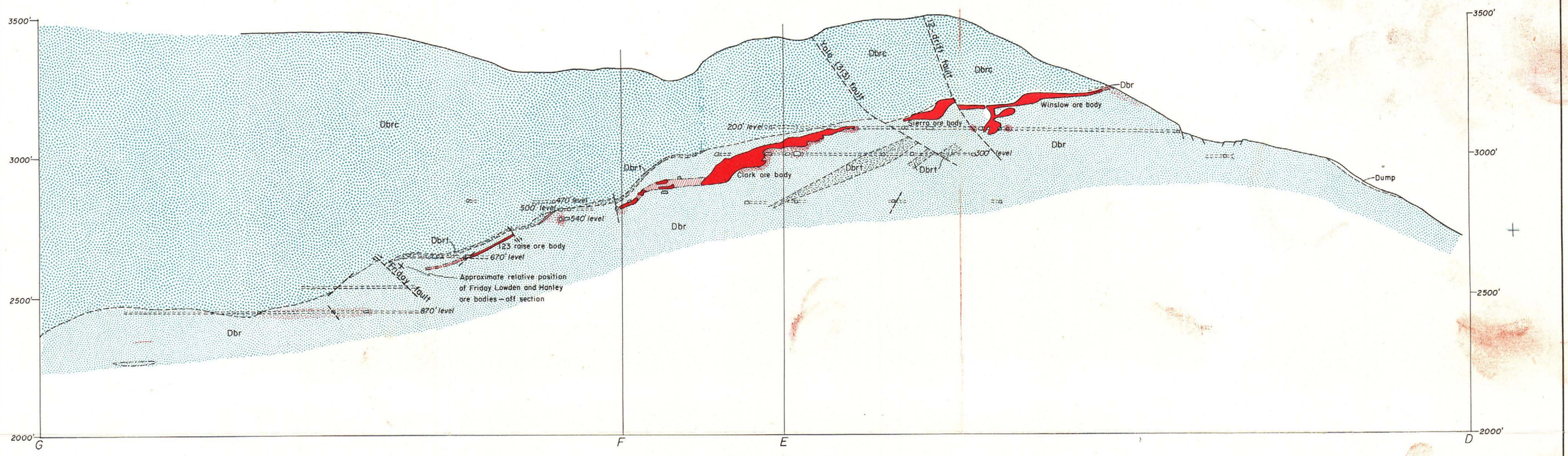
PLAN OF THE 500 FOOT AND 540 FOOT LEVELS OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

