

Geology and Quicksilver Deposits of the New Almaden District Santa Clara County California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 360

*Prepared in cooperation with the State of California,
Resources Agency, Department of Conservation,
Division of Mines and Geology*



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By EDGAR H. BAILEY *and* DONALD L. EVERHART

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GEOLOGY AND QUICKSILVER DEPOSITS OF THE NEW ALMADEN DISTRICT SANTA CLARA COUNTY, CALIFORNIA

By EDGAR H. BAILEY and DONALD L. EVERHART

ABSTRACT

The New Almaden district, situated a few miles south of San Jose in Santa Clara County, Calif., has yielded nearly 40 percent of the quicksilver produced in the United States. The area mapped as the district for this report includes about 80 square miles, extending south from the flat Santa Clara Valley across the moderately low foothills containing the mines to the more rugged crest of the California Coast Ranges.

The rocks underlying about three-fourths of the district, including all of the mineralized area, are assigned on the basis of lithology to the Franciscan group of Late Jurassic and Cretaceous age. The only diagnostic fossils found indicate that the age of a part of the group is lower Upper Cretaceous (Cenomanian). The group consists of lithic and feldspathic graywacke, siltstone, dark altered volcanic rocks, chert, limestone, and a subordinate amount of metamorphic rocks, including glaucophane schists—an assemblage regarded as a typical eugeosynclinal suite. The thickness of the group cannot be determined accurately because of structural complexities, but the part present in the New Almaden district is believed to be at least 10,500 feet thick and may be much thicker. The sedimentary rocks are believed to have been derived from the rapid erosion of a rising landmass, and deposited in a subsiding trough which filled to wave base only in a few places near the end of the depositional period. The accompanying igneous activity included local outpourings of lava onto the sea floor and eruption of fragmental material of similar composition which accumulated as pyroclastic beds. The chert is abundant only in the part of the Franciscan group that contains altered volcanic rocks, and it is believed to owe its origin to the reaction of hot lava with sea water.

The post-Franciscan sedimentary rocks, which do not occupy large areas, range in age from Upper Cretaceous to Recent. Two sedimentary units, differing in both lithology and degree of deformation, have been assigned on the basis of a few fossils to the Upper Cretaceous. The next younger sedimentary rocks are dated as middle Eocene by fossils occurring in limestone lenses near the base of a sequence of sandstones and shales. Rocks of early, middle and late Miocene age containing abundant fossils are divided into two formations, the rocks of which grade from sandstone through clay shale to diatomaceous shale. The sandy sedimentary rocks below the lowest diatomaceous bed have been assigned to the Temblor formation, and this bed and the overlying rocks have been assigned to the Monterey shale. Some included silic volcanic material indicates igneous activity during the middle Miocene. The younger sedimentary rocks in the district are all gravel deposits, which fill the larger valleys and occur as perched remnants on some of the lower foothills. They have been divided,

largely on the basis of their dissection and topographic position, into the Pliocene and Pleistocene Santa Clara formation and Quaternary alluvium.

Tabular masses of serpentine that have been intruded into the rocks of the Franciscan group are of particular interest because altered parts of them contained the quicksilver ore bodies. Some of these masses are conformable with the rocks of the group and are therefore sills; others are intruded along faults that dip more steeply than the bedding. The larger masses consist of blocks of unsheared serpentine embedded in a matrix of sheared serpentine; the smaller masses and the borders of the larger ones consist entirely of sheared serpentine. The internal structures and details of the contacts, together with theoretical considerations, suggest that the serpentine masses were intruded as serpentine, not as peridotitic magma. The age of the serpentine cannot be closely placed by the evidence available in the district, but by comparison with other occurrences in the Coast Ranges it is believed to be Late Cretaceous.

Silica-carbonate rock—the host rock for the quicksilver ore bodies—has been formed locally by hydrothermal alteration of the serpentine. On the thicker serpentine masses it commonly occurs as a thin peripheral shell, but some of the thinner masses are entirely converted to silica-carbonate rock. As the silica-carbonate rock was formed by replacement, it shows abundant relict textures inherited from the serpentine. The dominant minerals of the silica-carbonate rock in the New Almaden district are quartz and magnesite. The process of hydrothermal alteration that formed the rock consisted chiefly in bulk substitution of carbon dioxide for water, but a little magnesium was removed. The alteration took place in late Tertiary, probably early Pliocene time. Because of the difference in age between the serpentine and the silica-carbonate rock, the hydrothermal solutions causing the change cannot be genetically related to the serpentine or its primary magma, but they may represent the early stages of the quicksilver mineralization.

The structures within the district trend northwestward or westward, and are dominated by the structures in the rocks of the Franciscan group. As these rocks nearly everywhere show evidence of flowage, folding, or shearing, only the more continuous coarse structures can be traced through them. The Franciscan rocks dip in general to the north, but an anticlinal flexure helped to localize many of the large ore bodies of the New Almaden mine. The post-Franciscan rocks that antedate the alluvial gravels occupy synclinal troughs that are nearly everywhere separated from the rocks of the Franciscan group by faults, but they are less crumpled than the Franciscan. The gravels are locally tilted and cut by normal faults of relatively small displacement.

The faults in the district are nearly parallel in strike to the rocks of the Franciscan group, but dip more steeply. The larger displacements are believed to be dominantly strike slip, the block southwest of a fault having moved northwestward, but the direction and amount of displacement can be directly determined for only a few of the faults. Along the largest faults there are wide shear zones formed before the deposition of the late Upper Cretaceous rocks; so the first movement occurred in early Upper Cretaceous time. Other faults were active after the deposition of the upper Miocene rocks, and a minor amount of faulting took place after the deposition of the Pliocene and Pleistocene gravels. Many of the younger faults followed older shear zones and indicate recurrent movement along these zones.

The most pronounced structural break is the Ben Trovato shear zone, which trends west-northwestward, parallel to the nearby San Andreas fault, through the central part of the district. It extends beyond the limits of the district, and in places it has a width of more than 4,000 feet. Its apparent horizontal offset is about 10 miles. A second shear zone, which is partly covered by younger rocks and partly obliterated by intrusive bodies of serpentine, diverges from the Ben Trovato shear zone east of Los Gatos and extends eastward across the district. It has been followed by the post-Miocene Shannon fault. Many of the other faults diverge from the shear zones at small angles, and they are believed to have less offset.

Steep fractures, trending north to northeast, traverse only the silica-carbonate rock, but these are of special interest because they bear a close relation to many of the ore bodies. These fractures generally extend into the silica-carbonate rock from the margins of the intrusive bodies for only a few score feet, and are widest close to the contact with the rocks of the Franciscan group. The fact that they have a uniform trend, regardless of the attitude of the silica-carbonate rock or of the serpentine sill from which it formed, indicates that they originated in response to a regional force, and therefore they may be regarded as tension fractures.

Quicksilver ore in place was recognized for the first time within the present confines of the United States on Mine Hill in 1845, but the bright red cinnabar that cropped out there had earlier attracted the attention of Indians and Mexican settlers. The subsequent development of the New Almaden mine, largely in Mine Hill, had resulted by the end of 1948 in a production of 1,046,198 flasks of quicksilver, which sold for \$50,000,000. The ores of the Guadalupe mine, whose outcrops were found a little later, have yielded about 112,600 flasks of quicksilver, placing this mine sixth in rank among California producers. The other mines in the district were also first developed many years ago, but although they have been intermittently active, they have made only a comparatively small production. Since 1890 the production from the district has been small as compared with its earlier output.

The mineralogy of the quicksilver ore bodies is simple. The only ore mineral of much economic importance is cinnabar, although locally native mercury impregnates and enriches the ores. Accompanying sulfides, present in only small amounts, include pyrite, stibnite, chalcopyrite, sphalerite, galena, and bornite. The gangue minerals introduced by the mineralizing solutions are dominantly quartz and dolomite with some hydrocarbons, but a few other minerals occur here and there.

Most of the quicksilver ore is of primary origin, although one alluvial deposit containing nuggets of cinnabar ore has been mined. The typical primary ore bodies were composite;

the cinnabar in them was deposited in part by replacement of silica-carbonate rock along steep northeastward-trending fractures, and in part by filling of the open spaces provided by the fractures. The replacement extended only a few inches outward from these fractures, but within this limit it was so complete that commonly more than 50 percent of the replaced rock was cinnabar. In many of the ore bodies the steep fractures occurred in swarms, so closely spaced that much of the intervening silica-carbonate rock was converted to rich ore. In most places the fractures were filled with quartz and dolomite containing very little cinnabar, but in some places the vein filling was sufficiently mineralized to form ore even where the walls were not mineralized.

The ore bodies that have been mined were large and exceptionally rich. The largest was about 200 feet wide and 15 feet thick, and extended down the dip for about 1,500 feet. The ore furnished in the first 15 years of mining at the New Almaden mine contained more than 20 percent quicksilver, but to obtain this amazingly high grade the ores were cobbled and hand sorted. In the course of time the grade steadily declined to less than 0.5 percent, owing to the utilization of lower grade ores and less careful mining and sorting. The remarkable richness of much of the ore, however, is well indicated by the fact that the average grade of all the ore furnished in the hundred years during which the New Almaden mine was productive is only a little less than 4 percent quicksilver, or about a flask of quicksilver per ton.

The ore bodies in the district are not distributed at random; nearly all are restricted to certain rocks and certain structural environments. A consideration of these lithologic and structural factors together with the geology of the area indicates that some places in which there is a reasonable hope of finding ore remain unexplored. Nearly all the ore bodies were formed in silica-carbonate rock, although this rock occupies only a very small part of the district. Furthermore, only the silica-carbonate lying close to the contact with the rocks of the Franciscan group is particularly favorable for ore deposition, and most of the ore bodies were richest within a few feet of this contact. The distribution of the ore bodies along the contacts apparently was influenced by two other structural factors, whose importance varied with the steepness of the contacts. Where the contacts were steep, swarms of cross fractures took a dominant part in localizing ore bodies, but where the contacts were inclined at less than 45°, the shape of the contact itself was of equal or greater importance; along such contacts the ore bodies tended to form at the crests of domes or plunging anticlines.

The quicksilver ore is believed to have been deposited during the Pliocene epoch by hydrothermal solutions rising from a deep-seated source. These solutions followed fractures which were best developed in the silica-carbonate rock near contacts with rocks of the Franciscan group. Deposition of the cinnabar took place through a vertical interval extending from near the surface to a depth of about 2,000 feet, and in a temperature range believed to have been from 50° to 150°C. The richest ore bodies were localized along gently dipping contacts, where the solutions spread out and stagnated under a capping of relatively impervious sheared rocks of the Franciscan group; but along steep contacts replacement by solutions flowing through fractures took place even where structural traps were absent. Although most of the ore bodies are in the silica-carbonate rock formed along the top sides of serpentine sills,

some equally rich ones were formed in similar rock along the lower side of the sills.

The descriptions of the various mines of the district are intended chiefly to be of aid to those interested in their further development, but the descriptions also contain details of geology and ore controls that will be of service to those desiring a thorough understanding of the deposits. Following each description is a section devoted to a comprehensive analysis of the possibilities for further development. In this section we have considered the known sources of submarginal ore and have also tried to indicate where ore of high grade might perhaps be obtained. As mining in the district was carried on during the last 40 years without adequate exploration and development, the amount of submarginal ore that is readily accessible is small. On the other hand, the geologic structures in some of the mines, when considered along with the factors responsible for the localization of the rich ore bodies, indicate that intelligent and aggressive development, supported by adequate funds, can be expected to reveal new ore bodies. Such ore bodies, if as rich as those previously mined, would be minable even during periods when the value of quicksilver is low.

A history of the New Almaden mine extends through a period of more than 100 years. The cinnabar was first used by Indians as a pigment. While California was under Mexican rule, the mine was developed according to ancient Spanish mining methods. Later, after the admission of California to the United States, title to the property was obtained by an American mining company through a series of legal battles fought through State and Federal Courts and finally settled by international arbitration. The mining history is exceptionally interesting because it begins with primitive methods and extends through a period when new techniques for mining the ores and new methods of recovering mercury from them were first introduced at New Almaden; in essence, it provides a history of mining and metallurgy for the mercury mining industry of the United States.

INTRODUCTION

SCOPE OF THE REPORT

The first recognition of quicksilver ore in the United States was made in 1845 in the New Almaden district, and since then the district has yielded nearly 40 percent of all the quicksilver produced in this country. Most of its production came from the famous New Almaden mine, which is one of the great quicksilver mines of the world, but the district contains other formerly productive mines, including the Guadalupe, which ranks sixth among the quicksilver mines of California. In spite of its prominence, the district had been little studied until a comprehensive geologic investigation was made during and after World War II by the Geological Survey. The prime purpose of this study was to determine whether this district should be regarded as exhausted, or whether it may still contain hitherto unknown ore bodies. Because the New Almaden quicksilver deposits are similar in origin and environment to many others in California, parts of this report may be applied equally

well to several other quicksilver districts in the State.

The mines lie in an area of unusual sedimentary and volcanic rocks making up the Late Jurassic and Cretaceous Franciscan group, which is exposed in, or believed to underlie, at least 30,000 square miles in California. As the parts of the district containing these rocks are of great economic interest, they have been studied more intensively and mapped in greater detail; other parts containing only younger formations have been mapped and studied less thoroughly.

LOCATION AND ACCESSIBILITY

The area mapped for this study as the New Almaden district includes about 80 square miles in the west-central part of Santa Clara County, Calif., about 9 miles south of San Jose and 50 miles southeast of San Francisco. (See fig. 1.) On the General Land Office grid it includes parts of T. 8 and 9 S., R. 1 W., and R. 1 and 2 E., Mount Diablo meridian, and it lies in the northern third of the Los Gatos 15-minute quadrangle. The mines of the district were once served by a branch line of the Southern Pacific railroad, but this line was abandoned and the track removed many years ago; the mines are now reached by good paved and ballasted roads extending from San Jose and Los Gatos. Branch roads lead to many ranches and summer homes remote from the mineralized belt, so that few parts of the district are more than a few miles from a passable road.

TOPOGRAPHY

The topography in most of the district reflects the dominant northwesterly trend of the bedrock structures, so that the main ridges and valleys trend northwestward. (See fig. 2 and pl. 1.) In the northern part of the district, however, the bases of the mountain ridges have been overlapped by the alluvium filling the southern part of the Santa Clara Valley, which slopes gently northward to San Francisco Bay. The alluvium nearly everywhere separates the northernmost of the three principal ridges in the district from the other two, and alluvial tongues extend up some of the valleys in the next ridge to the south. The other two main ridges are less distinctly separated, because the longitudinal valleys between them lie above the general slope of the Santa Clara Valley and they are therefore sharply incised and devoid of alluvial filling.

The northernmost ridge—the Santa Teresa Hills—emerges from the alluvium at an altitude of about 200 feet in its western end and attains a maximum height of 1,150 feet at Coyote Peak near the eastern edge of the district. The next ridge to the south, across the valley of Alamitos Creek, is of special in-

GEOLOGY AND QUICKSILVER DEPOSITS, NEW ALMADEN DISTRICT, CALIFORNIA



FIGURE 1.—Index map of the western part of central California showing the location of the New Almaden district and other quicksilver districts on which detailed reports have been prepared by the U. S. Geological Survey. Also indicated are the areas covered by the U. S. Geological Survey Atlas, Santa Cruz and San Francisco Follios 163 and 193.



Figure 2.—Shaded contour map of the northern half of the Los Gatos quadrangle showing the main topographic features of the New Almaden district and places referred to in this report.

Base from U. S. Geological Survey
New Almaden quadrangle, California, 1916

terest because it contains all the highly productive quicksilver mines. It is known, in its central part at least, as Los Capitancillos Ridge. At its northwest end it rises abruptly from the Santa Clara Valley to an altitude of about 800 feet, and to the southeast it rises gradually to 1,750 feet on Mine Hill. Farther to the southeast it is more dissected, but, nonetheless, its higher peaks reach approximately the same altitude. This ridge is sharply cut in three places by the transverse Guadalupe, Alamitos, and Llagas Creeks, which flow into Santa Clara Valley, and longitudinal tributaries of these creeks separate it on the south from the third parallel ridge.

This third ridge, the Sierra Azul, is a part of the backbone of the California Coast Ranges and is considerably higher than either of the others. It extends for several miles with altitudes only a few hundred feet above or below 3,400 feet, but near the western boundary of the district it also is breached by Los Gatos Creek, which flows at grade with the Santa Clara Valley.

The slopes of the hills vary considerably in steepness. In general, the Santa Teresa Hills are fairly subdued, the Los Capitancillos Ridge moderately rugged, and the Sierra Azul decidedly rugged. In spite of the general ruggedness of the area, the crests of all the main ridges are characterized by general slopes and local flats. Landslides, ranging in length from a few tens of feet to a mile, are common topographic features on the Los Capitancillos Ridge and the lower slopes of the Sierra Azul. On these same ridges in areas where no distinct slides can be recognized, there are extensive slopes of excessively rocky soil which has moved downslope by creep for long distances. The canyons in these areas are V-shaped, but their troughs are so charged with loose rock that they offer very limited exposures of bedrock.

CLIMATE AND VEGETATION

The climate of the district is generally mild but varies somewhat with the altitude. In the Santa Clara Valley the temperature drops a little below freezing a few times each winter, and summer temperatures rarely exceed 100°F; the usual daily variation in temperature, however, is rather great. Precipitation generally occurs only during the winter and spring, and the wet and dry seasons are reported (Clark, W. O., 1924, p. 40-42, 49) to be more sharply contrasted in the Santa Clara Valley than in any other part of the United States. The precipitation in the valley, which averages 20 inches per annum (Grunsky, 1908, p. 496-543), falls almost entirely as rain; snowfall is so rare that whenever it comes there is a virtual holiday in

San Jose. In the higher parts of the district the temperature range is somewhat greater, owing largely to colder winter nights; and the average rainfall is about 40 inches per year. Some snow falls in the mountains each winter, but generally it melts quickly.

The vegetation reflects the climatic differences due to altitude, although it is also influenced in a smaller degree by other features, such as northerly or southerly exposure, kind of soil, and drainage. The broad valleys, which apparently were once carpeted with grass or wild oats and studded with oaks are now largely covered with prune and apricot orchards. Some parts of the lower hills still retain the wild oats and oak trees, but other parts are planted with vineyards. Higher ground supports a thicker growth of trees with an undergrowth of poison oak in many places. Everywhere, however, there are scattered patches of grassland, and extensive areas, particularly at altitudes above 1,700 feet, are blanketed with "chaparral," a dense head-high growth of shrubs intermixed with small trees; the more abundant species are—

- Eastwood manzanita (*Archlostaphylos glandulosa*)
- California scrub oak (*Quercus dumosa*)
- Wartleaf ceanothus (*Ceanothus papillosus*)
- Chaparral broom (*Baccharis consanqui*)
- Chamise greasewood (*Adenostoma fasciculatum*)

The wetter parts of the stream valleys, at altitudes above 2,000 feet, support scattered growths of various conifers.

The vegetation in some areas is so closely controlled by the underlying rock that the distribution of the rocks may be roughly traced by the character of the vegetation. Such special lithologic control of the vegetation is discussed with the appropriate rock description.

PREVIOUS WORK

Despite the prominence of the New Almaden district as the foremost quicksilver producer in the United States for more than a century, very little has been published about the geology of either the mine or the district. The only lengthy discussion of the geology is the one by G. F. Becker (1888, p. 310-331, 467-468) in his monograph dealing with most of the domestic quicksilver deposits known in 1888. However, his broad statements concerning the geology and ores and his generalized surface map were based on fieldwork of rather brief duration. The most valuable contribution in Becker's report so far as this district is concerned consists of the excellent planimetric maps of the New Almaden mine workings. Forstner (1903, p. 168-187) added a few geologic observations in 1903, but he was much handicapped by the inaccessibility of

many of the workings. Bradley (1918, p. 154-168) likewise was unable to get into many of the mine workings in 1918, and as a result relied largely on previous publications for descriptions of the local geology. In 1929 C. N. Schuette (1931, p. 411-417), on the basis of his familiarity with the parts of the New Almaden mine accessible since 1916 and his study of available company maps and records, included a discussion of its geology and ores in a summary of the salient features of quicksilver mines of the world. More recently, Ransome and Kellogg (1939, p. 450-457) briefly described the geology and ores of the district in a summary account of the quicksilver mines of California, but again because of the inaccessibility of the mines, their principal contribution to geologic knowledge of the area consisted of the inclusion of a reconnaissance geologic map of the district made by John V. S. Tolman.

In addition to these published articles we have had the benefit of private reports to the mine owners prepared by Luther Wagoner,¹ Samuel B. Christy (1889), John A. Church (1892), Charles C. Derby (1908), J. H. Farrell,² H. W. Gould,³ and C. N. Schuette (1935). The second of these, based on Dr. Christy's 16 years of intermittent study in the New Almaden mine, was of particular value because it contained some geologic maps of workings that have been inaccessible for nearly half a century.

PRESENT INVESTIGATION

The U.S. Geological Survey investigation leading to this report extended over a period of 6½ years (1941-47), and many geologists contributed to the resultant product. The authors, however, assume full responsibility for the final maps and text. In 1939, as a result of the urgent need to develop quicksilver resources for wartime uses, the Survey began a coordinated investigation of quicksilver districts in the United States under the direction of Edwin B. Eckel. Because of the shortage of geologists and the more urgent requirements elsewhere, no specific study of the New Almaden district was then made, but half a dozen of the Survey geologists then studying other quicksilver deposits began reconnaissance mapping of the district during times when they could be spared from other assignments. This preliminary mapping served to delimit the potentially mineralized area, and it also indicated that an exceptional amount of detailed study would be required before the complex

geologic features could be adequately understood. In mid-1941 Lowell S. Hilpert and Paul Averitt were assigned to study the district, and they were joined in June 1942, by G. Donald Eberlein. Their work, because of its urgency and time limitations, was devoted to deciphering the important structural control for the ore deposits by rapid, but locally detailed, surface and underground mapping.

In September 1942, at the request of the U.S. Bureau of Mines, a drilling and sampling project was conducted jointly by the Bureau and the Survey at the Guadalupe mine, and this was followed, late in 1943 and during the first half of 1944, by diamond drilling at the New Almaden mine. The geologists assigned to the project were kept so occupied by the work it involved that they could make little headway toward mapping either the district or the New Almaden mine. In the spring of 1944 nine Survey geologists, including the writers of this report, were assigned to prepare, under the direction of Aaron C. Waters, detailed geologic maps of the extensive accessible workings of the New Almaden mine and to complete a detailed map of the surface above the mine workings. Shortly after the reassignment of Waters to other work late in 1944, the project was suspended for 3 months. Early in 1945 the writers returned to the district to complete the underground mapping, to prepare detailed maps of the areas overlying the New Almaden mine and the Guadalupe-Senator mines, to make a geologic map of the district, and to prepare this report. They carried on fieldwork and the necessary office work continuously until October 1947, except that Everhart was assigned for 1 year to another job; throughout the last year they were very capably assisted in the geologic mapping by Donald H. Kupfer.

Many Survey geologists have thus contributed to the final product. Where particular credit or responsibility for a geologic idea, part of a map, or a cartographic technique is due, their contributions are acknowledged; but as so many ideas "just grow" from informal discussions, the writers no doubt have failed in some cases to give due credit. They are grateful, however, to all their colleagues for their individual and collective contributions. Preliminary mapping of the district was done by Paul Averitt, Arthur E. Bradbury, James B. Cathcart, Robert R. Compton, G. Donald Eberlein, and W. Bradley Myers; aid in the detailed mapping of the accessible underground workings of the New Almaden mine was given by Randall E. Brown, Juanita Crawford, G. Donald Eberlein, Lowell S. Hilpert, David A. Phoenix, George W. Walker, Aaron C. Waters, and Robert G. Yates.

¹ Wagoner, Luther, 1881, Unpublished report on the Guadalupe mine.

² Farrell, J. H., 1923, Unpublished private report on the Senator mine, October.

³ Gould, H. W., 1925, Unpublished private report on the Guadalupe mine, November.

The California State Division of Mines aided in financing a part of the field investigation leading to this report, and the writers are indebted to Dr. Olaf P. Jenkins, who was then Chief of the Division, for his unfailing interest in the geology and economic potentialities of the district.

Many of the old photographs included with this report were supplied by Mr. Laurence E. Bulmore, of Berkeley, Calif., who has made an extensive collection of photographs and other historical material pertaining to the early history of the mine. He also kindly supplied information bearing on the local history during the period from September 1878 to December 1899, when his father, Robert R. Bulmore, was cashier and later general agent for the Quicksilver Mining Co.

During the field investigations the Survey parties received wholehearted cooperation from the local mining companies and mine operators. The owners and operators of the New Almaden and Guadalupe mines made all their records and maps available to the Survey. Mr. C. N. Schuette, manager of the New Almaden Corp., and Mr. George F. Kirk, operator of the Guadalupe mine, both gave much information about the history of their respective mines and volunteered all pertinent facts regarding their more recent operations. Mr. H. F. Austin, who operated an interesting cinnabar placer deposit in Almaden Canyon, provided information about that deposit. Many other miners and local residents, too numerous to mention individually, helped by their continued interest and assistance to facilitate the investigation.

MAPPING METHODS

The methods used in mapping geologic features as exposed on the surface or in a mine depend on a great many conditions, such as amount of exposure, complexity and attitude of structures, character and persistence of rock units; they also depend on the time available and the ultimate objective of the study. For proper evaluation of the resultant maps the critical reader must know something about these factors and about the mapping techniques that were adopted to take advantage of the favorable features and minimize those less favorable. Terrains underlain by rocks of the Franciscan group and the closely associated intrusive serpentine bodies present inherent difficulties to the geologist; quicksilver deposits likewise are characteristically erratic and irregular, and therefore hard to delineate. The following paragraphs briefly summarize the techniques used in the work on the New Almaden district and in the mines.

Enough time was available for mapping in as much detail as seemed to be justified by the probable usefulness of the results. Because of the difference in practical application of the various parts of the geologic map of the district (pl. 1), it represents two different methods of mapping. In general, the area containing the mineralized belt, lying to the north of a line between Los Gatos and a point 1 mile west of the southeast corner of the district, was mapped in detail, whereas the rest, except for a few important local areas, was covered only by reconnaissance mapping methods.

Within the area studied in detail, only the Franciscan rocks and serpentine were believed to be potential ore bearers; all the younger rocks, therefore, were examined and mapped less thoroughly. In the Franciscan terrain exposures are poor, being estimated to amount to no more than 0.1 percent of the area, and generally it was not possible to set up a stratigraphic succession or rely on "key beds." Every contact was followed as closely as possible, however, by the use of available outcrops and by identifying rock fragments in the residual soil. The detailed part of the map is believed to be in accord with all outcrops and reliable float, although the way in which the outcrops are grouped into rock masses is subject to interpretation. In the area studied by reconnaissance methods no attempt was made to follow every contact. In extreme instances, particularly in the south-central part of the district, traverses were so widely spaced as to omit on-the-spot examination of areas more than half a square mile in extent; however, as is indicated by the recorded data on the district map, traverses were generally no more than two thousand feet apart. Consequently, some small rock bodies, only a few hundreds of feet or less in area, have doubtless been omitted from the reconnaissance part of the map; but their omission probably does not seriously detract from a reasonable understanding of the regional geology.

The accuracy of position of a contact as shown on a geologic map depends not only on the certainty with which it can be located in the field but also on the precision with which it can be placed on the field map. The topographic base used for the New Almaden district mapping was a 2.6 enlargement of the Geological Survey's 15-minute topographic map of the Los Gatos quadrangle, surveyed in 1915-16 and published at a scale of 1:62,500. Aerial photographs were used in the field in conjunction with these enlargements, and much of the geology was first plotted on the photographs, but owing to inaccuracies of the enlarged topographic base, some adjustment of contacts from

their real position to their apparent position in relation to the contours was necessary. To get the best fit to the topography, and yet retain the proper inter-relationship of the various geologic units, most of these adjustments were made in the field.

On the larger scale maps of the areas over the New Almaden mine (pl. 3) and the Guadalupe and Senator mines (pl. 14), the geologic contacts are much more accurately placed than on even the more detailed part of the district map. On each of these larger scale maps the contacts were controlled by stadia shots in those parts where new topography was sketched; elsewhere they were as closely placed as possible by using Brunton compass bearings on known points on the topographic base, and by careful pacing. As the larger scale maps are accurate, no adjustment of contacts to obtain agreement with the topography was necessary.

The geologic maps of the underground workings of the New Almaden mine are based on data from many sources, and, as on the surface maps, the accuracy of the geology shown on them varies from place to place. As might be expected in a mine more than 100 years old and containing more than 30 miles of workings, many parts are inaccessible. When the mine was mapped in 1944-45, practically all the workings below the 800 level were flooded, and the most ancient workings, which lie near the surface, were largely caved or filled. However, between 1865 and 1904 the Quicksilver Mining Co. had prepared a very accurate and complete planimetric map of the open workings at a scale of 40 feet to the inch. This map, which was an outstanding example of mine mapping for its period, is preserved on a large roller in a maphouse on Mine Hill. It has been used as a base for all inaccessible workings, and data from a few even older maps were incorporated to add workings which apparently were inaccessible by 1865; but even so, a few workings that are known to exist have been omitted for lack of any kind of map. The mining after 1904 was rather irregular and consisted mostly of cleaning out and enlarging old stopes; as a result the company map, although very good for the access workings, was not reliable in the stopes. To verify the company's mapping and obtain control points in the stopes, the Survey field parties ran several miles of closed traverses by means of tape, Gurley compass, and planetable, and also mapped the walls of all accessible workings.

Altitudes throughout the mine presented greater problems than did the planimetric control because only a few points of known altitudes are indicated on the company maps. Because the shapes of gently inclined

geologic contacts, particularly in the stopes, are of great importance in establishing the structural controls for the ore bodies, it was necessary to obtain reasonably accurate vertical control throughout the mine. For those parts of the mine that were open, levels were run by means of closed foresight and backsight traverses, using 6-foot folding wooden carpenter's rules as handy level rods. In the inaccessible areas altitudes were generally known for all levels at the shafts and at important junction points, but elsewhere they were estimated on the basis of the exceptionally steep gradient of $1\frac{1}{2}$ feet per hundred at which levels were run during the period of mining.

As is discussed in greater detail on pages 110-121, the ore-controlling contacts of the open parts of the New Almaden mine are generally irregular in both strike and dip, and in many places they dip at low angles. To show their true shape in the stopes, they have been contoured at known elevations at regular intervals of from 5 to 10 feet by means of hand leveling from points of known altitudes. Detailed maps of the New Almaden mine prepared by using these methods are of great value to a few persons, but they were not believed to be of sufficient value to the general reader to justify publishing them with this report. However, 20 such large maps of the accessible workings of the mine at a scale of 40 feet to 1 inch have been placed in open file and can be consulted at the U.S. Geological Survey offices in Menlo Park, Calif., and Washington, D.C., or at the office of the California State Division of Mines in the Ferry Building in San Francisco, Calif. The major features of the geology shown on these maps have been incorporated in the smaller scale composite level maps accompanying this report, and especially suitable parts of them are used herein as text figures.

The geologic features shown on the maps of the inaccessible workings of the New Almaden mine were compiled from monthly surveyor's records, and although not accurate in detail, they probably serve to give the broad features of the ore control and geology. This could not have been accomplished without the efficient help rendered by Virginia S. Neuschel, of the Survey, who spent 2 months of the summer of 1945 in transcribing the notes from chronological order to an order based on the space relations of the workings and in plotting the data on base maps.

In the outlying mines, no attempt was made to use the very time-consuming contact-contouring technique, but, instead, the geology was plotted waist high on levels or shown by sections and sketches in irregularly floored stopes.

GENERAL GEOLOGY

The rocks of the New Almaden district range in age from Late Jurassic to Recent, but they represent a depositional history that was interrupted by several major breaks. The oldest assemblage consists of the heterogeneous Franciscan group of Late Jurassic and Cretaceous age, which occupies nearly three-fourths of the district. It contains graywacke, siltstone, mafic volcanic rocks, chert, limestone, and minor amounts of metamorphic rocks, including glaucophane schists. This assemblage is regarded as typical of eugeosynclinal accumulations in orogenic belts, and, as might be expected, the rocks nearly everywhere exhibit small-scale folds and shears and show abundant evidence of rock flowage. Intrusive into the rocks of the Franciscan group are many tabular bodies of serpentine, a few of which are of special interest because they have been hydrothermally altered during the late Tertiary to silica-carbonate rock—the host rock for the quicksilver ore bodies.

Upper Cretaceous deposits include two groups of rocks differing in both lithology and degree of deformation. The more deformed group, and probably the older, consisting of several thousand feet of conglomerates, graywacke, and shale, is exposed only in the higher parts of the Sierra Azul in the south-central part of the district. The other unit of Upper Cretaceous age, consisting of gently folded sandstone and shale, is found in the northern part of the area, principally in the Santa Teresa Hills. This unit may be the equivalent of part of the Chico formation, but because of the uncertainty of correlation, it is herein designated as the Upper Cretaceous rocks of the Santa Teresa Hills. Overlying this unit is a relatively thin sequence of limestone, sandstone, and shale of middle Eocene age, which is so poorly exposed that it has not been assigned a formation name.

The next record of sedimentation is furnished by rocks of lower, middle and upper Miocene age. These are at least 3,800 feet thick, and grade upward from conglomerate and sandstone to diatomaceous shale. The older part of this sequence has been referred to the Temblor formation, whereas all beds above the lowest diatomaceous shale are included in the Monterey shale. Some included felsic volcanic material reveals igneous activity in the area during the middle Miocene.

The post-Miocene deposits consist largely of alluvium, which fills the Santa Clara Valley, floors major canyons, and in places lies along the base of the foothills as perched gravels. Largely on the basis of their dissection and topographic position these gravels have been assigned to two formations. The

older deposits have been correlated with the Santa Clara formation of Pliocene and Pleistocene age, whereas the younger ones are grouped as Quaternary alluvium.

