UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary

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W. C. Mendenhall, Director

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QUICKSILVER DEPOSITS OF THE MAYACMAS AND SULPHUR BANK DISTRICTS CALIFORNIA

A PRELIMINARY REPORT

BY

C. P. ROSS

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(Pages 327–353)

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QUICKSILVER DEPOSITS OF THE

MAYACMAS AND SULPHUR BANK DISTRICTS, CALIFORNIA

A PRELIMINARY REPORT

By Clyde P. Ross

ABSTRACT

The Mayacmas and Sulphur Bank quicksilver districts, in northern California, have been active intermittently since the fifties and together have yielded about half a million flasks of quicksilver--more than a fifth of the total production of the State. Both districts are currently productive, and it is timely to consider how much of this strategic metal they are likely to produce in the present emergency. The results of study by a Geological Survey party in 1938 indicate that, although the high annual yields of the boom days are no longer to be expected, each of the two districts might, if prices remain at or above $150 a flask, produce 2,000 flasks or more annually for several years to come. This estimate is based on the assumption that some new ore will be discovered.

Deposits of copper, chromite, borates, sulphur, and other minerals are known to occur in the area, but they appear to be of slight economic value at present and are not further discussed in this report.

In both districts the oldest formation is the Franciscan, whose beds are greatly deformed and are locally metamorphosed. Much ultrabasic rock, which has mainly been converted to serpentine, has been intruded into the Franciscan formation, most of it in irregular but more or less sill-like masses. The serpentine has locally been further changed to a silica-carbonate rock. Other intrusive rocks occur in small amount. The Franciscan formation and the intrusive rocks are overlain by Pliocene and later volcanic rocks.

Most of the quicksilver deposits lie near the footwalls of the serpentine bodies, where they may be enclosed in serpentine, in silica-carbonate rock, or in the Franciscan formation; but the largest deposit, the Oat Hill, is in the Franciscan far from any exposed serpentine. Some deposits are in younger intrusive rocks, and a few are in Recent lava. The ore is localized where relatively abundant openings have been accessible to the solutions. Concentration under impermeable bodies has locally aided in the formation of ore shoots, but in several mines no evidence of such a process has been recognized. Deposition may have been confined to the zone in which ascend-

ing solutions of magmatic origin mingled with ground water. This zone, though geologically shallow, probably extends beyond the depths to which it would be profitable to mine ore shoots that are so small and erratically distributed as those hitherto found in the area.

INTRODUCTION

Nearly all of the outstanding quicksilver mines in California north of San Francisco Bay, and many of the smaller ones, are clustered in Lake County and the adjacent parts of Napa and Sonoma Counties. In the summer of 1938 a party consisting of J. R. Bovyer, George Crowl, J. W. Harding, Jr., and the writer spent nearly 3 months in studying the mines then active in this region. Although there are more than 50 quicksilver mines in the region, most of them were inactive and largely inaccessible in 1938. All the mines at which much work was then being done are grouped in four small areas, the locations of which are shown in figure 47, and geologic study was confined to these areas. Maps of these areas are reproduced on plates 47 to 50.

Only the more pertinent results of the investigation are outlined in this preliminary report.

The work was facilitated throughout by the hearty cooperation of the mining men in both districts, many of whom gave freely of their time and information. Much valuable information was furnished also by geologists of the State Division of Mines and of the University of California.

HISTORY

Cinnabar was discovered in both districts in the fifties, but it was first actively mined in 1864 at Mayacmas and in 1873 at Sulphur Bank, where, as the name indicates, the early mining was mainly for sulphur. Both districts, like other districts throughout California, not only profited by the quicksilver boom of the seventies but continued to flourish in the early

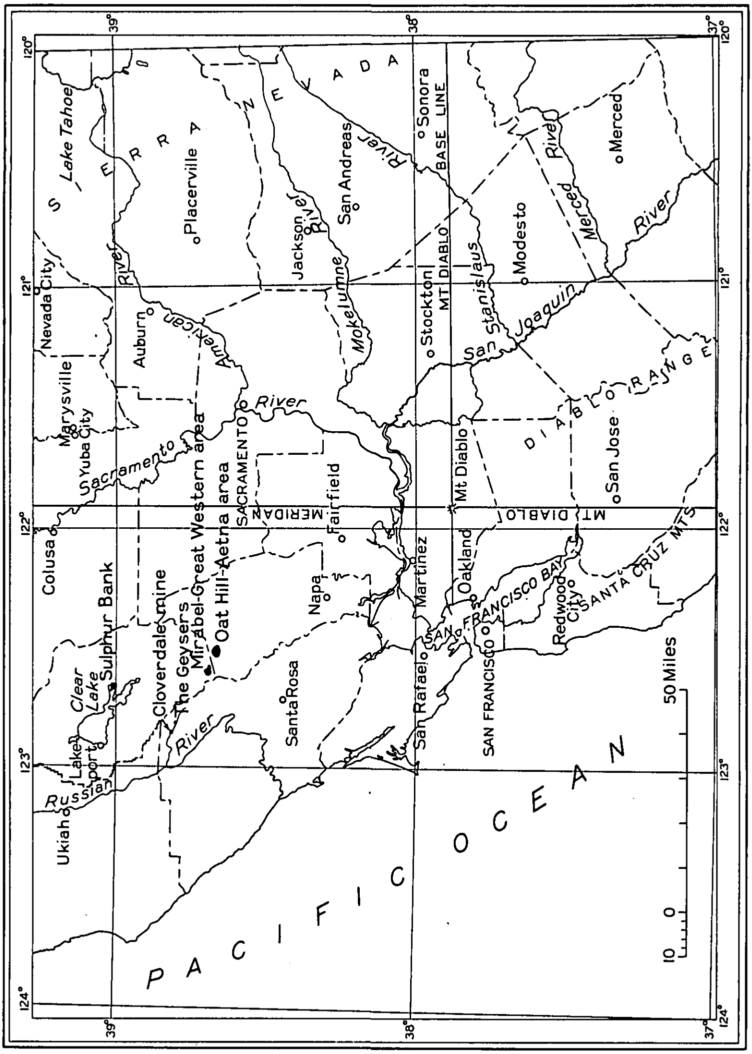
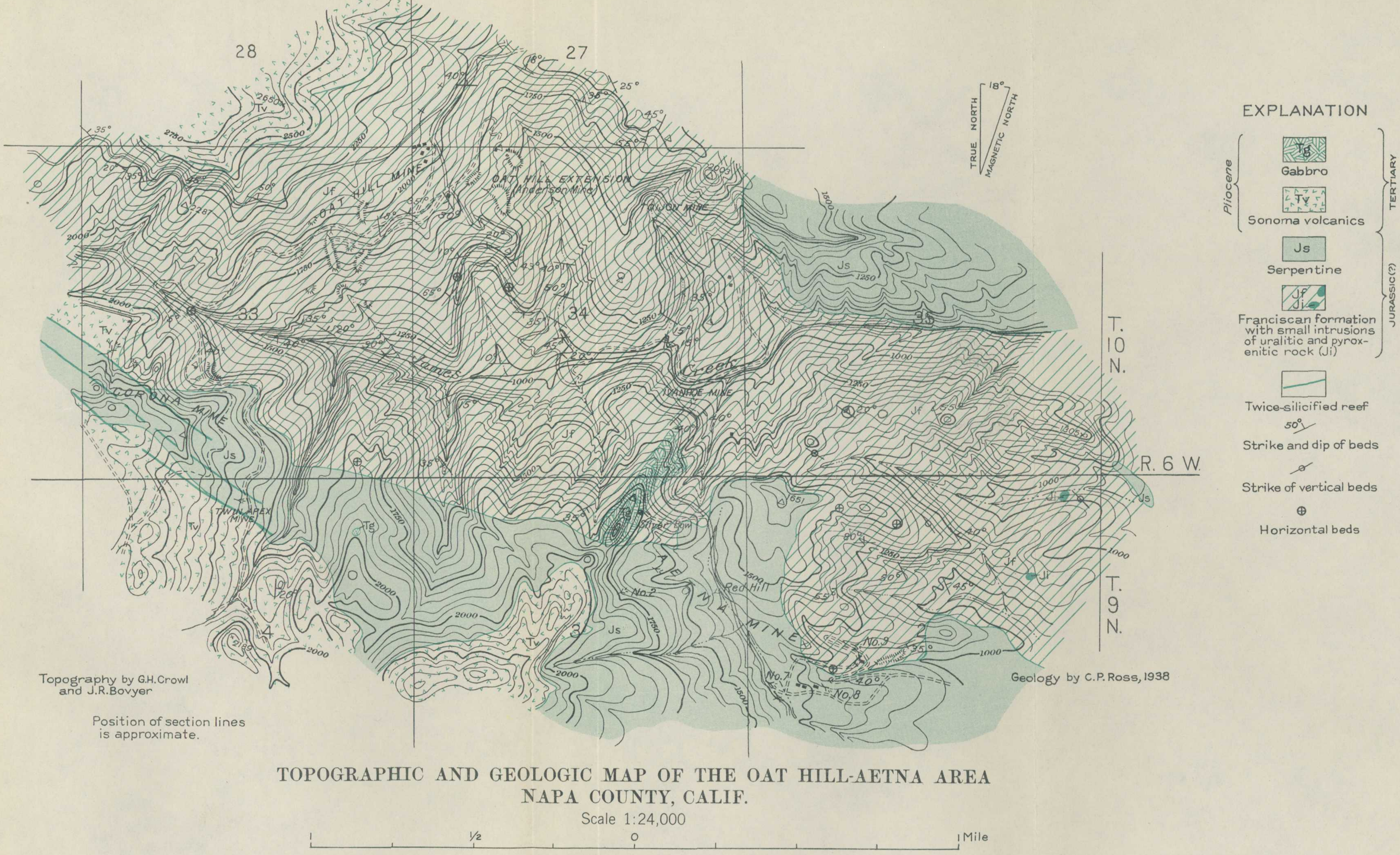