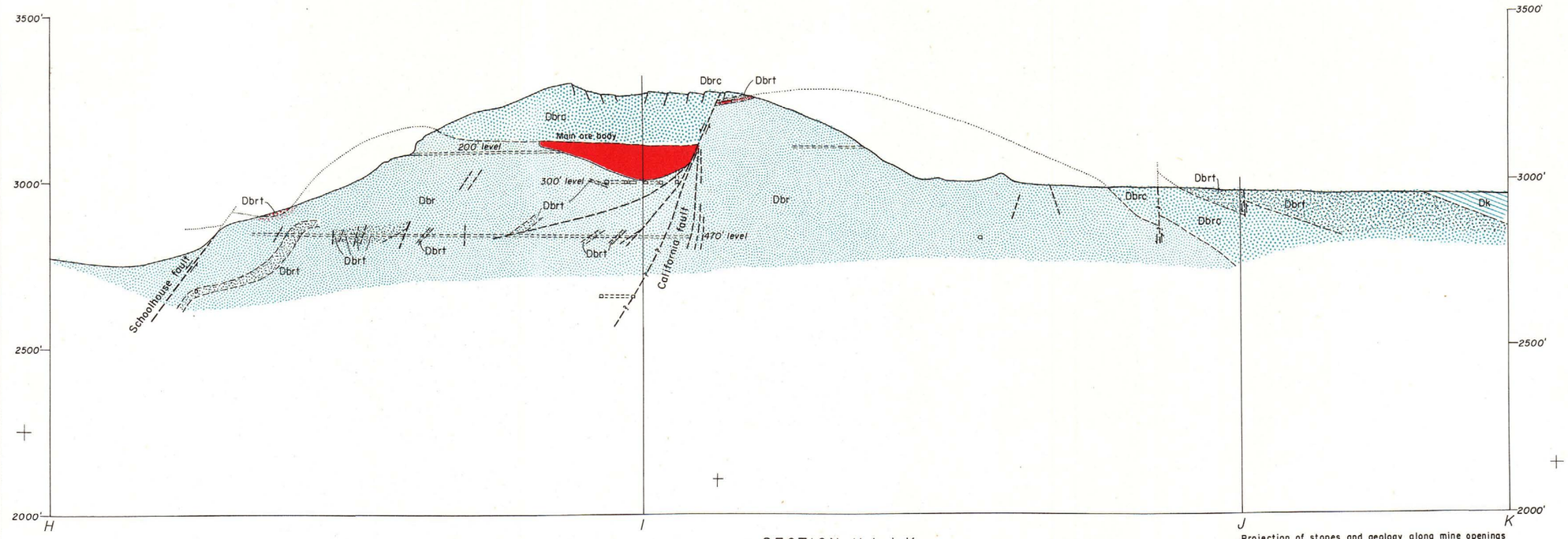
Datum is mean sea level



SECTION A-B-C



SECTION D-E-F-G



SECTION H-I-J-K

Projection of stopes and geology along mine openings from United States Smelting Refining and Mining Company; projected geologic contacts by A. R. Kinkel, Jr., and W. E. Hall, United States Geological Survey