The structural features of the district consist of folds and faults trending westward or northwestward. The oldest rocks in general dip northeastward, but they have yielded to deformational forces by extensive crumpling, folding, flowing, and faulting. The major faults are believed to have largely strike-slip displacement, and they are generally marked by shear zones rather than single planes of slippage. The most notable of these shear zones—the Ben Trovato, which trends obliquely through the central part of the district—attains a width of more than a half a mile. The rocks of intermediate age, though also deformed, have remained more cohesive and form simple continuous folds cut by narrow faults. The young alluvial formations are little tilted, and show traces of faults only by topographic scarps less than 100 feet in height.

The following sections describe the 21 distinctive cartographic rock units mapped in the district. Some of these contain only a single kind of rock, whereas others, such as the greenstone of the Franciscan group, contain several distinct but related lithologic types. Correlations between isolated exposures of rocks of the different cartographic units were made largely on the basis of lithologic similarity, as fossils were too rare in nearly all of them to be of much aid.

FRANCISCAN GROUP

The oldest and most extensive assemblage of rocks in the district has been assigned primarily on the basis of lithology to the Franciscan group, which includes rocks of both Jurassic and Cretaceous age. All the diverse rock types commonly found in this group throughout the California Coast Ranges occur in the New Almaden district, and their relative abundance and general lithology in this district are believed to be typical of the central part of the Coast Ranges. The group consists mainly of medium- to fine-grained graywacke (p. 13) and dark shale; it contains a somewhat smaller amount of generally altered mafic volcanic rocks usually classed as “greenstones,” and small amounts of conglomerate, limestone, and chert. Another rock, serpentine, which accompanies the group in many places, is considered by some as a part of the group; but it is somewhat younger, because it is intrusive into the other rocks. Because of the distinctive character of the group, both lithologically and structurally, and because of its importance to California geologists and quicksilver

miners, it has been more thoroughly studied than any of the younger formations in the district, and is therefore described in more detail.

All the rocks of the Franciscan group in the New Almaden district show at least incipient metamorphism in some places, but most of the rocks of the group are so little changed that in the field they appear unmetamorphosed. The typical rocks do not show slaty cleavage, foliation or schistosity, prominent development of stress minerals, or crystalloblastic textures. In a few areas of relatively small extent, however, some of the rocks of the group are crystalloblastic, schistose, or even gneissic, having obviously been subjected to special metamorphic processes that have not affected the rest of the group. These distinctly metamorphosed rocks consist largely of schist, amphibolite, and crocidolite-bearing metachert, probably formed from the normal graywacke, greenstone, and chert. Because of their unusual and seemingly erratic distribution, these metamorphosed rocks of the Franciscan group are usually discussed together, rather than treated separately as special metamorphic phases of the various rocks from which they are derived, and they will be discussed together in this report. These metamorphosed rocks have attracted a disproportionate amount of attention because of the interest aroused by a few uncommon minerals found in them, and this, together with the fact that the group was referred to in early reports as the Metamorphic series, has led to a widespread but erroneous belief that the Franciscan group consists largely of crystalline schists.

The name Franciscan (series) was first used by Andrew C. Lawson (1895a, p. 342-356; 1895b, p. 399-476), and it has been adopted by all geologists working in the California Coast Ranges. Other names, however, had previously been applied in several important publications to rocks now included in the Franciscan group. As early as 1856, Blake (p. 153) used the name San Francisco or California sandstone in a report containing a description and map of the sandstone around San Francisco Bay. Nine years later Whitney (1865, p. 19-108) described the entire group, together with the serpentine, using the terms San Franciscan sandstone, metamorphic rocks, and metamorphosed Cretaceous. Becker (1888) applied various terms, including Neocomian, Metamorphic series, and Knoxville, to the rocks older than the Chico (Upper Cretaceous) formation of the Coast Ranges. Since these early studies a great many reports dealing directly or indirectly with the Franciscan group have appeared.

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CLASTIC SEDIMENTARY ROCKS

The most abundant and widespread of the Franciscan rock types are the clastic sedimentary rocks, which in the New Almaden area amount to more than two-thirds of the assemblage. Although the sedimentary rocks are widely distributed throughout the district, no single exposure serves to show the variety of rocks included in this single cartographic unit. However, one easily accessible, and fairly representative, series of exposure is afforded by the roadcuts along the first 2 miles of State Highway 17 south of Los Gatos.

The clastic sedimentary rocks are characterized by a high content of feldspar which is mostly sodic plagioclase, and except in the conglomerate, by a marked angularity of grains; in many there is an uninterrupted gradation in grain size from the coarsest clasts to the finest matrix material. Rocks with the grain size of sandstone predominate, siltstone is common, shale less so, and conglomerate is rare in the district. The rocks are poorly sorted; the sandstones are true graywackes and the siltstones and shales contain a large proportion of minute mineral grains rather than clay minerals. In spite of the variety of clastic rocks in the sedimentary pile, which is more than ten thousand feet thick, they are so distributed that it is impossible to divide the sequence into mappable units consisting wholly, or even largely, of either coarse or fine sediments. Within sequences that are chiefly graywacke are local sections several hundred feet thick consisting largely of siltstone and shale, but attempts to map these failed because the shale is not persistent along the strike. Conglomerate lenses interbedded with the graywacke are also too thin and too limited in extent to provide mappable units.

The physical characteristics of the clastic sedimentary rocks on microscopic, hand specimen, and outcrop scale indicate that they were deposited rapidly, in part at least, by turbidity currents. Such poorly sorted sedimentary rocks, together with the intercalated chert, minor limestone, and soda-rich volcanic rocks, make up an assemblage found in many parts of the world. They are regarded as typical of the accumulations that build up in a structural trough along the margin of a continent when rapid deformation accompanies deposition, and are generally referred to as eugeosynclinal deposits.

GRAYWACKE

Graywacke, which in most reports is referred to as Franciscan sandstone, makes up more than half of the Franciscan group. Nearly all varieties are distinguished easily from the other rocks in the district even though the graywacke exhibits much greater variation in color, in mineral content, and in general appearance than do most sedimentary units. All varieties are dark-colored poorly sorted dirty rocks containing abundant grains of feldspar and some rock fragments. (See fig. 3.) The variations they show are partly the result of original sedimentation and partly the result of late processes leading to differing degrees of induration, metamorphism, and deformation.

Several thick sequences of graywacke separated by volcanic rocks are found in the district, and it was at first thought that these might be mapped as sepa-



FIGURE 3.—Massive graywacke of the Franciscan group; actual size. To bring out the texture the specimen was polished and etched with hydrofluoric acid, which makes this dark-gray rock appear much lighter than it really is. Irregular white patches and veinlets are calcite. An analysis of this rock is given in column 2, table 1.

rate units or formations. An elaborate scheme of field classification based on proportions of feldspar to quartz, grains to matrix, light-colored grains to dark-rock fragments, and other criteria was attempted; but attempts to develop cartographic units by this means failed because the differences between sequences were no greater than the variations within a single sequence. In general, however, the older rocks occurring in the southern part of the district were found to be more feldspathic, whereas the younger rocks contain more lithic fragments.

The exposures of graywacke are generally less than a hundred feet across, but locally, as on Mount Umunhum, exposures are fairly continuous over half a square mile. In some large areas, notably in the Santa Teresa Hills, outcrops of these rocks are almost nonexistent. The average individual outcrop does not exceed 10 feet in length and consists of exceptionally massive rock cut by several sets of joints. In many such isolated knobs of graywacke bedding can be distinguished only with difficulty, although in places the alinement of mica flakes or shale fragments indicates the attitude of an otherwise massive rock. The true character of the sequence is better seen in artificial exposures, as in roadcuts or mine workings. In these exposures the graywacke generally shows more bedding and can be seen to be somewhat folded and cut by faults, as shown on figure 4. Where interlayered with shale it may also show individual beds



FIGURE 4.—Deformed graywacke exposed in roadcut between Bald Mountain and the crest of the Sierra Azul. The irregular folds and low-angle thrust faults, such as are shown here, are abundant throughout much of the district, but in many places sufficient shale accompanies the graywacke to permit rock flowage to predominate over simple folding and faulting.

that have been plastically deformed so that their present thicknesses are quite different from their original thicknesses.

Original variation in the thickness of beds of graywacke, or the accompanying beds of shale or tuff, however, are the general rule, and no systematic relation between the thickness of the graywacke and other interbedded rock was observed. Most exposures show a completely erratic distribution of beds of different thicknesses, although locally there are sequences of thick or thin beds. The maximum thickness of beds seen in artificial exposures rarely exceeds 5 feet, though surface outcrops several times as wide without apparent bedding are not uncommon. Sharply limited thin layers of graywacke and shale also can be seen in some places. Lenticular beds were observed, especially where thin layers of graywacke are interbedded with shale or tuff, but more commonly slippage along breaks that are nearly parallel to bedding has formed lenticles that do not necessarily reflect original lenticular bedding. Graded

bedding, with the graywacke grading upward to shale by an imperceptible decrease in grain size, accompanied by a darkening of color, is present in some of the sedimentary rocks but cannot be seen in most places. Current bedding on a small scale was observed in thin-bedded sedimentary rocks in some exposures in the mines, but apparently it is rare as it was not observed in the poorer surface exposures. Flintings were noted on the lower surfaces of the graywacke layers, but they are rarely found. None of the sedimentary rocks contain ripple marks. Veinlets of either quartz or calcite, or both, are abundant, and the weathered surfaces of rocks partly replaced by calcite are covered with small irregular pits.

The lithic graywackes that are most abundant in the central part of the district contain a high proportion of mafic rock fragments and seem to grade into tufts and breccias mapped as greenstone. They also contain in places erratically distributed greenstone pebbles, or even boulders of greenstone several feet in diameter.

Because of the scarcity of exposures, the geologist mapping in the Coast Ranges must often rely on the character of the residual soil, and therefore a few comments on the soils developed on graywacke may be of value. Where the graywacke is highly feldspathic, the soils are light buff or tan and differ in color from the reddish soils yielded by most greenstones. Although we found a few areas of altered tuffaceous greenstones that also yielded light-colored soils, these were so small that we believe mapping areas mantled with light-colored soils as graywacke will cause only a very occasional error. Where the graywacke contains abundant fragments of greenstone, it gives rise to reddish soils identical in color to some soils derived from tuffaceous or massive greenstone. In areas so mantled the geologist should rely on the small rock fragments that can commonly be found in the soil; in their absence no criteria is really reliable, but we found that soils developed on graywacke were generally more gritty than those on greenstone, probably owing to the persistence of quartz.

Megascope features

The most consistent features of the graywacke are its dirty appearance and its high content of feldspar, which normally slightly exceeds quartz in amount. It contains highly angular grains, which are generally monomineralic, and somewhat more rounded rock fragments. The monomineralic grains are mostly of feldspar and quartz and between 0.25 and 1.0 mm in diameter, but a few detrital grains of minerals of the epidote group and zircon are commonly present. Although all the graywackes contain rock fragments, the proportion is quite variable, ranging from a few percent to three-fourths of the rock. Most of the fragments are of basic lavas, but fragments of shale are generally present and locally abundant. Carbonized wood fragments, such as are abundant elsewhere in the Franciscan group, are uncommon in the New Almaden district. The indeterminate matrix is dark colored, and ranges in amount from thin films between closely packed grains to perhaps as much as 20 percent. Where the matrix is highly siliceous, as in much of the more feldspathic graywacke, the fractures tend to go through the grains; where it is more chloritic or clayey, however, the breaks go around the grains. None of the rocks, however, contain more than a little clay, and none contain an appreciable quantity of red ferruginous oxides. The color generally is some shade of gray or light green, but where the graywacke is weathered, as in most outcrops, it ranges in color from dark gray to buff or light tan and locally is reddish.



FIGURE 5.—Photomicrograph of feldspathic graywacke of the Franciscan group. Crossed nicols. Angularity of grains and lack of sorting are typical. Grains are chiefly plagioclase (pl) and quartz (Q).

Microscopic features

Enough thin sections were studied to indicate that the graywacke varies widely in relative proportions of component minerals and in amount of matrix, but many more sections would have to be studied before definite limits could be assigned to the variations. (See figs. 5, 6.) All the sections contain angular grains of sodic plagioclase, quartz, and rock fragments, separated by a fine-grained matrix composed of the same materials and recrystallized fine-grained

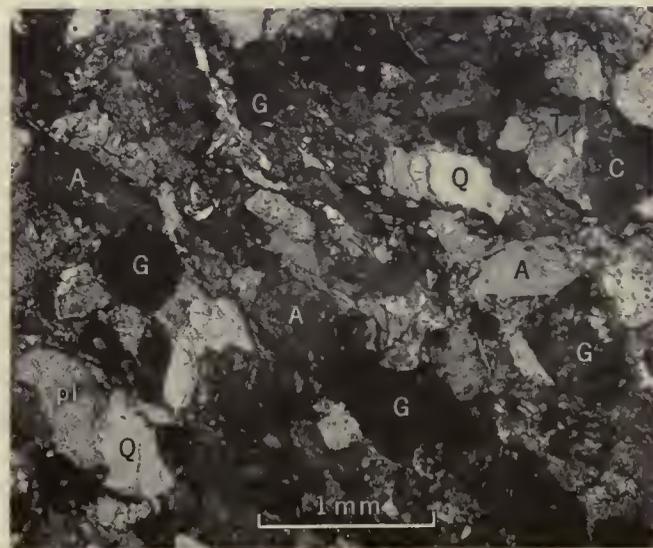


FIGURE 6.—Photomicrograph of lithic graywacke of the Franciscan group. Crossed nicols. Contains monomineralic grains of plagioclase (pl) and quartz (Q), and grains of greenstone (G), altered tachylite (T), argillite (A), and chert (C).

aggregates of chlorite, sericite, and perhaps other minerals. A few detrital grains of augite, epidote, clinozoisite, or zoisite are generally present, and some varieties contain several percent of biotite or muscovite or both. Other detrital minerals occurring in minor quantity are chlorite, sphene, zircon, garnet, ilmenite, leucoxene(?), and magnetite. Tourmaline and hornblende, reported from other localities by Taliaferro (1943b, p. 135), were not found.

The quartz grains, which make up from 10 to 35 percent of the graywackes, are commonly angular, but some are subangular. A few well-rounded grains were observed, as was a single grain showing a definite euhedral shape. The quartz is clear, generally contains liquid and gas-filled cavities, and rarely includes needles of zircon. Many of the grains show undulatory extinction, and some are composites of several crystal units separated by sutured boundaries.

Feldspar grains generally account for from one-third to two-thirds of the monomineralic grains, and feldspars are also common constituents of the rock fragments. The monomineralic grains are generally angular or subangular, and a surprisingly small proportion show straight edges that coincide with the cleavage direction. In some sections many of the feldspar grains appear to be euhedral crystals modified only to the extent of having slightly rounded corners. The feldspar is generally cloudy enough to be easily distinguished from the clear quartz but fresh enough to show sharp lamellae in the grains that are twinned. Much of the feldspar, however, is untwinned, and this, together with the incipient alteration, makes the determination of the relative abundance of different kinds of feldspar difficult. To ascertain the ratio of potash feldspar to plagioclase 10 thin sections were etched with hydrofluoric acid and stained with sodium cobaltinitrite solution, which differentially stains the potash feldspars a bright yellow. Two of these thin sections contained a few grains of potash feldspar, but in the others none was found; this admittedly inadequate sample suggests that orthoclase is a minor constituent of only some of the graywacke. The relative amounts of albite, oligoclase, and andesine have only been approximated by comparing indices of the feldspars with the index of balsam along the edges of thin sections, which is a rather unsatisfactory method because many of the feldspars are so clouded with alteration products that a reliable comparison cannot be made. This method leads to the tentative conclusion that albite is by far the most common plagioclase, oligoclase is generally present, and andesine is rare. Features that might be suggestive of a granitic source for the feldspars, such

as graphic intergrowths, myrmekite, or microcline, were not found.

Rock fragments may make up from less than 10 percent to more than 75 percent of the clasts in the graywacke. Most of the fragments are mafic lavas or greenstones, similar in texture and mineral content to the massive greenstones of the Franciscan group, and a single thin section will generally include several varieties of greenstone fragments. Some of them consist of completely altered mafic glass, others contain albite and scattered relicts of pyroxene in an altered fine-grained or glassy groundmass, and still others are composed largely of plagioclase with only a little altered groundmass. Less common are fragments of shale, phyllite, and chert showing varying degrees of recrystallization. Shale fragments are generally tabular and invariably bent around adjacent grains of quartz and feldspar, whereas the fragments of mafic volcanic rock have rounded and irregular shapes due to distortion of the original grains by flowage to form a better fit with adjacent grains.

The term "matrix" as applied to graywacke needs to be defined before it can be discussed because in many of these rocks there is no clear break in grain size between the coarsest and finest material. The matrix, however, is generally considered, as it will be here, to include the material between grains that is itself so fine grained as to be only partly determinable under high magnification (about 0.002 mm in diameter) and the somewhat coarser material that is recrystallized from this fine-grained paste. The quantity of matrix in the Franciscan graywacke varies from an amount large enough to provide a groundmass in which the other grains are clearly isolated to a thin, scarcely discernible film between closely packed grains. Much, and perhaps all, of the matrix is recrystallized. It contains quartz, sericite, chlorite and probably also albite and actinolite. In some varieties it replaces the margins of feldspar grains or rock fragments giving these a fuzzy outline. In addition to the normal matrix in some varieties there are small areas in which the matrix is replaced by calcite.

Chemical features

The few chemical analyses that have been made of graywackes of the Franciscan group are shown in table 1, and for comparison we have included an average of 30 graywacke analyses from other localities and an average of 40 granodiorite analyses. The new analysis given in column 2 is of a specimen collected from the center of a 10-foot boulder that had been blasted apart, and it appears to be entirely fresh. A photograph of this rock is shown in figure 3.

TABLE 1.—Analyses of graywacke from the Franciscan group, with average of 30 graywacke and 40 granodiorite analyses for comparison

	1	2	3	4	5	6	7
SiO ₂	56.84	67.26	68.50	68.84	71.72	68.1	65.01
TiO ₂	n.d.	1.76	.60	.25	.35	.7	.57
Al ₂ O ₃	11.37	12.37	12.82	14.54	13.23	15.4	15.94
Fe ₂ O ₃	1.46	.59	1.29	.62	.30	1.0	1.74
FeO.....	4.95	4.03	3.37	2.47	3.58	3.4	2.65
MnO.....	.22	.08	.02	nil	nil	.2	.07
MgO.....	3.10	2.34	2.21	1.94	1.81	1.8	1.91
CaO.....	7.62	3.33	1.82	2.23	1.80	2.3	4.42
Na ₂ O.....	3.26	2.96	6.03	3.88	2.72	2.6	3.70
K ₂ O.....	.86	1.17	1.26	2.68	1.29	2.2	2.75
H ₂ O.....	1.45	.31	.28	.35	.15	2.1	1.04
H ₂ O ⁺	3.24	2.50	2.11	1.60	2.53		
P ₂ O ₅.....	.10	.15	.16	.35	.09	.2	.20
CO ₂	5.10	.56	n.d.	.14	.32		
BaO.....	n.d.	n.d.	n.d.	.04	n.d.		
ZrO ₂	n.d.	n.d.	n.d.	.05	.04		
SO ₃	n.d.	n.d.	n.d.	.15	n.d.		
Total.....	99.57	99.41	100.47	100.13	99.93	100.0	100.00

NOTE.—Description of sample and locality as follows:

1. "Neocomian Sandstone" from headwaters of Bagley Creek, Mount Diablo, Calif. W. H. Melville, analyst. From Melville, 1891, p. 412.
2. New analysis. Graywacke (NA-450) from a point 3,450 ft N. 66½° E. of the apex of Mine Hill, New Almaden district, Santa Clara County, Calif. Mrs. A. C. Vlisidis, U.S. Geological Survey, analyst.
3. Sandstone of the Franciscan group from Sulphur Bank, Calif. W. H. Melville, analyst. From Becker, 1888, p. 82.
4. Fresh sandstone of the Franciscan group from quarry of the Oakland Paving Co., Piedmont, Calif. James W. Howson, analyst. From Davis, 1918, p. 22.
5. Fresh sandstone of the Franciscan group from junction of Buckeye Gulch and Hospital Canyon, Carhona quadrangle, Stanislaus County, Calif. Analyzed by Herdsman Laboratory, Glasgow; analyst not known. From Taliaferro, 1943b, p. 136.
6. Average of 30 graywackes. From Tyrrell, 1933, p. 26. Fe₂O₃ given as 3.4 percent assumed to be in error, as that figure makes the total 102.4 percent.
7. Average of 40 granodiorites calculated to 100 percent by R. A. Daly. From Daly and others, 1942, p. 2.

Except for the analysis given in column 1, which was made from a graywacke containing an abnormal amount of calcite that probably occurred as veins, the analyses exhibit the range in composition no greater than might be expected in these unsorted sediments. As compared with the "average graywacke," the Franciscan rocks contain less aluminum and more magnesium and sodium, which suggests that they contain more fragments of soda-rich mafic volcanic rocks than does the "average graywacke."

The similarity of the graywacke to granodiorite in chemical composition has been pointed out by Taliaferro (1943b, p. 137, 138), and may be checked by comparing columns 2-4 with column 6. The correspondence is fairly good except for three notable departures: the ratio of FeO to Fe₂O₃ is considerably higher in the graywacke than in the granodiorite, the CaO content is much lower, and the ratio of Na₂O to K₂O is higher.

SILTSTONE AND SHALE

Siltstone and shale make up less than 10 percent of the Franciscan group in the New Almaden district. Two varieties are common. One, a tan to light-gray phyllitic siltstone, is confined to the southwestern part of the area, where it is interbedded with the feldspathic graywacke in the lowest part of the Franciscan group that is exposed in the district. The other, consisting of dark-gray to black siltstone and shale, oc-

curs throughout the section, but it is most abundant in a belt trending northwestward through the central part of the district, where it is associated with greenstones that belong to a younger part of the group. A less common third variety, containing considerable iron oxide and commonly having a red or green color, is everywhere closely associated with the cherts and is described with them on page 28.

Megascopic features

The older light-colored siltstone crops out locally along the first ridge southeast of Los Gatos, in deeply worn trails or on ridge tops nearly devoid of soil or brush. These rocks are not abundant, and they generally occur in thin beds intercalated with highly feldspathic graywacke; but locally, as in the upper drainage area of Limekiln Canyon, they apparently attain a thickness of several hundred feet without being interbedded with coarser sedimentary rocks. The siltstone is generally more contorted than the surrounding massive arkose. Bedding can be distinguished with certainty only in the coarser layers, for the siltstone is invariably phyllitic, breaking into flakes along subparallel parting planes that only approximately coincide with its original bedding. The parting surfaces are shiny, and under the hand lens they show a myriad of very small unoriented light-colored mica flakes. In thin sections these rocks are seen to consist mainly of well-sorted angular grains of quartz and feldspar; but they also contain several percent of muscovite, which appears to be partly detrital and partly authigenic. Clay minerals are also present in apparently small but undetermined amounts.

The younger and darker fine-grained sedimentary rocks are believed to be largely siltstone because of their fissile to irregular fracture, but they include some shale and mudstone with conchoidal fracture. The color of the siltstone ranges from gray to black, but most of it where fresh has a somewhat greenish cast and where weathered is lighter colored. Exposures of unaltered siltstone and shale without interbedded coarser rocks are rarely found except in artificial cuts or in sharply incised ravines, but along borders of serpentine masses the siltstones have locally been so hardened that they form good outcrops. In many exposures the siltstone occurs only as thin seams interbedded with graywacke, but in some places, as in Rincon Canyon 3,000 feet upstream from its junction with Guadalupe Canyon, sections as much as 500 feet thick are exposed that consist largely of siltstone. In other places thin layers of siltstone are interbedded with greenstone tuff; good examples of these intercalations can be seen in many of the upper workings of the New Almaden mine, but they are

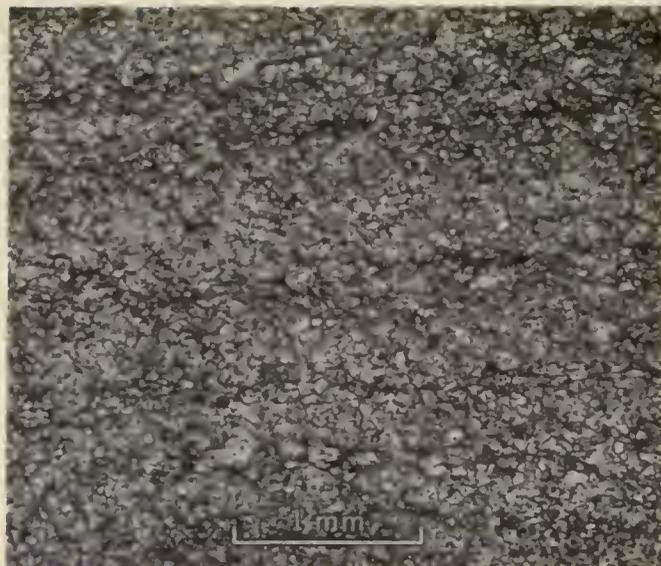


FIGURE 7.—Photomicrograph of siltstone of the Franciscan group. Note the abundance of angular fragments, largely plagioclase and quartz, and the relatively small amount of clay or fine-grained matrix material. Bedding runs horizontally across photomicrograph.

rarely exposed at the surface. Very locally in the siltstone, small elliptical concretions of limestone 6 to 8 inches in diameter are developed. A few of these concretions found in a thin-bedded dark rock exposed at the base of the Calero Dam proved to be of unusual interest because they contained fragments of marine megafossils.

Microscopic features

The small amount of microscopic work done on these fine-grained rocks shows that they have approximately the same mineral content as the graywacke, except that they contain a little more mica, clay, and carbonaceous matter (fig. 7). Wood fragments large enough to distinguish with a hand lens are fairly common in the Franciscan siltstones elsewhere in the Coast Ranges, but not in those of the New Almaden district.

Chemical features

An analysis of black siltstone of the Franciscan group from Fern Peak (formerly called Fern Hill) in the New Almaden district is given in table 2, column 1. As compared with the analysis of graywacke shown in the next column, the siltstone contains less silica and a little more aluminum, iron, and magnesium. It also contains a little less calcium, even when the calcium necessary to form calcite from the carbon dioxide is excluded. These differences indicate that the siltstone contains more fragments of mafic rock and a little more clay than the analyzed graywacke. A comparison of the siltstone of the Franciscan group

with average shales may be made by referring to table 2, column 3, which gives a composite of 78 analyses of shales. The analyzed rock from the New Almaden district contains more silica, magnesium, and sodium and less aluminum, ferric iron, calcium, potassium, and combined water than the average shale. It also has a potash-soda ratio of less than 1. These differences are those that would be expected from the low clay content of the siltstones of the Franciscan group and the soda-rich character of all the clastic sedimentary rocks of the group.

TABLE 2.—Analysis of siltstone of the Franciscan group, with analyses of graywacke and a composite of 78 shales for comparison.

	1	2	3
SiO ₂	62.54	67.26	58.38
Al ₂ O ₃	14.81	12.37	15.47
Fe ₂ O ₃	2.02	.59	4.03
FeO.....	5.47	4.03	2.46
MnO.....	.05	.08	Trace
MgO.....	3.38	2.34	2.45
CaO.....	1.40	3.33	3.12
Na ₂ O.....	2.90	2.96	1.31
K ₂ O.....	2.13	1.17	3.25
H ₂ O ⁻82	.31	5.02
H ₂ O ⁺	2.91	2.50	
TiO ₂.....	.87	1.76	.65
P ₂ O ₅.....	.15	.15	.17
CO ₂.....	.08	.56	2.64
S.....	.05	.....	.26
Organic.....	.96	.....	.81
Total.....	100.54	99.41	100.02
Less O-S.....	.03	.....	.....
Total.....	100.51	99.41	100.02

NOTE.—Description of sample and locality as follows:

1. Black siltstone (NA-315) from Fern Peak, New Almaden district, Santa Clara County, Calif. Mrs. A. C. Vlisidis, U.S. Geological Survey, analyst.
2. Graywacke, see table 1, this report.
3. Composite of 78 shales from Clarke, 1924, p. 631. SO₃ recast as S; BaO omitted

ALTA

A distinctive variety of rock composed largely of sheared shale envelopes the serpentine masses. Many of the quicksilver deposits in the Coast Ranges are closely associated with this rock, which has become widely known to California quicksilver miners as alta. It received this Spanish name, meaning "hanging wall," from the Mexican miners in the early days, because it commonly overlay the ore bodies that were found along the upper margins of altered serpentine sills. The alta, however, has been found to be just as common along the lower sides of the serpentine sills, where in places it forms the footwall for ore bodies. Similar rock also occurs along fault zones that traverse rocks of the Franciscan group.

The alta, like a fault breccia or mylonite, owes its character as much to shearing as to original lithology, but siltstone or shale is everywhere its most abundant



FIGURE 8.—Alta lying above intrusive serpentine contact on the 500 level in the Harry workings of the New Almaden mine. Serpentine converted to silica-carbonate rock (sc) and cut by a few dolomite veinlets. Alta contains larger fragments than in most places and consequently shows sheared texture somewhat better.

constituent. In most places the alta also contains some of the other rocks of the Franciscan group, together with small pods and lenses of serpentine or silica-carbonate rock. (See fig. 8.)

Two processes seem to have operated together to form the structures that are characteristic of the alta. One is shearing, and as most of the serpentine bodies in the mine area are sill-like the shears in the alta, which are parallel to the intrusive contact, are also closely parallel to the bedding. The other process is compression—perhaps due to the intrusion—applied at right angles to the bedding. These two processes operating together have caused stretching of the individual rock layers and a flowage of the shale. Where thin layers of graywacke or tuff are interbedded in the alta they commonly have been drawn out into isolated lenticular pods forming a boudinage structure. Where thicker beds of massive greenstone or graywacke are included they, too, are broken and drawn apart, but the larger disconnected pieces commonly retain more angular shapes. As the alta grades from highly sheared rock near the intrusive contact to the less sheared normal Franciscan rocks, it is possible in places to observe all transitions from alta that resembles fault gouge to bedded rocks of the Franciscan group. (See figs. 9, 10.)

In mine workings the appearance of the alta is striking because its texture is emphasized by the varied colors of the rocks in it. The shale, which predominates, is all jet black; pods of tuff are altered to light cream-colored clays; and pods of serpentine

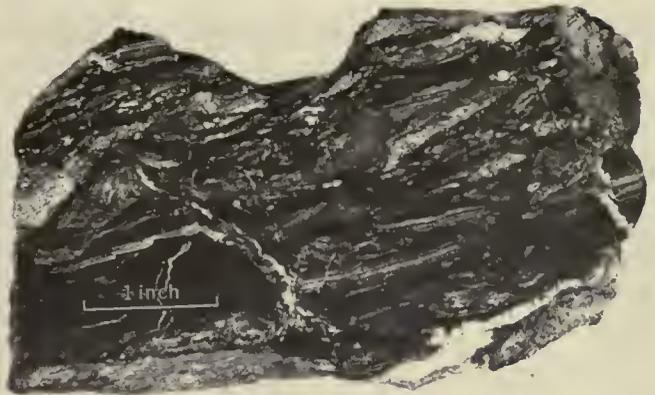


FIGURE 9.—Hand specimen of alta showing fragments of graywacke and siltstone. This specimen is not typical of most alta; it was selected because the shearing has not obliterated all the original bedding, as it has in more typical specimens.

or silica-carbonate rock are generally green. The graywacke, although not very light colored, is enough lighter than the black shales to make a contrast. In most surface exposures, however, the intense black color of the shale has been lightened by weathering to such a degree that the augenlike texture of the alta is not conspicuous.

Chemical features

Largely because of the prevalent jetblack color of the shale in the alta, the writers suspected that it might differ from the normal shale of the Franciscan



FIGURE 10.—Photomicrograph of alta. The coarser grained layers are indurated and have yielded by breaking, whereas the finer material has flowed. The same structural relations are commonly seen in exposures, where dimensions are measurable in feet rather than in fractions of a millimeter as in this thin section.

TABLE 3.—*Analyses of alta and siltstone from the Franciscan group, New Almaden district, Santa Clara County, Calif.*

[A. C. Vlisidis, U.S. Geological Survey, analyst]

	1	2
SiO ₂	54.67	62.54
Al ₂ O ₃	14.91	14.81
Fe ₂ O ₃.....	.15	2.02
FeO.....	5.37	5.47
MgO.....	3.77	3.38
CaO.....	3.26	1.40
Na ₂ O.....	1.93	2.90
K ₂ O.....	2.95	2.13
H ₂ O ⁻50	.82
H ₂ O ⁺	3.42	2.91
TiO ₂.....	.76	.87
P ₂ O ₅.....	.19	.15
MnO.....	.10	.05
CO ₂	6.22	.08
S.....	.23	.05
Organic.....	1.22	.96
Total.....	99.65	100.54
Less O-S.....	.12	.03
Total.....	99.53	100.51

NOTE.—Description of sample and locality as follows:

1. Alta (NA-412) from the Relief drift, New Almaden mine, Santa Clara County, Calif.
2. Black siltstone (NA-315) from Fern Peak, New Almaden district, Santa Clara County, Calif.

group in having a higher content of microcrystalline pyrite or dark chlorite; chemical analyses were therefore made to see whether any constituents had been introduced from the bordering serpentine. Table 3 gives an analysis of alta taken from close to the intrusive contact, where the serpentine had been converted to silica-carbonate rock; for comparison the table also gives an analysis of siltstone from the Franciscan group. These analyses indicate that perhaps the specimen of alta for analysis was poorly selected, for it apparently was carbonatized by the hydrothermal solutions that formed the silica-carbonate rock. Otherwise, the only significant features are the lower silica and ferric iron content of the alta, which may also be attributed to hydrothermal alteration. No difference that would adequately account for the darker color of the alta is apparent, and it seems likely that this darker color is due to the wider dispersal of the organic matter by intimate shearing.

CONGLOMERATE

True conglomerate constitutes only a very small part of the Franciscan group in the New Almaden district, although graywacke beds containing scattered rock pebbles or pieces of shale are not uncommon. The conglomerate that was noted formed relatively thin lenses which could nowhere be traced for more than a hundred feet. Most of these lenses lie in the central part of the district, and conglomerates are

apparently very rare or lacking in the lower part of the Franciscan group exposed in the southern part of the district.