Figure 47.--Index map of part of northern California showing the location of the Sulphur Bank district and the areas that have been geologically mapped in the Mayacmas district.

eighties, after quicksilver mining in the State as a whole had begun to decline. Nearly two-thirds of all the quicksilver thus far produced at Sulphur Bank was mined before 1890, but in the early nineties the Mirabel, and to a less extent some other properties, were so productive as to cause a local boom. In the first 15 years of the twentieth century both districts, and especially Sulphur Bank, were comparatively inactive; even the stimulus given to quicksilver mining in the United States by the first World War had almost no effect on the Mayacmas district and resulted in only a small production at Sulphur Bank. Since 1928 there has been a revival of mining in both districts, slightly checked by the drop in price in 1931-33. In 1938 mining was active, but it was evident that several of the mines would have to find new ore bodies soon if production was to continue.

The general course of production in the two districts is shown graphically on plate 51. This chart and other production data given in the present report are based partly on figures assembled by A. L. Ransome and J. L. Kellogg 1/ and partly on records filed in the Bureau of Mines and released for publication by the companies concerned. Allowing for unrecorded production from small operators, the total for the two districts through 1938 is roughly 500,000 flasks. This is nearly 50 percent of the total production of all quicksilver mines in California except the New Almaden and New Idria, which have been so much more productive than the others as to be in a class by themselves, though the Oat Hill mine, in the Mayacmas district, ranks next to these two among the quicksilver producers in the United States.

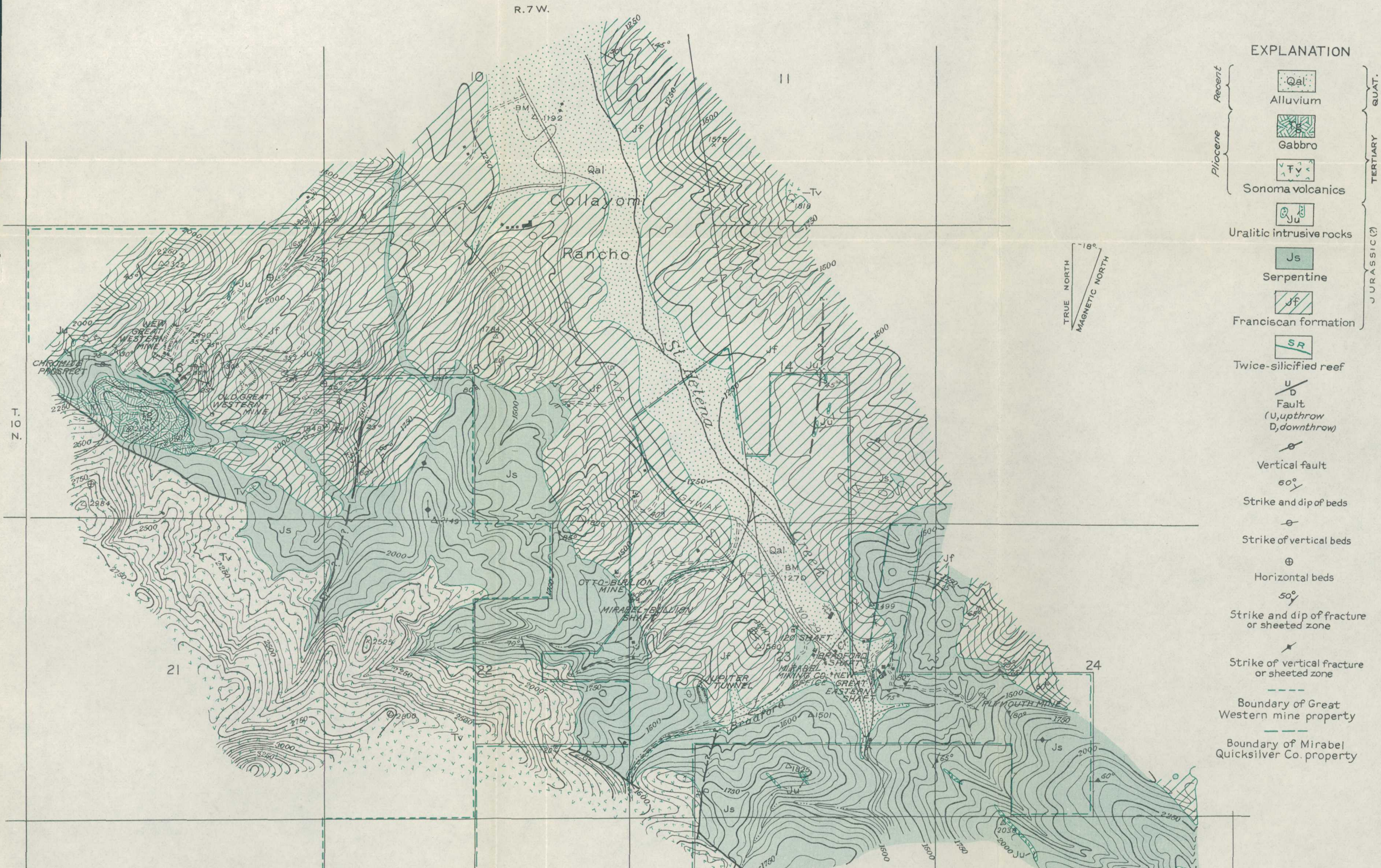
1/ Ransome, A. L., and Kellogg, J. L., Quicksilver resources of California: California Jour. Mines and Geology, vol. 35, No. 4, pp. 353-476, 1939.