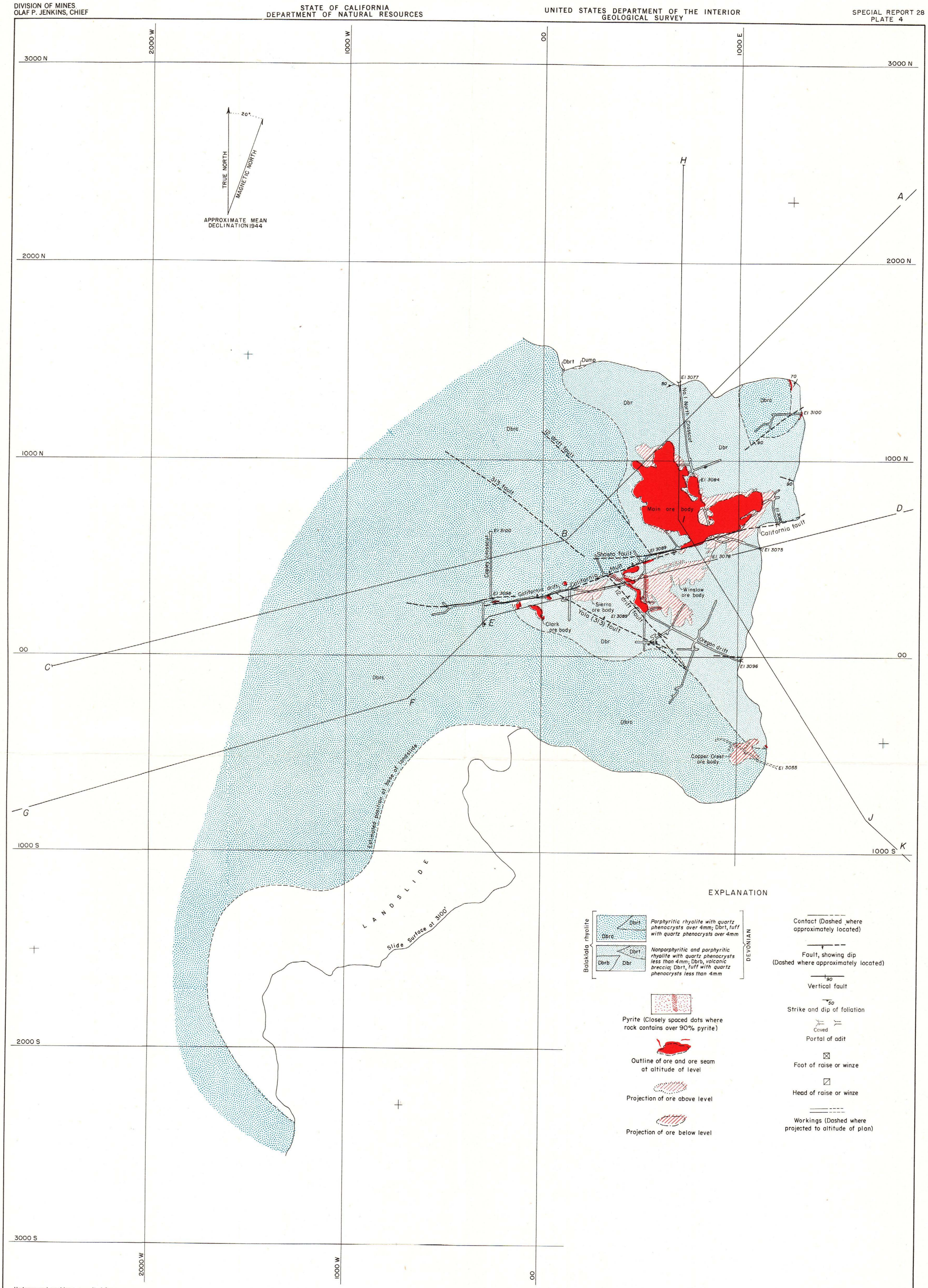
EXPLANATION

- Dk — Kennett shale (DEVONIAN)
- Balaklala rhyolite (DEVONIAN):
  - Dbrt, Dbrc — *Rhyolite with quartz phenocrysts over 4mm; Dbrt, tuff*
  - Dbrt, Dbr — *Rhyolite with quartz phenocrysts less than 4mm; Dbrt, tuff (includes lapilli tuff, crystal tuff, and tuffaceous sediments)*
- Pyrite (Closely spaced dots where rock contains over 90% pyrite)
- Contact (Dashed where approximately located)
- Fault, approximately located (Showing relative movement)
- Probable fault
- Ore body on section
- Ore body projected to section
- Workings, (dashed where projected to section)

GEOLOGIC SECTIONS OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

Datum is mean sea level



EXPLANATION

Balaklala rhyolite — DEVONIAN

Dbrt, Dbrc: *Porphyritic rhyolite with quartz phenocrysts over 4mm; Dbrt, tuff with quartz phenocrysts over 4mm*

Dbrt, Dbrb, Dbr: *Nonporphyritic and porphyritic rhyolite with quartz phenocrysts less than 4mm; Dbrb, volcanic breccia; Dbrt, tuff with quartz phenocrysts less than 4mm*

Pyrite (Closely spaced dots where rock contains over 90% pyrite)

Outline of ore and ore seam at altitude of level

Projection of ore above level

Projection of ore below level

Contact (Dashed where approximately located)

Fault, showing dip (Dashed where approximately located)

90 Vertical fault

50 Strike and dip of foliation

Caved Portal of adit

Foot of raise or winze

Head of raise or winze

Workings (Dashed where projected to altitude of plan)