Megascopic features

A typical conglomerate lens no more than 10 feet thick is exposed on Cemetery Hill about 1,400 feet southeast of the New Almaden furnace (coordinates 50 N., 3,500 W., pl. 3). This conglomerate consists of well-rounded pebbles and boulders as much as 9 inches in diameter, but averaging about 2 inches, set in a fairly abundant graywacke matrix that appears similar in all respects to the feldspathic graywacke of the Franciscan group. The rock is cut by fractures which pass through the pebbles without deviation, and some of the fractures are lined with quartz. Where the rock is weathered the pebbles, which are somewhat more resistant than the matrix, protrude to form a knobby surface. A count of a hundred of the pebbles gave the results shown in table 4. Pebbles of variously metamorphosed sedimentary and igneous rocks are about equally abundant. Only about 10 percent of them are pebbles that could possibly have been derived by erosion of slightly older strata in the Franciscan group, and it is very likely that all of them were derived from pre-Franciscan formations. Pebbles of such distinctive rocks as glaucophane schist or amphibolite, which are found elsewhere (Taliaferro, 1943b, p. 141-143) in

TABLE 4.—*Pebbles of a conglomerate of the Franciscan group exposed on Cemetery Hill, New Almaden district, Santa Clara County, Calif.*

	Number of pebbles
Sedimentary rocks:	
Black fine-grained feldspathic quartzite.....	9
Gray medium-grained silicified graywacke.....	5
Light-gray fine-grained arkose.....	13
Tan fine-grained clayey arkose.....	4
Gray silicified(?) siltstone.....	1
White quartz conglomerate, metamorphosed.....	1
Gray to black chert.....	21
Total.....	54
Igneous rocks:	
Aplite.....	1
Quartz porphyry.....	3
Lavas with quartz phenocrysts.....	4
Tuffs and breccias with quartz.....	5
Mafic breccias and tuffs.....	1
Light-colored altered lavas.....	9
Greenstones, mostly metamorphosed and silicified.....	19
Diabase.....	3
Total.....	45
Vein quartz.....	1
Total included in count.....	100

conglomerates of the Franciscan group, were sought but not found; serpentine pebbles also are lacking.

Another variety of conglomerate was found as float in several places in the district. It consists of smooth round pebbles of black chert, $\frac{1}{8}$ to $\frac{1}{2}$ inch in diameter, closely packed in a siliceous matrix. The rock as a whole is gray, very hard, and resistant, and fragments of it are found in stream canyons far below its outcrops. The rock is unusual in being largely composed of a single variety of rock pebbles, which apparently were derived from a distant land mass.

ORGANIC AND CHEMICAL SEDIMENTARY ROCKS LIMESTONE

Limestone constitutes only about 0.1 percent of the Franciscan group in the New Almaden district, but it is nevertheless important for several reasons. To geologists the limestone is helpful because it forms a discontinuous key-horizon that aids in deciphering the structure of the area, and because it has yielded the few fossils that give some local evidence regarding the age of the Franciscan group. The limestone also possesses economic interest because it has supplied several limekilns in the district, and in the future it may be used in making cement, for a similar limestone is now used at the Permanente Cement Co. plant a few miles to the northwest of the Almaden area.

The limestone exposed in the New Almaden district is doubtless equivalent in part to the Calera limestone of the Franciscan group (Lawson, 1914, p. 5, 22), which was observed within a few miles of the northwest corner of the district in mapping the Santa Cruz quadrangle (Branner and others, 1909). A similar limestone is prominent also southeast of the district, in the adjoining San Juan Bautista quadrangle (Allen, 1946, p. 25).

About 100 separate bodies of limestone are shown on the geologic map of the district (pl. 1). They occupy a belt that extends southeastward from the hills south of Los Gatos to Longwall Canyon, beyond which it swings northward and northwestward to reach the vicinity of the Calero Reservoir, where the limestone occurs in scattered blocks. (See fig. 56.) Farther east, in the adjacent Morgan Hill quadrangle, the same limestone crops out in more continuous exposures 2 miles south of the mouth of San Bruno Canyon.

Nearly all the limestone bodies are comparatively small, and the size of many of the smaller mapped outcrops had to be exaggerated on the map to make their position apparent. The most extensive outcrops, none of which are quite 2,000 feet long, occur

in two general areas—one close to the southeast corner of the district and the other near its western edge and south of Los Gatos. The thickest body, which crops out on Mine Hill about 800 feet southwest of the modern furnace, appears to be about 10 feet thick, but it may be isoclinally folded. Most of the limestone masses that have been quarried are only about 50 feet thick, although in some of the quarries they appear thicker because of repetition by faulting. Many of the outcrops, however, appear to represent beds less than 15 feet thick, and in a good many the limestone forms isolated, roughly equidimensional blocks less than 8 feet in diameter. Because of the variation in thickness of the limestone from place to place, it is believed to have been deposited as lenses, of which only a few were as much as 50 feet thick; these lenses, in turn, may subsequently have been broken and pulled apart by orogenic movements to form the smaller blocks.

Megascopic features

The limestone is one of the most easily recognized rocks in the area. It forms some characteristic bold outcrops that, because of their striking white color, can scarcely be overlooked, and it gives rise to bouldery float that serves to indicate its presence on grassy or wooded slopes. Probably, therefore, very few outcrops of limestone are omitted from the geologic map (pl. 1). The limestone shows some variation from place to place, and it includes two principal varieties, which seem to have been deposited at slightly different times.

The more widespread of the two varieties, which is the older, corresponds to the typical Calera limestone; it generally shows fairly well-developed bedding, and in most exposures it contains gray or white chert in elongate discontinuous thin lenses flattened parallel to the bedding (see fig. 11). The poorly developed parting layers, which are from a few inches to several feet apart, commonly contain a thin film of shale and may be either fairly regular or stylolitic on a small scale. In most outcrops these thin layers provide the only record of any interruption in the deposition of the limestone, but locally the limestone occurs as thin lenses intercalated with tuffaceous and calcareous shales. (See figs. 12, 13.) The color of the freshly broken surfaces is generally black or dark gray, but in some varieties is white or pink. The darker varieties have a strong fetid odor, due to petroliferous material and hydrogen sulfide. Most of the lighter colored varieties contain minute Foraminifera, which appear to the unaided eye as small transparent dark specks but can be seen under a hand



FIGURE 11.—Bold outcrop of the Calera-type limestone occurring in the Franciscan group. The more resistant lenses are dark chert, which accompanies the limestone in most places.



FIGURE 13.—Calera type of limestone of the Franciscan group interbedded with tuffaceous and calcareous shale, as exposed in roadcut 1 mile west of horseshoe bend in Guadalupe Canyon. Beds on the left side of the photograph yielded the Upper Cretaceous Foraminifera described by Cushman and Todd and by Küpper (p. 25).



FIGURE 12.—Thin beds of limestone (ls) of the Franciscan group interlayered with tuffaceous shale (T). Roadcut along Los Gatos-Santa Cruz highway, one-half mile south of Los Gatos.

lens to have organic shapes. Much of this limestone shows no recrystallization even in thin section, except that the replaced Foraminifera may consist of sutured calcite grains somewhat coarser than the rest of the rock; however, locally it is recrystallized. Coarsely crystalline calcite fills fractures, and in recemented breccias it amounts to nearly half of the rock. Pyrite, generally altered to limonite, is fairly common, and the more impure varieties contain altered tachylite and a small amount of quartz and plagioclase.

The second variety of limestone, which is stratigraphically a little higher in the section, crops out on the south slope of Los Capitancillos Ridge as isolated bodies, of which the most prominent is about 2,000 feet southwest of the apex of Mine Hill. This limestone differs from that found lower in the section in that it is everywhere fairly coarsely crystalline, contains numerous lenses and pellets of glauconite, and lacks chert and Foraminifera.

An unusual oolitic limestone, unlike any known to have been reported heretofore from the Franciscan group,⁴ forms large conspicuous outcrops in Longwall Canyon about 1 mile west of its junction with Llagas Canyon. These outcrops are massive, and where the limestone is purest they show no bedding. Solution has commonly roughened their upper surfaces, and where they are jointed, the cracks have been enlarged by solution. This oolitic limestone is dull battleship gray, and the purest consists almost entirely of oolites about 2 mm in diameter, embedded in a matrix of smaller oolites averaging about 0.1 mm in diameter (figs. 14, 15). The substances forming the nuclei of the larger concentrically layered oolites are shell fragments, bryozoan(?) fragments, carbonatized vesicular mafic glass, and aggregates of smaller oolites. No Foraminifera were found in the rock. The more common impure facies, which grade into tuffs and shales, contain shale fragments, considerable glauconite, and sparse grains of quartz and feldspar; they also contain some interesting but generally fragmentary fossils of gastropods and echinoids. The oolitic limestone could not be traced continuously to typical Calera-type limestone beds and cannot be definitely correlated with either of the two limestone units, but because it crops out along their projected strike, the writers believe that the oolitic limestone is merely an unusual variety of the Calera-type limestone, deposited at the same time and under nearly the same conditions.

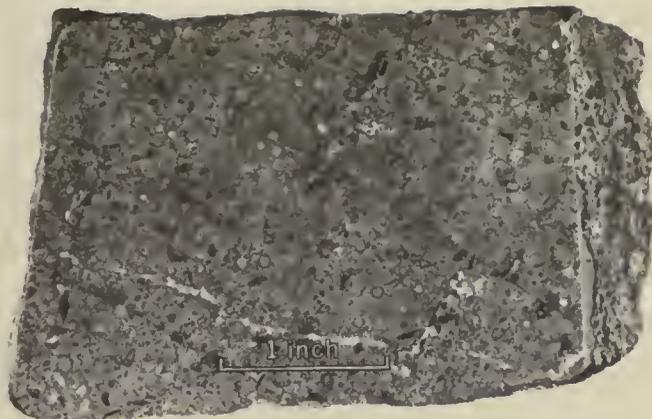


FIGURE 14.—Oolitic limestone of the Franciscan group from Longwall Canyon in the southeastern part of the New Almaden district. An analysis of this limestone is given on page 24.

Insoluble residues

A study of the insoluble residues of the limestone from several parts of the district has been made by Pantín⁵ to determine whether the isolated outcrops in the New Almaden district could be correlated by this means with the thick section of Calera limestone exposed in the quarry of the Permanente Cement Co. several miles to the north. He found the insoluble residues to consist of allogenic gray silt, very fine grained sand, clay, and chert, and authigenic glauconite, pseudocubic crystals of quartz, barite, chert, lignite, limonite pseudomorphs after pyrite, and limonite replacements of microfossils. In different parts of the section these insoluble minerals were present in different proportions, and their aggregate quantity ranged from 2 to 15 percent. On the basis of their distribution Pantín was able to correlate the sampled outcrops of

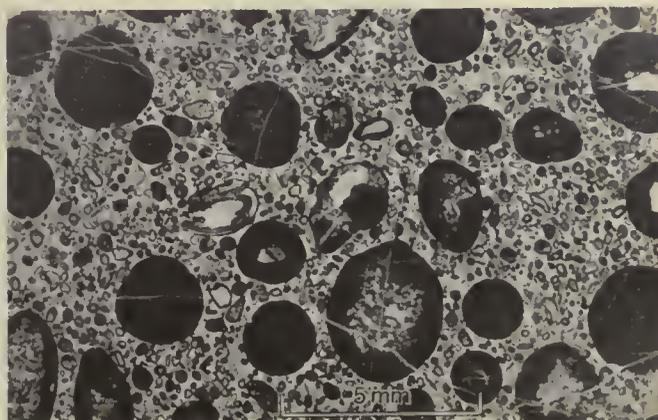


FIGURE 15.—Photomicrograph of oolitic limestone of the Franciscan group. Note the groups of small oolites that form the cores for some of the larger oolites.

⁴ This oolitic limestone may possibly be the same rock described in California State Mining Bur., 12th Rept. of the State Mineralogist, p. 394, 1894.

⁵ Pantín, José Henrique, 1946, Insoluble residues of the Calera limestone in Santa Clara County, California: Stanford Univ., unpublished master's of science thesis, November.

the New Almaden district with various parts of the better developed section at the Permanente quarry in the Santa Cruz quadrangle. He concluded (p. 74) that ". . . the zones in the limestone can be correlated over considerable distances by means of insoluble residues * * *" and "the correlation means that the limestone in different areas must have been laid down simultaneously, under similar environmental conditions, if not as a part of a continuous bed."

Chemical features

The limestone of the Calera type, exclusive of the interlayered lenses of chert, consists largely of calcium carbonate with only a very small quantity of magnesium, iron, aluminum, and phosphate. No analyses of this type of limestone from the New Almaden district are available, but three analyses of the similar limestone quarried near Permanente Creek, a few miles northwest of the district, are shown in table 5. The bulk analyses shown in table 6 are of the same limestone; they were kindly provided by the Perma-

TABLE 5.—Analyses of Calera-type limestone from near Permanente Creek, Santa Cruz quadrangle, California

	1	2	3
SiO ₂	2.08	1.56	1.52
Al ₂ O ₃.....	.56	.47	.47
Fe ₂ O ₃.....		.22	
Mn ₂ O ₃	n.d.	.05	n.d.
CaO.....	54.44	54.43	54.84
MgO.....	.20	.21	.14
CO ₂	42.92	42.99	43.33
SO ₂	Trace	n.d.	Trace
P ₂ O ₅.....		.06	
H ₂ O.....	.05	.15	n.d.
Total.....	100.25	99.99	100.45
CaCO ₃	97.36	97.42	98.17

NOTE.—Description of sample and locality as follows:

1. Limestone from Permanente Canyon. W. L. Lawson, analyst. From Lawson, 1914, p. 5.
2. "Black Mountain" limestone from Permanente. S. A. Tibbets, analyst. From Huguenin and Costello, 1921, p. 185. Recast to show oxides rather than carbonates.
3. Same as 1.

TABLE 6.—Bulk analyses of Calera-type limestone from quarries of the Permanente Cement Co. near Permanente Creek, Santa Cruz quadrangle, California

	1	2	3	4	5	6	7	8	9	10
SiO ₂	29.23	18.4	17.5	16.7	15.9	15.2	13.4	11.3	7.24	4.18
Al ₂ O ₃	1.26	1.5	1.4	1.5	1.5	1.5	1.4	1.3	.60	.66
Fe ₂ O ₃.....	.54	.7	.7	.7	.7	.7	.6	.6	.42	.32
CaO.....	38.04	43.3	43.8	44.4	44.9	45.4	46.4	47.8	50.96	52.74
MgO.....	.24	.3	.4	.3	.4	.4	.4	.3	.04	.05
Loss on ignition.....	30.66	34.3	34.7	35.1	35.7	36.1	37.1	38.3	40.48	41.90
Total.....	99.97	98.5	98.5	98.7	99.1	99.3	99.3	99.6	99.74	99.85
CaCO ₃	68.4	77.3	78.2	79.3	80.2	81.0	82.9	85.3	91.39	94.67

1, 9, and 10) From Logan, 1947, p. 315.

2-8) Obtained from Permanente Cement Co. by the writers.

nente Cement Co. These latter analyses include the siliceous chert lenses, but extrapolation to a silica-free rock shows perhaps even better than any single analysis the low magnesium content of the calcite, for such an extrapolation yields a theoretical rock containing 55.5 percent CaO and but 0.1 percent MgO.

An analysis by A. C. Vlisidis, U.S. Geological Survey, of the unusual oolitic limestone of the Franciscan group from the north bank of Longwall Canyon in the southeastern part of the New Almaden district follows.

SiO ₂	0.91
Al ₂ O ₃.....	.61
Fe ₂ O ₃.....	.30
MgO.....	.77
CaO.....	55.11
TiO ₂.....	.10
P ₂ O ₅.....	.31
MnO.....	.01
CO ₂	42.24
Total.....	100.36
CaCO ₃	96.0

This analysis shows the similarity in chemical composition between the Calera-type limestone and the oolitic limestone. Minor differences are due to the fact that the oolitic rock contains fragments of dark volcanic rock, whereas the impurities in the other limestone are chiefly quartz and clay. As the oolitic limestone contains virtually no chert lenses, it offers good commercial possibilities, even though the exposed bodies are somewhat smaller than some of the bodies of Calera-type limestone in the district.

Fossils

A microfauna and a few megafossils were obtained from the limestone of the Franciscan group in the New Almaden district. The microfossils, which were all Foraminifera, occur in abundance in most of the Calera-type limestone, but generally they cannot be freed from this rock for study. To Señor José Pantín,

a former graduate student at Stanford University who worked on the Calera-type limestone at the writers' suggestion, goes the credit for noticing the locality shown in figure 13 in which some Foraminifera had been freed from the limestone by weathering; subsequent investigation resulted in finding other Foraminifera in tuffaceous limy shales interbedded with the limestone. This locality yielded the Foraminifera which have been described by Cushman and Todd (1948, p. 90-98) and Küpper (1955, p. 112-118). It lies in a road cut in the SW $\frac{1}{4}$ of sec. 24, T. 8 S., R. 1 W., and it can easily be reached by traveling south 0.23 mile along a poor dirt road that branches from Shannon Road at a point 0.7 mile west of Guadalupe Creek. Cushman and Todd believed the fauna to be diagnostic of a Lower Cretaceous age, and Glaessner (1949, p. 1615-1617) upon comparing their illustration with forms found in the Mediterranean region suggested that the age be restricted to the upper part of the Lower Cretaceous (Albian-Aptian). Küpper, who obtained better material than that available to Cushman and Todd, reported, "The evidence thus favors correlating * * * with strata classified as Cenomanian in Europe and Africa."

Rather poorly preserved megafossils were found in the oolitic limestone along the middle part of Longwall Canyon in the southeastern part of the district. Although small fragments of fossils, and also wood fragments, are fairly common in this rock, few of the fossils are complete, and as the rock is brecciated and recrystallized, only weathered surfaces

yielded useful fossils. A diligent search resulted in the finding of only two specimens of the gastropod *Nerinea*, and several spines and a fairly complete test of an echinoid, *Cidaris* (fig. 16). According to R. W. Inlay (written communication, Oct. 29, 1948), the *Nerinea* must be either Jurassic or Cretaceous, but the *Cidaris* has not been identified closely enough to indicate its age. In addition to the above fossils from the limestone, fragments of *Inoceramus* were found in limy concretions in shale of the Franciscan group near the north end of the Calero Dam, but they were too small to be determined specifically.

CHELT

Chert constitutes less than 0.5 percent of the rocks of the Franciscan group in the district, but because of its resistance to weathering, it seems much more abundant than it really is. Its areal distribution in the district, and in the geologic column, is not uniform, for it is much more abundant along the belt of greenstone trending westward through the central part of the district than it is elsewhere. This belt includes all the major quicksilver mines, but, although quicksilver mines have been developed in the chert of the Franciscan group elsewhere in California (Bailey, 1946, p. 219-221), only minute amounts of cinnabar have been found in the chert in the New Almaden district. Manganese ores also have been mined from cherts of the Franciscan group elsewhere in the State, but in this district only a few scattered occurrences of manganeseiferous chert have been prospected.

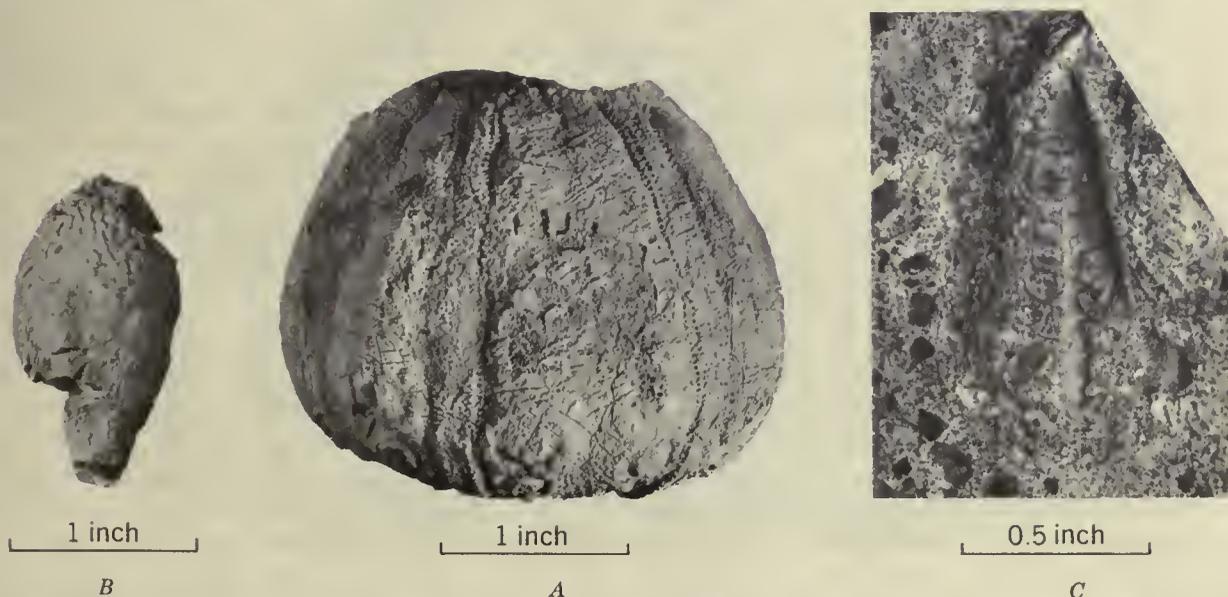


FIGURE 16.—Fossils from the limestone of the Franciscan group in the New Almaden district. A, *Cidaris* sp., side view. Natural size. B, *Cidaris* sp., spine. Natural size. C, *Nerinea* sp., ground to show internal structure. $\times 2$.

Megascopic features

The cherts of the Franciscan group show considerable diversity of character, probably because they do not all have the same origin. Davis (1918, p. 235-432) has well described the field occurrences and lithology of the various kinds of chert in other parts of the Coast Ranges, and because his descriptions could apply equally well to the cherts of the New Almaden district, only the more significant features will be repeated in this report. The typical chert of the Franciscan group is well bedded, generally rhythmically bedded, and red or green. A more unusual kind, locally associated with the well-bedded chert, exhibits botryoidal surfaces and distinctive internal structures which are described below. Less abundant but more typical of the older part of the Franciscan group is a massive nearly white chert, which also occurs sporadically in the younger part of the sequence. Other light-gray to white chert occurs as thin lenses or nodules in the limestone of the Franciscan group, and is not separated from the limestone on the maps accompanying this report. Still other chertlike rocks clearly formed by silicification of mafic tuffs are not considered to be true cherts and are included with the greenstone on the geologic maps.

The most striking feature of the good outcrops of bedded chert is their ribbed appearance, due to rhythmic bedding of layers of chert and shale of the same color, either red or green. The layers of chert are generally between 1 and 2 inches in thickness, whereas the shale partings are in most places not more than a quarter of an inch thick and are commonly much thinner. The individual chert layers are blunt-ended lenticles that extend at most only a few tens of feet; some of these layers vary in thickness, the bulges of one layer commonly being compensated by thinning in an adjacent layer. Sharp chevron folds a few feet across and minor faults at low angles to the bedding planes are common. At sharp bends in the folded cherts as at the axes of chevron folds, the chert is likely to be appreciably thicker but unfractured, suggesting that the deformation may have taken place while the chert was still plastic (see fig. 17).

Fractions, not related to the folds and found in almost all the well-bedded chert, form two systems of joints, both of which are nearly perpendicular to the bedding and commonly intersect on the bedding surfaces at angles of about 120°. In many places these fractures are small faults that make little steps on the bedding surface; in other places no displacement is noticeable. Some cracks are open near the upper bedding surface like mud cracks; elsewhere they



FIGURE 17.—Sharp folds in bedded chert of the Franciscan group. The absence of fractures through the axial parts of the folds is typical, and has been cited as evidence of folding during submarine slumping before lithification.

are tight. Locally, the cracks are filled with silica, which resists weathering and forms ribs; or they are filled with calcite, which weathers away and forms grooves. Surfaces of the chert broken across the bedding are generally smooth and conchoidal; bedding surfaces are slightly pitted or pimply. Examination under the hand lens shows the minor surface irregularities to be due, in part at least, to the unequal weathering of small grains of clear silica that has replaced, or filled in, the Radiolaria that abound in some of the cherts.

The chert exhibiting botryoidal surfaces is uncommon in the district; it is exposed only in a group of outcrops half a mile north of the summit of Fern Peak and is found as float on a small knob about a quarter of a mile south of Tulare Hill. Its color at both places is brownish red with greenish patches. The outcrops near Fern Peak are small, not exceeding 20 feet in diameter and generally much smaller, and are roughly equidimensional. These are made up of smaller bodies that are shaped somewhat like a cauliflower. Each cauliflower has a nearly flat lower surface that shows some flattened botryoidal bumps and a roughly hemispherical upper surface on which are superposed smaller hemispheres or more irregular flattened bumps and ridges not more than a couple of inches across. The bumps are separated by sharp but wide V-shaped grooves, and in most places they appear to have been packed on top of each other so that the surface closely resembles that of certain kinds of spatter cones. Equally distinctive are the internal structures of the botryoidal chert (fig. 18). These feathery areolate structures appear to have resulted from shrinkage of an originally very hydrous gel

forming openings, which later were largely filled with white quartz; small quartz crystals line cavities that were not completely filled. In some specimens the botryoidal surfaces are visible within the mass, whereas in others, which have an equally well-developed botryoidal shell, the internal structures do not indicate successive botryoidal layers. Conversely, some chert breccias not exhibiting the surface structures show internal structures that appear to have resulted from dehydration shrinking (fig. 18). These evidences of dehydration, however, are found only in small, generally isolated, masses of chert, and they are not typical of either the rhythmically bedded or massive chert lenses that account for 99 percent of the chert in the Franciscan group.

The light-colored chert that occurs mainly in the lower part of the Franciscan group is exposed in small outcrops generally less than 30 feet long and only a few feet wide. These outcrops are too small and too erratic to be shown on the map of the district, but chert, interbedded with arkose, was observed in several places along the ridge extending northwestward from El Sombroso. This chert is massive, without shale partings, and only in a few places does it contain separation planes that indicate its bedding. Light-colored quartz is the dominant mineral, but some lenses contain a little oxidized pyrite, which has mis-

led prospectors into believing that the siliceous lenses were gold-quartz veins. No Radiolaria were noted in any of these light-colored older cherts.

Microscopic features

In thin section the bedded chert is seen to be largely a mixture of quartz and chalcedony, which generally is clouded with red iron oxide dust. Some varieties are composed of a very fine grained aggregate of quartz, others contain chalcedony, and still others have a matrix of silica that appears almost isotropic but has an index of refraction slightly greater than that of balsam. This material, which apparently has puzzled others (Lawson, 1895b, p. 423) and deserves further study, is probably a cryptocrystalline aggregate of chalcedony and quartz, with overlapping crystals which tend to compensate each other between crossed nicols. In thin section, clear areas having the outlines of Radiolaria stand out in contrast to the clouded matrix, and where the Radiolaria are unusually well preserved, the spines and mesh structures, as well as the general outlines of the microfossils, can be distinguished (fig. 19). Most of these clear areas consist of quartz a little coarser grained than that composing the matrix, but some consist of chalcedony, whose fibers may radiate from one or more centers of growth. In a few thin sec-



FIGURE 18.—Vertical cut through part of a "cauliflower" of botryoidal chert showing internal structure. The specimen is oriented as it occurs in nature. Dark is red-brown chert; light is milky quartz.

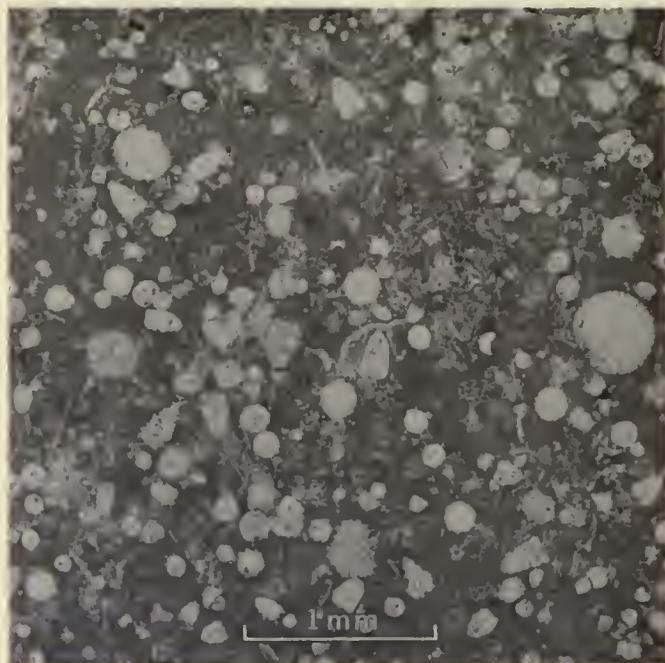


FIGURE 19.—Photomicrograph of chert of the Franciscan group containing numerous remains of *Radiolaria*.

tions cut normal to the bedding, thin seams of chlorite deformed after the fashion of stylolites are visible. Most thin sections of the chert contain at least a few veins of clear sutured quartz, and some of these are veined and partly replaced by later calcite.

Associated shales

The shaly rocks associated with the well-bedded chert are distinctive owing to their content of iron and the resulting color, which is red or less commonly green, in contrast to the tan, gray, or black of typical siltstone and shale of the Franciscan group. They are faintly laminated. Although some are actually shale, others are so coarse grained as to feel gritty and should be classed as siltstone. They contain chlorite and very fine goethite or hematite dust imbedded in an unidentified fine-grained matrix which makes up most of the rock.

Chemical features

No analyses of either the cherts or the shales that accompany them in the New Almaden district have been made. Complete and partial analyses of the typical chert and shale of the Franciscan group made by Davis (1918, p. 268-269), together with analyses of a graywacke and black shale of the Franciscan group and a composite of 78 shales for comparison, are shown in table 7. Comparison of the three couplets of chert and associated shale indicates that a mere addition of silica to the shale might yield the corresponding chert, but a very large quantity of silica would be required. The shales associated with the cherts differ chiefly from the average shale, column 10, in having a higher content of silica, and ferric iron, and a lower content of aluminum, calcium, and potassium. They compare more closely

TABLE 7.—Analyses of cherts and shales of the Franciscan group

	1	2	3	4	5	6	7	8	9	10
	Chert	Shale	Chert	Shale	Chert	Shale	Graywacke	Average of 2, 4, 6	Black siltstone	Composite of 78 shales
SiO ₂	93.54	69.98	95.08	63.47	96.37	68.22	64.61	62.2	62.54	58.51
Al ₂ O ₃	2.26	11.69	2.17	10.14	2.17	11.31	12.92	10.9	14.81	15.55
Fe ₂ O ₃.....	.48	6.23	2.82	14.60	2.82	8.75	1.66	9.7	2.02	4.03
FeO.....	.79	1.08	n.d.	n.d.	n.d.	n.d.	5.63	1.1	5.47	2.50
MnO.....	.23	.49	n.d.	.08	n.d.	.13	.25	.2	.05	-----
MgO.....	.66	1.29	n.d.	2.41	n.d.	2.39	3.53	1.9	3.38	2.44
CaO.....	.09	.38	n.d.	.74	n.d.	.99	1.27	.7	1.40	2.99
Na ₂ O.....	.37	.73	n.d.	n.d.	n.d.	n.d.	3.71	.7	2.90	1.28
K ₂ O.....	.51	3.72	n.d.	n.d.	n.d.	n.d.	.98	3.6	2.13	3.28
H ₂ O.....	.21	1.03	n.d.	1.44	n.d.	1.39	1.65	1.3	.82	1.31
H ₂ O ⁺72	2.92	n.d.	3.91	n.d.	4.42	3.68	3.7	2.91	3.69
P ₂ O ₅	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.11	-----	.15	-----
Total.....	99.86	99.61	100.07	96.79	101.36	97.60	100.00	100.0	98.58	95.58

NOTE.—Description of sample and locality as follows:

1. Brownish-red chert from Bagley Canyon, Mount Diablo. W. H. Melville, analyst. From Melville, 1891, p. 411.
2. Brownish-red shale associated with 1. W. H. Melville, analyst. From Melville, 1891, p. 411.
3. Siliceous red chert from Red Rock Island. E. F. Davis, analyst. From Davis, 1918, p. 268.
4. Partial analysis of red shale accompanying 3. E. F. Davis, analyst. From Davis, 1918, p. 269.
5. Red chert from Point Richmond. E. F. Davis, analyst. From Davis, 1918, p. 268.

6. Partial analysis of red shale accompanying 5. E. F. Davis, analyst. From Davis, 1918, p. 269.
7. Altered graywacke of the Franciscan group from headwaters of Bagley Creek, Mount Diablo. W. H. Melville, analyst. From Melville, 1891, p. 412. Recast by the writer to exclude 5.10 percent CO₂ calculated as CaCO₃, and remainder calculated to total 100 percent.
8. Average of 2, 4, and 6; recalculated to total 100 percent.
9. Black siltstone of the Franciscan group, New Almaden district; minor oxides omitted, see table 2.
10. Composite of 78 shales from Clarke, 1916, p. 546. Noncomparable constituents (CO₂, SO₂, P₂O₅, BaO, TiO₂) omitted.

with the analyzed graywacke, column 7, and black siltstone, column 9. However, they contain more total iron, which is also more oxidized, and they contain less aluminum and magnesium. Unlike many of the other rocks of the Franciscan group, the shales occurring with chert have a potash-soda ratio of more than 1.

Fossils

Although the Radiolaria of the chert in some places are remarkably well preserved, they are not sufficiently diagnostic to date the Franciscan group more closely than Jurassic or Cretaceous. Hinde (1894, p. 236), who studied the Radiolaria from Angel Island in San Francisco Bay and Buri-Buri Ridge in San Mateo County, reported as follows:

The majority of them evidently belong to simple spheroidal and ellipsoidal forms, included in Haeckel's suborders *Sphaeroidia* and *Prunoidia* * * * The most distinctive feature * * * [is] the number and variety of forms of the genus *Dictyomitra* present.

Some of the better preserved Radiolaria found in the New Almaden district are shown in figure 19.

Origin

The interesting problem of the origin of the chert in the Franciscan group has been dealt with by several of the geologists most familiar with the rocks of the California Coast Ranges. It has not been particularly studied during this investigation, but a summary of the various suggested origins is given here, along with some pertinent data gathered in the course of our work, for the benefit of those who may not wish to read the extensive literature on this subject.