TOPOGRAPHIC AND GEOLOGIC MAP OF THE OAT HILL-AETNA AREA NAPA COUNTY, CALIF.

Scale 1:24,000

1940



Position of section lines and property boundaries is approximate.

Topography by G. H. Crowl, J. R. Bovyer, and J. W. Harding, Jr.

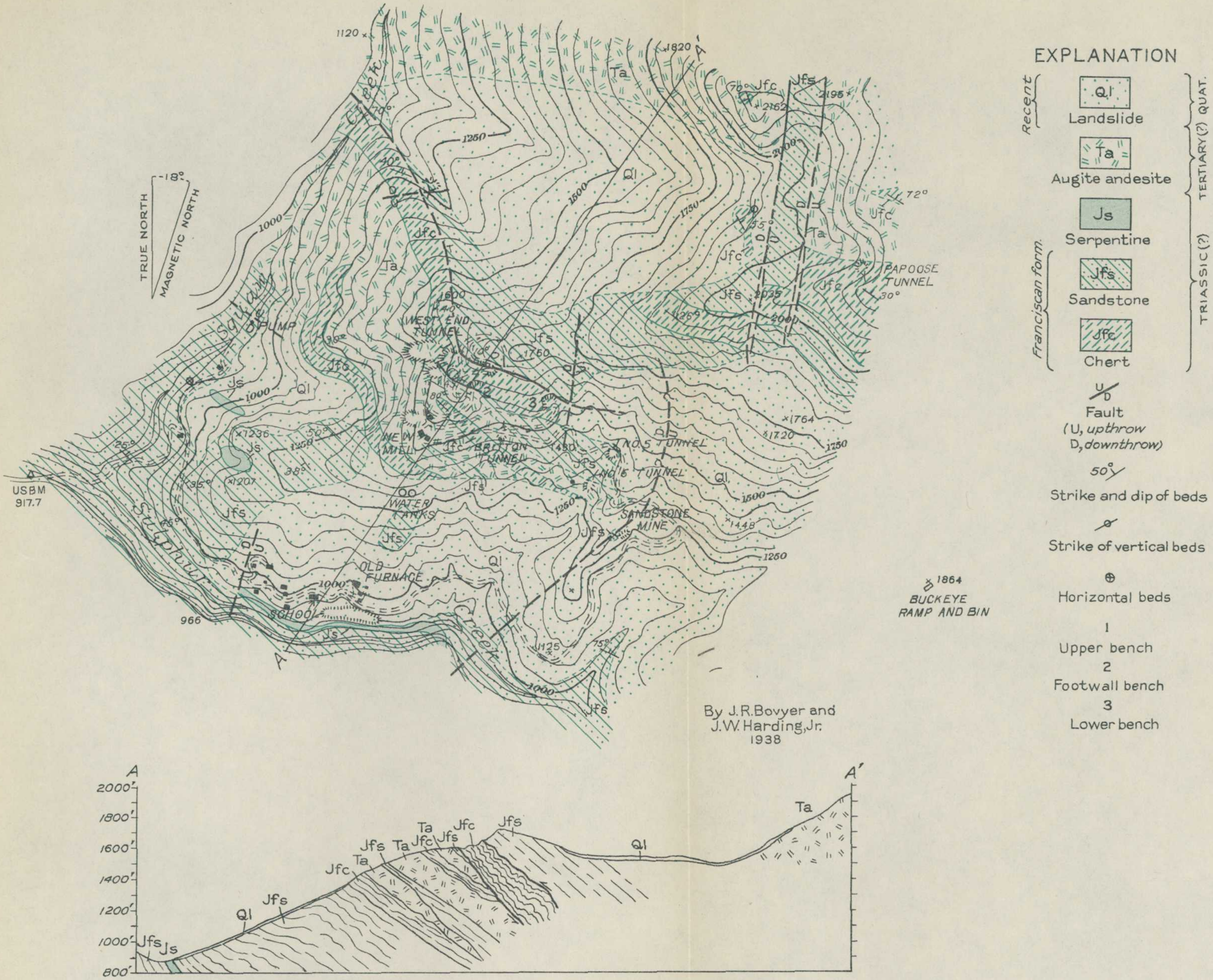
Geology by C. P. Ross, 1938

TOPOGRAPHIC AND GEOLOGIC MAP OF THE MIRABEL-GREAT WESTERN AREA, LAKE COUNTY, CALIF.