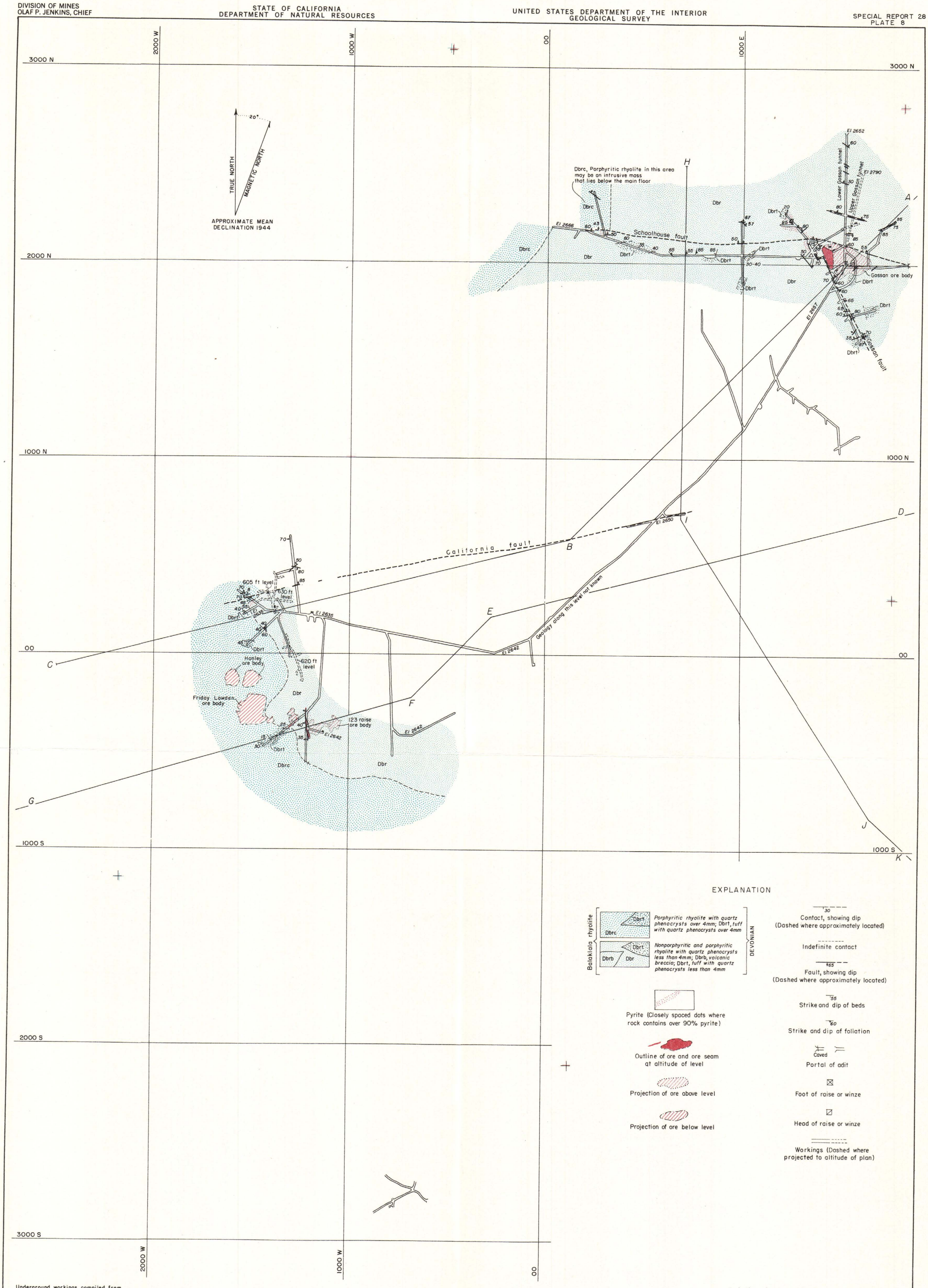
Underground workings compiled from United States Smelting Refining and Mining Company maps
Coordinates are those used by the mining Company

Projections of stopes and geology along mine openings from United States Smelting Refining and Mining Company; projected geologic contacts by A. R. Kinkel, Jr., and W. E. Hall, United States Geological Survey

PLAN OF THE 200 FOOT LEVEL OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

Datum is mean sea level



EXPLANATION

Balaklala rhyolite — DEVONIAN

Dbrc, Dbrt: *Porphyritic rhyolite with quartz phenocrysts over 4mm; Dbrt, tuff with quartz phenocrysts over 4mm*

Dbrb, Dbr, Dbrt: *Nonporphyritic and porphyritic rhyolite with quartz phenocrysts less than 4mm; Dbrb, volcanic breccia; Dbrt, tuff with quartz phenocrysts less than 4mm*

Pyrite (Closely spaced dots where rock contains over 90% pyrite)

Outline of ore and ore seam at altitude of level

Projection of ore above level

Projection of ore below level

30 — Contact, showing dip (Dashed where approximately located)

Indefinite contact

65 — Fault, showing dip (Dashed where approximately located)

55 — Strike and dip of beds

60 — Strike and dip of foliation

Caved — Portal of adit

Foot of raise or winze

Head of raise or winze

Workings (Dashed where projected to altitude of plan)