Although many of the early workers described observations bearing on the origin of the chert, or suggested possible sources for the silica, the first to make a thorough field and laboratory study of the problem was Davis (1918, p. 353-408). He concluded, after dismissing many other possibilities, that the silica came from submarine siliceous springs of magmatic origin, that most of the silica was chemically precipitated and the Radiolaria were only incidental fossils, and that the rhythmic bedding and wedging out of beds were best explained by colloidal segregation of silica from the intermixed shaly material. Taliaferro (1933, p. 51, 54) believed that the source of the silica must lie in siliceous water that accompanied the outpourings of volcanic material. At first he suggested that the greater part of the silica was supplied by magmatic water, but some silicic acid may have been liberated by the interaction of hot basic lavas with sea water. In a later report Taliaferro (1943b, p. 147-148) stated, "a considerable amount [of the silica]

might have resulted from the interaction of hot lava and sea water." Trask and others (1943, p. 58) and Trask and Pierce (1950, p. 219-221) in their reports on the manganese deposits of California gave evidence suggesting that the chert was deposited in local basins, but reached no conclusion regarding the source of the silica. Bramlette (1946, p. 55), who studied intensively the cherts of the diatomaceous Monterey formation in California, suggested that possibly the solution of the thinner shelled siliceous organisms may have provided the silica for the chert during diagenetic changes or low-grade metamorphism of the Franciscan rocks. Another suggestion formerly entertained, that the cherts result entirely from the accumulation of radiolarian tests under abyssal conditions, does not seem to fit observations made in the Franciscan rocks, and it has been generally abandoned.

Most of our observations having a bearing on the origin of the chert consist of relationships between the chert and greenstone. These can be seen on the geologic map of the district, which shows that chert is most abundant in areas containing greenstone, and that more than three-fourths of the chert lenses are either enclosed in greenstone or border a mass of greenstone. Probably equally significant is the fact that nearly all the chert in contact with greenstone lies on the upper side of the greenstone masses. Some chert lenses, however, are apparently enveloped by clastic sedimentary rocks, and although some of the lenses are stratigraphically only a few hundred feet above the greenstone masses, others would seem to be truly far removed from any igneous rocks. The map also indicates that the ratio of chert to greenstone is about 1:250, which is pertinent if one considers the possibility of the silica being derived by reaction of sea water with hot lava. Whether or not this ratio is representative of the Franciscan group cannot now be determined because of the lack of detailed maps of much of the extensive area occupied by Franciscan rocks.

The association of the chert and greenstone strongly suggests that the cherts in the Franciscan group are in some way genetically related to the greenstone. The writers believe it likely that the silica and iron of the chert and accompanying shale was derived chiefly, if not entirely, by reaction of the hot mafic lava with sea water. At shallow depth sea water, even though heated nearly to its boiling point, is incapable of dissolving much more silica than can be retained on cooling to normal sea temperature; but, under pressures that exist at a depth of 10,000 feet or more, many times as much silica could be dissolved. Hot silica-laden waters so formed would rise and be cooled to

normal sea temperature giving up their excess silica, which would probably settle as silica gel. Thus, a reaction between sea water and erupting lava in deep water offers a possible mechanism for both introducing silica into sea water and getting it out again in the form of silica gel. The outpourings of mafic lava that accompanied deposition of the Franciscan sediments were chiefly submarine, and reaction between magma and sea water would be expected. Violent submarine eruptions giving rise to the glassy fragmental greenstones probably provided optimum conditions for reaction between the magma and sea water, and even the submarine flows with pillow structure would provide large areas of contact between magma and water. That a reaction between hot basalt and sea water yielding silicic acid can take place was demonstrated by Van Hise and Leith (1911, p. 515-516, 525), but the writers are not aware of controlled experiments which would indicate the quantity of silica that might be released by this reaction at elevated pressures. However, if the lavas before reaction contained about 50 percent silica and a little less than 1 percent of it was lost by reaction with the water, this would supply sufficient silica to form all the chert in the district.

Although the exact quantity of silica taken up by the sea water is unknown, it is reasonable to assume that the water when cooled to sea temperatures would be supersaturated and would yield silica gel. This would flocculate and settle by gravity to form a mass with a density greater than the adjacent sea water, and such a mass might be expected to flow as a density current if it formed on even a very low angle slope. This flowage into basins may explain why some chert masses apparently occur a considerable distance from volcanic rocks.

The process of collection of the silica, expulsion of the water and iron-rich compounds, and the development of rhythmic bedding has been commented on by many geologists who have studied rhythmically bedded cherts in various parts of the world. No theory has met with wide acceptance. Davis treats the problem of the rhythmic bedding in the cherts of the Franciscan group exhaustively and gives the results of several experiments in which he obtained rhythmic separation of silica gel from clay (Davis, 1918, p. 386-402). As a result of his experiments and careful field observations Davis concluded that the bedding in these cherts owed its origin to colloidal segregation, but it is not clear whether he believed the entire sequence of beds in a lense of chert was formed by segregation of a single mass of gel or from several superposed masses. Although the peculiar lenticular character of the beds in the rhythmically bedded sequences were duplicated in part by Davis' experiments, he was unable to form

more than a few such layers, whereas in nature sequences involving hundreds of beds are not unusual. Taliaferro believes each layer was deposited separately and solidified before the deposition of subsequent layers, and as evidence for this he cites the occurrence of chips of chert in the partings between layers (Taliaferro, 1943b, p. 149). The unusual botryoidal cherts of the New Almaden area are believed to be most easily explained as having been built up by rapid consolidation of silica gel oozing from a submarine orifice, and they also suggest rapid solidification of the silica gel.

VOLCANIC ROCKS (GREENSTONES)

The varied mafic volcanic rocks interbedded with the sedimentary rocks of the Franciscan group in the New Almaden district are believed to be fairly representative of the volcanic rocks found in the group throughout the California Coast Ranges, although they do not include quite all the varieties that have been reported. Because they are so chloritized and otherwise altered that precise field classification is impossible, they have been grouped under the general term of "greenstone," in accordance with the usual practice of geologists of the Coast Ranges. They crop out over an area of about 20 square miles, or one-third of the part of the New Almaden district that is underlain by rocks of the Franciscan group. They form bodies that are lenticular but well defined, and these bodies are mapped as cartographic and stratigraphic units. (See pl. 1.)

The greenstones are apparently all derived from extrusive rocks, and many, if not all, are of submarine origin. They differ widely in grain size and texture: the coarsest are of ophitic or diabasic texture, others are variolitic or pilotaxitic, and still others are pyroclastic breccias or tuffs. In spite of textural differences all contain nearly the same mineral assemblage, a fact suggesting similarity in the chemical composition of their parent magmas. The typical primary minerals are sodic plagioclase and subcalcic or titanian augite, but a few of the lavas contain a little olivine. In addition, material formed by alteration of mafic glass (or tachylite) is found in the diabasic rocks and is very abundant in the finer grained volcanic rocks; in part of the district altered mafic glass is the major constituent of accumulations of tuff and breccia more than 500 feet thick.

The alteration of the volcanic rocks to greenstones has been widespread, and varied in both kind and degree. In much of the greenstone deuteric alteration has formed minerals of the epidote group from pyroxenes, antigorite from the olivine, and a saussuritic aggregate from the plagioclase. In some of it the origi-

nal glass is replaced by albite, indicating a type of spilitic alteration. Very low grade regional metamorphism may be responsible for extensive chloritization, and may have also caused the widespread irregular veining of the rocks with quartz and calcite. The greenstones of small areas have been still further metamorphosed to form amphibolites, which are discussed with the other more highly metamorphosed rocks of the Franciscan group on pages 39-40.

In the descriptions given in the following paragraphs the greenstones are grouped according to whether they were originally lava flows or pyroclastic rocks.

LAVAS

The greenstones derived from mafic lava flows are more abundant and more widely distributed than those derived from pyroclastic rocks. The lavas differ widely in texture, and their groundmasses range from holocrystalline to glassy. The coarser varieties doubtless grade into the aphanitic varieties in many places, but owing to the poor exposures such transitions were observed only in individual pillows, some of which have diabasic centers and glassy rims. An attempt to subdivide the lavas into diabasic and aphanitic textural types was made during the field mapping in hope of establishing a stratigraphic sequence, but this attempt failed because of the intermixing of the varieties and the scarcity of exposures. It was evident, however, that the aphanitic rocks are the most abundant, and that the diabasic rocks occur most commonly within the larger masses of greenstone.

The character of the exposures of the massive greenstone varies with differences in the original character of the lava and in its mode of alteration. The best exposures are those formed by lavas exhibiting pillow structure, for these are among the most resistant rocks in the district; in several places they form rugged cliffs. Bold outcrops are also found where the lavas are silicified, but generally these are small and erratically distributed. The more widespread diabasic and amygdaloidal lavas are well exposed in some canyon bottoms, but elsewhere they underlie large areas that contain only widely spaced subdued outcrops, surrounded by a characteristic red-brown soil containing fragments of the altered greenstone.

Megascopic features

The unweathered greenstones are dark green to black, but in outcrop they are generally weathered and reddish brown. The coarser varieties are readily recognized, for they have diabasic textures in which the tabular crystals of feldspar, oriented at random, are large enough to be distinguished with the naked eye. The feldspar is usually the only mineral that can

be identified megascopically, but because of its generally altered character, it is greenish white and opaque rather than glassy; and although it is plagioclase, its twinning is not always visible. In the finer grained lavas the textures are not apparent and individual minerals cannot be determined even with a hand lens. These rocks, however, commonly show such features as pillow structure, flow banding, and vesicles, which aid in their recognition. Vesicles, where present, are generally filled with either calcite or deep-green nontronite. Irregular veins of both quartz and calcite are abundant in some of the greenstone.

Microscopic features

Although thin sections of the lavas reveal only minor variation in kind or proportion of the primary minerals, they show wide differences in texture and grain size and in the character of their secondary minerals. (See figs. 20-23.) The principal primary minerals are sodic plagioclase and either subcalcic augite or titan-augite; accessory minerals are magnetite, ilmenite, leucoxene, sphene, rutile, and apatite. Mafic glass was originally present in most varieties, but has everywhere been altered to chlorite. Olivine was once present in a few of the greenstones, but it has been completely replaced by either antigorite or iddingsite. Other common secondary minerals identified are albite, chlorites, epidote and clinozoisite, quartz, calcite, and nontronite. A more thorough study of some of the finer grained aggregates of secondary minerals would no doubt reveal other species.

The textures of most of the greenstones as seen in thin section are well preserved in spite of the advanced stage of alteration. Most of the coarse-grained lavas are holocrystalline; the coarsest contain plagioclase tablets 3 mm long and pyroxene prisms a little longer. In the aphanitic rock, however, glass was an important constituent, amounting in some to as much as 40 percent. Among the holocrystalline rocks an intergranular texture is more common than a truly diabasic texture; in the aphanitic rocks the texture is widely varied and no single kind of texture variety predominates. Porphyritic textures are uncommon, although a little of the greenstone has an aphanitic groundmass containing scattered phenocrysts of albite as much as 4 mm long.

The plagioclase, which before secondary alteration amounted to from 30 to 60 percent of the lavas, is generally euhedral in form, although in those rocks that have undergone severe deuteric alteration renewed growth of plagioclase has formed crystals that are somewhat sutured and interlocked. Much of the plagioclase is partly saussuritized or replaced by chlorite, epidote, or calcite, but nearly all the greenstone



FIGURE 20.—Greenstone without vesicles and only a little altered glass. Ophitic texture formed by radial aggregates of somewhat altered andesine (and) enclosed in larger crystals of subcalcic augite (A). Dark areas are leucoxene formed at the expense of ilmenite. Groundmass of altered glass consists of chlorite, nontronite, and small crystals of epidote.

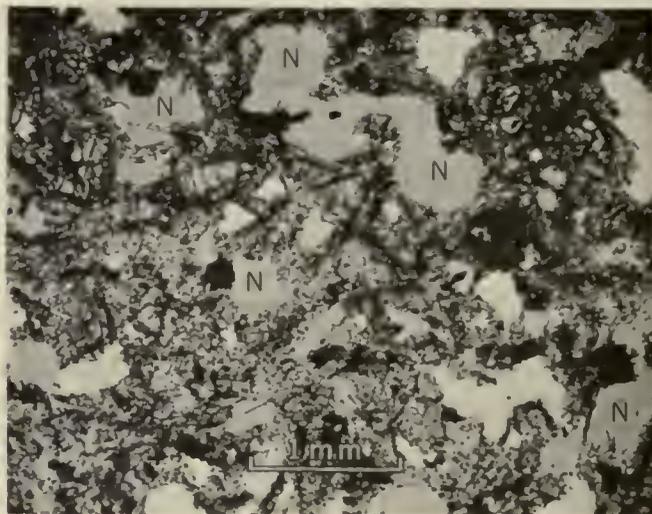


FIGURE 21.—Greenstone without vesicles but with considerable altered glass. Texture is largely intergranular, but some augite envelopes crystals of albite. Mafic glass altered to nontronite (N). Plagioclase contains minute crystals of epidote.

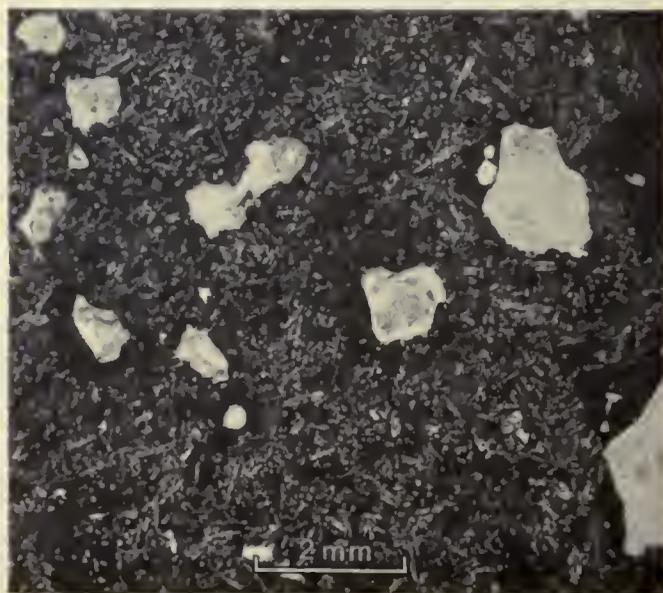


FIGURE 22.—Greenstone with vesicles but little altered glass. Both andesine and augite are in thin needles forming a pilotaxitic texture. Vesicles are filled with chlorite locally replaced by calcite.

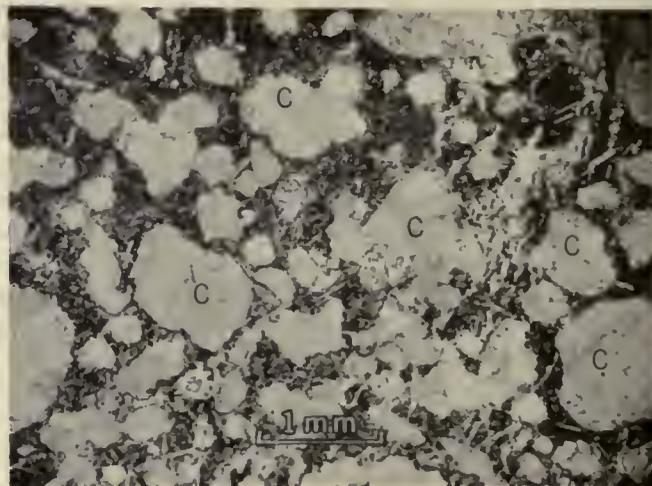


FIGURE 23.—Greenstone with abundant vesicles filled with calcite (C). Section shows microlitic texture of minute laths in glassy groundmass, but also contains a few phenocrysts of albite, replaced along borders and cleavages by calcite, and still fewer equant crystals of augite.

PHOTOMICROGRAPHS OF GREENSTONES OF THE FRANCISCAN GROUP SHOWING VARIATIONS IN TEXTURE, CONTENT OF ALTERED CLASS, AND VESICULARITY

contains unreplaced feldspar that gives sharp extinctions so that its composition can be determined. Albite twinning is prevalent; zoning was observed in some sections but is not common. Although the feldspars of these rocks are invariably too soda rich to be normal for such mafic rocks, the individual crystals in most specimens show no ragged borders, irregular patches, or other features suggesting that the sodic plagioclase has replaced a more calcic feldspar. In the coarser grained lavas and phenocrysts the plagioclase is invariably albite (An_{2-7}). In a little of the aphanitic lava plagioclase as calcic as An_{40} was noted, but in most the plagioclase is near albite.

Pyroxenes are important constituents of the greenstones of the Franciscan group, making up from 20 to 35 percent of their volume. They deserve more thorough study than has been made for this report, but enough work has been done to indicate that they belong to several varieties. The optic-axial angle ($2V$) of a few crystals of augite was determined by Dr. C. M. Swinney, of Stanford University, by means of universal stage. The angles noted in 2 sections ranged from 36° to 43° , indicating subcalcic augite (Benson, 1944, p. 111-118), and estimates of the optic-axial angle of other pyroxenes in thin sections we examined indicate that this is the most common variety. Another variety of pyroxene, found only as stubby euhedral crystals in the finer grained lavas, shows the purplish tints of titan-augite. Still a third variety having a plumose or radial habit did not yield sufficiently good interference figures to permit a reliable estimate of the optic-axial angle, which appears to be large, and this pyroxene remains undetermined.

Basaltic glass is believed to have been abundant originally in much of the lava, although it now has everywhere been completely converted to a mixture that includes chlorite, probably nontronite, and other fine-grained minerals not determined. The material believed to have once been glass has a mottled appearance, and encloses a myriad of skeleton crystals and microlites of magnetite and plagioclase.

The most abundant secondary minerals are chlorites, which commonly make up from 15 to 25 percent of the altered lavas. They replace the original basaltic glass and augite and form a minor part of the saussuritic aggregates replacing plagioclase. Clinocllore is the predominating variety, and although several other varieties have been distinguished, they have not been sufficiently studied to warrant assigning specific names to them. Epidote and clinzoisite are widespread in fine-grained aggregates replacing plagioclase, and in some rocks they occur as secondary euhedral crystals large enough to be readily identified.

Both quartz and calcite locally replace much of the groundmass of the lavas, or fill vesicles in them, but these minerals are more common in veinlets. Where the age relation between the two minerals is clear, the calcite is invariably the later.

PYROCLASTIC ROCKS

Pyroclastic rocks, including breccias, tuffs, and altered tachylitic tuffs, make up at least a fifth of the greenstone of the New Almaden district. They are commonly much altered and are recognized chiefly by their fragmental or bedded character coupled with their mafic composition. They are exposed principally in two bands. One band, which is narrow but persistent, extends eastward from a point about 1 mile north of the Calero Reservoir through the eastern part of the Santa Teresa Hills, and continues beyond the eastern border of the district. The other, which is broader but less continuous, extends from a point on the west edge of the district just south of Los Gatos and crosses the central part, passing through the Guadalupe and New Almaden mine properties, and continuing nearly to the southeast corner.

The pyroclastic rocks are divided into two groups for description. In one group the main original constituent was obviously tachylite, whereas in the other group it was not.

NONTACHYLITIC TUFFS AND BRECCIAS

The nontachylitic tuffs and breccias make up most of one thick body of greenstone that extends from the vicinity of the Almaden Reservoir, in Almaden Canyon, northwestward through the central part of Mine Hill and along the north slope of Los Capitancillos Ridge to the vicinity of the Senator mine. As these rocks are readily weathered, they are exposed on the surface only in sharply incised canyons and roadcuts. In good exposures, however, particularly those in the workings of the New Almaden mine, the tuffs are seen to be generally interbedded with black shale, but in some places they are interbedded with graywacke, chert, and lavas of the Franciscan group. In the New Almaden mine a good exposure of alternating thin beds of tuff and shale can be seen in the upper part of the raise that extends from the 700 level to the Far West stope, and a well-exposed thick section of tuff containing only a little shale is cut by the Day tunnel just south of the crosscut to the Santa Rita shaft (pl. 4).

Megascopic features

The appearance of the nontachylite breccias and tuffs is so varied as to defy simple description. They exhibit a wide range of colors and textures, and they have suffered varying degrees and kinds of alteration,

which has affected their other physical properties, such as hardness and manner of fracturing. Their colors, which seem to reflect those of the rocks with which they are associated, range from dark to light green or brownish green in the chloritized tuffs associated with massive greenstone to lighter buffs or reddish or purplish browns in the tuffs associated with sediments. Those tuffs that have been hydrothermally altered and contain abundant clays, such as many exposed in the workings of the New Almaden mine, are light buff, light gray, or locally nearly white in color. Where the textures are least obliterated the tuffs are marked by very fine banding, which is due in some places to different concentrations of light and dark material, and elsewhere to differing degrees of oxidation of their iron oxides or to differing sizes of their minute angular clastic grains. (See fig. 24.) In the coarser tuff breccias the textures are more obvious, with poorly to moderately well-sorted angular fragments, generally less than an inch in diameter, embedded in a matrix of fine-grained clastic material.

Microscopic features

As seen in thin section the original pyroclastic nature of most specimens is masked by alteration, but in some sections layering and vague clastic texture are discernible. The original minerals identified in a few of the fresher rocks are broken tablets of plagioclase, subhedral clinopyroxene, magnetite, and a little quartz; where the texture is coarse, fragments can be distinguished (fig. 25). Material that has replaced mafic glass is present in some, but no curved shards, such as are commonly found in tuffs, were recognized. The commonest alteration products include chlorite, quartz, calcite, celadonite, and clays. The earliest of these is the chlorite, which is derived mainly from the ferromagnesian minerals and glass but also to some extent replaces the feldspars. Quartz, which has been the next mineral to form in some of the altered tuffs, occurs as granular aggregates replacing the rock and as veinlets. Later calcite, as replacements and veins, is common. Near the ore bodies of Mine Hill hydrothermal solutions extensively altered the tuffs to clay minerals before the introduction of most of the quartz and calcite.

TACHYLITIC TUFFS AND BRECCIAS

Tachylitic rocks, both tuffs and breccias, composed almost entirely of altered basaltic glass, have not been reported from other areas underlain by rocks of the Franciscan group so far as we know, but in the New Almaden district they underlie extensive areas and make up a considerable part of the greenstone of the district. They occur in two principal areas: one is a

wide band that extends eastward from Los Gatos Creek to the Guadalupe mine, the other is a narrower band containing scattered bodies and extending along the north side of Longwall Canyon. The rocks are particularly well exposed both along Los Gatos Creek, south of Los Gatos, and near the middle fork of Longwall Canyon, in the southeastern part of the district. The fresher tachylitic rocks are readily recognized from their unusual textures, dark- to light-green color, and the serpentinelike appearance of their fragments. The fine-grained varieties, especially where weathered, closely resemble graywacke; but they can be distinguished from it by their general lack of quartz, their slippery feel, and their relict textures.

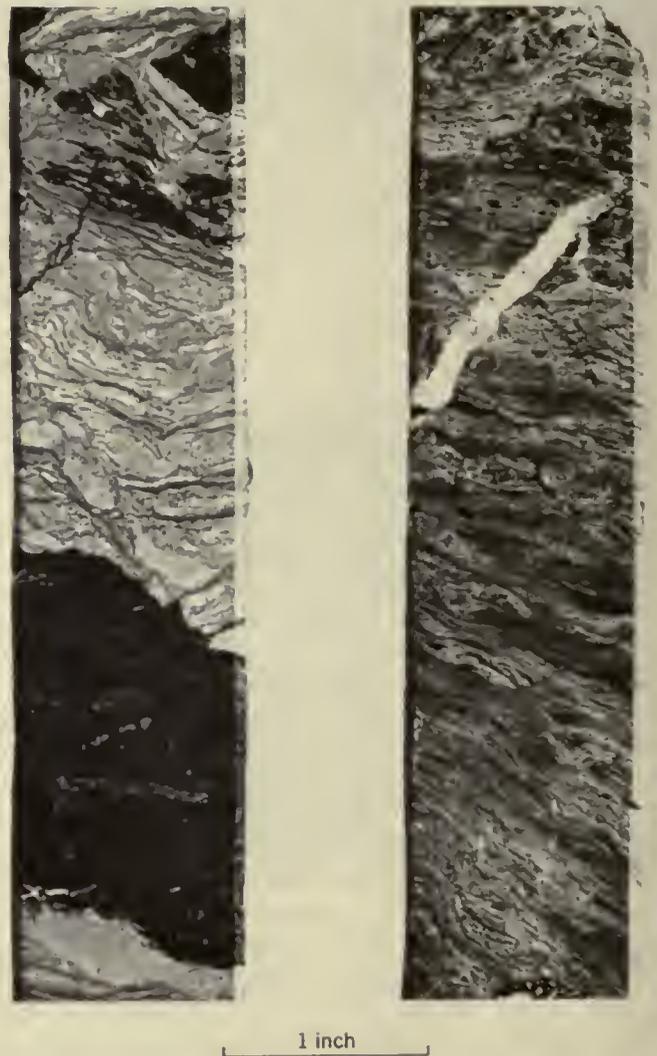


FIGURE 24.—Polished sections of drill cores showing two of the more common kinds of tuffaceous greenstone in the Franciscan group. Core on left shows cream-colored tuff bleached by hydrothermal solutions interlayered with black shale. Right core shows layers of red, purple, and green tuff containing a few larger fragments identifiable as altered mafic glass.

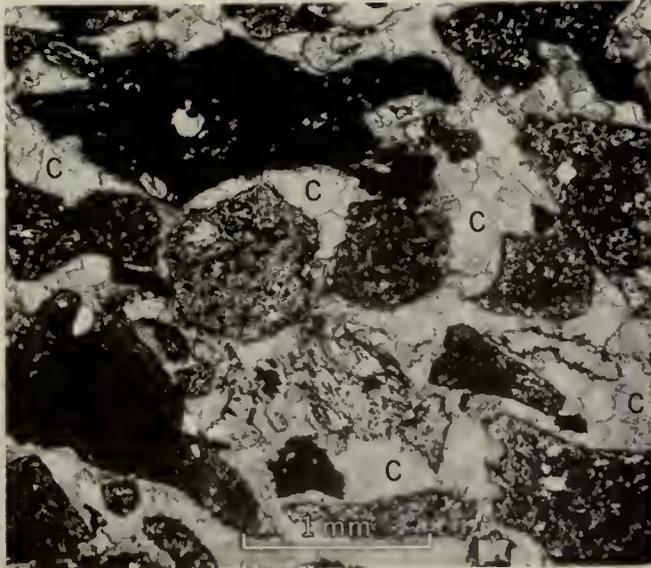


FIGURE 25.—Photomicrograph of calcareous tuff from the Franciscan group. The fragments are various mafic rocks, most of which contain some altered tachylite; the matrix is calcite (C).

Megascope features

The appearance of outcrops of the tachylitic rocks depend upon the grain size of the rock and the degree of weathering. The finer grained rocks are generally little weathered, moderately well exposed, massive, and dark green; the more fissile varieties tend to part much like a schist, giving rise to indistinctly bedded outcrops. In hand specimen these tuffaceous rocks appear massive, breaking with a hackly fracture and possessing a distinctive but fine-grained texture that is easily recognized though hard to describe. This texture is characterized by irregular roughly elliptical masses of greenish altered glass so closely packed in a matrix of chlorite that they appear to have deformed one another. Many of the elliptical masses contain smaller flattened black or deep-green amygdules, and almost all show concentric bands of various shades of green. In the typical tuffs the fragments are about 1 mm in diameter, but these rocks grade to breccias having fragments, dominantly of vesicular basalt, as much as 6 inches in diameter. (See fig. 26.) In outcrop the fragments of vesicular lavas are generally weathered reddish brown, although where fresh they are green to black. The breccias show only crude bedding and sorting, and their having contained a glassy matrix could hardly be recognized except in the freshest specimens.

Microscopic features

Thin sections of the tachylitic tuffaceous rocks are striking in appearance because of the relict textures

imparted by the original glass, as is shown in figure 27. The tachylitic glass has all been replaced by microcrystalline aggregates of doubly refracting minerals, some of which are extremely fine grained and have not been identified with certainty. Some of these alteration products are chlorite, and some appear to be microcrystalline feldspar; none appears to be palagonite. The few mineral grains found in the tuffs and apparently of primary origin are crystals of augite and very sodic albite. The deep-colored filling of the small vesicles that can be seen with a hand lens is probably nontronite, and other smaller vesicles are filled with albite (An_2). A matrix of very fine grained, nearly isotropic chlorite is generally present. The coarser breccias contain, in addition to shards, tachylitic lapilli and glassy and diabasic volcanic fragments that are similar in composition and microscopic texture to other greenstones of the Franciscan group. Some of the tachylitic rocks are extensively replaced by calcite, and others contain veins and replacement masses of albite associated with a little quartz.

CHEMICAL COMPOSITION OF THE GREENSTONE

Two new chemical analyses of greenstone of the Franciscan group, together with three older ones, are presented in table 8, which also includes some average analyses of diabase and spilite for comparison. With so few available analyses of these rocks, which are altered in such various ways, it is unsafe to draw any general conclusions regarding their composition; it does seem advisable, however, to point out a few of the problems awaiting further study.

Mafic rocks associated with the eugeosynclinal accumulations of graywacke, black siltstone, and chert, like the sedimentary assemblage of the Franciscan group, in other parts of the world are commonly rich in sodium, contain abundant albite, and are classed as spilites. Pillow lavas, such as are common in the Franciscan group, likewise, are in many places spilitic. Largely because of these facts the greenstones of the Franciscan group are regarded by many as spilites (Reed, 1933, p. 83). In the New Almaden district much of the greenstone contains albite, and the most calcic plagioclase identified in the greenstones was andesine. In other areas, however, the greenstones are reported to contain only labradorite (Weaver, 1949, p. 113–114), or original andesine-bytownite locally altered to albite-oligoclase (Taliaferro, 1943b, p. 145). Thus, from a consideration of the feldspars alone, one might conclude that the greenstones of the Franciscan group were normal diabbases locally en-



FIGURE 26.—Polished surface on breccia composed chiefly of fragments of altered tachyllite. Color zoning within individual fragments is typical of the altered mafic glass in the district; dark horseshoe-shaped bands due to weathering.

riched with sodium, and that all of them in the New Almaden area were so enriched. The analysis given in column 1 is of the least altered diabasic greenstone found in the district. In thin section the rock can be seen to contain completely fresh augite, plagioclase that is somewhat clouded by alteration products but still fresh enough to give good measurements of extinction angles, and a groundmass that was originally glass but is now completely chloritized. The plagioclase, which appears to be primary, is andesine (An_{35}). If olivine was ever present, it was in small amount and is now replaced by chlorite. A few thin veins of quartz and chlorite cut the rock, and a few small patches of calcite are also present. The analysis contains such a moderate amount of sodium and such a large amount of calcium that one would expect the plagioclase to be more calcic if the normal process of crystallization had been followed.

The analysis given in column 2 is of the altered tachylitic tuff shown in figure 27. It consists chiefly of chlorite derived from the original glass, but it also

contains a few crystals of plagioclase and augite. The plagioclase is albite (An_2), and although it is completely unaltered, some grains appear to have recrystallized. The effect of metamorphism that has taken place since the glass reacted with sea water cannot be determined, and the present composition could, of course, be very different from that of the chilled glass originally deposited. If there has been no postdepositional loss of sodium, the present low value for sodium and the low sodium-calcium ratio are indeed surprising.

These two analyses from the New Almaden district are inadequate to show anything other than the problem involved in trying to learn from chemical analyses the original chemical character of the now-altered volcanic rocks. These two rocks are not rich in sodium in spite of the soda-rich character of their plagioclase, and they are not chemically comparable to either normal diabase or spilite. The three other analyses of greenstones of the Franciscan group given in columns 3-5, table 8, show a higher sodium content, but in



FIGURE 27.—Photomicrograph of section of altered tachylitic tuff of the Franciscan group. The shards, which were originally mafic glass, are completely altered to a fine-grained aggregate of chlorite. A few small crystals of albite and augite are visible in the shards. Vesicles are filled with nontronite and secondary albite. The matrix is fine-grained chlorite similar to that which has replaced the original tachylite.

analyses 3 and 4 at least the sodium-calcium ratio is considerably less than in normal spilites. Many more analyses will be needed before one can safely state that the greenstones of the Franciscan group are soda-

rich spilites, or can draw conclusions regarding a process of spilitization that they may have undergone. In the New Almaden area we know that the plagioclase, which appears in sections to be primary, contains an abnormal amount of soda for such mafic rocks; whether or not this reflects a magma rich in sodium, or even sodium-rich rocks, remains an open question.

METAMORPHIC ROCKS

Metamorphic rocks having a truly gneissic or schistose texture, and consisting largely of minerals formed by metamorphic processes, constitute an exceedingly small, but very interesting, part of the Franciscan group. These metamorphic rocks are so strikingly different and so much more highly metamorphosed than the typical sedimentary and igneous rocks of the Franciscan group, which show only incipient metamorphism, that they must have been formed by some additional metamorphic processes. Two varieties, hornblende rocks and glaucophane rocks, occur in sufficiently large areas to be shown on the map of the district, plate 1. Other varieties described below are of such local occurrence that they are not represented on the map, but elsewhere in the California Coast Ranges they are widespread, though not abundant. The distribution and character of the metamorphic rocks in the New Almaden district is believed to be representative of those occurring in the Franciscan

TABLE 8.—Analyses of greenstones of the Franciscan group, with composite analyses of diabase and spilite for comparison

	Diabase	Altered tachylitic tuff	Fourchite	Hornblende Pseudodiabase	Pseudodiabase	Average diabase	Average spilite	Average spilite
	1	2	3	4	5	6	7	8
SiO ₂	48.19	44.90	46.98	49.08	51.28	50.48	51.22	46.01
Al ₂ O ₃	13.85	9.94	17.07	14.68	15.05	15.34	13.66	15.21
Fe ₂ O ₃	2.82	3.10	1.85	1.95	2.42	3.84	2.84	1.35
FeO.....	7.82	8.82	7.02	9.63	8.01	7.78	9.20	8.69
MgO.....	7.28	14.25	8.29	6.69	6.07	5.79	4.55	4.18
CaO.....	11.28	9.38	12.15	10.09	7.08	8.94	6.89	8.64
Na ₂ O.....	2.67	1.17	2.54	4.60	4.43	3.07	4.93	4.97
K ₂ O.....	.32	.27	.53	.20	.12	.97	.75	.34
H ₂ O ⁻15	.86	4.86	.28	2.97	1.89	1.88	2.48
H ₂ O ⁺	3.26	4.95						
TiO ₂	1.94	1.84	.....	1.18	.39	1.45	3.32	2.21
P ₂ O ₅.....	.20	.17	.09	1.72	1.33	.25	.29	.61
MnO.....	.17	.15	.....	.23	.13	.20	.25	.33
CO ₂.....	.24	.02	.....	.15	.25	.20	.94	4.98
Total.....	100.19	99.82	101.38	100.48	*99.53	100.00	100.72	100.00

* 0.1 NiO omitted.