Scale 1:24,000

1 ½ 0 1 Mile

1940

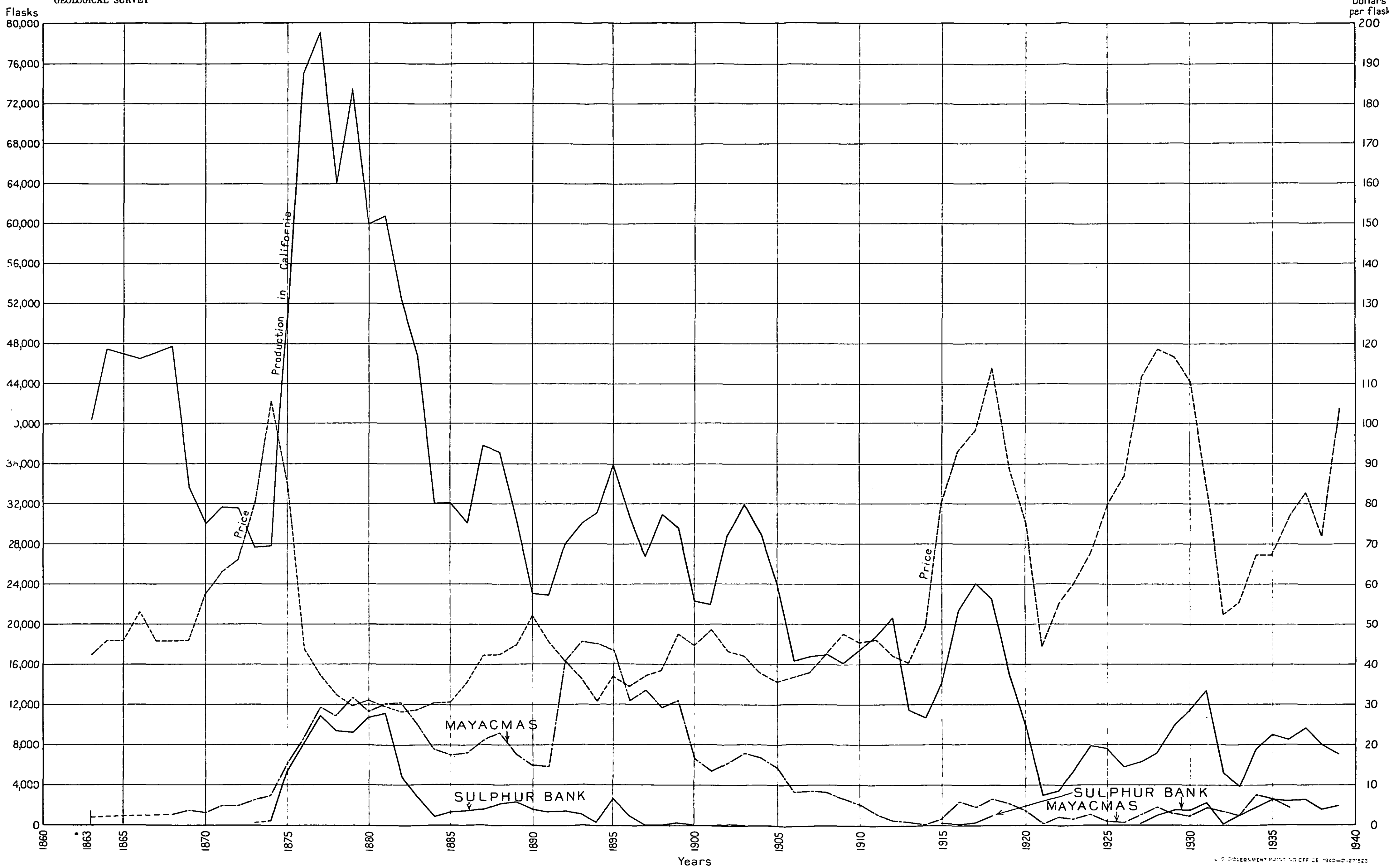


TOPOGRAPHIC AND GEOLOGIC MAP AND SECTION OF THE CLOVERDALE MINE AND VICINITY, SONOMA COUNTY, CALIF.

Scale 1:24,000

0 ½ 1 Mile

1940



GRAPH SHOWING PRODUCTION OF QUICKSILVER FROM THE MAYACMAS AND SULPHUR BANK DISTRICTS, CALIF.

GEOLOGY

The region that contains the quicksilver deposits of northern California is mainly underlain by sedimentary rocks of the Franciscan formation (Jurassic?). The Franciscan strata are cut by fairly large bodies of serpentine and by dikes and other small bodies of several kinds of igneous rock. The intrusive rocks may range from Jurassic to late Tertiary in age. Volcanic rocks correlated with the Sonoma volcanics (Pliocene) still overlie large areas and may once have covered all of the Mayacmas district and much of the surrounding region. Still younger volcanic rocks crop out around Clear Lake. The pre-Tertiary rocks have been folded, faulted, overthrust, and locally metamorphosed. The Tertiary and later rocks are gently flexed and much faulted.

Franciscan formation

The great mass of sedimentary beds that underlies the areas mapped is correlated with the Franciscan formation (Jurassic?) on the basis of general character. Within the areas studied more than 90 percent of the Franciscan formation consists of sandstone; the rest is chert, shale, and conglomerate. The sandstone is gray to green and weathers yellow. It is feldspathic and somewhat argillaceous. The rock commonly appears thick-bedded, but where it is contorted, as it is near the margins of intrusive bodies and along faults, close-spaced bedding planes are conspicuous. Most of the sandstone that is unaltered or but slightly metamorphosed breaks down readily into sand where weathered. Here and there, in areas that are rarely more than a few hundred feet wide and mostly near small intrusive masses, the sandstone is changed into a hard, locally schistose, rock containing glaucophane and other metamorphic minerals.

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Chert has been mapped only in the vicinity of the Cloverdale mine, but it was plentiful in the workings of the Great Western, now inaccessible, and is present in small bodies at other localities. It is thin-bedded and interleaved with films and thin layers of shale. Both the chert and the shale are mostly brown to red but locally green.

Shale, though not abundant, is widely distributed in lenses rarely more than 20 feet thick. Much of it consists of brown, gray, or nearly black clay that weathers in lozenge-shaped fragments and rarely shows distinct bedding.

Serpentine

The Mayacmas district contains several bodies of serpentine, and small bodies of this rock occur near Sulphur Bank. The serpentine is believed to have been formed by hydrothermal alteration of peridotite and, locally, of pyroxenite. The larger serpentine bodies lie roughly parallel to the bedding planes of the enclosing Franciscan rocks and are thus sill-like. Detailed mapping shows, however, that the contacts conform to the bedding only in the most general way and that there are irregular projecting tongues and dikes, some of which connect one sill-like body with another.

Most of the serpentine rock is of the pistachio-green variety that breaks with smooth, glistening surfaces. Some is darker and more massive and shows vestiges of an original porphyritic texture on weathered surfaces. Both varieties are so thoroughly serpentinized that residual grains of the original igneous minerals rarely exceed 25 percent and are commonly less than 10 percent of the volume.

Much of the serpentine has been further altered into a peculiar material called silica-carbonate rock or calc-silica rock, presumably a product of hydrothermal processes that continued after the intrusive rocks had been converted to serpentine. The rock is fine-grained and is largely composed of opal, chalcedony, and carbonates. It varies widely in appearance. In some of it the irregularly schistose texture of the serpentine survives as an ill-defined banding. Some of it is intricately brecciated. Much of the rock where unstained is light-colored, with some bands darkened by disseminated chromite and irregular areas colored light green by nickel silicate. In most exposures the rock is stained in various shades of brown, red, and black by oxides of iron and manganese. Where the carbonate has been leached out or where locally abundant pyrite has been oxidized, the rock is somewhat cavernous.

The silica-carbonate rock merges so gradually into the serpentine that any boundaries that might be drawn between the two on the maps would be arbitrary. The rock, therefore, has not been separately mapped, with the exception of a few reefs that stand out conspicuously as a result of differential weathering. (See pls. 47 and 48.)

The rock that composes these reefs is similar to the silica-carbonate rock but appears to have passed through a second period of silicification. The material contains less carbonate and more of pyrite or its oxidized products than the typical silica-carbonate rock. It forms steep, elongate masses in shear zones along faults. In many places closely spaced shear planes are visible. In some localities, notably near the Mirabel workings, the silica-carbonate rock is locally sheared but not siliceous enough to stand in topographic relief. In places the silicification in the twice-silicified reefs extends upward into the Sonoma volcanics; the later silicification, at least, must therefore have occurred long after the intrusion of the serpentine.

Other intrusive rocks

The region contains many small dikes and irregular bodies of rather calcic and generally fine grained intrusive rocks, commonly so much altered that their original character cannot be accurately determined. These rocks probably have a wide range in age, but few individual masses give clear evidence on this point. They are more abundant than the mapping shows, for some bodies do not crop out, their presence being indicated only by chips in the soil or by local igneous metamorphism in the sandstone. For purposes of mapping and description they have been divided, somewhat arbitrarily, into (1) uralitic rocks and pyroxenite, (2) gabbro, and (3) augite andesite and related rocks.