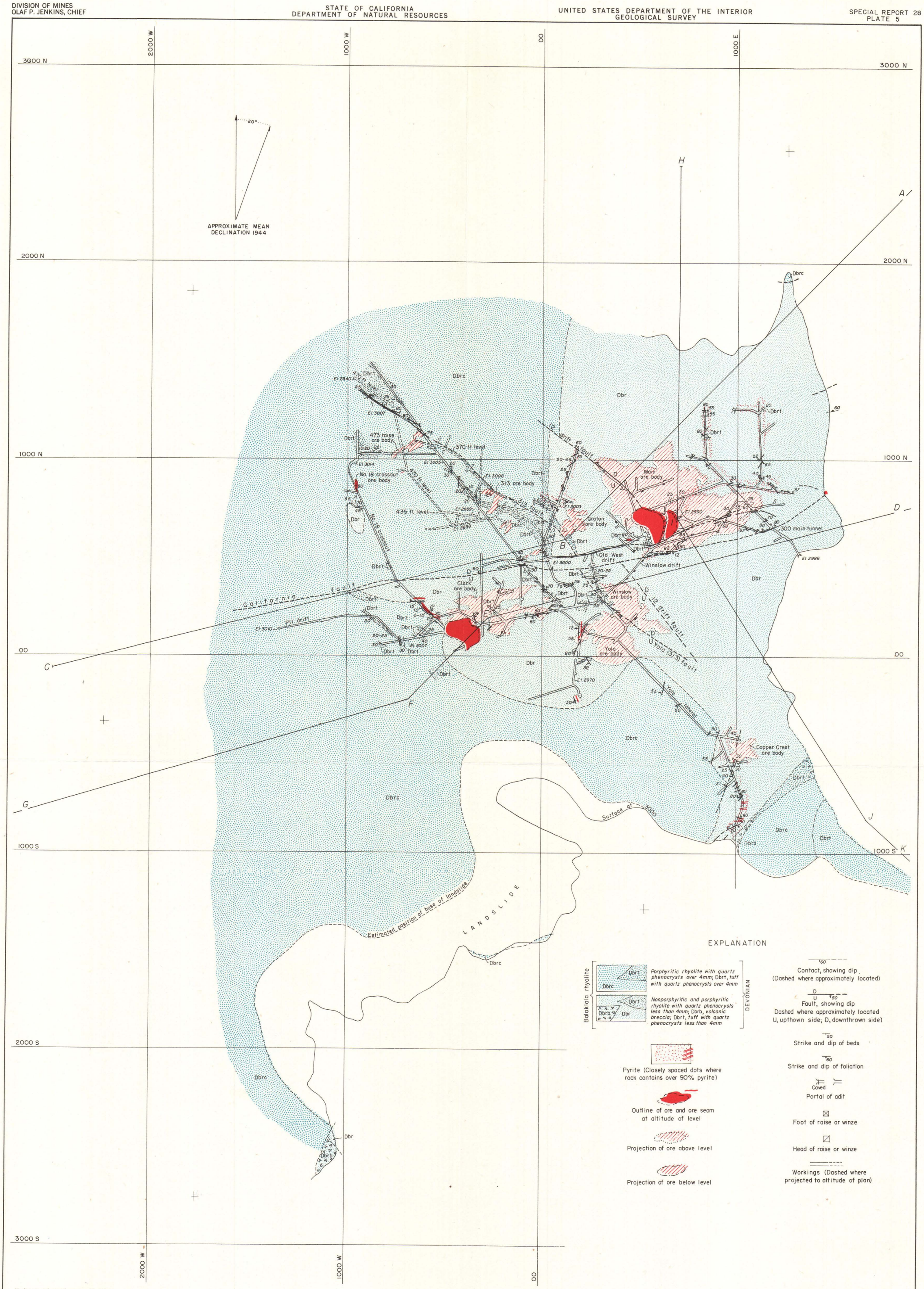
Underground workings compiled from United States Smelting Refining and Mining Company maps. Coordinates are those used by the mining Company

Projections of stopes and geology along mine openings from United States Smelting Refining and Mining Company; projected geologic contacts by A. R. Kinkel, Jr., and W. E. Hall, United States Geological Survey

PLAN OF THE 670 FOOT LEVEL OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