NOTE.—Description of sample and locality as follows:

1. Diabasic greenstone (NA-224), from crest of ridge 3.45 miles S. 70° E. of apex of Mine Hill, New Almaden district, Santa Clara County, Calif. A. C. Vlisidis, analyst. Plagioclase is Abs.
2. Tachylitic tuffaceous greenstone (NA-325), from point of 1,100 ft alt, 3.44 miles S. 55½° E. of apex of Mine Hill, New Almaden district, Santa Clara County, Calif. A. C. Vlisidis, analyst. Phenocrysts are Ab₅₀ and vesicles locally filled with Abs.

3. Fourchite from Angel Island, Marin County, Calif. From Ransome, 1894, p. 231.
4. Hornblende pseudodiabase, from near Mount St. Helena, Calif. W. H. Melville, analyst. From Becker, 1888, p. 98.
5. Pseudodiabase, from near Knoxville, Calif. W. H. Melville, analyst. From Becker, 1888, p. 99.
6. Average of 90 diabases, calculated by Daly and others, 1942, p. 2.
7. Average spilite according to Sundius, 1930, p. 9.
8. Average spilite according to A. K. Wells, 1923, p. 69.

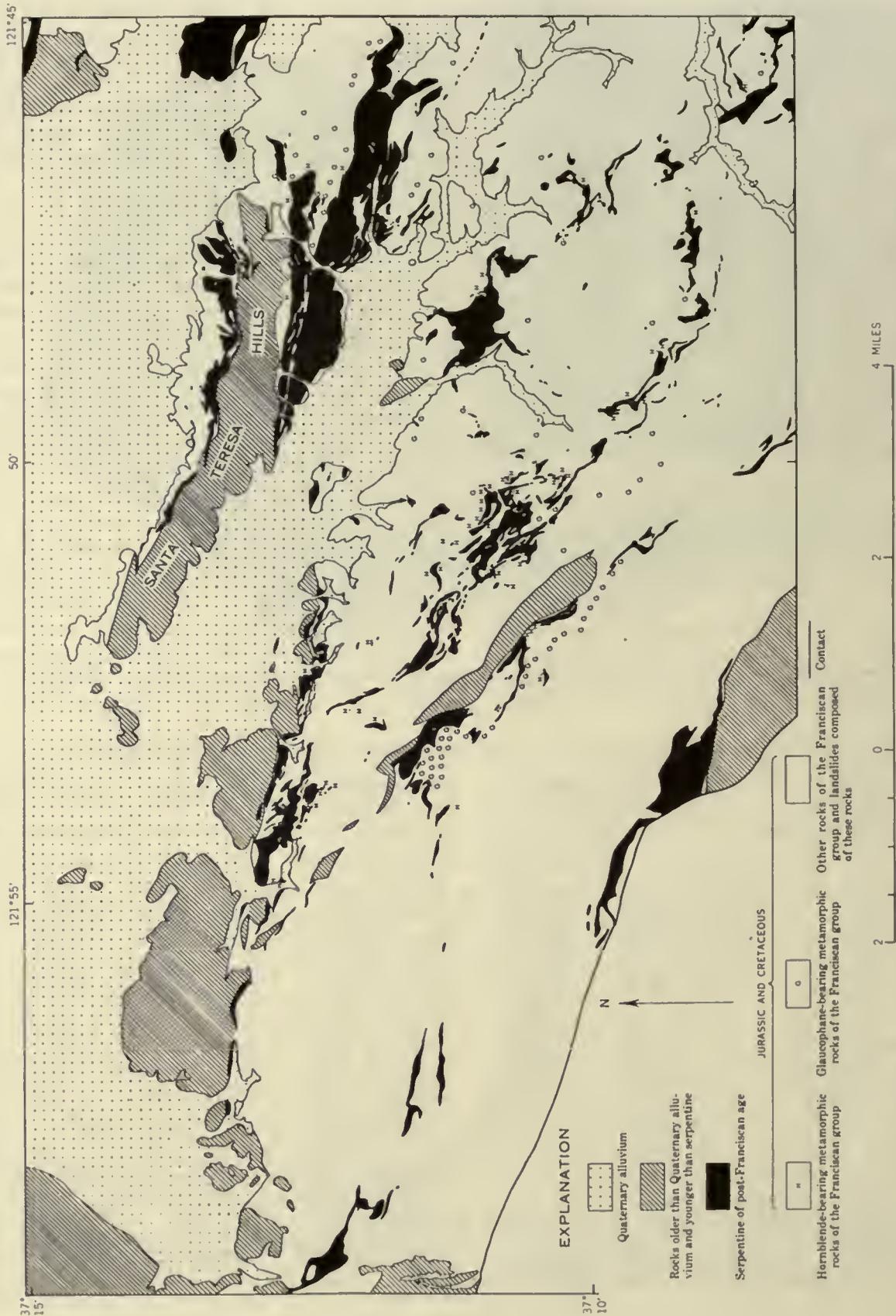


FIGURE 28.—Map showing distribution of metamorphic rocks of the Franciscan group and serpentinite in the New Almaden district.

group throughout much of its wide extent, although in a few areas, such as one a few miles west of Healdsburg, in Sonoma County, the metamorphic rocks are more abundant and better developed.

HORNBLENDE ROCKS

Hornblende schists, and similar but less schistose rocks called amphibolites, are among the most common metamorphic rocks in the district, but because they are not so striking as the beautiful blue glaucophane rocks they are more easily overlooked. Most of them crop out on Mine Hill or in the vicinity of the Guadalupe mine, but small bodies also occur along the margins of serpentine masses extending southeast of Mine Hill and in the central part of the Santa Teresa Hills. (See pl. 1 and fig. 28.) Their field relations are commonly obscure because these rocks weather readily to form a characteristic red soil, through which the more resistant kinds protrude as low knobs. Where roadcuts or adits offer good exposures, one may observe that the distribution of the hornblende rocks is spotty, and in areas of knobby outcrops not all of the intervening rock is metamorphic. Consequently, most of the larger areas mapped as hornblende rock actually contain a "matrix material" of greenstone tuff as abundant as the hornblende rocks, although in some areas, such as the one about half a mile west of the Guadalupe mine, the amount of amphibolite is considerably greater than the amount of admixed greenstone.

Megascopic features

Although typically the hornblende rock is entirely dark green or almost black, some that contains albite is flecked with light areas elongated parallel to the schistosity. The diameters of the constituent mineral grains are variable, but in most specimens the average grain size is a little more than 1 mm. Surfaces broken parallel to the poorly developed schistosity are rough and irregular, but owing to the amphibole cleavage planes, they exhibit a sparkle by which the hornblende rocks may be distinguished from the coarser varieties of greenstone. Less typical, but more easily recognized, are foliated hornblende gneisses with alternating bands rich in hornblende, albite, or epidote, and a few varieties contain porphyroblasts of pink garnet, which form an obvious flaser texture. Irregular veins of albite, quartz, epidote, or chlorite cut these rocks in many places.

Microscopic features

The principal minerals found in thin sections of the hornblende rocks are hornblende, epidote, chlorite, albite, and garnet; minerals found in smaller quantity include common actinolite, blue-green actinolite, zoisite, clinozoisite, zircon, apatite, sphene, leucoxene, pyrite, and magnetite. The hornblende forms stubby subhedral crystals that are generally oriented only to the extent of having their *c* axes nearly in the plane of schistosity. It is common hornblende and shows little variation among the specimens examined; most of it is moderately deep colored and pleochroic with *X* pale yellowish green, *Y* olive green, and *Z* faintly bluish green; birefringence ranges from 0.020 to 0.028; the extinction angle between the slow ray and the *c* axis is about 20°; *2V* is large, and the optic sign is negative. The other amphiboles occur in minor amounts as needles in albite or as thin overgrowths on the hornblende. (See fig. 29.) The plagioclase in all specimens examined is albite; it occurs mainly as intricately sutured interlocking crystals in irregular veinlets or as interstitial patches. The minerals of the epidote group generally form subhedral crystals which tend to be concentrated in layers. Garnet forms fractured porphyroblasts several millimeters in diameter, and in many specimens it is partly converted to



FIGURE 29.—Photomicrograph of hornblende-albite gneiss. Hornblende (H), albite (A), epidote (E), and blue-green sodic amphibole (sa). Note that sodic amphibole occurs in crystal continuity with hornblende along path of albite veinlets.

chlorite, as shown in figure 30. Chlorite also occurs in irregularly sheared veins and as abundant sharply bounded pseudomorphs, probably after epidote. Sphene is very abundant, amounting to more than 4 percent of some specimens. Quartz occurs only in veins.

The relative proportions of the component minerals vary considerably, but hornblende is the most abundant. It makes up more than 95 percent of some specimens, and none of the other minerals makes up more than a third of any specimen examined.

GLAUCOPHANE ROCKS

Metamorphic rocks containing glaucophane are somewhat more abundant in the district than those containing nonsodic amphiboles. They are also more widespread, and in a general way the area in which they crop out surrounds the area containing the hornblende rock. Most of the outcrops of the glaucophane rocks lie in the eastern half of the district in two zones that run parallel to the strike of the surrounding rocks, but scattered outcrops occur outside these zones, as shown in figure 28. The northern zone trends westward through the east-central part of the Santa Teresa Hills where the glaucophane rocks crop out in an area of graywacke as prominent isolated knobby boulders generally not exceeding 15 feet in diameter. The southern zone trends northwestward from near the junction of Berrocal and Almaden Canyons for a distance of more than 3 miles, and although glaucophane rocks within this zone are exposed only in patches, the lack of outcrops of other rocks neces-

sitated mapping parts of it as continuous bodies of glaucophane rock. In this zone, a little less than 2 miles from the eastern edge of the district, an especially well-developed glaucophane-lawsonite schist forms a readily accessible isolated knob a few hundred feet in diameter adjacent to the road in Llagas Canyon.

Megascope features

The glaucophane-bearing rocks are characterized by a gray-blue color imparted to them by the soda amphibole glaucophane, and by wetting the rock this color can be considerably emphasized. These rocks are mostly foliated, with alternate bands rich in glaucophane or lawsonite, but in some specimens there is no orderly segregation of the minerals. In small part they are true schists, but much of the rock that is foliated shows little tendency to split parallel to the foliation. Some of the nonfoliated rock contains relict diabasic textures indicating derivation from mafic igneous rocks, but most of the glaucophane rocks are so completely recrystallized that they show no relict textures of any kind. (See fig. 31.) Locally, porphyroblasts of albite are developed in the schists.

Microscopic features

The minerals found in the thin sections examined include glaucophane, crossite, lawsonite, albite, muscovite, chromian muscovite or fuchsite, chlorite, stilpnomelane (Hutton, 1948, p. 1373-1374), garnet, quartz, calcite, rutile, sphene, leucoxene, and magnetite. The form and arrangement of the constituent mineral grains varies with the structure of the rock. Glaucophane in the schists is commonly in long prismatic crystals without terminal faces, whereas in some of the more massive rocks it tends to form stubby subhedral crystals with frayed borders. In the schists most of the prismatic crystals lie with their *c* axes in the plane of the schistosity and also show a linear orientation, but in the more massive rocks they have no obvious preferred orientation. The glaucophane prisms are rarely more than 2 mm long, but in some specimens their apparent length is increased by cross fractures filled with later sutured quartz. In the coarser grained nonfoliated rocks mottling and zoning shown by differences in the color of single glaucophane crystals is common, and overgrowths of small needles in optical continuity are not unusual. Crossite was found in a single section as an overgrowth on glaucophane. Lawsonite occurs in equant anhedral crystals as much as 2 mm in diameter, but more commonly forms aggregates of minute crystals or subhedral tablets less than 1 mm in diameter. Several sections contain intergrowths of lawsonite and quartz simulating graphic



FIGURE 30.—Photomicrograph of garnet-hornblende gneiss. Garnet (G), hornblende (H), and chlorite (C). Note chlorite replacing borders of garnet porphyroblasts indicating some retrograde metamorphism.



FIGURE 31.—Glaucophane-quartz schist cut and polished at right angles to plane of schistosity. The light-colored augenlike areas are quartz, as are most of the transverse veinlets. In some specimens there are similar veinlets of glassy albite. The variations in composition and grain size suggest relief bedding.

structure. Polysynthetic twinning occurs in the lawsonite, but it is so uncommon as to be of little value in identifying the mineral. The stilpnomelane is all of the ferric variety, with intense pleochroism in yellow to yellow brown. Fuchsite was tentatively identified only by its brilliant green color and blue to green pleochroism, and, if present, it is rare. Garnet also is generally rare, but many small subhedral crystals of garnet form a conspicuous part of some quartzitic schists derived from chert. Calcite occurs chiefly in irregular veins, but it is also found in ragged interstitial patches which are thought to have formed during the recrystallization of the rock.

The relative proportions of the minerals in the glaucophane rocks vary considerably. Glaucophane makes up almost all of some of the massive rock; it constitutes 25 to 60 percent of the common glaucophane-lawsonite schists but only a few percent of the comparatively rare quartz-lawsonite schists. Lawsonite rarely amounts to more than 40 percent, but some is present in all thin sections of the glaucophane rocks. The micas rarely exceed 5 percent of the rock, and in some sections sphene is equally abundant.

The relationship between the original bedding and the foliation of the glaucophane rocks can be determined with certainty in only a few outcrops, and in these the two are parallel. It seems likely that the planar orientation of the mineral grains and the foliation of the rock is controlled by the bedding, as has been suggested by Taliaferro (1943b, p. 168), for the foliated rocks are derived from sediments or tuffs, whereas the nonfoliated rocks seems to be derived from diabasic greenstone or massive graywacke. The glaucophane needles in some of the schists have a linear arrangement for which no explanation has been found.

CHLORITE-LAWSONITE ROCK

An unusual chlorite-lawsonite rock occurs near the mouth of Almaden Canyon, 10,100 feet N. 57° E. of the top of Mine Hill, as a single 15-foot rounded boulder surrounded by graywacke. This boulder is gray-green, and its surface is studded with lawsonite tablets as much as 15 mm in diameter. As seen along a transverse split in the boulder, the schistosity of the chlorite is well developed and nearly flat in the central part, but curves to follow the outline of the boulder near its periphery. Although the lawsonite

is scattered all through the boulder, it is coarsest and most abundant in a layer that follows the periphery. Where the tablets are abundant, the rock superficially resembles a coarse diabase. (See fig. 32.)



FIGURE 32.—Polished surface on chlorite-lawsonite rock showing deceptive pseudodiabasic texture resulting from random orientation of euhedral tablets of lawsonite.

Thin sections of various parts of the boulder show it to be composed almost entirely of variable proportions of lawsonite and chlorite, with the latter generally conspicuous. Most of the chlorite is of a nearly isotropic variety, but another variety showing anomalous gray-green interference colors locally forms coarse decussate groups. The lawsonite occurs as sharply bounded unoriented tabular crystals with large (001) and narrow (110) faces, but it also appears in thin sections as broken fragments lying along fractures that are healed with chlorite. Leucoxene, occurring as fine dust, is the only other mineral recognized.

QUARTZ-MUSCOVITE SCHISTS

Quartz-muscovite schists, both with and without sodic plagioclase, were found on Mine Hill, where they are closely associated with hornblende-bearing metamorphic rocks. Except for their schistosity and shiny muscovite-covered parting planes, they resemble the sheared feldspathic graywacke of the Franciscan group, from which they doubtless were derived. In thin section the quartz, which is the dominant mineral, is invariably seen to be sutured, to have undulatory extinction, and to contain many liquid inclusions. Albite occurs in one section as elastic grains with overgrowths of the same mineral in optical continuity. The muscovite forms tabular crystals largely concentrated along the parting planes. Each thin section of quartz-

mica schist that was examined also contains several percent of euhedral crystals of garnet, although in some sections they are largely replaced by chlorite. A little chlorite is also found with the muscovite along the parting planes, but it does not exceed 5 percent in any of the sections examined.

QUARTZ-ACTINOLITE SCHIST

Quartz-actinolite schist containing nearly equal amounts of fine-grained sutured quartz and minute needles of actinolite, together with a little chlorite and leucoxene, is interbedded with graywacke of the Franciscan group in the upper part of Longwall Canyon. It is an unusual rock in the district, and probably was derived from an impure tuff.

ACTINOLITE-CHLORITE ROCKS

Small nodular masses of semioriented closely packed actinolite prisms with interstitial chlorite are found along the margins of serpentine bodies in a few places in the Santa Teresa Hills; similar rocks occur in areas of hornblende schists along the road a little less than a mile south of the junction of Guadalupe and Los Capitancillos Canyons. Such nodular masses are common elsewhere in the Franciscan metamorphic rocks of the California Coast Ranges, but they are exceedingly rare in the New Almaden district. Taliaferro (1943b, p. 181) suggests that they have been formed from serpentine by an endomorph reaction.

METACHERT

Most of the chert in the district shows no obvious metamorphic change, but in places we found scattered boulders of varicolored "metachert" displaying unusual minerals or textures. Some of the changes that have produced these metacherts probably took place at low temperature, during the transformation of a silica gel to a hard siliceous rock; other changes, resulting in the formation of minerals that indicate higher temperatures or pressures, are true metamorphic changes. Because of the inherent difficulty of separating the rocks showing diagenetic changes from those which are truly metamorphosed, all these unusual varieties of chert are herein considered together.

"Orbicular jaspers"⁶ and yellow cherts with a microspherulitic texture are fairly common as isolated boulders. Most of these consist of massive chert, and they are believed to result directly from the radial growth of chalcedony (length-slow variety termed "lutecite") during the crystallization of a silica gel. An unusual orbicular jasper rock, shown in figure 33,

⁶ "Orbicular jasper" is the term widely used for such rocks by amateur mineral collectors and lapidary enthusiasts.

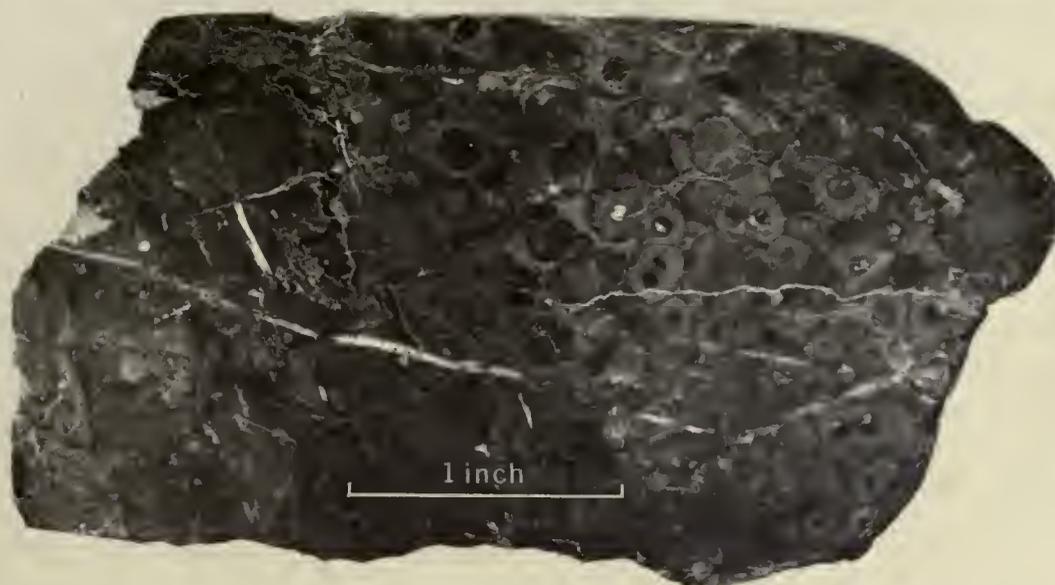


FIGURE 33.—Polished surface on silicified tuffaceous greenstone showing typical "orbicular jasper" structure resulting from radial growth of chalcedony fibers in the replacing silica.

indicates a two-stage process of formation in which a brecciated greenstone was partly replaced by ferruginous silica and later it recrystallized to form an orbicular jasper. Similar rocks occurring a few miles east of the district in the Morgan Hill quadrangle are valued by lapidary enthusiasts and have found their way into thousands of collections in California. With further recrystallization of the chert, the chalcedony is replaced by a mosaic of sutured quartz and the iron oxides generally are expelled to the periphery of the quartz grains. Where the rock is still more metamorphosed, the iron forms scales of specular hematite as much as half a millimeter in diameter. Although the hematite is generally most abundant in areas of clear quartz or in vugs that also contain a little carbonate, one thin section showed strings of minute hematite scales which appeared to have replaced crocidolite.

Crocidolite-bearing chert, characterized by its toughness and patches of inky blue color, occurs in boulders along zones that also contain other varieties of metamorphic rocks. Thin sections of these rocks show that the silica is present in the form of sutured quartz appreciably coarser grained than the silica of the unmetamorphosed chert. The crocidolite generally is concentrated in veinlets, but in some places it surrounds individual quartz grains and in others it has a random distribution (fig. 34). In some metachert, aegirine replaces the central part of clots of crocidolite and forms the margins of quartz-aegirine veins. Such crocidolite-bearing cherts are fairly common in the California Coast Ranges, and have been studied

in greater detail by Louderback and Sharwood (1908, p. 659) and by Ransome (1894, p. 211-219).

ORIGIN OF METAMORPHIC ROCKS

To emphasize the difficulty of explaining the origin of the metamorphic rocks in the Franciscan group, it is only necessary to point to the many and varied agencies to which the metamorphism has been ascribed. These include dynamometamorphism, regional metamorphism, and additive contact metamorphism, and it has even been suggested that the metamorphic rocks are merely fragments of an older underlying formation dragged up along faults. The most recent con-



FIGURE 34.—Photomicrograph of metachert containing needles of crocidolite (dark) in a groundmass of quartz. Plane light.

tribution to the problem is a noteworthy discussion by Taliaferro (1943b, p. 159-182), who concluded that the rocks owed their origin to selective and non-selective additive metamorphism along the contacts of basic and ultrabasic intrusives, being formed only in those places where the quantity of volatiles and solutions escaping from the magma during its emplacement was large. Primarily because of the areal distribution of the metamorphic rocks in the New Almaden district, we do not believe that the origin of all the various metamorphic rocks can be ascribed to contact metamorphism caused by the ultramafic intrusive rocks.

The problem of the origin of these rocks is twofold: first, what were the original rocks, and, second, under what conditions were those rocks reconstituted? Geologists who have studied these rocks in recent years seem to agree that the more widespread and abundant types were formed by metamorphism of the various rocks in the Franciscan group, although it has been suggested that the chlorite-actinolite and chlorite-actinolite-talc rocks may have been derived from serpentine. In the New Almaden district the field relations and textures of many of the rocks indicate their derivation from rocks of the Franciscan group; and, it seems likely, though it cannot quite be proved, that they were all derived from these rocks.

The hornblende schists and amphibolites can be traced directly to tuffaceous greenstones; they occur in patches along a belt of tuff beds, which for reasons unknown are especially susceptible to metamorphism. Some of the glaucophane schists contain relict textures identical with those of the lavas of the Franciscan group, and others show the incipient development of glaucophane in normal-appearing graywacke. Still others, to judge from their mineral content and general appearance, seem to have been derived from cherts. The crocidolite-bearing rocks, also, are believed to be derived from normal cherts of the Franciscan group, for it was possible to collect specimens showing the alteration through small stages. The quartz-muscovite schists grade into feldspathic graywacke, from which they were probably derived. The actinolite-chlorite rocks, found only as polished nodules along the borders of a few serpentine bodies, may be fragments dragged up by the serpentine, or they may be altered mafic rocks; but it seems unlikely that they were derived from serpentine, which nowhere shows a marginal metamorphosed zone containing any actinolite or chlorite.

Evidence as to the metamorphic process might be gained from the areal distribution of the rocks and from their texture, mineralogy, and chemical compo-

sition. Of these, only the distribution and mineralogy are well known for the rocks of the New Almaden district, but a general idea of the bulk chemical composition can be obtained from the mineralogic composition. In regard to texture the preponderance of oriented platy and linear minerals in the metamorphic rocks is significant.

All the larger masses of hornblende-bearing metamorphic rocks are restricted to the central part of a favorable tuff bed on Mine Hill and to another tuff bed, or possibly a faulted segment of the same bed, near the Guadalupe mine. Most of the masses border serpentine sills; but in a few places along the same favorable bed small masses of hornblende rocks are found at a considerable distance from any known serpentine mass. Conversely, serpentine borders the bed in a few places without the development of any hornblende-bearing metamorphic rocks. Elsewhere in the district there are many other serpentine bodies that border tuffaceous greenstones, yet they have produced no apparent metamorphism. A particularly good example of the latter type can be seen along the Day tunnel of the New Almaden mine south of the New Arzilla stope (pl. 4) where a bed of unmetamorphosed greenstone is included between two serpentine sills, each of which is several hundred feet thick.

The textures of the hornblende-bearing metamorphic rocks shed little light on the problem of their origin. They are generally somewhat schistose, but they show little linear orientation. Foliation is developed in some, but most are apparently nonfoliate. Where field relations are clear, the foliation appears to be parallel to the bedding, and probably it was caused by differences in the chemical composition of individual beds.

The hornblende-bearing rocks probably resulted from the recrystallization of the tuff beds under relatively low pressures, owing chiefly to their depth of burial. Without chemical analyses it is not possible to know whether the metamorphic rocks differ chemically from the tuffs from which they were derived, and although they all have mineral assemblages that could conceivably result from simple recrystallization, volatile fluid escaping from nearby serpentine sills may have helped to cause the recrystallization. The general lack of metamorphic effects along these sills, however, casts considerable doubt upon the ability of the serpentine sills to effect metamorphism; yet the general association of hornblende rocks with serpentine suggests that in certain places, probably where the composition or the water content of a tuff bed was particularly favorable, the serpentine may have

been effective in "triggering" the metamorphic reaction.

The origin of the glaucophane-bearing metamorphic rocks is even more obscure, partly because these appear to be derived from many of the rocks of the Franciscan group rather than from a single rock type or favorable bed and partly because of their erratic distribution. The largest masses in the district are associated with both greenstones and sedimentary rocks of the Franciscan group; some border serpentine intrusions but many others do not. More than 50 bodies, many of them less than 20 feet long, are isolated outcrops surrounded by unaltered graywacke or siltstone. The majority of these small isolated masses are probably in shear zones, but such an environment cannot be demonstrated for all of them. Nevertheless, the most striking feature of the glaucophane-bearing rocks is their close areal relationship to shear zones, faults, or structural "knots."

In texture the glaucophane-bearing rocks are in general more distinctly foliated than the hornblende-bearing rocks, and although some show no obvious mineral orientation, many others show both planar and linear parallelism. The foliation is parallel to the original bedding, where the relation can be determined, but it has been seen in only a few outcrops. The textures of the rocks are thus of little help in ascertaining the metamorphic process by which they were formed.

No chemical analyses of the glaucophane rocks of the New Almaden district are available, but several analyses of similar rocks from elsewhere in the Coast Ranges are given in an excellent paper by Smith (1906, p. 183-242). He concluded, on the basis of these analyses, that no new materials, except possibly water, had been added in the formation of the glaucophane rocks. Taliaferro (1943b, p. 178-179), on the other hand, cites analyses to prove the introduction of material during the metamorphism of a chert to a quartz-glaucophane rock. He apparently does not take into account, however, the shaly parting layers, which are excluded from the analyses of chert but were doubtless incorporated into the glaucophane schist. It does seem likely, however, that in the formation of some glaucophane-bearing rocks of the California Coast Ranges small amounts of soda and other materials have been introduced, and that other constituents have been lost. On the whole, however, the rocks are not appreciably more sodic than the rocks of the Franciscan group from which most of them were derived; they could easily have been formed by a reconstitution of the elements in the original rock accompanied by a little metamorphic diffusion.

Despite the schistose appearance and relatively complete recrystallization of the glaucophane-bearing rocks, the presence of stilpnomelane, epidote, albite, and chlorite indicates that they are probably the equivalent of the more usual assemblages of the greenschist facies and represent relatively low-grade metamorphism (Turner, F. J., 1948, p. 99-100). They appear to have formed in the New Almaden district along tectonic zones. This distribution may have resulted from the development of high-pressure areas during deformation, the generation of heat by shearing, the availability of solutions, or by several of these combined. In places the glaucophane rocks are adjacent to serpentine masses, but as these serpentine bodies are of the type thought to have been squeezed into their present position as serpentine (p. 54-57), they were probably incapable of any pronounced thermal or hydrothermal metamorphism. In many more places in the district the glaucophane-bearing rocks do not lie adjacent to serpentine, and it would appear unlikely that they have any direct relationship to these rather impotent intrusives.

The origin of the less common crocidolitic meta-cherts is not known. In areal distribution these rocks are comparable to the glaucophane-bearing rocks, and it seems likely that they have a common origin. The presence of aegirine, however, suggests a moderately high temperature of formation.

AGE OF THE FRANCISCAN GROUP

Fossils diagnostic of the age of the Franciscan group in the New Almaden area have been found only in the limestone, which on the basis of Foraminifera has been dated as early Late Cretaceous (Cenomanian), see page 24-25. The next younger rocks in the district are also Late Cretaceous in age, but we know neither the part of the Late Cretaceous they represent nor their stratigraphic relation to the Franciscan, because they are in fault contact with this group.

The time span represented by the Franciscan group elsewhere in the State is imperfectly known for many reasons. Few fossils have been found. Correlations over a wide area are based on similarity of lithology, and it is possible that rocks assigned to this group in different areas were deposited at different times. The base of the formation is nowhere exposed; the upper contact is controversial. Taliaferro (1943b, p. 190-202, 208-212) cites several localities where beds assigned to the Franciscan group grade upward into fossiliferous Knoxville (Upper Jurassic) shales, with which cherts and greenstones are interbedded. On the basis of these relations, and previous fossil discoveries which he carefully summarizes, Taliaferro

assigned the group to the Late Jurassic (Tithonian). Subsequent to the publication of this summary, an ammonite, *Douvilleiceras* sp., of unquestioned Early Cretaceous (Albian) age, was discovered in San Francisco, which is generally regarded as the type locality of the Franciscan group. This discovery and its significance is described in an article by Schlocker, Bonilla, and Imlay (1954, p. 2372-2381).

The information now available indicates that some of the rocks of the Franciscan group were deposited in Late Cretaceous (Cenomanian) time, and some were deposited in Early Cretaceous (Albian) time. Other beds, correlated with this group chiefly on the basis of their content of greenstone and chert, are said to grade upward into, or be overlain by, Knoxville shales, and therefore they are at least as old as Late Jurassic. It thus appears that we are dealing with either a thick formational unit ranging in age from Late Jurassic to Late Cretaceous, or that we are dealing with two similar sequences, one of Tithonian or older age and the other Albian and Cenomanian age, and have failed to find criteria by which they can be distinguished. Until this problem can be solved, it seems best to designate the Franciscan rocks as Late Jurassic and Cretaceous.

THICKNESS OF THE FRANCISCAN GROUP

The thickness of the Franciscan group cannot be determined accurately in the district because of its structural complexity, and because neither its base nor top is present. The part of the group that is present is believed from a study of cross sections to be at least 10,500 feet thick, and it may be considerably thicker.

The minimum thickness of the part of the Franciscan group present in the area can be approximated by utilizing the partial sections exposed in the various fault blocks. The older part of the group, consisting of feldspathic graywacke, buff siltstone, and overlying greenstone and limestone, forms a block in which no major faults were found in the area between Blossom Hill and the Limekiln fault. (See section A-A', pl. 1.) The sedimentary rocks are about 6,000 feet thick, and the overlying greenstone is about 1,500 feet thick. On Los Capitancillos Ridge northeast of the Enriquita mine another unfaulted section more than 4,000 feet thick contains 3 sequences of greenstone separated by sedimentary rocks. A positive correlation between these 2 partial sections cannot be made, but a minimum thickness for the rocks exposed in the 2 blocks can be obtained by assuming that the greenstone at the top of the older block is the equivalent of the lowest greenstone exposed in the Los Capitancillos block. Using this assumption, we find that

there are about 3,000 feet of additional section present on Los Capitancillos Ridge, making a minimum thickness of 10,500 feet for the composite of the 2 blocks. Some of the deep workings in the New Almaden mine, however, passed through thin greenstone layers lying deeper in the section than the greenstone exposed on the surface, and if this is correlated with the greenstone of the older block, the composite section would be 2,000 feet thicker.

The relation of the rocks of the other blocks south of the Shannon fault to these two sections are not well known; but the blocks contain limestone, which can probably be used as a key bed, and this suggests that they contain equivalent sections. No limestone occurs in the Franciscan group north of the Shannon fault zone, and no correlation across this fault is possible in the New Almaden area.

ORIGIN OF THE FRANCISCAN GROUP

The assemblage of rocks in the Franciscan group is typical of eugeosynclinal accumulations found in orogenic belts throughout the world. The geosyncline in California was at least 550 miles long and more than 150 miles wide. If the assemblage of more metamorphosed but otherwise lithologically similar rocks found on the Palos Verdes Hills (Woodring and others, 1946, p. 12-13), on Santa Catalina Island, on the islands off Lower California, and in the Western Cape region of Lower California (Beal, 1948, p. 36-37) are included in the group, the length of the geosyncline was more than 1,000 miles. The feldspathic character and angularity of the grains in the graywacke indicate that this rock was derived from a rugged, probably actively rising, landmass not far distant from the site of deposition. Taliaferro (1943b, p. 187-188) has concluded from the composition of the pebbles in the conglomerates, and from a general coarsening of the sediments westward, that the principal landmass lay to the west of the depositional trough. This conclusion may be justified, but the lack of fragments showing myrmekitic or graphic intergrowths in the sedimentary rocks of the Franciscan group, and the scarcity of orthoclase suggest that the Santa Lucia granodiorite was not an important source, either because it was not exposed by erosion or because it had not yet been intruded.