The uralitic and pyroxenitic rocks, which are not distinguished from each other on the maps, are much altered and are commonly surrounded by aureoles of metamorphic minerals in the sandstone, which is locally schistose. These rocks resemble the intrusive basalt, diabase, gabbro, and pyroxenite that Davis [2/] believes to have been formed at about the same time as the Franciscan strata; they may, therefore, be of Jurassic age. The gabbro has been sericitized and the andesitic rocks contain secondary carbonate and quartz. Both are locally very fresh and resemble some of the flows in the Sonoma volcanics. As the minerals in the altered portions are such as might have originated relatively close to the surface it seems likely that most, if not all, of the gabbro and andesitic rocks were formed in the same period of magmatic activity as the Sonoma volcanics.

2/ Davis, E. F., The Franciscan sandstone: California Univ., Dept. Geology, Bull., vol. 11, No. 1, p. 45, 1918.

Sonoma volcanics

The lava and tuff that form the higher parts of the Mayacmas Range are believed to represent eastward extensions of the Sonoma volcanics (Pliocene).[3] Within the Mayacmas district they consist mainly of tuff, pyroxene andesite, and relatively silicic flows, in part rhyolite. Most of the tuff is at or near the base of the formation, whose total thickness appears to exceed 2,000 feet.

Upper Pliocene (?) and Quaternary rocks

On the southern shores of Clear Lake are flows of rhyolite, dacite, obsidian, andesite, and basalt, breccias of varied composition, and subordinate clastic deposits. These rocks have been described in detail by Anderson.[4] He regards the oldest of them as possibly upper Pliocene but more probably lower Pleistocene in age; the youngest of them are Recent. At Sulphur Bank the eroded edges of folded Franciscan beds are overlain by a nearly flat, bedded deposit of clay with embedded fragments of lava, sandstone, and other material. This deposit, whose maximum thickness may be 100 feet, is overlain by a somewhat more extensive flow of nearly black exceptionally fine grained lava. The flow, which has a maximum present thickness of about 100 feet, is commonly called a basalt, although, as Anderson[5] has pointed out, some petrographers prefer to call it an augite andesite. It is of this rock that the low hill called Sulphur Bank consists. Along the shore of Clear Lake just north of Sulphur Bank are outcrops of red scoriaceous

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3/ Dickerson, R. E., Tertiary and Quaternary history of the Petaluma, Point Reyes, and Santa Rosa quadrangles: California Acad. Sci., Proc., 4th ser., vol. 2, pp. 551-554, 1922. Morse, R. R., and Bailey, T. L., Geological observations in the Petaluma district, Calif.: Geol. Soc. America Bull., vol. 46, pp. 1437-1455, 1935.

4/ Anderson, C. A., Volcanic history of the Clear Lake area, California: Geol. Soc. America Bull., vol. 47, pp. 629-664, 1936.

5/ Anderson, C. A., idem, p. 651.

breccia. Anderson calls this "agglutinate" and suggests that its outcrops mark the sites of volcanic vents. The basalt flow is overlapped on its northern and western edges by thin sediments obviously laid down in Clear Lake when it was deeper.

All the post-Franciscan rocks at Sulphur Bank are believed to be of post-Pleistocene age, although Forstner 6/ has suggested correlation of the clayey deposits beneath the flow with certain sedimentary beds at a nearby locality that are regarded by Anderson as of early Pleistocene or late Pliocene age.

Structure

The Franciscan rocks are bent into gentle folds, which trend northwestward in the Mayacmas district and northward near Clear Lake. Except in areas of local contortion, the dips are moderate, and over large areas they are nearly flat. The Sonoma volcanics are even more gently flexed but are inclined in places as much as 30°.

In some places the Franciscan strata are overturned, crumpled, and broken by thrust faults. The only known thrust fault large enough to map within the small areas studied in detail is at the Cloverdale mine (pl. 49), but several smaller ones were seen. Most of these are thought to be minor fractures that have resulted from local contortion. The steep, straight mountain front south of Sulphur Bank may be the fault-line scarp of a thrust fault. In most places the exceedingly intricate crumpling in the sandstone beds is more conspicuous than the fractures. The areas of contorted rocks are irregular in form and distribution, but contortion is most commonly developed on the margins of serpentine masses and in fault zones.

The principal normal faults in the Mayacmas district belong to two sets, both of which affect the Sonoma volcanics. The faults of one set trend roughly N. 60° W. and, locally at

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6/ Forstner, William, The quicksilver resources of California: California Min. Bur. Bull. 27, pp. 64-65, 1903.

least, have the downthrow on the south side. These faults bound in part the remnants of the volcanics. The displacements on them, so far as observed, are not large.

The faults of the second set, which are regarded as conjugate to those of the first, range in trend from north to about N. 15° E. Some of them are mapped on plates 47 and 48. They are steep faults and are apparently normal, with downthrow commonly on the west side. At many places their walls are marked by striae that pitch southward at angles of as much as 45°, indicating that the movement had a relatively large horizontal component. Some of the irregularities in the boundaries of the Sonoma volcanics and serpentine masses are due to these northward-striking faults. Some faults of this set, such as those shown on plate 52, are not clearly exposed except in mine workings.

In the vicinity of Sulphur Bank the faults, like the folds, differ somewhat from those of the Mayacmas district. The two principal faults mapped by Anderson [7] strike about N. 25° E. and N. 15° W. respectively. The basalt flow at Sulphur Bank is cut by several minor faults that strike N. 5°-65° E. The downthrow on some is to the northwest, on others to the southeast, but the vertical displacement is nowhere much more than 20 feet, and in places along the courses of these faults the basalt has been flexed rather than broken. Slickenside grooves, most of them nearly horizontal, are locally visible. Some of the minor slips exposed in quarries may have been produced by mere slumping and readjustment along joints while the basalt and the soft beds beneath it were being altered by hot water and gases, which are still surging through them. In the now inaccessible underground workings beneath the basalt, however, there is believed to be a strongly marked crush zone, which may accom-

7/ Anderson, C. A., op. cit., pp. 638-639, pl. 2.

pany a fault of some magnitude. This belief is based in part on published descriptions, which are incomplete and somewhat contradictory, but mainly on diamond-drill records and other information supplied by the Bradley Mining Co. This fault zone, apparently, trends about N. 65° E., dips gently southward, and is roughly accordant with the bedding planes of the Franciscan rocks.

QUICKSILVER DEPOSITS

Although deposits of chromite, copper, silver, and manganese occur in and near the Mayacmas district, only the quicksilver deposits of this district and the Sulphur Bank district are to be discussed here. In both districts the principal quicksilver mineral is cinnabar and the gangue consists mainly of wall rock and carbonates but locally contains chalcedony, opal, and quartz. The deposits are associated with fracture zones along serpentine contacts, with minor normal faults and thrust faults, and with joints in igneous rocks. At Sulphur Bank the ore now mined is in the lower part of a Recent lava flow. There are striking differences in detail between the lodes of the two districts, and those of the Mayacmas district may have been formed somewhat earlier than those of Sulphur Bank; but the resemblances seem so much more fundamental than the differences that all the deposits are believed to have been formed in much the same way and during a single period of mineralization.

Mineralogy

Cinnabar is the most abundant metallic mineral in both districts. Most of it was deposited in open spaces and forms crystals, but a little of it has replaced other minerals. The pulverulent variety of cinnabar called "paint" is widespread but not abundant enough to be of commercial importance. It is clearly later in origin than the crystalline material and may in part have been formed through surface agencies.