Datum is mean sea level



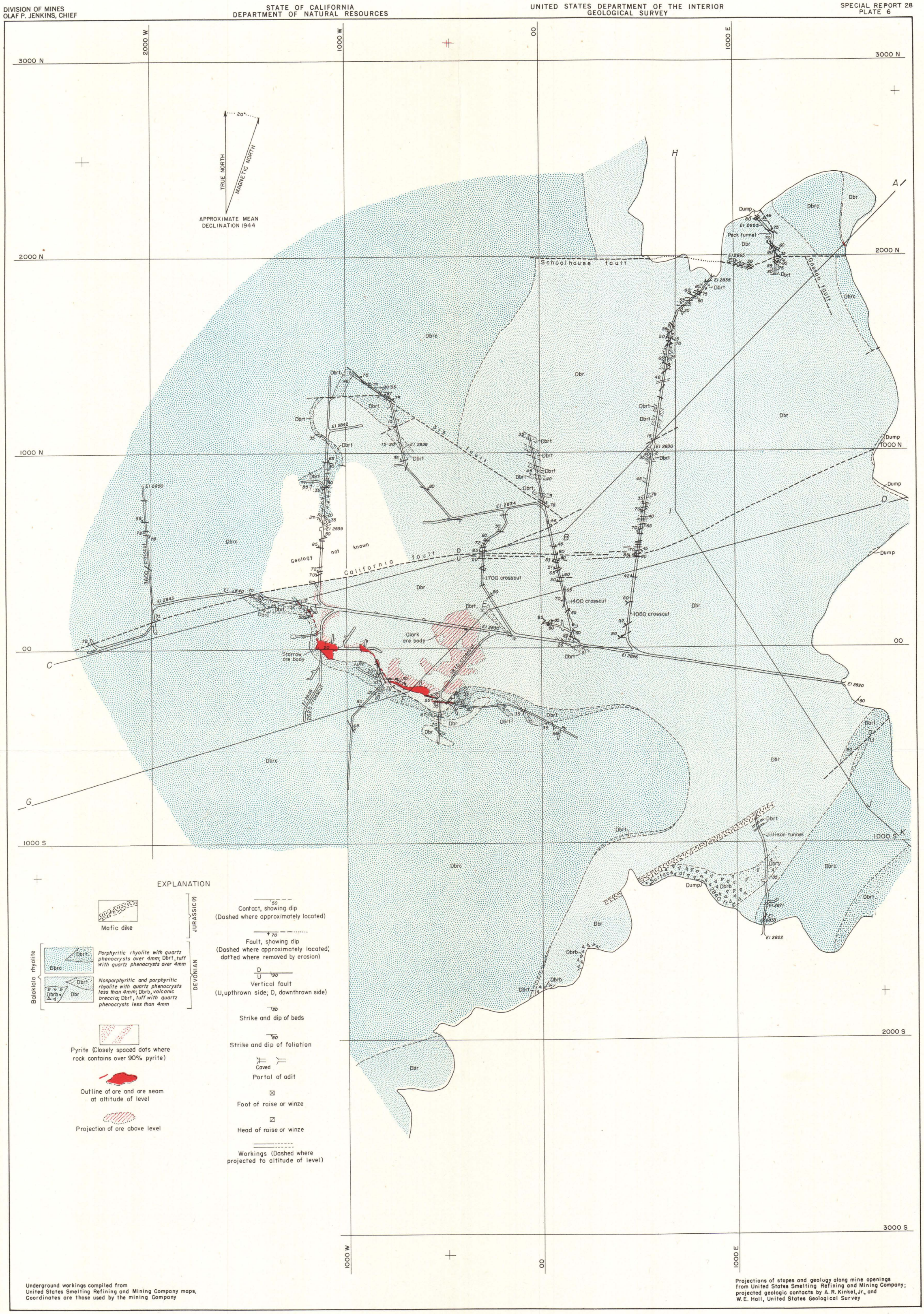
Underground workings compiled from United States Smelting Refining and Mining Company maps
Coordinates are those used by the mining Company

Projections of stopes and geology along mine openings from United States Smelting Refining and Mining Company; projected geologic contacts by A. R. Kinkel, Jr., and W. E. Hall, United States Geological Survey

PLAN OF THE 300 FOOT LEVEL OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