That the group accumulated rapidly is indicated by the character of the sedimentary rocks, the scarcity of fossils, and the great thickness of the volcanic rocks. Despite this rapid accumulation, however, some progressive changes are shown by the differences between the older and younger parts of the group. The older part contains little volcanic material, chert, or conglomerate, and in general is better sorted and more

feldspathic; the younger part contains a larger proportion of lithic graywacke, considerable greenstone and chert, and some limestone and conglomerate. These differences are believed to reflect an increase in orogenic and igneous activity during the deposition of the group. Probably the older sediments were deposited in deeper water and farther from their source. The oolitic character of some of the limestone in the younger part, together with the abundance of shale flakes and the presence of conglomerate, indicates that some of the geosyncline was shallow, at least at times, during the accumulation of the younger part of the Franciscan group.

SERPENTINE

Serpentine occupies less than 10 percent of the New Almaden district; however, because some of it is hydrothermally altered to silica-carbonate rock—which is the host for all the rich quicksilver ore bodies—it merits special attention. Of particular importance is the consideration of the character of the ultramafic material when it was intruded, for this influences the shape and nature of the walls of the intrusive masses along which the ore bodies were localized. The unusual opportunity to study the serpentine bodies and their contacts afforded by the perfect exposures in the mine workings has led us to conclude that all the masses were intruded as serpentine, rather than formed in place by hydration of an ultramafic igneous rock.

Distribution

The serpentine of the district is exposed along linear zones that trend eastward or southeastward, nearly paralleling the structures of the rocks of the Franciscan group. Disregarding a small exposure in the extreme northeast corner of the district, the northernmost zone lies along the northern slope of the Santa Teresa Hills and is most prominent in the large mass of serpentine forming Tulare Hill, on the east edge of the district. The next zone to the south extends eastward from the vicinity of the Guadalupe and Senator mines to the east boundary of the district. It cannot be traced continuously, for about midway in its course it is covered by the alluvium in the broad valley of Alamitos Creek; the eastern end, however, is especially thick and well exposed in the Santa Teresa Hills. The next zone to the south branches from the last in the vicinity of the Senator mine and extends southeast to the Enriquita mine, east through the New Almaden mine area, and southeast from Mine Hill across Fern Peak. Beyond Fern Peak it swings eastward along the north side of Longwall Canyon, becoming more broken and irregular close to Llagas Canyon. Part of this zone seemingly crosses Llagas

Canyon and extends southeast at least as far as Uvas Canyon, east of the mapped area; another part swings northward around an arc and then continues northwest to the prominent serpentine hill at the mouth of Almaden Canyon. The next main zone of serpentine bodies to the south extends from Los Gatos Creek, on the west edge of the district, to the upper part of Llagas Canyon. It is less continuous than the other zones, for near El Sombroso there are gaps of nearly a mile in which no serpentine was found, although a more thorough search in this heavily wooded area might reveal additional small bodies. The southernmost zone of serpentine extends northwestward from the upper part of one of the tributaries of Almaden Canyon and crosses the main divide of the Sierra Azul just south of Mount Umunhum.

The serpentine masses vary widely in size and shape. The largest mass in the district extends along the Santa Teresa Hills, where it has an exposed length of $4\frac{1}{2}$ miles and an average width of about half a mile. Several others exceed 1 mile in length, whereas the smaller bodies range downward in size to isolated pods only a few feet long. The smallest masses can best be observed in the mine workings, where one may see sill-like apophyses and pods, in many places less than 1 foot thick, bordering the larger sills. The outcrop patterns of the serpentine masses vary according to their geologic structure. Some of the masses are sill-like bodies conformable with the enclosing rocks of the Franciscan group; others occupy fault zones and are unconformable. The conformable bodies are tabular and generally tilted with the enclosing rocks, giving rise to irregular outcrop patterns, whereas the bodies lying along faults are generally vertical or very steep and give rise to more linear patterns. Examples of the conformable bodies are seen on Mine Hill and in the area to the east and southeast, whereas good examples of the fault-controlled bodies are found along the more southerly zone that extends eastward from Los Gatos Creek and lies north and east of El Sombroso.

Megascopic features

Two varieties of serpentine having different structure and texture are common in the district. They grade into each other, but since most exposures can readily be classed as of one or the other variety, each merits a separate description. One of them, here termed "sheared serpentine," is intensely sheared, foliate, and shiny; it ranges in color from white through light green to a moderately deep green in fresh exposures. It forms very few extensive bodies, but is a marginal phase of many of the larger masses. The other, termed "blocky serpentine," contains massive

rounded blocks of unsheared serpentine in a completely sheared matrix (fig. 35). The proportion of matrix to blocks, as seen in artificial cuts where exposures are perfect, varies within wide limits; the sheared matrix may form only thin separations between massive blocks that nearly touch one another, or it may be relatively abundant, containing only here and there a small rounded pod of unsheared serpentine. All gradations in the relative amounts of sheared matrix and un-sheared blocks may be found. The blocks, where fresh, are dark green, nearly black, in color and have a pseudomorphitic texture wherein ragged crystals of bastite a quarter of an inch long, derived from pyroxene, are scattered through a matrix of deep-green granular serpentine derived from olivine. Many blocks also contain magnetite, either disseminated as individual crystals a little less than 1 mm across, or concentrated in veinlets.

The field appearance of the serpentine masses depends on how much they are sheared and on whether they crop out in the low foothills or in the higher mountains. The large masses are generally blocky and can be distinguished as serpentine from a distance. In

the lower foothills these give rise to distinctive greenish or drab-colored slopes studded with groups and trains of closely spaced boulders as much as 20 feet in diameter (fig. 36). From a distance many of these slopes display a crude banding, caused by alternation of bands of large and small boulders, or by a succession of more sheared and less sheared zones. This banding generally is nearly parallel to the contacts of the serpentine mass, but in parts of the large and exceptionally well-exposed mass in the Santa Teresa Hills it can be seen to diverge from the contacts at angles as great as 30°.

The margins of the masses in the foothills are sharply marked in many places by slight topographic bulges in the peripheral serpentine and a shallow, but perceptible, flattening of the slopes just below (fig. 37). This topographic expression tends to be obscured, however, by small landslides, which are common along these contacts and give rise to small seeps or springs. In some areas in which the serpentine is well exposed, linear grass-covered patches devoid of boulders are conspicuous; these patches are generally underlain by septa of sedimentary or vol-



FIGURE 35.—Blocky serpentine exposed in fresh roadcut. The blocks are irregular in shape, but have silken-sided surfaces and rounded corners and edges. They invariably show undistorted relict textures inherited from the original peridotite or dunite. Between the blocks the serpentine is intensely sheared and does not exhibit any relict textures.



FIGURE 36.—Typical houlder strewn surface developed on area underlain by blocky serpentine in the lower parts of the New Almaden district. This kind of surface results from the erosion of the sheared serpentine matrix leaving the unshaped blocks as residual boulders.

canic rocks of the Franciscan group. In the lower parts of the district the blocky masses of serpentine support, in addition to sparse grass, a growth of scattered bushes and a few struggling oak or bay trees, whereas similar bodies in areas of greater altitude generally support a dense, locally impenetrable, growth



FIGURE 37.—View of margin of a serpentine mass in the low foothills of the New Almaden district. The short but pronounced steepening of slope at the contact is typical. Note in lower right the water trough that utilizes the small flow from a contact spring; such springs and seeps are fairly common along the lower margins of serpentine masses.

of manzanita bushes. By the unusual gray-green color of the manzanita leaves it is possible in many places to recognize serpentine masses from a distance even where none of the boulders project above the bushes, and in a few places it is possible to delineate the masses fairly accurately by outlining the manzanita thickets.

The boulders that weather from the blocky serpentine range in diameter from about 6 inches to more than 20 feet, but the majority are between 1 and 4 feet in length. The largest boulders are mostly subrectangular, the smaller ones nearly spherical. In fresh exposures the boulders are coated with the sheared matrix material and are shiny and smooth, but in most places they are weathered and have rough dark-colored lichen-covered surfaces. The roughness of the surface is due to differential weathering. The bastitic pseudomorphs after pyroxenes are more resistant than the serpentine derived from olivine and protrude from the surface. Most surfaces are partitioned by a rectangular network of narrow veins of antigorite which are perpendicular to the surface of the boulder and penetrate the rock for only about 1 inch; such veins are easily weathered, producing a surface that appears intricately cracked. Larger veins of chrysotile asbestos cut completely through the rock; these veins are more resistant and stand out on weathering, as do also some thick veins of porcelaneous serpentine. About 1 inch below the surface of the boulders, where the antigorite veinlets pinch out, there is commonly a zone of fractures or veins, and on intense weathering these tend to open, causing some spalling of the crust. Some boulders show parallel banding due to the concentration of bastite in layers $\frac{1}{2}$ to 3 inches thick, and where the rock is weathered, these layers stand in relief.

Sheared serpentine forms a large part of many of the smaller serpentine bodies, particularly the more linear ones, and some of the smaller bodies consist entirely of the sheared variety. Such masses, except where they are silicified, afford poor outcrops or are not exposed at all except in artificial cuts. Generally, however, they are covered with a distinctive soil, which is black and very sticky when wet, but when dry, is dark-gray, hard, and traversed by wide polygonal joint cracks. Fortunately, this soil contains minute shreds of sheared serpentine, for without these shreds it could easily be confused with the soil resting on the black *alta*, which is derived from the sedimentary rocks of the Franciscan group along the margins of the serpentine. Landslides are common in the larger masses of sheared serpentine, and along the upper scarps of these landslides are found the best

natural exposures of the serpentine. In the higher country the sheared serpentine, like the blocky variety, supports a growth of manzanita, and in some places at lower altitudes tarweed is particularly abundant on it. During a few days in the early summer it is particularly easy to outline the masses of sheared serpentine on a soil covered slope, for the grass in the soil derived from serpentine remains green a little longer than it does in the soils derived from other rocks. By making use of these criteria, generally one may locate and crudely outline masses of sheared serpentine rather quickly, but determining their exact outlines is difficult and cannot everywhere be done with certainty.

Where the sheared serpentine is silicified, whether in larger masses or in septa between boulders of un-sheared serpentine, it forms on weathering jagged, spired, and crudely tabular angular outcrops, which show at a glance the prevalent direction of shearing. In a few outcrops of silicified sheared serpentine snow-white puff balls of magnesite, generally a little less than 1 inch in diameter, are conspicuous; these balls of magnesite, however, being resistant to weathering, commonly fall out, leaving a pock-marked surface.

Massive serpentine derived from dunite containing

no pyroxenes is rare in the area, but it was found in several small scattered exposures. It can be distinguished only where it is un-sheared, but there it is readily recognized in both fresh and weathered exposures by its granular texture, lack of bastitic pseudomorphs, and typical irregular veining by various serpentine minerals (fig. 38). Where it is slightly weathered, it assumes a light-gray, nearly white color and is not unlike a fine-grained sandstone; examination with a hand lens, however, invariably reveals the presence of minute black crystals of picotite, easily recognized by their submetallic subadamantine luster. In most places, however, the serpentine derived from dunite is more intensely weathered, and part of the rock has been hardened through a width of about a quarter of an inch along many irregular veinlets and fractures; the hardened zones are deep green and resistant, and the intervening serpentine is whitened and leached out, so that the surface is full of highly irregular deep cavities from $\frac{1}{4}$ to 1 inch in diameter.

Microscopic features

As the serpentine minerals are variable in optical properties and variously grouped under different names, it is appropriate to discuss the nomenclature used in this report before describing the appearance of the serpentine in thin section. A survey of the



FIGURE 38.—Polished surface on fresh serpentine derived from dunite. The latest veins are a waxy porcelaneous serpentine that replaces older serpentine minerals. This porcelaneous material is apparently what was originally referred to by Lodochnikov as "serpophite." (See p. 50.)

extensive literature on serpentine and serpentine minerals reveals that dozens of varietal names have been used, but many of these have been discarded. Some now used as mineral names were originally intended merely as varietal rock names. Other names connotated textures, some of which were inherited from the replaced minerals, whereas others resulted from the crystallization of the serpentine mineral itself. Recent X-ray and thermal studies made of serpentine are still not reconciled, and there remains considerable uncertainty, and some disagreement, as to just how many serpentine minerals there are, and just what are the limitations to their variable physical and optical properties.

Because it is not possible to differentiate precisely the various serpentine minerals, they will be divided in this report, according to the simplest optical tests, as follows:

Fibers.....	Length-slow....	Chrysotile
	Length-fast....	Fibrous antigorite
Plates.....	Length-slow....	Antigorite
	Length-fast....	Not found
Amorphous, or nearly so.....		Serpophite

This grouping follows for the most part accepted usage, except that fibrous antigorite, the most common of the serpentine minerals in the district, has often been misidentified as normal antigorite because of its low birefringence and the difficulty of ascertaining whether it is fibrous or platy. In addition, we include under the term "chrysotile" material with lower birefringence than is customary. "Serpophite" is used for designating the structureless nearly isotropic mineral that generally occurs as a pseudomorph after olivine, following usage that is generally accepted by English-speaking geologists even though it differs somewhat from the original intent of Lodochnikov (1936), who proposed the term. The senior author is indebted to Mr. V. P. Sokoloff for translating lengthy sections of this ponderous volume for him. Lodochnikov's best definition of serpophite seems to be the one given on pages 34 and 35, but it leaves much to be desired. The term is loosely used for "macroscopically dense, structureless, varieties of serpentine, having waxy or enamellike luster, and light to dark color." According to Lodochnikov (p. 34), serpophite occurs chiefly as veinlets, and apparently he intended the term to be used in megascopic, rather than microscopic, descriptions. "Bastite" is used as a varietal term for any serpentine mineral that forms pseudomorphs after either an orthorhombic or monoclinic pyroxene with coincidence of *c* axes.

The study of thin sections of serpentine derived from dunite, which consists almost entirely of olivine, provides the logical starting point for the study of the process of serpentinization because of the small number of minerals involved. These sections will therefore be described first, even though in the New Almaden district serpentine derived from dunite is much less common than serpentine derived from rocks containing pyroxenes as well as olivine.

The least-serpentinized dunite found in the area contains less than 30 percent of residual olivine, as shown

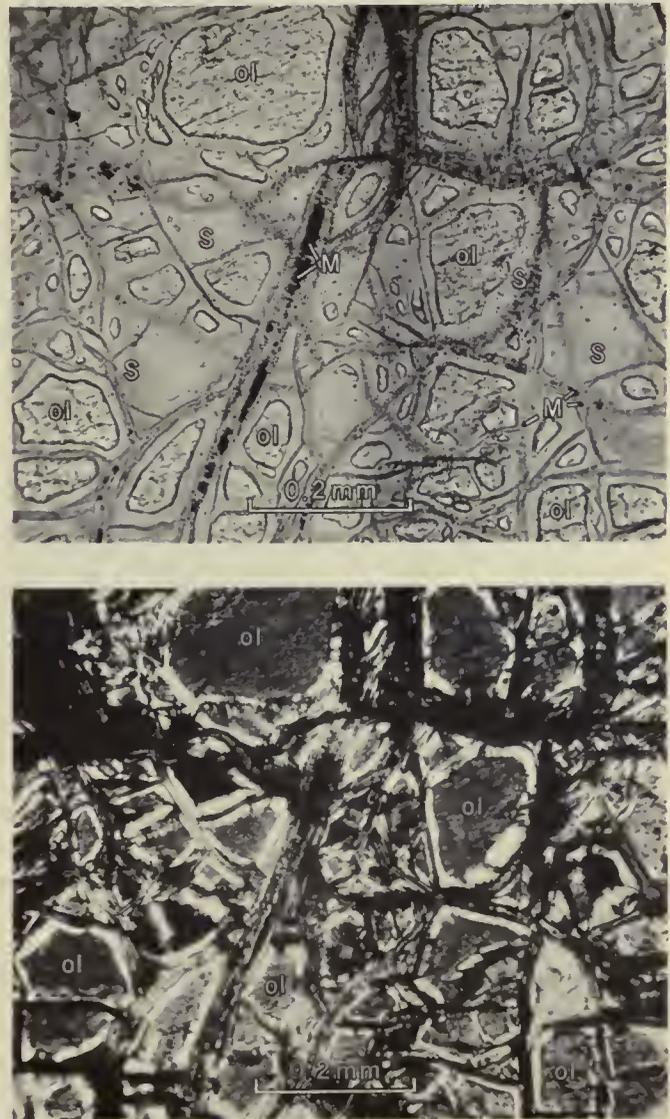


FIGURE 39.—Photomicrographs of dunite partly replaced by serpentine minerals, showing development of typical meshwork. Olivine (ol), serpentine minerals (S), and magnetite (M). Upper, Plane light. Lower, Section oriented so that olivine residuals are near the extinction position. Note that all of these show the same illumination, indicating that they are all parts of a single crystal and unrotated. Mineral horizons between olivine residuals is fibrous antigorite; narrow veinlets are chrysotile. Crossed nicols.

in figure 39; however, because many small unreplaced granules of olivine are evenly distributed throughout the rock, it is possible to deduce with a fair degree of certainty the character of the original dunite. Most of the olivine grains were anhedral, although some had a few crystal faces; the largest grains were more than 3 mm long, but the average length was about 1 mm. In shape they ranged from equant grains to slightly embayed prisms with a length four times their width. The resultant texture was xenomorphic granular, like that normally found in fresh dunites. The only original mineral other than olivine is chromite or picotite, which occurs as subhedral grains about 0.1 mm in diameter.

The first step in the process of serpentinization is fracturing, which is closely followed by replacement of the olivine by fibrous antigorite and the filling of cracks with chrysotile. The fractures are variously controlled; a few are parallel to cleavage within single olivine grains, others radiate from chromite grains, and still others extend continuously through several differently oriented olivine grains. The fractures all belong to a single system, for they terminate and bend at their junctions. The widest fractures are also the longest and straightest, and in section these form a polygonal pattern, each polygon of which may be further divided into small polygons by smaller and less continuous fractures. The resultant fracture pattern is the basis for the familiar mesh structure developed from olivine. The olivine bordering these fractures is replaced by a wave of fibrous antigorite growing from the cracks toward the olivine, and simultaneously the fractures are filled with a chrysotile of low birefringence, which generally encloses magnetite dust. When the chrysotile has filled the narrow fractures it replaces the fibrous antigorite previously formed along the walls.

The development of these two serpentine minerals probably results from a single reaction, so that the two are nearly contemporaneous. Nowhere was either mineral found without its companion, and the two occur in a fairly constant ratio of about three parts of fibrous antigorite to one of chrysotile. The reaction apparently stops when the fibers of antigorite attain a length of about 0.03 mm, unless, as happens in many places, additional fractures open parallel to the original one are filled with more chrysotile. If the process of serpentinization is stopped at this point, the partly serpentinized dunite will contain many residual sub-angular fragments of olivine, like "eyes," in the mesh of serpentine minerals. The olivine fragments are fresh, and their contacts with the fibrous antigorite are sharp. The several remnants from each olivine

crystal extinguish exactly together, which indicates that they have not rotated during serpentinization and suggests that the process has been strictly one of replacement involving no significant expansion. With increasing serpentinization the remaining olivine is replaced by serpophite, which has a slightly higher index of refraction and much lower birefringence than the fibrous antigorite; and invariably the original contact between antigorite and olivine is preserved as the contact between antigorite and serpophite. At the same time the magnetite dust is collected into larger isolated crystals or strings of crystals along the wider veinlets. The borders of chromite grains become fuzzy, and in reflected light the grains are seen to be coated with magnetite. At the same stage in the alteration process magnetite also replaces the chromite along fractures.

The serpentine of the district is mostly derived from a harzburgite, a rock containing olivine and orthopyroxene, but some of it is derived from lherzolite, which contains these minerals and also clinopyroxene. The distribution of the harzburgite and lherzolite is unknown, for the two pyroxenes cannot readily be distinguished in the field; both rocks, however, are known to occur in a single body of serpentine. Although the pyroxenes in most of the serpentine have been replaced by bastitic minerals, the amount of pyroxene originally present in an unshered serpentine is easily estimated from the proportion of bastite pseudomorphs. In most of the serpentine this proportion is between 10 and 25 percent, but the dunite previously mentioned contains no pyroxene, and certain bands and segregations in the ultramafic rocks contain more than 85 percent of pyroxene replaced by bastite.

No systematic variation in degree of serpentinization, either from the margins of a mass inward or from the surface downward, was found. The process of serpentinization of the typical peridotites, including both harzburgites and lherzolites, can be fairly well traced by studying various thin sections of rock collected throughout the district, if they are properly arranged in increasing order of serpentinization, as was done in this study; it should be emphasized, however, that the result is a synthesis rather than a report of the changes effected in a single body of peridotite.

Of the least serpentinized peridotite studied in thin section, a little less than half consisted of primary minerals, including olivine, enstatite, and a clinopyroxene that is probably angite. (See fig. 40.) The olivine originally occurred as rounded anhedral grains, whereas the pyroxenes generally show some crystal faces

and irregular or embayed outlines where they adjoin the rounded grains of olivine. Some of the enstatite poikilitically encloses small olivine crystals, but this is uncommon. The olivine grains are of about the same size as those in the dunite, and the pyroxene crystals are commonly from 1 mm to several millimeters long. The alteration of the olivine in the freshest rocks has advanced only to the stage at which a few of the cores are replaced by serpophite. The pyroxenes are very slightly replaced along cleavage traces by bastitic chrysotile of low birefringence, forming jagged edges where these intersect crystal boundaries. The only accessory mineral found was a pale-yellow picotite, which is largely anhedral; this mineral tends to enclose olivine and to be enclosed by pyroxene, and even in the least altered sections it is slightly replaced and rimmed by magnetite. Sections of more altered peridotite show that the orthopyroxene is replaced by a pale-green magnetite-free chrysotile of low birefringence at the same stage in which the cores of the olivine grains are being replaced by serpophite. The clinopyroxene generally remains little altered until most of the orthopyroxene is completely serpentinized, and where it forms thin tabular intergrowths with the orthopyroxene, laminae of orthopyroxene may alternate with laminae of bastitic chrysotile. With still further serpentinization the clinopyroxene is converted to an intricate intergrowth of needles quite unlike the orderly bastite, but in most sections of completely serpentinized peridotite no pseudomorphs of clinopyroxene were recognized. Where the serpentinization of the clinopyroxene is complete, the picotite is largely replaced by magnetite, and the iron oxide freed from the olivine has collected into strings of fairly well formed magnetite crystals following the larger fractures. Some lenticular and otherwise irregular veins of normal chrysotile also are commonly found in these completely serpentinized rocks.

The sheared serpentine generally shows in thin section only scattered fragments of bastitic pseudomorphs and a few grains of residual picotite or magnetite by which one may infer its ultimate origin from an ultramafic igneous rock. Because the shearing has destroyed all the original textures, one can draw no conclusions regarding the serpentinization process from examinations of thin sections. The field relations, however, as well as the chemical composition, are such that there can be no doubt that the sheared serpentine has the same origin as the more massive varieties.

To this point the serpentinization process is largely one of hydration, and, since the process appears to be a pseudomorphic replacement, some silica and magnetite, and perhaps also chromium, must have been re-



FIGURE 40.—Photomicrographs of serpentine derived from peridotite. Upper, Shows complete replacement of olivine and partial replacement of large pyroxene on left. Plane light. Lower, Partly replaced pyroxene consists of parallel growth of orthopyroxene (in extinction position) and clinopyroxene (narrow light bands) Crossed nicols.

moved from the rock. Additional changes, which have affected only isolated areas, consist of further veining with chrysotile and recrystallization of the serpentine minerals to platy antigorite accompanied by shearing. The widespread alteration of serpentine to form silica-carbonate rock is a radically different change, believed to have been caused by hydrothermal solutions having their source outside the serpentine. This alteration, which took place at a much later time than the original serpentinization, is treated at length on pages 58-64, after the description of the silica-carbonate rock.

Chemical composition

Chemical analyses of 3 serpentine rocks of the New Almaden district are shown in table 9, along with 3 other analyses of serpentine rocks from elsewhere in the Coast Ranges and a composite of 24 serpentines from other regions for comparison. The 3 analyzed rocks from the district are from the underground workings of the New Almaden mine and are unweathered. Two of them are from the central parts of large massive blocks and contain no megascopic veinlets of chrysotile; the third, which also contains no veinlets, is a minutely sheared variety of serpentine from the border of a large sill. The analyses show no significant difference between the blocks and the sheared matrix material, and thus confirm our belief that the matrix is merely a sheared part of the rock rather than a foreign material that has engulfed the blocks. Also worthy of note is the high water content, which indicates, as do also the thin sections, how complete has been the serpentinization of the original rock. Comparison of all the analyses suggests that the serpentines of the New Almaden district are representative of those in the California Coast Ranges, and that they are closely similar to the average of serpentines from other parts of the world represented in column 7.

Some partial chemical analyses of other serpentine rocks from the New Almaden district and nearby areas are shown in table 10. These would seem to indicate that the fresh serpentine from the mine contains a slightly greater amount of magnesium and less silica than the other apparently fresh samples of serpentine taken from the surface and shallow cuts.

Origin

The problem of the origin of such an unusually hydrous rock as serpentine has been one of the more

TABLE 9.—Analyses of serpentine rocks from the New Almaden district and from elsewhere in the California Coast Ranges, together with a composite of 24 serpentines from other regions for comparison

	1	2	3	4	5	6	7
SiO ₂	35.98	*36.43	37.36	39.98	36.57	40.50	39.48
Al ₂ O ₃	3.19	*3.04	*1.42	1.12	.95	.78	1.44
Fe ₂ O ₃	6.36	*3.68	*3.69	13.19	7.29	4.01	5.08
FeO.....	1.72	*3.72	*3.65	1.05	.37	2.04	2.74
MnO.....	.09	.09	.09	n.d.	.10	.13	
MgO.....	37.60	36.99	38.54	30.49	40.27	37.43	37.67
CaO.....	None	None	None	.46	.14	.39	.36
Na ₂ O.....	None	None	None	.28	.31	.28	.23
K ₂ O.....	None	None	None	.25	Trace	.16	.11
H ₂ O ⁺	14.16	15.00	13.50	13.26	12.43	10.94	11.48
H ₂ O ⁻94	2.81	.89
Cr ₂ O ₃.....	.29	*.38	.25	Trace	.33	.41	.38
CO ₂.....	.84	.54	.88	n.d.	n.d.	n.d.	n.d.
S.....	.04	.14	.07	n.d.	n.d.	n.d.	n.d.
NiO.....	†.2	†.2	†.1	n.d.	.31	.11	.17
TiO ₂	†.05	†.04	†.01	Trace	n.d.	n.d.	n.d.
Total.....	100.52	100.25	99.56	100.08	100.01	99.99	100.03

*Determinations made by J. J. Fahey, U. S. Geological Survey.

†Determined spectroscopically by K. J. Murata, U. S. Geological Survey.

NOTE.—Description of sample and locality as follows:

1. Unsheared fresh serpentine from the New Almaden mine, Santa Clara County, Calif. (Coordinates 1535 N.—5130 W., alt 1,183 ft.). F. A. Oonyer, analyst.
2. Unsheared fresh serpentine from the New Almaden mine, Santa Clara County, Calif. (Coordinates 2427 N.—4703 W., alt 974 ft.). F. A. Oonyer, analyst.
3. Sheared but not veined fresh serpentine from the New Almaden mine, Santa Clara County, Calif. (Coordinates 1610 N.—5100 W., alt 1,183 ft.). F. A. Oonyer, analyst.
4. Serpentine from the Mayaemas Range, near Missouri mine, Sonoma County, Calif. H. E. Kramm, analyst. From Kramm, 1910, p. 329.
5. Serpentine described as "bastite with fine seams of chrysotile" from Mount Diablo, Calif. W. H. Melville, analyst. From Turner, H. W., 1891, p. 406.
6. Serpentine from Mount Diablo, Calif. W. H. Melville, analyst. From Turner, 1891, p. 406.
7. Average of 24 serpentines of the "magma type." Average given is average of other average analyses from Massachusetts, Finland, Newfoundland, Southern Rhodesia, and Cuba, given by Hess, 1938, p. 330.

elusive problems of igneous and metamorphic geology for many years, and its solution is, of course, beyond the scope of this report (see Benson, 1918; Hess, H. H., 1933). Some suggestions as to what seems to be the most probable origin of the serpentine bodies in the district, however, are justified, even if they serve only to indicate that many features of these bodies as exposed in the California Coast Ranges are not yet en-

TABLE 10.—Partial analyses of serpentine rocks from the New Almaden district and adjacent area

[All analyses by Permanente Cement Co.; provided through courtesy of Messrs. E. A. Hassan, Jr., and W. R. Woodman. Analysts unknown]

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	44.9	44.0	42.7	42.4	41.9	41.4	41.4	41.13	40.5	40.5	42.1
Al ₂ O ₃	1.1	1.9	1.7	.9	1.4	2.2	1.0	8.27	2.6	10.9	1.6
Fe ₂ O ₃ *.....	7.6	7.2	7.5	7.9	8.3	8.4	8.0	8.5	8.5	10.9	7.9
MgO.....	34.5	27.7	33.5	32.0	31.1	32.2	32.1	36.12	30.7	31.9	32.2
CaO.....	n.d.	1.6	n.d.	n.d.	n.d.	n.d.	n.d.	.60	2.2	†.9	1.4
H ₂ O ⁺	11.4	16.3	14.2	15.4	16.6	14.7	15.6	11.82	14.2	16.0	14.8
H ₂ O ⁻5	4.7	2.5	3.8	5.1	2.4	4.2	1.88	3.0		
Total.....	100.0	103.4	102.1	102.4	104.4	101.3	102.3	99.82	101.7	100.0	100.0

* Total Fe reported as Fe₂O₃, which results in totals being too high.

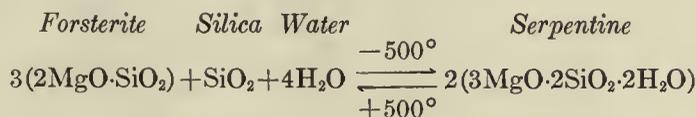
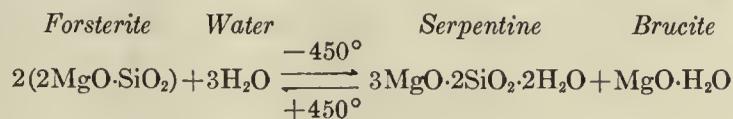
† Reported as "rest."

NOTE.—Description of sample and locality as follows:

1. Fresh massive serpentine from large mass at mouth of Almaden Canyon. Contains some unaltered enstatite, auzite, olivine, and picotite.
2. Highly sheared but fresh-appearing serpentine from railroad cut on north side of Tulare Hill, in northeast corner of the New Almaden district.
3. Sheared serpentine from 1 mile northwest of Coyote Peak, New Almaden district.
4. Fresh massive bastite serpentine block embedded in sheared matrix; from hill north of Edendale, 2 miles north of central part of New Almaden district.
5. Serpentine from Hillsdale area, north of the New Almaden district.
6. Highly sheared serpentine from margin of mass at mouth of Almaden Canyon.
7. Massive bastite block and sheared serpentine matrix from Hillsdale area, north of the New Almaden district.
8. Sheared serpentine from one-half mile east of Quadautpe mine.
9. Bulk analysis of serpentine quarried from north side of large intrusive body at mouth of Almaden Canyon.
10. Average of 1-10; H₂O⁻ omitted.

tirely explained and are well worth further study.

The chemical reactions involved in the formation of serpentine are relatively simple. They can most easily be shown by equations based on reactions involving the pure magnesium member of the olivine group, forsterite; and although the natural olivine occurring in dunite or peridotite does contain some iron, its pres-



Bowen and Tuttle's experiments were performed at pressures as much as 40,000 pounds per square inch, equivalent to the lithostatic pressure at a depth of about 6 miles. In this range, each of the reactions takes place near the indicated temperature, with pressure having very little effect, suggesting the temperature of the reaction would be little changed even at greater pressure or depth. Two important conclusions can be drawn from these equations, namely:

1. Serpentine cannot exist at temperatures appreciably above 500°C, or in the presence of excess magnesia above 450°C.
2. Forsterite by hydration alone forms serpentine and brucite, but with the addition of silica (or loss of magnesia) forms serpentine. If volume relations remain equal, as in the direct replacement of forsterite by serpentine, both magnesia and silica must be removed.

Three different theoretical conditions for the state of the serpentine bodies when intruded would seem to be possible, and each of these has been proposed for serpentines in other areas (Benson, 1918). First, the material may have been a liquid or partly crystallized ultramafic magma, which, after solidification to peridotite, became hydrated in place by solutions either having their origin in deeper parts of the magma chamber, or in the adjacent wall rocks, or in a completely unrelated younger magma. Second, the material may have been intruded at a low temperature as an extremely hydrous magma which crystallized either directly or indirectly through an olivine stage to serpentine, without the addition of water (Hess, 1938, p. 321-344 and Sosman, 1938, p. 353-359). And third, the serpentine bodies may have been injected plastically as serpentine forming the so-called "cold intrusions" (Clark, B. L., 1935, p. 1060, 1074; Bailey, 1942,

ence will not alter the conclusions presented below.

The pressure-temperature fields of stability of the minerals in the MgO-SiO₂-H₂O system have been investigated by Bowen and Tuttle (1949, p. 439-460), and their results provide important data regarding the reactions of forsterite and water. The two pertinent equations are as follows:

p. 150-151; Bailey, 1946, p. 211; and Eckel and Myers, 1946, p. 94).

The first of these possibilities, involving the emplacement of a peridotitic magma, its solidification in place, and its subsequent hydration, has been accepted by many for the serpentine bodies in the California Coast Ranges (Kramm, 1910, p. 315-349) and seems to be required to explain the few masses which show differentiation banding. It also has been believed by some to explain satisfactorily the prevalent blocky variety of serpentine if one invokes expansion during the hydration process to account for the internal shearing in the masses (Taliaferro, 1943b; p. 154-155). The source for the water, if considered at all, is generally regarded to be the same magma, for in most parts of the Coast Ranges there are no other intrusive rocks that can supply the large quantity of water required.