Native quicksilver is present in most of the mines but is abundant in only a few, such as the Socrates and Rattlesnake mines, in the Pine Flat area.[8/] This area, southeast of the Cloverdale mine, was not visited in 1938, because none of its mines were then producing. Mines in which a large proportion of the quicksilver is native metal are at a disadvantage because of added health hazards and difficulties in mining and treatment.

The other metallic minerals in the lodes include pyrite, chalcopyrite and its oxidation products, stibnite, and several nickel minerals. Pyrite is widely distributed but is not abundant in any of the mines visited except the Corona. The ore from this mine is reported to have contained enough pyrite to interfere with furnace treatment, and its oxidation introduced enough sulphuric acid into the mine water to be annoying. The other minerals are too sparsely distributed to be valuable unless, as is conceivable, nickel may locally be plentiful enough to be recovered as a byproduct under favorable conditions. Stibnite was recognized only at one place, where needles of it, in an aragonite gangue, were being deposited from hot water that issued on the floor of a quarry opened in basalt about 6 months previously. The water must have come up through the sediments immediately beneath the basalt.

The introduced gangue minerals include several carbonates, several forms of silica, clay minerals, and several bituminous substances. The carbonates identified are calcite, dolomite, ankerite, and magnesite. Some veins, notably on Mirabel

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8/ Bradley, W. W., Quicksilver resources of California: California Min. Bur. Bull. 78, pp. 192-195, 1918.

ground, consist mainly of carbonates; and calcite and other carbonates are locally disseminated in the wall rocks. Quartz, chalcedony, and opal occur in many places but are rarely abundant as vein filling. The silica-carbonate rock consists largely of chalcedony, opal, and quartz, which are believed in the main to antedate the lodes. The upper-central part of the basalt flow at Sulphur Bank has been almost completely replaced by opal, and the lode was seen in the now inaccessible underground workings to contain unconsolidated "cheesy" and gelatinous silica.[9]

At Sulphur Bank some parts of the basalt outside the ore zones are completely replaced by clay minerals, which form a subordinate part of some of the ore. In the Mayacmas district clay minerals occur as constituents of fragments of sedimentary rock included in the lodes, but they are not abundant except in gouge and in the so-called "black alta," a gougelike material composed of sandstone that has been softened by formation of clay minerals, crushed, and blackened by bituminous matter.

Bituminous substances are widespread in the lodes, though rarely abundant. They include gas, oil, and rubbery and waxy solids, as well as the indefinite dark substances that impregnate the "black alta" at Mayacmas and parts of the basalt at Sulphur Bank. Some of these substances are integral components of the lodes. They are, indeed, so much more plentiful in the ore and in the adjacent altered rocks than in any rocks far from the lodes that they clearly have some genetic relation to the ore.

Native sulphur was so abundant in the upper, intensely opalized part of the lava at Sulphur Bank that the quarry was originally opened as a sulphur mine, but sulphur is relatively

9/ Le Conte, Joseph, and Rising, W. B., The phenomena of metalliferous vein formation now in progress at Sulphur Bank, California: Amer. Jour. Sci., 3d ser., vol. 24, p. 29, 1882.

scarce in the other mines of the region. Sulphates of several kinds are widespread in the mines, but most of them were formed by oxidation after the mines were opened.

Hot springs are fairly plentiful in this part of California. The varied composition of their waters is shown in the analyses listed by Waring.[10] At Sulphur Bank hot water and gases are still passing abundantly through the mineralized rocks. Quicksilver is reported to have been detected in the water or the deposits at several localities in the region, including Sulphur Bank, but it has not been conclusively proved that the water now issuing from any of the hot springs carries quicksilver in solution.

Structural relations

Mayacmas district

The deposits in the Mayacmas district exhibit so much variety in structural detail that each mine offers its own special problems. Structural complexity is well exemplified in the Mirabel and Great Western mines. (See pls. 52 and 53.) Many of the deposits lie along serpentine contacts, especially along the footwall sides of sill-like masses. Most of those that lie wholly within the serpentine are near contacts, but some are in shear zones that diverge from the contacts. Most of the ore shoots in serpentine are enclosed in silica-carbonate rock; a notable example of this relation occurs in the Great Western mine. The twice-silicified parts of silica-carbonate masses that in places weather as conspicuous reefs contain little cinnabar, though ore bodies are found in nearby fracture zones. The ore shoots in general are confined to roughly tabular zones of brecciation in which angular fragments of the country

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10/ Waring, G. A., Springs of California: U. S. Geol. Survey Water-Supply Paper 338, pp. 83-109, 156-162, 1915.

rock, which is usually silica-carbonate rock, are cemented by cinnabar, carbonates, and other minerals introduced during mineralization. The breccia zones rarely have distinct walls, and in places they are very irregularly shaped. Only in the more thoroughly brecciated silica-carbonate rock is there room between the fragments for enough cinnabar to constitute ore. Cinnabar may line the walls of fractures in the unbrecciated rock nearby, but the transition from ore to very low grade material is commonly abrupt. Some of the ore in the Great Western workings (pl. 53) is associated with slivers of "black alta," most of which retain traces of the bedding of the sandstone from which they were derived. Commonly the ore is in silica-carbonate rock on the footwall side of the "black alta"; and C. N. Schuette, who was in charge of exploration work at this mine in 1938, regarded the "black alta" as an impermeable dam beneath which the cinnabar in the ascending solutions was concentrated.

The sedimentary rocks close to serpentine bodies are so broken and contorted in places that they contain an exceptional number of open bedding planes and other fractures. Many openings of this kind are lined with cinnabar and associated minerals. Where the sedimentary rocks along the contact are sufficiently crushed, ore bodies may occur either within the sedimentary beds or directly on the contact between them and the serpentine. In part of the old Great Western workings,[11/] for example, thin-bedded, brittle chert is abundant close to the contact, and cinnabar lines openings in the shattered chert.

Some of the lodes are in sedimentary rocks far from serpentine masses. The ore bodies of the Oat Hill mine, which ranks third in production among California quicksilver mines, and of several smaller mines are in crush zones in sandstone. In the

11/ Forstner, William, The quicksilver resources of California: California Min. Bur. Bull. 27, p. 54, 1903.

workings accessible in 1938 these crush zones were indefinite and discontinuous. The cinnabar lines bedding planes, joints, and fractures of various kinds, and some of it may have crystallized in the pores of the sandstone. Introduced gangue minerals are less abundant in ore bodies in sandstone than in the breccias in silica-carbonate rock. In and near much of the ore in sandstone some fractures were lined with films of "black alta." In a few places, notably in the Silver Bow workings on the Aetna property, cinnabar lines joint fissures in small Tertiary (?) intrusive bodies surrounded by sandstone. The ore in sandstone does not seem to differ essentially from that in these igneous rocks, either in origin or in the size, distribution, and tenor of the shoots. So far as could be seen in 1938 the ore bodies in both rocks are smaller, more irregular in form, and less sharply bounded than many of the ore shoots in silica-carbonate rock. The great extent of the old workings at Oat Hill, shown by the old maps, may fairly be taken as proof that ore shoots far larger than any now exposed were mined. Apparently these shoots were on relatively persistent and systematically disposed faults, along which there may have been crush zones that contained as high a proportion of open space as most of those in the silica-carbonate rock.