Datum is mean sea level



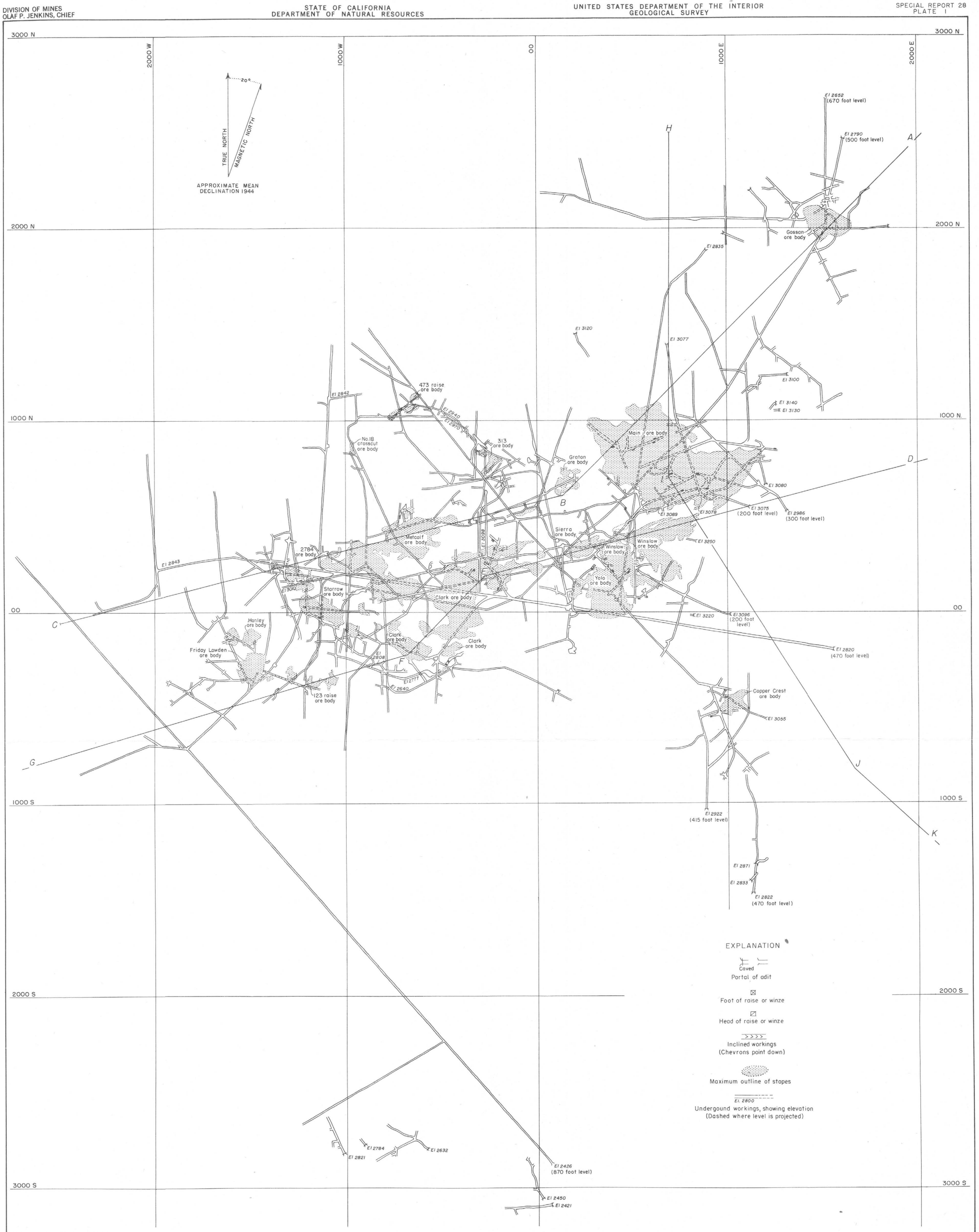
Underground workings compiled from United States Smelting Refining and Mining Company maps. Coordinates are those used by the mining Company

Projections of stopes and geology along mine openings from United States Smelting Refining and Mining Company; projected geologic contacts by A. R. Kinkel, Jr., and W. E. Hall, United States Geological Survey

PLAN OF THE 470 FOOT LEVEL OF THE MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

Datum is mean sea level



Underground workings compiled from
United States Smelting Refining and Mining Company maps
Coordinates are those used by the mining Company

COMPOSITE PLAN OF UNDERGROUND WORKINGS, MAMMOTH MINE, SHASTA COUNTY, CALIFORNIA

0 400 800 1200 Feet

Datum is mean sea level