Many objections to this theory of origin have been raised. One of them is that the melting point of peridotite is so high that a peridotite magma would be expected to produce widespread metamorphic effects in the surrounding rocks, whereas these effects are generally lacking. The temperature of such a magma would be about 1,400°C (Daly, 1933, p. 67), although it has been pointed out that the presence of abundant water or other mineralizers would lower this perhaps a few hundred degrees. Such mineralizers, however, if present, would presumably migrate at least to a small extent into the wallrocks, and therefore would promote the development of metamorphic aureoles around the serpentine bodies.

Any proposed source for the water can likewise be countered by objections in the light of experimental work by Bowen and Tuttle (1949, p. 439-460). If the water were included in a peridotite magma, on cooling to a temperature of 900°C the rock would be

completely crystallized as enstatite and olivine, and water remaining could only be in the vapor phase. It would, therefore, seem impossible for enough water to remain in the pore space of the rock, even if it consisted of loosely packed crystals, to produce more than incipient serpentinization, whereas the New Almaden rocks are thoroughly serpentinized. If the water were slowly added from deeper seated parts of the magma chamber, one might expect the serpentinization to be more complete; but one would also expect it to be most complete in structural traps or in places where the rock was excessively sheared. No such distribution of more and less serpentinized rock is apparent, however, in this district; all the serpentine bodies, regardless of size or degree of shearing, are serpentinized to about the same degree.

Younger intrusive rocks of appropriate age are lacking and cannot be depended upon as the source for the water. Assimilation of water from the surrounding sediments, which are notable for their lack of porosity and permeability, seems also unlikely, especially in sufficient quantity to serpentinize masses hundreds of feet thick. Moreover, unless the water were charged with silica, its reaction with olivine would form brucite as well as serpentine, not serpentine alone (Bowen and Tuttle, 1949, p. 452).

Many phenomena seem to forbid our invoking expansion by hydration to account for the internal shearing in the masses. As has been pointed out, the blocks in the serpentine bodies are massive and unsheared, and show pseudomorphic textures after peridotite with apparently unrotated remnants of olivine crystals, which would seem scarcely possible if expansion were effective. To obtain serpentine from peridotite this pseudomorphism, of course, requires a loss of material, principally magnesia and some silica, and the process is therefore one of replacement rather than simply hydration. Inasmuch as the matrix of sheared serpentine has exactly the same chemical composition as the blocks it encloses, it becomes unreasonable to suppose that the matrix owes its origin to a simple hydration process involving expansion, rather than to the same replacement process that formed the serpentine of the blocks. Other objections to the proposed expansion in place are found in the lack of local outward bulges along the contacts, and in the complete absence of any veinlets of serpentine minerals in the bordering wall-rock, such as might be expected to result from the squeezing out of any residual liquid by the expansion process.

Intrusion of low-temperature serpentine magma has been shown by Bowen and Tuttle (1949, p. 453) to be impossible. It was also discarded by us because it

failed to explain the internal structures of the serpentine bodies.

The theory of origin that best fits our observations assumes that the serpentine masses were plastically injected as serpentine. This allows two possibilities. The material may have begun its upward migration as a crystal mush resulting from the cooling of a magma, and have been serpentinized during intrusion by loss of temperature concurrent with hydration by absorption of water from the surrounding rocks. Or, as appears more likely, the serpentine masses may represent plastic injections from a deeper seated mass, which had the composition of peridotite but had already been serpentinized.

The writers visualize the serpentine as having formed from solid peridotite at an unknown depth, largely by a process of replacement involving the escape of large amounts of magnesia and some silica into the walls of the surrounding chamber. Subsequently the serpentine mass was broken up and squeezed plastically into its present positions. An exceedingly small amount of the serpentinization probably did take place, however, after the brecciation of the rock; this is indicated by the peripheral development of serpentine minerals in small fractures around the margins of the blocks, generally at right angles to their margins but locally parallel to them.

This concept is believed to explain adequately the hydration of all the serpentine, regardless of the size of the body in which it occurs or of position within the body. It explains the textures of the unsheared blocks, which could only have formed in a solidified rock, and it further permits the differentiation banding seen in some of the blocks. This concept also explains the general lack of either thermal or hydrothermal alteration along the walls of the intrusive bodies, for the temperature must have been less than 500°C, above which serpentine cannot exist. It will account for the blocky structure of the inner parts of the larger bodies, the more sheared condition of their margins, and the thorough shearing of the smaller bodies.

That serpentine is capable of plastic intrusion is shown by the known examples of "cold intrusions" of serpentine into some of the younger rocks of the Coast Ranges, by its ability to form extensive slides on surfaces with a low angle of slope, and by the way the floors and walls of some mine workings in serpentine even at relatively shallow depths tend to move inward. The degree of plasticity required for the intrusion of the serpentine masses, particularly the small tongues and apophyses bordering some of the larger masses, is perhaps the chief objection to this concept, and is

something that should be determined experimentally. From the chemical nature of the rock, however, it seems not at all unlikely that the conversion of a minute fraction of the serpentine to magnesium-silicate gel may perhaps aid the intrusion by acting as a lubricant.

Age

The age of the serpentine bodies in the California Coast Ranges has been variously placed by geologists who have worked in different parts of the region. In addition, serpentine was formerly treated as an integral part of the Franciscan group, much as the greenstones are treated, chiefly because it is particularly common in areas of rocks assigned to the Franciscan group.

Taliaferro (1943b, p. 153) has noted serpentine in the late Upper Jurassic Knoxville formation, but Anderson (1945, p. 956-957) maintained that the serpentine masses in the Knoxville formation were all plastically injected. Yates and Hilpert (1946, p. 239) have shown that Knoxville sedimentary rocks contain detrital serpentine and are also invaded by serpentinized peridotite, and they conclude that there were serpentine intrusions of at least two ages. Near Wilbur Springs, in southern Colusa County, in the Lower Cretaceous Paskenta formation there are extensive sedimentary beds hundreds of feet thick consisting almost wholly of serpentine detritus. These are most easily explained by the extrusion of serpentine onto the sea floor during Early Cretaceous time. Still younger rocks have been invaded by serpentine elsewhere in the Coast Ranges (Clark, B. L., 1935, p. 1060, 1074; Bailey, 1942, p. 150-151; and Eckel and Myers, 1946, p. 94).

Injections of serpentine into the younger rocks of the Coast Ranges are generally believed to be plastic injections, but the intrusions into the older rocks are commonly believed to represent intrusions of molten magma. Because the writers believe that it is likely most of the older serpentine bodies were injected plastically as serpentine, rather than as peridotitic magma, the time of intrusion is believed to be dependent upon orogenic forces rather than the time when molten magma was available. On this hypothesis, once the serpentine is formed at depth it is available for intrusion at any time thereafter, although, of course, through geologic periods the thickening of the overlying cover by sedimentation makes its injection from the substructure to high levels increasingly less likely. However, previously injected serpentine may be later remobilized, and in the New Almaden area there is some evidence that this has taken place.

GABBROS AND RELATED ROCKS

The intrusive body lying along the main divide south of Mount Umunhum and shown on the map of the district as serpentine contains perhaps as much gabbroic rock as serpentine. The gabbroic rocks are partly serpentinized themselves and are so intricately intermixed with the normal serpentines that mapping them as a separate unit, if it could have been done at all, would have required more time than it seemed to be worth. Because these gabbroic rocks are of rather small extent, they have not been studied in any great detail.

Areas underlain by the gabbroic rocks have a distinctive appearance. They generally have a rather subdued topography, are covered with a moderately dense growth of brush in which manzanita predominates, and are overlain by a deep reddish soil. Large rounded boulders of relatively fresh rock protrude from the soil here and there, and, particularly on gentle slopes, smaller boulders and pebbles tend to form a surficial pavement. Natural exposures of rock in place are scarce, but some good exposures are afforded by road cuts. Here the gabbroic rocks may be seen to vary widely in both texture and mineral content within a few feet or even inches. Some patches are fine grained, others are coarse grained, and still others have a pegmatitic texture and contain large poikilitic crystals of pyroxene or hornblende. The rocks range in color from white to deep green or nearly black, depending on the amount of feldspar, intermediate varieties being speckled or mottled. A single exposure may show nearly all these variations, and in some places the rocks are distinctly banded, different minerals being concentrated in either layers or concentric zones. In most exposures they are also cut by autoinjection dikes, which tend to be somewhat more feldspathic than the average gabbro.

The principal minerals that can be identified with a hand lens are feldspar, pyroxene, hornblende, serpentine minerals, and mafic accessories, such as magnetite, chromite, and picotite. A limited amount of microscopic study showed that the original feldspars were calcic labradorite and bytownite, and that the other common minerals were olivine, augite, and hornblende. Virtually all the original minerals have been altered in varying degrees. The plagioclase is not highly altered in most sections; in some, however, it is saussuritized, and in others fine-grained secondary albite forms a "groundmass" between the larger grains. The serpentine minerals antigorite and serpophite have replaced the olivine to such an extent that only a few residual cores of olivine were noted. A few

sections contain considerable fine-grained chlorite. The genetic relation between the gabbroic rocks and the serpentine remains an unsolved problem, but the two rocks do not appear to have formed by any sort of segregation in place.

SILICA-CARBONATE ROCK

"Silica-carbonate rock" is the term applied in this report to a rock that is derived from serpentine by hydrothermal alteration and is composed principally of silica (quartz, or chalcedony, or opal) and a carbonate (generally ferroan magnesite). This rock is of special importance in the New Almaden district, as in many other quicksilver districts in the Coast Ranges, because it is the host rock of all the more productive bodies of quicksilver ore. The different varieties that occur in California are variously referred to by miners as "vein rock," "ledge matter," "quicksilver rock," "ore rock," "opalite," "opaline," and "silica-carbonate rock." Because many of these terms have been used to apply to other kinds of rocks, it is fortunate that the most acceptable term, "silica-carbonate rock," is also the most widely used. The term generally has been applied only to rocks derived from serpentine, but in recent years, "silica-carbonate rock" has also been applied elsewhere (Faust and Callaghan, 1948, p. 11-74) to rocks of different origin and mineral composition.

Distribution

The distribution of the silica-carbonate rock in the New Almaden district is much more restricted than that of the serpentine bodies from which it is derived. (See pl. 1.) Most of the outcrops of silica-carbonate rock are scattered along the Los Capitancillos Ridge, in a zone that includes Mine Hill and extends north-westward 1 mile beyond the Guadalupe mine. A second zone of outcrop, less continuous and partly covered, diverges from the first one east of the Senator mine and extends eastward across the valley of Alamos Creek into the Santa Teresa Hills. The first of these zones contains all the highly productive mines of the district; the second, although it contains some cinnabar, is little prospected. A third zone, containing only small pods of silica-carbonate rock, extends along the north side of the Santa Teresa Hills, where it has yielded a little quicksilver at the Santa Teresa and Bernal mines.

Not only is the silica-carbonate rock restricted to the serpentine bodies lying in these zones, but it is even further restricted to certain parts of them. Although some small serpentine bodies that are thin and sheared are completely replaced, the thicker, more massive ones

are generally replaced only along their sheared margins and have, in effect, an armorlike shell of the hard silica-carbonate rock. There is no relation between the size or thickness of the serpentine bodies and the thickness of the shell of silica-carbonate rock developed around them, nor is there any relation between the thickness or extent of the shell and the occurrence of quicksilver ore. The largest exposed body of silica-carbonate rock—the one that lies north and west of the Guadalupe mine—is perhaps 1 mile long and a few hundred feet wide, but it is sparsely mineralized only here and there. On the other hand, many small bodies of silica-carbonate rock, as well as some of intermediate size, contain extensive bodies of minable quicksilver ore. It must therefore be concluded that small bodies are as likely to contain ore as larger ones. Furthermore, the distribution of the silica-carbonate rock from the surface downward does not show any marked change within the depths explored by the mines. In the New Almaden mine a remarkably large amount of silica-carbonate rock is found in the upper levels, where the serpentine sills are fairly flat, but, according to the company records, large masses of "vein rock" were also cut in workings lying as much as 500 feet below sea level, or 1,750 feet directly below the present erosion surface.

Megascopic features

The silica-carbonate rock varies widely in appearance, but most of it is readily recognized because of its pseudomorphic textures inherited from serpentine and because of its areal relation to serpentine masses. The variations in the silica-carbonate rock result partly from original differences in the mineralogy and texture of the parent serpentine and partly from variation in the kind and grain size of the replacing silica and carbonate minerals. In the silica-carbonate rock of the New Almaden district the silica is nearly all quartz; opal and chalcedony are so uncommon that in a general description they can be disregarded. In addition, the source rock is mainly peridotite, and silica-carbonate rocks derived from dunite are too uncommon to merit more than a brief mention. The principal variations in the rock in this district, therefore, depend chiefly on the quantity of shearing in the original serpentine, on the coarseness of the component minerals, and on the relative abundance of quartz and carbonate.

Most of the silica-carbonate rock is derived from the sheared serpentine, and in many places it retains the sheared structure and also contains residual unaltered minute crystals of chromite or picotite. Where fresh, silica-carbonate rock of this origin has a lenticular



FIGURE 41.—Silica-carbonate rock derived from sheared serpentine. The white veinlet is dolomite. This specimen is typical of the rock that is the host for nearly all the quicksilver ore bodies in the district.

lar or streaked-out appearance, although it shows very little tendency to break parallel to the shear planes inherited from the serpentine. (See fig. 41.) Locally, it may show textures interpreted as resulting from complete replacement of chrysotile veinlets or bastite pseudomorphs, but more commonly these textures have been removed by shearing before the alteration of the serpentine. The different lenticules and streaks are generally gray and green of various shades, and the sheared texture is accentuated by veining with light-colored dolomite or quartz. Hence the overall color of most of the silica-carbonate rock is green or greenish gray, but an unusually siliceous kind found only west of the Guadalupe mine is almost black. The hardness and mode of fracturing of the rock depend upon the proportion of silica to carbonate, and in a

less degree upon their grain size and distribution. Carbonate-rich rock resembles fine-grained marble, being fairly soft and having an irregular fracture, whereas rock rich in silica is more like chert, being hard and having a relatively smooth conchoidal fracture. The more common intermediate varieties are in most places surprisingly hard and tough, but they break with a rough fracture.

Weathering generally makes a radical change in the appearance of the silica-carbonate rock, because the ferroan magnesite is removed by weathering, leaving only hydrated ferric oxides and silica. All degrees of exposure are seen in the district. In a few places, where the weathered rocks contained little silica, they do not crop out at all, but instead give rise to an ochreous soil containing only a few siliceous

fragments. Such material, as seen in shallow adits or opencuts, is a porous, locally brittle ocher, not easily recognized. Siliceous skeletons of bastite pseudomorphs or vaguely lenticular textures are discernible in places, and nearly everywhere the ocher will yield chromite or picotite if panned. Where the rock is somewhat more siliceous, it crops out as white to brown rounded boulders having pitted surfaces, due to the carbonate having been removed and a framework of silica left behind. As might be expected, the blocky siliceous variety of silica-carbonate rock forms prominent knobs or ledges.

Silica-carbonate rock, derived from blocky serpentine is not abundant, but excellent exposures of it can be seen in the Day tunnel of the New Almaden mine, about 2,000 feet from its portal. Here the walls are unevenly encrusted with various white secondary salts in a manner that brings out the structure of the rock. Where the walls are not too heavily coated, one can see every small detail of the sheared matrix and un-sheared blocks nearly as well as in the best exposures of unaltered blocky serpentine, even though the serpentine is completely converted to a hard variety of silica-carbonate rock. The part derived from the sheared matrix is similar in all respects to the silica-carbonate rock previously described, but that derived from the un-sheared blocks retains a porphyritic appearance resulting from the selective replacement of the bastitic pseudomorphs occurring in the serpentine. In some of the blocks, however, the serpentine derived from olivine is largely replaced by fine-grained gray magnesite, and the accompanying bastite pseudo-

morphs are replaced by more coarsely crystalline white carbonate enclosing a bright-green platy mineral, probably a chlorite. In such rock the pseudoporphyritic texture is very pronounced because of the color contrast between the grayish "groundmass" and the pale apple-green "phenocrysts" (fig. 42). A few blocks of fine-grained silica-carbonate rock that has replaced serpentine derived from dunite were found in the same general part of the Day tunnel, and in these it was possible to distinguish a mesh texture inherited from the serpentine. Such examples of silica-carbonate rocks derived from massive serpentine are unusual and of small extent. They are of special interest, however, because of what they reveal about the process through which the silica-carbonate rock was formed. It replaced the serpentine with so little volume change that no effects due to expansion or contraction are apparent.

Microscopic features

Thin sections that show all stages of alteration from serpentine to silica-carbonate rock were examined. Those sections showing the least replacement contain in addition to the serpentine minerals only a little carbonate, whereas sections that show more advanced alteration contain quartz as well as carbonate and little or no serpentine. Although the alteration does not everywhere take place in the same way, the following statements will describe the general process as inferred from a study of the entire suite of sections. To show most clearly how some of the serpentine minerals are replaced before others, the rock derived from the un-sheared serpentine is described first, even though it is not the most common variety.

The alteration of un-sheared serpentine begins with the crystallization of magnesite in the mesh of antigorite and chrysotile that has replaced olivine. This carbonate first forms a network of irregular veinlets, which have ragged edges because the crystals grow outward from cracks as replacement of the serpentine advances. (See fig. 43.) The bastitic pseudomorphs are not generally attacked at this stage, but in places the carbonate fills narrow sharply bordered cracks that traverse them. The larger veins of chrysotile, on the other hand, are especially susceptible to replacement by a carbonate that retains a fibrous aspect even though it is actually in rather equant crystals. (See fig. 44.) Further alteration of the serpentine results in rosettes of magnesite in the serpoplite cores of the mesh and in the bastite pseudomorphs, and at the same time the meshwork of carbonate becomes better defined and coarser. With continued alteration more carbonate may be added, but a more striking change



FIGURE 42.—Polished surface on silica-carbonate rock derived from slightly sheared serpentine. The light areas on the left are pseudomorphs after crystals of pyroxene.



FIGURE 43.—Photomicrograph of altered serpentine showing early stage of development of silica-carbonate rock in which magnesite (dark) has replaced the chrysotile veinlets and a little of the fibrous antigorite bordering them.



FIGURE 44.—Photomicrograph of magnesite replacement of thick veins of chrysotile; note typical fibrous aspect of the carbonate thus formed.

is the replacement of the remaining serpentine by quartz. The earliest quartz fills in between the carbonates as an aggregate of minute grains with rounded outlines, but in a more advanced stage of alteration the quartz recrystallizes into larger crystals showing many straight sharp crystal faces. (See fig. 45.) Where alteration has been very intense, as in some of the ore bodies, quartz locally replaces the carbonate, and both late quartz and dolomite fill small fractures in the silica-carbonate rock. The magnetite of the serpentine disappears at an early stage, the iron doubtless being incorporated into the ferroan magnesite;

but chromite or picotite generally remains unaltered.

The alteration of sheared serpentine to silica-carbonate rock probably is a very similar process, although the selectivity of the replacement is not so marked (fig. 46). As in the unsheared serpentine, replacement by carbonate takes place first along fractures, but here the more open fractures are generally those that have resulted from shearing, rather than from the original replacement of the olivine by ser-

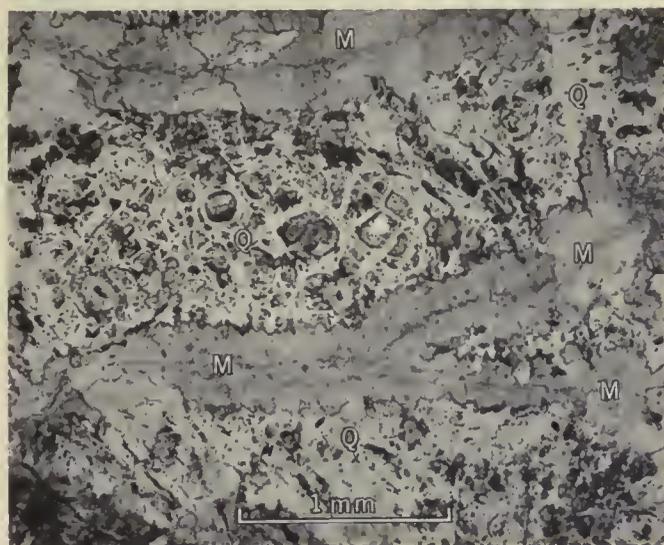


FIGURE 45.—Photomicrograph of silica-carbonate rock derived from serpentine that was derived from dunite. Coarse veins are magnesite (M); remainder is largely quartz (Q) with finely divided dark iron oxides. Note the meshwork typical of replacement of olivine by serpentine minerals is now outlined by the iron oxides in the quartz.

pentine minerals. Again the carbonate replacement is followed, and also partly overlapped, by replacement by quartz, the earliest quartz being very fine grained and the latest coarse.

Chemical composition

Chemical analyses of some silica-carbonate rocks, and of parts of the unaltered serpentine bodies from which they were derived, are given in tables 11 and 12. These show the silica-carbonate rock to be composed chiefly of about 35 percent silica and 60 percent magnesium carbonate, with several percent of picotite or chromite. The analyzed sample of silica-carbonate rock is typical of that in which most of the ores have been formed and represents the most common variety in the district. Some of the rock, of a kind best seen west of the Guadalupe mine and everywhere barren, would show on analysis a much larger percentage of silica and less magnesite. Where carbonate is especially abundant an appreciable part of it may be dolomite rather than magnesite, as such occurrences of

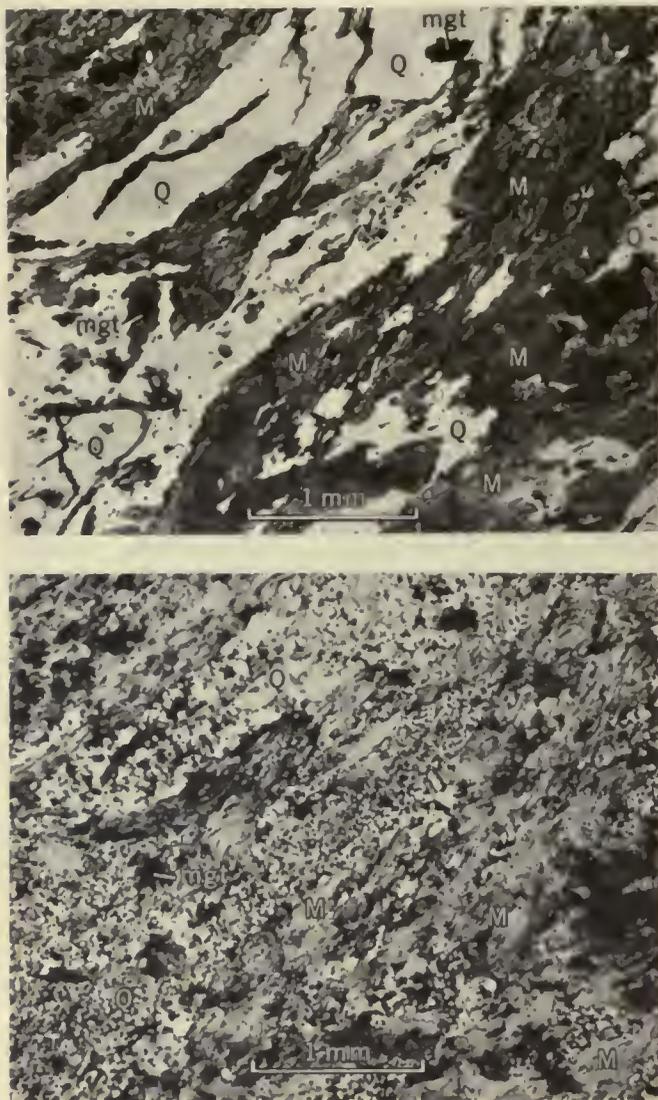


FIGURE 46.—Photomicrographs of silica-carbonate rock derived from sheared serpentine. Magnesite (M), Quartz (Q), and magnetite (mgt). Section also contains minute needles of millerite too small to show in the photomicrographs. Upper, Plane light. Lower, Crossed nicols.

dolomite have been reported in other quicksilver districts. This, however, is probably uncommon, for these rocks are derived, by simple carbonatization, from serpentines containing little or no calcium.

Considerable dolomite is present in the "dolomitic transitional rock" of tables 11 and 12. This rock, which is coarsely crystalline and relatively incoherent, occurs in the New Almaden mine only between the unaltered serpentine and the normal variety of silica-carbonate rock, and because of this relationship it was regarded as representing an intermediate stage in the alteration and was mapped as a "transitional rock." The chemical analyses, however, show that the rock is not intermediate in chemical composition, as

was first supposed, for it has an abnormally high content of lime and low content of silica. It was probably formed in a late stage of rock alteration, during which

TABLE 11.—Analyses of rocks from the New Almaden mine showing change from serpentine to cinnabar-bearing silica-carbonate rock

	1	2	3	4	5
	Massive serpentine	Sheared serpentine	"Dolomitic transitional rock"	Barren silica-carbonate rock	Silica-carbonate rock with cinnabar
Major elements determined chemically					
[All analyses by F. A. Conyer except those marked (*), which are by J. J. Fahey, U.S. Geological Survey]					
SiO ₂	35.98	37.36	3.36	35.32	34.78
Al ₂ O ₃	3.19	*1.42	1.04	.84	.72
Fe ₂ O ₃	6.36	*3.69	1.11	1.74	2.06
FeO.....	1.72	*3.65	3.56	3.70	3.08
MnO.....	.09	.09	.03	.08	.09
MgO.....	37.60	35.54	23.14	25.87	26.14
CaO.....	None	None	22.46	.98	1.56
Na ₂ O.....	None	None	None	None	None
K ₂ O.....	None	None	None	None	None
H ₂ O ⁺	14.16	13.50	1.73	.37	.64
CO ₂.....	.84	.88	42.74	30.34	30.22
P ₂ O ₅	None	None	None	None	None
S.....	.04	.07	n.d.	n.d.	.61
Cr ₂ O ₃.....	.29	.25	.18	.15	.16
SO ₃	None	n.d.	.45	.64	n.d.
Total.....	100.27	99.45	99.80	100.03	100.06

Minor elements determined spectrographically

[K. J. Murata, U.S. Geological Survey, analyst. Elements sought but not found: Au, Ag, Pt, Pd, Be, Zn, Cd, Ge, In, Tl, Ph, Sn, La, Y]

Cu.....	0.002	0.001	-----	-----	0.001
Ni.....	.2	.1	0.09	0.1	.09
Co.....	.005	.005	.003	.005	.004
TiO ₂.....	.05	.01	.02	.006	.01
ZrO ₂	-----	-----	-----	-----	.003
SrO.....	-----	-----	.3	.002	.005
BaO.....	<.001	<.001	.002	.001	.002
B ₂ O ₃.....	.04	.03	-----	.01	.01

Location of samples referred to mining company coordinates:

1. 1535 N.-5130 W.; alt 1,183 ft.
2. 1610 N.-5100 W.; alt 1,183 ft.
3. 1650 N.-5080 W.; alt 1,183 ft.
4. 1660 N.-5075 W.; alt 1,183 ft.
5. 1685 N.-5035 W.; alt 1,183 ft.

the open fractures in the silica-carbonate rock were filled with dolomite. As it is present only locally and nowhere contains any ore, it has been included with the serpentine on the composite geologic maps of the New Almaden mine (pls. 5-10).

Origin

The process whereby serpentine is converted to silica-carbonate rock has already been partly implied in the description of the microscopic features of these rocks. It is chiefly a replacement process, wherein the structures of the serpentine are retained during the conversion of serpentine to a mixture of quartz and magnesite. The process is not, however, entirely a simple molecular replacement; for at an early stage the crystals of both magnesite and quartz become too large to preserve the finest serpentine structures that can be seen in thin sections, and, moreover, a limited

TABLE 12.—Analyses of rocks from the New Almaden mine showing change from serpentine to silica-carbonate rock

	1	2	3
	Massive serpentine	"Dolomitic transitional rock"	Silica-carbonate rock
Major elements determined chemically			
[All determinations by F. A. Gonyer, except those marked (*), which are by J. J. Fabey, U.S. Geological Survey]			
SiO ₂	*36.43	27.64	31.22
Al ₂ O ₃	*3.04	3.44	.94
Fe ₂ O ₃	*3.68	3.74	2.22
FeO.....	*3.72	5.22	2.58
MnO.....	.09	.07	.08
MgO.....	36.99	31.86	28.78
CaO.....	None	2.42	.04
Na ₂ O.....	None	None	None
K ₂ O.....	None	None	None
H ₂ O ⁺	15.00	10.03	.59
CO ₂.....	.54	15.04	33.16
P ₂ O ₅	None	None	None
S.....	.14	Trace	.02
Cr ₂ O ₃	*.38	.36	.24
SO ₃	n.d.	n.d.	n.d.
Total.....	100.01	99.82	99.87

Minor elements determined spectrographically

[K. J. Murata, U.S. Geological Survey, analyst. Elements sought but not found Au, Ag, Pt, Pd, Be, Zn, Cd, Ge, In, Tl, Pb, Sn, La, Y]

Cu.....	0.002	0.004	.....
Ni.....	.2	.2	0.08
Co.....	.006	.009	.004
V ₂ O ₅.....	.007	.008	.....
TiO ₂.....	.04	.09	.008
ZrO ₂.....	.....	.....	.....
SrO.....	.....	.008	.003
BaO.....	<.001	.001	.002
B ₂ O ₃.....	.05	.01	.02

Location of samples referred to mining company coordinates:

1. 2427 N., -4703 W.; alt 974 ft.
2. 2410 N., -4710 W.; alt 975 ft.
3. 2385 N., -4725 W.; alt 980 ft.

TABLE 13.—Average chemical composition of serpentine and silica-carbonate rock from the New Almaden mine, together with calculations to show chemical changes involved in the formation of silica-carbonate rock from serpentine

	1	2	3	4	5
	Serpentine	Silica-carbonate rock	Percent X sp gr serpentine	Percent X sp gr silica-carbonate rock	Gain or loss serpentine to silica-carbonate rock (g per cc)
SiO ₂	36.59	33.77	90.01	95.23	+5.22
Al ₂ O ₃	2.55	.83	6.27	2.34	-3.93
Fe ₂ O ₃	4.54	2.01	11.16	5.67	-5.49
FeO.....	3.03	3.12	7.45	8.80	+1.35
MnO.....	.09	.08	.22	.23	-.01
MgO.....	37.71	26.93	92.77	75.94	-16.83
CaO.....	None	.86	.00	2.43	+2.43
H ₂ O.....	14.22	.53	34.98	1.49	-33.49
CO ₂.....	.75	31.24	1.84	88.10	+86.26
Cr ₂ O ₃.....	.31	.18	.76	.51	-.25
Total.....	99.79	99.55			
Avg sp gr.....	2.46	2.82			

1. Average of 3 serpentines: 1 and 2 of table 11 and 1 of table 12.
2. Average of 3 silica-carbonate rocks: 4 and 5 of table 11 and 3 of table 12.
3. Column 1 X Avg sp gr of 2.46.
4. Column 2 X Avg sp gr of 2.82.
5. Column 4 minus 3.

SERPENTINE
Sp gr=2.46

SILICA-CARBONATE ROCK
Sp gr=2.82

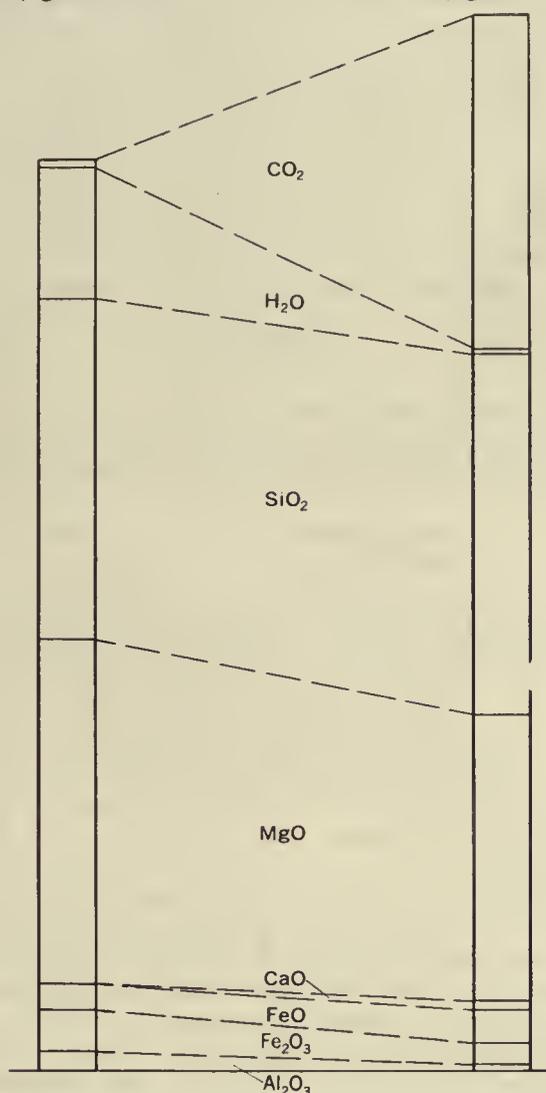
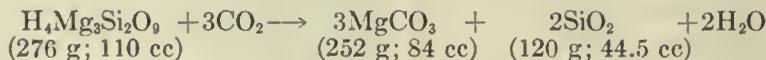


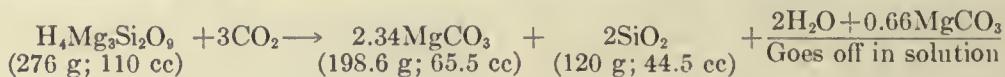
FIGURE 47.—Diagram showing gains and losses by weight of principal oxides in hydrothermal alteration of a unit volume of serpentine to silica-carbonate rock, assuming volume for volume replacement.

amount of migration of the constituents is indicated by the arrangement of the replacing minerals. Nevertheless, the preservation of the larger textures and structures indicates there has been no appreciable change in volume, and a consideration of chemical analyses along with specific gravities shows that in spite of limited migrations the change is principally one of simple dehydration and carbonatization. The chemical changes are shown in table 13 and also in figure 47. Columns 1 and 2 of the table present the averages of three analyses of serpentine and of silica-carbonate rocks derived from nearby parts of the same serpentine bodies. As the specific gravity of serpentine and silica-carbonate rock is different, columns 3

and 4, based on percentage times the average specific gravity of the rocks, show the relative amounts of the various oxides present in a unit volume of the average rocks. Column 5 shows the gains and losses of the oxides involved in the change from serpentine to silica-carbonate rock, and the same is presented graphically in figure 47. It is readily apparent that the principal changes are loss of water and a gain of carbon dioxide, but there is also some loss of magnesia. Other minor changes indicated are a loss of aluminum and ferric iron and a gain of silica and ferrous iron,



If the process were strictly one of replacement, however, the quantities indicated on the right side of the equation would be too large, and it is necessary to assume that



Using the values given and the amount of magnesium carbonate in the average silica-carbonate rock (column 2, table 13), one obtains a theoretical amount of 34 percent silica if only magnesium is lost and there is no volume change. This agrees so closely with the analytical value of 33.77 percent that there can be little doubt that the process of replacement of serpentine by magnesite and quartz also involved a loss of magnesium.