The Cloverdale mine (pl. 49), near the northwest end of the Mayacmas district, contains ore bodies in sedimentary rock that are perhaps more nearly comparable with those in the old Great Western workings than with those in the Oat Hill mine. The ore of the Cloverdale mine is on the under side of a thrust fault and mainly in chert. Small bodies of serpentine crop out on the slope below, but they are not known to contain ore. The better ore is to some extent localized along subsidiary fractures nearly normal to the thrust, mostly beneath but in part above the thrust zone. If the rock above the thrust were serpentine instead of being mainly sandstone, conditions would be essentially the same as at the Great Western mine.

Sulphur Bank

The deposits at Sulphur Bank differ strikingly from all those in the Mayacmas district: they are mainly in a Recent lava flow, and in an area where solfataric activity, which may have been instrumental in forming them, is still going on. The clastic beds that lie between the basalt and the contorted Franciscan rocks are themselves disturbed and contain some cinnabar, but most of the ore in the present quarries is in the basalt. Much of it is in a roughly lenticular mass of partly decomposed basalt near the base of the flow. The central part of this altered mass rests directly on the young clastic rock but nowhere extends out to the periphery of the flow. The basalt directly above the mineralized lens has been almost completely converted into opal. The inaccessible underground ore bodies are in a shatter zone in Franciscan rocks, and descriptions indicate that they differ little from those in similar rocks in other parts of the region. The thoroughly opalized rock, now largely removed by quarrying, contains sulphur but little cinnabar. The joints, exfoliation surfaces, and random crevices in the less thoroughly altered basalt are lined with cinnabar and associated minerals. In 1938 the quarry operations south of the Basalt shaft had been extended downward into almost fresh basalt, not distinguished on plate 50. Films of cinnabar lined cracks and other small openings in the fresh basalt. Cinnabar is a little more conspicuous near the top of the lens of partly decomposed basalt and close to the small faults that cut this lens than elsewhere. The mined bodies tend to be elongated northwest, roughly parallel to the average trend of the more conspicuous fractures. Detailed sampling might show more definite relation between the ore and the faults or other structural features.

Origin

The quicksilver lodes originated in structurally favorable locations through the agency of waters genetically similar to those that give rise to hot springs. These waters have traveled far and have been profoundly modified since they left their magmatic source. This in part accounts for the small amounts of metallic minerals other than those of quicksilver in the lodes. Such variations as exist among the different deposits result mainly from environmental factors; that is, the shape of each ore body depends on the shape of the breccia zone or other permeable body in which it formed, and the gangue minerals depend in some measure on the character of the wall rocks, or, more strictly, on the composition of the groundwater that derived its mineral content from those rocks. The quicksilver and certain other constituents of the lodes were brought up in hot solutions from some deep magmatic source but, as in most hot-spring waters, a large part of the volume of the solutions that formed the deposits was of surficial origin. Thus the mineralizing solutions were dilute and incapable of vigorous chemical attack on the rocks they traversed except under special circumstances like those at Sulphur Bank. Here the rising solfataric fluids have been oxidized near the surface so as to produce sulphuric acid, which attacked the basalt. Sulphur Bank, therefore, is an example of what Allen 12/ terms "sulphate areas." The water and gases now rising at Sulphur Bank probably contain a larger proportion of constituents of magmatic origin

12/ Allen, E. T., Neglected factors in the development of thermal springs: Nat. Acad. Sci., Proc., vol. 20, p. 347, 1934.

than those of most of the hot springs in the surrounding region, but it is unlikely that any of the present emanations closely resemble those that produced the quicksilver deposits.

The quicksilver lodes of both districts have been modified locally by weathering. Some of the pyrite has been oxidized, and part of the "paint" cinnabar may represent material that has been redistributed through weathering. Weathering, however, has not modified the original deposits enough to be of economic importance.

MINES

In the present brief report it is not possible to do more than point out some of the salient features of the mines as they were in the summer of 1938. The greater part of the workings that were productive in the early days are now inaccessible, and in some mines recent development is too meager to have uncovered much.

Aetna and neighboring mines.--The Aetna property, at the southeast end of the Mayacmas district, is estimated to have produced about 76,300 flasks of quicksilver up to the end of 1938. Its tunnels have a vertical range of nearly 900 feet, and the workings, which once totalled roughly 20,000 feet, are now mostly caved in the stoped areas. They originally explored several different veins, mostly in serpentine, but partly in gabbro and sandstone. Operations in 1938 were almost entirely confined to power-shovel cuts in silica-carbonate rock in the low-grade border zone above some of the old stopes. The possibilities underground do not appear to have been exhausted.

In the area between the Aetna and Oat Hill properties there are several small mines and prospects. These include the Ivanhoe, Toyon, and Oat Hill Extension properties and placer diggings along James Creek. The ore shoots so far discovered underground have been small, but some are fairly rich. Part of the small amount of cinnabar that has been recovered by desultory placer operations at times of high water is thought to have been reconcentrated from the eroded dumps of the old Oat Hill mine.

Oat Hill mine.--The Oat Hill mine, high on the slope north of James Creek, is reputed to have produced about 160,000 flasks of quicksilver. It is estimated to contain 21 miles of workings, with a vertical range of 875 feet. A few of the stopes were as much as 500 feet long and most came up nearly to the surface. There appear to have been at least 10 separate veins, all in sandstone of the Franciscan formation. These data are abstracted from published descriptions [13/] as very little could be seen in 1938. Some of the ore mined in the early days was rich but the recoveries in 1936 and 1937 averaged just over 4 pounds to the ton. Production increased in 1938 and, after a shutdown was resumed in 1939. The Corona and Twin Peaks mines, west of the Oat Hill, were inactive and inaccessible in 1938. Neither has ever produced much.

Mirabel Quicksilver Co.--Farther northwest, the Mirabel Quicksilver Co. controls 1,395 acres, which includes the Bradford, Great Eastern and several smaller mines. The production from this property up to the end of 1938 was about 35,897 flasks. The average yield in 1938 was almost 14 pounds of quicksilver to the ton, the highest for any mine in the vicinity. Most of the recent activity has been at the Great Eastern, but some good stopes have also been opened in an extension of the Bradford workings.

The Bradford, formerly the principal mine in this part of the district, was developed to a depth of more than 500 feet,

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13/ Bradley, W. W., op. cit., pp. 88-89. Becker, G. F., Geology of the quicksilver deposits of the Pacific slope: U. S. Geol. Survey Mon. 13, p. 358, 1888. Forstner, William, op. cit., pp. 89-91.

but most of its old workings are inaccessible. The following data are summarized from maps and a manuscript report by W. M. Randol, former manager. Most of the ore shoots trend nearly north on fracture zones in a complex of serpentine and sandstone. Most of the stopes are above the 300-foot level. One ore shoot was essentially continuous from the surface to that level. It was richest at the 180-foot level, where it was 80 feet long and 30 feet wide. Another ore body was 180 feet long and 15 feet wide at the 300-foot level, and there was still another shoot 150 feet long and from 12 to 20 feet wide. According to Randol a detached ore body was productive from the surface to the 120-foot level, at which level it was 130 feet long and 15 feet wide. The recent work in the Bradford mine is near this place and has resulted in discovery of several lenses of excellent ore which were being actively developed in 1938.

Early work in the Great Eastern was apparently not very successful. This mine should not be confused with the better-known mine of the same name in Sonoma County. Recent work extends to the 500-foot level (pl. 52). The modern workings are grouped within a rectangle that is 525 feet in a north-south direction and 460 feet from east to west. There are at least 3 ore bodies within this area mostly in silica-carbonate rock. Much of the ore recently mined has yielded nearly 10 pounds of quicksilver to the ton. Since 1938 the Mirabel property has continued to be one of the most productive in this part of the State. The Plymouth, Mirabel-Bullion, and other smaller properties controlled by the same company await redevelopment. There are several small mines in the general vicinity of the Mirabel property. The Otto-Bullion was the only one of these in operation when visited, and both development and production at all of them have been small.

Great Western mine.--The Great Western mine, about 2 miles northwest of the Mirabel, is the second largest mine in the Mayacmas district (see pl. 53). Its recorded production to the end of 1939 has been 103,433 flasks, nearly 80 percent of which was produced before 1896. In 1935 the ore yielded an average of 12 pounds to the ton, being second only to the ore of the Mirabel in richness. The mine is mainly in serpentine, but the workings extend into sandstone of the Franciscan formation on the northwestern flank of the intrusive body and into chert on its southeastern flank.

The earliest work here, described by Becker,[14] was high on the hill, close to the modern workings. Some time after Becker's visit, a furnace was erected and much more extensive workings were driven at several places on the slope southeast of it. These old workings are now inaccessible but have been described by Forstner.[15] At the time of Forstner's visit the mine contained 18,000 feet of drifts and 1,150 feet of shafts and had a maximum depth of 750 feet. Since then a few thousand feet of additional workings have been driven, mostly from a haulage tunnel that passes through the hill northwest of its crest. The workings accessible in 1938 extended 200 feet vertically above and somewhat more than 150 feet below the haulage tunnel. A Herreshoff furnace has been installed at the present camp in a small stream basin, also on the northwest side of the ridge. Some of the stopes in the old workings appear to have been moderately large. The ore bodies recently mined may have been passed by in the early days as too small to pay, for old workings are near many of them. Few of the modern stopes are as much as 50 feet long and most of them are less than 50 feet high. In 1939 little activity was reported at this mine.

14/ Becker, G. F., op. cit., pp. 359-362.
15/ Forstner, William, op. cit., pp. 52-55.

The area between the Great Western and Cloverdale mines contains many mines and prospects, but as this part of the district was almost entirely inactive in 1938 it was not visited. Among its more persistent producers may be mentioned the Helen, credited with 6,363 flasks up to the end of 1930,[16] the Culver-Baer with 10,973 flasks, and the Socrates with 3,286 flasks.

Cloverdale mine.--The Cloverdale mine is near the northwestern end of the Mayacmas district. This mine is old but was not very active in the early days. In the present century it has been a small but fairly steady producer; its total recorded production is a little more than 1,700 flasks. Some small lots of the ore have been of very high grade, but much of it has yielded only 5 pounds or less to the ton. The old workings are intricate; they extend horizontally about 1,500 feet by somewhat more than 500 feet and have a vertical range of more than 350 feet. Nearly all of them were inaccessible at the time of visit in 1938. At that time material said to contain only about a pound of metal to the ton was being mined by power shovel and treated in a mill specially devised by the operator, G. H. Burr. The ore bodies are in and below a thrust fault in Franciscan rocks.

Sulphur Bank mine.--The Sulphur Bank mine, on the shore of the southeastern arm of Clear Lake, was first opened for sulphur. An attempt was made, also, to concentrate and market borates from the water of the hot springs, but the nearby Borax Lake proved to be a more convenient source of these salts. Both sulphur and borates had ceased to be profitable when the mine was reopened for quicksilver in 1873. The first workings were open pits in the Recent basalt, but underground mining soon explored a breccia zone in Franciscan rocks. Work was extended

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16/ Schuette, C. N., Quicksilver: U. S. Bur. Mines Bull. 335, pp. 139-142, 1931.

to a depth of 417 feet, and 7 short levels were driven.[17/] A good deal of cinnabar was found in the underground workings, but so much difficulty was presented by the copious hot water and gases encountered that underground operations were abandoned, and later work has been done by quarrying. The irregular quarries now cover an area of about a million square feet and are almost wholly in the basalt, the base of which has been penetrated in only a few places. The basalt probably covers fully 4 times as much ground as the present quarries, but much of the marginal part of the flow may be unmineralized.

Up to the end of 1939 the mine had produced about 115,767 flasks, about 65 percent of which was obtained in the first 10 years of operation. The ore treated in the years 1935 to 1937 yielded about 9 pounds of quicksilver to the ton, but in 1938 and 1939 the average tenor was lower. Several times as much waste as ore has to be quarried.

OUTLOOK

This part of California has long been prominent among the quicksilver mining regions of the State, and it still contains many producing mines. It is therefore natural to hope that its prosperity may soon be greatly enhanced by the improved market for quicksilver, but this prosperity is just as dependent on the finding of new ore bodies as on high prices. The rise in production during the nineties resulted from discovery of new ore rather than from an especially favorable market. The incentive provided by high prices during the first World War failed to increase the output of the region greatly, because the search that was made did not result in the discovery of minable ore bodies, although, as we now know, such ore bodies were there and were subsequently found.

17/ Becker, G. F., op. cit., p. 263.

A few of the properties in the Mayacmas district are thought to have enough ore in sight to maintain the present rate of production for several years. The high prices of 1940 may accelerate production considerably, but, if so, the exhaustion of readily available ore will of course be hastened. A few of the mines are known to contain cinnabar-bearing rock that, although too lean to be worked profitably at normal prices, might yield a profit at the prices that have recently prevailed ($150-$200 per flask); but it is doubtful whether treatment of this low-grade material could materially increase the output of the district. Most of the mines, including several that were operating in 1938, contain so little known ore that they must find more of it before they can profit largely by the high prices of 1940. Perhaps the best that can be expected of the Mayacmas district, even at war prices, is a yield of about 2,000 flasks a year for a moderate number of years. The present activities have already persisted for more than 10 years, which is more than the whole life of many quicksilver districts.

All the quicksilver now being produced at Sulphur Bank is coming from a single mine. The Sulphur Bank property includes a large volume of ground that has not been mined, nor even tested, and it seems at least possible that this untested ground may on the average be rich enough to bring the production of the district up to 2,000 flasks a year, or even somewhat more, for several years.

In both districts there has been much prospecting, both on the surface and underground, but this prospecting has not been exhaustive, and further work may lead to the discovery of lodes now unsuspected or of new ore shoots in old mines. In the Mayacmas district surface prospecting should be directed especially to those places along the margins of serpentine masses where silica-carbonate rock is abundant and has been sheared or brecciated. Features of this kind are easily recognized, whereas most other features that indicate conditions favorable to ore deposition are less conspicuous. In the Sulphur Bank district it may be well to explore any area in which the effects of solfataric action are evident, especially the places where dark lava has been converted into white opaline material. Such material should not be expected to contain appreciable quantities of quicksilver, but cinnabar might be found immediately beneath it.