That the solutions responsible for the conversion of serpentine to silica-carbonate rock are not genetically related to the serpentine itself is indicated by two lines of evidence (1) the distribution of the silica-carbonate rock relative to the serpentine bodies in the district and (2) the age relations of the two. The geologic map of the district (pl. 1) shows that the silica-carbonate rock is virtually confined to two of the serpentine zones, in both of which it is abundant; the map shows also that some of the largest areas of serpentine are not accompanied by silica-carbonate rock. If the rock were formed by solutions that had their source in the serpentine or a related magma body, one might expect it to have a more widespread and regular distribution. Furthermore, the serpentine was largely intruded in the Late Cretaceous, whereas the silica-carbonate rock was not formed until after the middle Miocene.

Age

The determination of the age of the silica-carbonate rock is based in part on the abundance of pebbles and boulders of serpentine, without accompanying silica-carbonate rock, in a conglomerate of middle Miocene

although these changes are so small that they might be due to sampling errors or an insufficient number of analyses. Some calcium also has been added, but this was largely introduced in late veinlets of dolomite. The calcium, therefore, represents an addition, rather than an essential part of the reactions involved in the conversion of serpentine to silica-carbonate rock.

This conversion of serpentine to magnesite and quartz can be represented by the following equation (after Turner, F. J., 1948, p. 135):

silica or magnesium, or both, have gone off in solution. As the foregoing chemical analyses suggest the loss of magnesium, the equation may be revised as follows:

age exposed in a road cut about 5,000 feet southwest of the summit of Mine Hill. Supporting evidence is afforded by a small contorted mass of unbroken silica-carbonate rock enclosed by Miocene shale, exposed in a roadcut about 5,000 feet west of the bend in Guadalupe Canyon below the Guadalupe mine. This mass of silica-carbonate rock is believed to have formed after the injection of serpentine into the shales, for it is hard to imagine how so brittle a rock could have been so extremely contorted without being shattered. The contortion probably took place in the serpentine before it was altered.

The upper limit to the age of the silica-carbonate rock can be placed only relatively to the quicksilver ores, which are believed to be Pliocene in age. Between the formation of the silica-carbonate rock and the formation of the ores contained in it the rock was extensively fractured, but whether or not this resulted from forces applied during a long-extended period of hydrothermal alteration, responsible for the formation of the host rock and in its later stages the ores, could not be determined.

OTHER UPPER CRETACEOUS ROCKS

Rocks apparently younger than the Franciscan group, but also of Late Cretaceous age, crop out in two widely separated parts of the district. Because they differ in lithology and degree of deformation, they were mapped as separate cartographic units and are believed to have been deposited at different times: one of these is exposed only in the Sierra Azul in the south-central part of the district; the other is exposed

chiefly in the Santa Teresa Hills in the northern part. As the two units are nowhere in contact and have yielded only a few fossils, none of which are closely limited in range, their relative age is not known. The writers, however, regard the rocks of Sierra Azul as being the older, because they are more indurated and more intensely deformed than the rocks in Santa Teresa Hills.

Upper Cretaceous rocks of the Sierra Azul

The Upper Cretaceous rocks found in the Sierra Azul consist of several thousand feet of interbedded conglomerate, feldspathic graywacke, and shale. Within the mapped area graywacke constitutes more than half of the unit, and conglomerate and shale each constitute a little less than a fourth, but shale is much more abundant farther south. These rocks underlie only a small area along the northern slope of the Sierra Azul in the south-central part of the district (pl. 1), but, because they extend south into Santa Cruz County, their total area of outcrop is much larger than is indicated by the map accompanying this report. As these rocks are poorly exposed, and contain few fossils within the district, and as they are being studied by others in the area of better exposures to the south, we have not assigned a formational name to the unit.

The fresh graywacke is medium grained and light colored, but where it is weathered, it is speckled with white feldspars in a red matrix. The grains are sub-angular and subrounded and are only moderately well sorted. Locally, they are admixed with small pebbles or fist-sized clay balls. The principal minerals observed in the single thin section that was made are quartz, orthoclase, and albite; these are accompanied by a little muscovite, biotite, chlorite, and calcite. Staining tests made on a half-dozen specimens indicate orthoclase amounts to from 5 to 20 percent. Fragments of chert and mafic lava amount to about 10 percent, and some of the feldspars show myrmekitic intergrowths. The feldspathic graywacke differs from that of the Franciscan group in being slightly calcareous and in containing much more orthoclase, more matrix, and more clayey material in the matrix. It is poorly exposed, but is somewhat better exposed, on the average, than the graywacke of the Franciscan group; on hillsides it forms characteristic brushy slopes that are generally mantled with talus, and on hilltops it yields a reddish or pinkish soil.

The conglomerate forms beds commonly more than 10 feet thick, and in places these occur in groups separated by foot-thick beds of graywacke. Locally, the conglomerate beds crop out in bold relief, but more

commonly they are subdued and give rise to a reddish bouldery soil. Some of the boulders are as much as 1 foot in diameter, but the average is between 2 and 3 inches. The result of a pebble count made on the conglomerate exposed on a ridge road just south of the serpentine body near Mount Umunhum is shown in table 14, and a similar count from a conglomerate of the Franciscan group is given for comparison. The 2 conglomerates are notably different in the proportion of igneous and sedimentary rock pebbles; igneous rocks make up 90 percent of the pebbles in the conglomerate of the Sierra Azul, but less than 50 percent of those in the conglomerate of the Franciscan group. Only 16 of the 100 pebbles identified in the Sierra Azul conglomerate could possibly be derived from the Franciscan group, and it is likely that most of these are not. The matrix of the conglomerate of the Sierra Azul is similar to the graywacke with which it is interbedded, but in many places it is more silicified. The conglomerate is much fractured; in the more silicified parts the fractures cleave the pebbles and in the unsilicified parts they break around them. Calcite fills some of the fractures and locally replaced part of the matrix.

TABLE 14.—Pebbles from conglomerate in the Upper Cretaceous rocks of the Sierra Azul and the Franciscan group, Santa Clara County, Calif.

Rock	Sierra Azul Number of pebbles	Franciscan group Number of pebbles
Sedimentary rocks:		
Sandstone and quartzite-----	7	32
Chert-----	1	21
Conglomerate-----	-----	1
Slate-----	1	-----
Total sedimentary rocks-----	9	54
Igneous rocks:		
Granite-----	4	-----
Aplite-----	2	1
Quartz porphyry-----	-----	3
Volcanic rocks with quartz phenocrysts--	32	9
Volcanic rocks with feldspar phenocrysts and no quartz phenocrysts-----	35	20
Diabase-----	7	3
Greenstone without phenocrysts-----	11	9
Total igneous rocks-----	91	45
Vein quartz-----	-----	1
Total pebble count-----	100	100

The shale in the Upper Cretaceous rocks of the Sierra Azul is exposed in the New Almaden area in few places other than artificial cuts. In some road-cuts one may see beds of shale less than 1 foot thick rhythmically interbedded with graywacke, as is shown



FIGURE 48.—Interbedded graywacke and shale of Late Cretaceous age in the Sierra Azul as exposed in roadcut south of Loma Prieta and just outside the New Almaden district.

in figure 48; in other cuts the shale forms massive sections more than 100 feet thick with only a few interbedded layers of graywacke a few inches thick. The shale is olive drab, and in places is interlaminated with lighter colored silt. It commonly breaks with a

conchoidal fracture; but where it is shattered, it has a splintery or shoe-peg fracture. White or gray ellipsoidal limy concretions are scattered through the shale, but are not common in the district. Most of those observed were 1 or 2 inches thick and several inches long, but some measure more than 1 foot in length. Within the district no useful fossils were found in the limy concretions, but on Mount Chuai, 1 mile south of the district, similar shale beds contain septarian concretions in which we found fragments of *Inoceramus*.

No fossils were found in any of the other rocks of this unit within the mapped areas, but in the upper part of the southern branch of Almaden Canyon, at an altitude of 2,300 feet, the graywacke yielded specimens of a large *Inoceramus* (fig. 49) and many pelecypods similar to *Buchia*. Farther south, along the Loma Prieta road where it crosses the Santa Clara-Santa Cruz County line, fossils are fairly abundant. A few collected in this area by C. M. Gilbert and by us were examined by Dr. S. W. Muller, of Stanford University. He found no forms well-enough preserved to be determined specifically, but he recognized *Trigonia* (cf. *T. evansi*), *Glycimeris*, *Spondylus*, *Dentalium*, and various small thin oysters—an assemblage that he regarded as indicating Late Cretaceous age.



FIGURE 49.—Casts of *Inoceramus* sp. from rocks of Late Cretaceous age in the upper part of the south branch of Almaden Canyon.

Upper Cretaceous rocks of the Santa Teresa Hills

A sequence of sedimentary rocks of Late Cretaceous age, consisting of massive gray medium-grained arkosic sandstone and tan or greenish-gray shales, is exposed in the western part of the Santa Teresa Hills and in thin fault silvers north of the Senator mine. The sandstone is of special interest because it was used in the construction of the buildings of Stanford University and also of several well-known public buildings in San Jose and San Francisco.

The sandstone of this unit is fairly well exposed, even though it is deeply weathered as can be seen in quarries more than 30 feet deep. The weathered rock is generally found in clusters of large rounded boulders scattered along lines of strike, but continuous exposures measuring several hundred feet along the strike are exposed in the vicinity of the quarries. Where outcrops are sparse, the areas underlain by sandstone can easily be distinguished from those underlain by shale because they support a heavy growth of brush. The bouldery outcrops show little bedding, as the individual boulders commonly are derived from a single bed, but in places the attitude of the bedding is indicated by alinement of shale fragments or by thin shale partings. The best exposures of the sandstone are found in the vicinity of the westernmost rock quarry in the Santa Teresa Hills shown in figure 50. This quarry, having been cut into a dip slope of massive sandstone, is ideally situated to take advantage of both the jointing and the bedding in the rock. The individual beds as exposed in the quarry are as much as 6 feet thick and are separated either by thin shale partings or by layers containing abundant large flakes of shale. Some bedding planes are marked by thin layers containing small pebbles, most of which are of dark chert, but the rock shows little tendency to part along these pebbly layers. The shaly partings, where exposed by stripping, exhibit many large worm trails, and they commonly also show poorly formed ripple marks.

The characteristic, and locally spectacular, weathering of the sandstone is best developed on the slope above the quarry. Along this dip slope the least weathered rock is cut by a rectilinear pattern of joints, perpendicular to the bedding and spaced at intervals of 8 feet or more. Upslope from the quarry the joints have been widened by weathering, and the slope is more and more deeply dissected toward the crest of the hill. At the crest the edges of the dip-slope beds are exposed and the joint pattern gives way to piles of grotesque spheroidally weathered boulders. Some of these boulders have a diameter of about 40 feet, though most of them are somewhat smaller, and in



FIGURE 50.—One of the smaller quarries in the Santa Teresa Hills from which Upper Cretaceous sandstone was taken for use as a building stone. The thick beds and barren dip slope combined to make this an ideal site for a small quarry.

several places they are precariously perched on the dip slope of an underlying bed. Casehardening, due to a concentration of limonite near the surface of the rock, has formed on the rounded boulders crusts about 1 inch thick, which are generally cracked in a polygonal pattern so that they resemble bread crusts, as is shown in figure 51. Additional weathering along these surficial cracks widens them until only small knobs representing the centers of the polygons remain and when these knobs have weathered away the process is apparently repeated. Another type of weathering results in the formation of flat-bottomed caves. This process can be followed from the development of small flat basins with overhanging rims, resulting from the enlargement, by standing water, of natural depressions



FIGURE 51.—Dome formed by spheroidal weathering in massive sandstone of the Upper Cretaceous rocks in the Santa Teresa Hills. The casehardened surface and "bread crust" fractures are best developed on these domes.



FIGURE 52.—Iglolike rock in the Upper Cretaceous sandstone of the Santa Teresa Hills resulting from spheroidal and cavernous weathering. The lower surfaces of the caverns are flat and act as a collecting basin for rainwater, which, on standing, dissolves the cementing material from the rock beneath. When dry, the loosened sand is apparently removed by wind or animals.

on the gentle dip slopes, to flat-bottomed caves and pits that are found in the bouldery area. An extreme type of weathering, resulting from the hollowing of a spheroidal boulder, is the igloloike rock shown in figure 52.

Lithologically the Upper Cretaceous sandstone of the Santa Teresa Hills is fairly uniform throughout its extent. Where fresh it is light gray in color, but the more common weathered sandstone is buff colored. Some outcrops have a uniform reddish tinge, and some exhibit concentric or wavy bands of red and brown

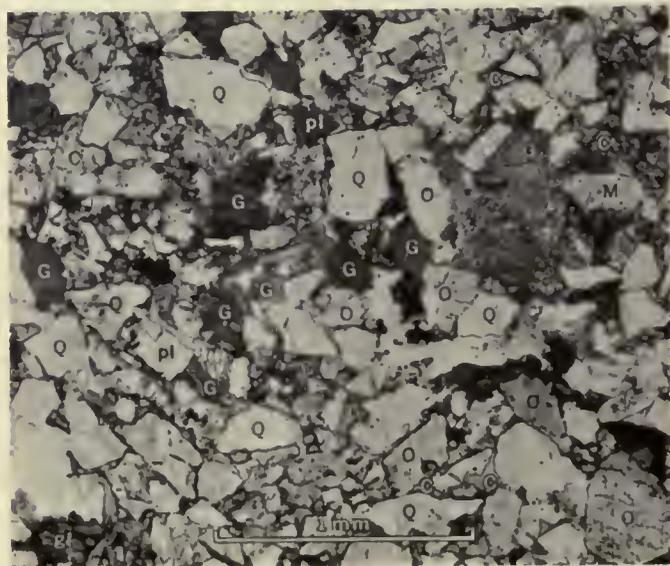


FIGURE 53.—Photomicrograph of arkosic sandstone of Late Cretaceous age from north of the Senator mine, showing glauconite that has replaced biotite. Glauconite (G), quartz (Q), orthoclase (O), plagioclase (pl), microcline (M), and calcite (C).

iron oxides. The sandstone is homogeneous, moderately well sorted, and medium to coarse grained. Most of the grains are subangular, a few are angular, and others are subrounded. Their average diameter is a little less than 0.5 mm, and nearly all the diameters fall within a range of 0.2 to 1.0 mm. Rounded grains of chert are found in some specimens; these are generally a little larger than the other grains, some of them being as much as 3 mm in diameter. Cementing material is present only in small amount and appears to consist of clay and limonite. Judging from a study of only a few thin sections of the rocks, they contain from 50 to 75 percent of quartz; up to 30 percent of orthoclase, myrmekite, and oligoclase; a few percent of microcline; and a little biotite, muscovite, glauconite, sphene, magnetite, and cloudy limonite. Rock fragments also are present but are not abundant. One variety of the sandstone, occurring north of the mouth of Almaden Canyon and also in one of the fault slivers north of the Senator mine, weathers to a rock with a striking chocolate-brown porous peripheral zone that is sharply separated from a core of unweathered gray fine-grained sandstone. In thin section this sandstone is seen to have a calcite cement and to include more than 5 percent of brown biotite which is largely altered through a green biotite stage to glauconite (Gallier, 1935, p. 1351-1365). (See fig. 53.)

The shales of Late Cretaceous age in the Santa Teresa Hills are not exposed, but they are believed to underlie several areas of rolling grasslands that have a sticky deep-brown soil containing sparse fragments of dark shale and scattered limy concretions. In one of the fault slivers north of the Senator mine, shale is exposed in a sharply incised canyon. In this small area at least, the shale is dark greenish gray and thin bedded, and breaks with a hackly or curved fracture. It resembles some of the shale and siltstone of the Franciscan group; however, it is more distinctly bedded and more clayey, and lacks the sheen characteristic of cleavage surface of the shales of the Franciscan group. At this locality, and also in the lowest shale beds in the Santa Teresa Hills, limy concretions averaging about 1 foot in diameter are characteristic. Two varieties of these concretions are common. One variety is generally dark brown and septarian, and has crack fillings of yellowish calcite; some of these concretions contain a few fossil fragments. The other variety is chalky on the surface and white or buff on the inside. These concretions contain minute spherical transparent bodies, which probably represent organic remains that are too poorly preserved to be identified.

Fossils are exceedingly rare in the Upper Cretaceous rocks of the Santa Teresa Hills. A fragment of a fos-

sil identified by L. W. Stephenson, of the U.S. Geological Survey, as *Baculites chicoensis* Trask was found in a concretion just above a small saddle 0.38 mile east of the summit of the 430-foot hill southwest of the Santa Teresa mine. In addition, two casts found in the sandstone of the Stanford University buildings have been identified by S. W. Muller as *Turritella chicoensis* Gabb. Both of these fossils are found in the Chico formation (Coniacian to Campanian) at its type locality, but they hardly seem to justify correlation over so great a distance.

The stratigraphic thickness of this unit in the New Almaden area, as determined from cross sections, is at least 1,200 feet; but the total original thickness was greater, for its base is not exposed and its upper limit is an unconformable contact with rocks of middle Eocene age. The thickness even of the rocks that are exposed is uncertain, because the unit is cut by faults of small but unknown displacement. Moreover, an exact measurement of the exposed thickness in any one place would have little significance, for the sequence is characterized by lenticular sandstone beds that thin out within short distances along their strike.

Possible correlation and age

Although isolated specimens of the rocks of Upper Cretaceous age from the Sierra Azul and the Santa Teresa Hills might be easily confused, the differences between the rock of the two areas are considerable. The Sierra Azul sequence contains thick beds of conglomerate, which are lacking in the Santa Teresa Hills. The fresh feldspathic sandstones of the two formations look much alike in hand specimens, but they are readily distinguished in the field because they weather differently and have different types of exposure. The graywacke found in the Sierra Azul weathers to form hard angular pieces of reddish or pinkish color, whereas the arkosic sandstone in the Santa Teresa Hills weathers to a tan-colored and generally friable rock; the graywacke of the Sierra Azul is poorly exposed, whereas the sandstone of the Santa Teresa Hills generally forms prominent outcrops of spheroidally weathered and casehardened boulders. The shales of the two formations differ chiefly in their mode of occurrence: in the Sierra Azul they are generally interbedded with many thin layers of graywacke, whereas the Santa Teresa Hills sequence contains thick strata of homogeneous shale.

The two formations generally differ, also, in the character of their folding. The rocks in the Sierra Azul are so tightly folded that they show dips as high as 70°, whereas the beds of the Santa Teresa Hills rarely dip so steeply as 45°. This, however, expresses only a part of the difference in degree of deformation,

for in finer detail the Sierra Azul rocks are much more crumpled and are cut by a multitude of small fractures and faults that are not found in the rocks of the Santa Teresa Hills.

Because of these differences, the two formations are believed to be distinct, even though both contain fossils indicating Late Cretaceous age. The differences in their lithology and deformation suggest that the Sierra Azul sequence is the older. Perhaps this sequence corresponds to the Pacheco group of Taliaferro (1943a, p. 130-134), and the Santa Teresa Hills sequence corresponds to a part of his Asuncion group, which was deposited after his Santa Lucia orogeny.

EOCENE ROCKS

A sedimentary sequence, of early middle Eocene age, consisting of fissile shale, fossiliferous limestone, and coarse-grained sandstone underlies the central part of the Santa Teresa Hills and a group of low hills east of the point where Guadalupe Creek emerges from the mountains onto Santa Clara Valley. Because this sequence occupies less than a square mile and is very poorly exposed, it is not assigned a formational name in this report. In the Santa Teresa Hills it lies unconformably on the previously described sediments of Late Cretaceous age with a small angular discordance, and it is overlain only by alluvium. Its thickness cannot be accurately determined, but it appears to be at least 900 feet thick. The limestone is much like the Eocene Sierra Blanca limestone of Nelson (1925) of the Santa Ynez Mountains, in Southern California, and the entire sequence is probably equivalent in age to the upper part of the Meganos formation or the Capay formation of Weaver and others (1944). The nearest known exposures of Eocene rocks represent the equivalent of the Domengine or Capay formation northeast of Morgan Hill, described by Gilbert (1943, p. 640-646).

The lowest part of the Eocene sequence in the Santa Teresa Hills consists chiefly of shale, and unexposed layers of shale are probably intercalated between the younger beds of sandstone. Shale underlies most of the eastern part of these hills, but even here it is nowhere exposed; it forms subdued grass-covered hills riddled with ground-squirrel burrows, and the largest observable shale fragments are found in the material excavated from these holes. The shale is light tan, fissile, and exceptionally powdery. Examined under the microscope, it appears to consist of clay minerals, calcite, some limonite, and only a few grains of quartz and feldspar.

Sandstone makes up most of the unit in the western part of the Santa Teresa Hills and also in the low

hills near the mouth of Guadalupe Canyon. Most of the sandstone lies stratigraphically above the shale, but the lowest beds seem to grade into shale along the strike towards the east. The outcrops of the sandstone are marked by concentrations of weathered low-lying rounded light-buff or light-gray boulders, the largest more than 5 feet in greatest diameter, and in most places the sandstone shows only a trace of bedding. Accumulation of iron oxides on and near the weathered surfaces results in casehardening, and beneath the surface it gives rise to brownish-red and pinkish blotches and bands. Iron oxide also imparts a pinkish-brown color to a distinctive sandy soil that forms on the sandstone. In parts of the area this soil supports thick growths of brush which contrast with the grassy areas underlain by shale.

The typical unweathered sandstone is light gray, coarse-grained, and poorly sorted. It contains angular clasts of glassy quartz, feldspar, and rock fragments cemented by interstitial fine-grained calcite. In the weathered rocks, the close-packed clasts are in contact, and the interstitial calcite has been leached away producing a porous texture. The clasts in some places are as much as 1.5 mm in maximum diameter, but they average only a little more than 0.5 mm. Quartz is relatively more abundant in the sandstone of Eocene age than in that of the Upper Cretaceous rocks of the Santa Teresa Hills, though sodic plagioclase, myrmekite, microcline, and orthoclase together may make up as much as 20 percent of the rock. In some places the feldspar has been partly altered to clay minerals, but elsewhere it is fresh. Detrital sericite, hornblende, and epidote occur in very small amount. Scattered throughout the rock are shale fragments that are commonly rimmed with stains of iron oxides.

A special phase of the sandstone, commonly occurring near lenses of limestone and referred to in the field as the "white sandstone," resembles the "glass sand" of the Meganos formation north of Mount Diablo. It contains about 20 percent of finely crystalline calcite cement, which is more than is found in the typical sandstone of the formation, and on weathered surfaces the grains stand out in stronger relief. Thin sections show large clastic grains of quartz and feldspar, surrounded by a calcite matrix which contains some quartz and feldspar fragments less than 0.1 mm in average diameter. Rocks representing all gradations between this "white sandstone" and sandy limestone may be observed, and in many places the sandstone contains echinoid spines, broken shells, and a few large Foraminifera.

Several lenses of limestone are interbedded with the

shale near the base of the unit in the Santa Teresa Hills. The thickest of these, exposed in a quarry near the Bernal mine, measures about 25 feet in thickness, but most are only 3 to 5 feet thick. Some of the lenses are several hundred feet long, but many are so small that each is indicated only by a few boulders. As these lenses contain several different kinds of limestone, their exposures differ in character. In general, however, the limestone is more resistant to erosion than the surrounding rocks, and its outcrops are marked by rounded boulders, by trains of low boulders, or more rarely by inclined rounded tablets flattened parallel to the bedding. The different kinds of limestone tend to grade into one another, but they may be divided for description into three varieties.

One variety of limestone, best exposed in the quarry near the Bernal mine, is flinty, generally massive, and poorly bedded. It weathers in such a way that the surface of its bouldery outcrops, and even most of the quarry faces, are encrusted with a dazzling-white fine-grained chalk; but fresh exposures of the rock are commonly mottled or locally banded in shades of tan or light gray. In places it is blotchy, containing irregular masses of medium-gray coarsely crystalline limestone, which, when freshly broken, has a faint odor of crude petroleum. Veinlets of clear coarsely crystalline calcite cut all the rock, and it contains numerous vugs, some of them as much as 1 inch in diameter, which are lined with crystals of calcite. In general, this variety of limestone is not very fossiliferous, but it does contain some small gastropods and pelecypods, the most abundant of which is *Pitar* cf. *P. Californianus* (Conrad).

A second variety of limestone occurs interbedded with the coarse-grained sandstone in the Santa Teresa Hills and appears to be stratigraphically higher than the limestone exposed in the quarry. It is generally characterized by a fragmental appearance, but its textural and mineralogic makeup differs from place to place. The rock appears to have been formed by mixing of coarse arenaceous material with highly fossiliferous calcareous material, for it is made up of lenses and irregularly interfingering masses of sandstone, fine conglomerate, and elastic limestone. The elastic limestone contains irregularly broken fragments of gastropods, pelecypods, Foraminifera, and reef-forming organisms, such as coralline algae and bryozoans, together with rounded chert pebbles and fragments of other rocks. T. Wayland Vaughan, of the U.S. Geological Survey, examined a small collection of fossils from three different limestone masses in the Santa Teresa Hills and identified *Asterocyclina aster*

Woodring, *Pseudophragmina* (*Proporocyclina*) *psila* (Woodring), *Gypsina?* sp., and *Operculinoides* sp. He writes (written communication, November 7, 1946): "These three lots represent a single horizon, that from which Woodring originally described the two species listed above." The horizon referred to is the Sierra Blanca limestone (Nelson, 1925) of the Santa Ynez Range in southern California believed by Woodring (1930, p. 145-170; 1931, p. 371-387) to be "probably well down in the middle Eocene or in the upper part of the lower Eocene." The fossil content of this limestone, which is remarkably like that of the limestone in the New Almaden area, was also studied by Keenan (1932, p. 53-84), who described it as containing echinoid fragments, small brachiopods like *Terebratalia*, oyster-shell fragments, *Discocyclina*, *Globigerina*, *Nodosaria*, nummulitoid Foraminifera, bryozoans, and calcareous algae. Keenan placed its age as "younger than Martinez (lower Eocene or Paleocene) and older than Tejon at its type locality, probably either upper Meganos or lower Domengine."

A third variety of limestone that is characterized by abundant tests of the large orbitoid *Discocyclina* is exposed in the low hills east of the point where Guadalupe Creek first reaches the Santa Clara Valley. It forms rounded, locally knobby outcrops on which the *Discocyclina* stand out in relief, in an area where no other rocks are exposed. The weathered surfaces are light tan to brownish gray in color, but the fresh rock is dark gray or grayish brown. This limestone is well stratified into beds about 3 feet thick, but individual beds are massive or somewhat brecciated. In some outcrops the limestone is largely made up of closely packed Foraminifera tests, but in others the fossils are more sparsely scattered through a matrix of finely crystalline calcite, together with small scattered angular grains of plagioclase, microcline, orthoclase, and pyrite. Glauconite also commonly occurs interstitially to the fossils, in fine aggregates up to several millimeters in diameter. No fragments of ferromagnesian minerals were found in this rock. This limestone was studied by Schenck (1929, p. 224-227), and is the type locality of *Discocyclina californica* Schenck. Other forms that Schenck described as occurring in this limestone are—"numerous smaller Foraminifera, bryozoans, calcareous algae (cf. *Archaeolithothamnion*), nummulitic Foraminifera, *Gypsina*, perhaps a stellate *Discocyclina*, gastropods, pelecypods, crustaceans, and an occasional brachiopod." The fossil content suggests that this limestone is a little younger than the strata in the Santa Teresa Hills; because of its isolated position and poor exposure, this cannot be verified by stratigraphic relations.

TEMBLOR AND MONTEREY FORMATIONS

Sedimentary rocks of early, middle and late Miocene age, including fossiliferous clastic limestone, conglomerate, coarse-grained sandstone, and siliceous and diatomaceous shales, interbedded with a few lenses of volcanic rocks, occur in the central and northwestern parts of the New Almaden district. They are assigned on the basis of lithology and a few fossils to the widespread Temblor and Monterey formations, which in other areas include early to late Miocene deposits. As the two formations intergrade, the placing of the contact is somewhat arbitrary; in mapping, the Monterey shale was regarded, in accordance with the suggestion of Bramlette (1946, p. 3-5), as including the lowest beds of the typical white porcelaneous shales, and the rocks lying below are regarded as a part of the Temblor formation.

The maximum aggregate thickness of the Miocene sedimentary rocks in the district, as determined from cross sections, is about 3,800 feet (pl. 1); but, because of the probable time overlap of different facies, it is possible that the sedimentary rocks now exposed were not quite so thick in any one place. On the other hand, the upper part of the section is everywhere unconformably overlain by other formations or removed by erosion so that the full thickness of the Monterey shale cannot be determined.

The rocks of Miocene age in the New Almaden district crop out in two main areas occupying about 5 square miles. One area is a broad band that extends eastward from Los Gatos through the low hills along the margin of Santa Clara Valley for nearly 7 miles. The other area, which contains several segments isolated by faulting, is a narrow band trending southeastward; its northwest end is 1 mile west of the Guadalupe mine, and its southeast end 1 mile west of Almaden Canyon. In some places, one of them east of the Senator mine, these rocks can be seen to lie unconformably on the older rocks of the district, but, for the most part, they form blocks bounded by faults. They are generally thrown into fairly open folds except close to faults, where they are steeply tilted or crumpled.

Temblor formation

The Temblor formation consists largely of calcite-cemented conglomerate and medium- to coarse-grained arkosic sandstone, the latter containing, in some places, numerous fragments of pelecypods, oysters, and barnacles; the upper part of the formation, however, is more heterogeneous than the lower, and contains, in addition to the rocks mentioned, some chocolate-colored organic shale, greenish-gray shale, and glauconitic



FIGURE 54.—View northeastward from Bald Mountain. Banded aspect of hill in center is due to outcrops of more resistant sandstone beds of the Temblor formation. Crest beyond is a part of Los Capitancillos Ridge; America mine is on left and opencuts of New Almaden mine on right.

sandstone. The arkosic sediments of the lower part are best exposed along a road that extends between Guadalupe and Almaden Canyons across the long ridge lying between Bald Mountain and Mine Hill. The roadcuts through a stratigraphic sequence at least 2,150 feet thick of predominantly massive and coarse-grained, white or light-buff, well-sorted sandstone, mostly in beds from 12 to 30 inches in thickness. Sequences of several resistant beds as much as 20 feet thick in aggregate thickness are exposed almost continuously along their strike in white, moss-covered outcrops, which give the hill the banded appearance shown in figure 54. The sandstone are all well cemented with calcite, and many beds contain numerous fragments of mollusca shells, which in some places are so concentrated as to form beds of organic limestone. Most of the fragments are of thick-shelled oysters, but two fairly complete pelecypods from the sandstone have been identified by Miss Myra Keen, of Stanford University, as *Mitilis expansus* Arnold(?) and *M. loeli* Grant.

Interalated with the sandstone are beds of conglomerate having a matrix similar to the sandstone in grain size and mineral composition. The pebbles and larger blocks in the conglomerate consist principally of a

typical assemblage of the older rocks found on the slopes of the Sierra Azul. In order of apparent abundance are pebbles of graywacke, chert, shale, amphibolite, serpentine, and greenstone. The pebbles are divisible on the basis of their origin into two classes. One class consists largely of typical rocks of the Franciscan group, together with some serpentine boulders which are peculiar in that their outer surfaces are weathered and stained a deep red. All sizes between pebbles less than half an inch in diameter and boulders as much as 2 feet in diameter are common; the shapes range from rounded to angular. The other class of pebbles consists of hard rocks, dominantly black chert, white vein quartz, and quartz porphyry; these are well rounded and very smooth, some having a polished surface. Some pebbles are more than 4 inches in diameter, but most are less than 1 inch. They are probably reworked pebbles from older conglomerate beds, such as the conglomerate of the Sierra Azul. Similar smooth fragments of hard rock are found in much of the sandstone in the lower Temblor, though in these rocks they are generally in smaller grains.

Stratigraphically, about 1,500 feet above the oldest exposed coarse-grained sandstone and conglomerate beds are layers of medium-grained buff sandstone of

different aspect. The lowest of these are widely spaced and thin, but within a hundred feet stratigraphically they become so numerous as to dominate the sequence. This medium-grained sandstone is a friable limonite-rich sand that forms faintly laminated beds about 5 feet thick. It crops out in only a few places, and where it is exposed in the ridge south of Mine Hill, it is deeply weathered. Quartz, orthoclase, and subordinate plagioclase in grains averaging about 0.5 mm in diameter are the predominant minerals, but the rock also contains a little muscovite and glauconite. It has a weak cement apparently consisting of limonite-stained clay; and oxidized grains of magnetite and hematite seen under the microscope offer a possible source for the ochreous iron oxides. The sandstone is not highly fossiliferous, but inch-long echinoid spines are conspicuous in some layers, and in others a few well-preserved molds were found. These were identified by Miss Myra Keen, of Stanford University, as formed by *Pecten discus* Conrad, *Pecten andersonia* Arnold, and *Natica* sp.

Above the medium-grained buff sandstone south of Mine Hill lie interbedded organic shale, siltstone, and glauconitic arkosic sandstone. The total thickness of these beds may be as much as 400 feet, but they crop out in only a few places and are well exposed only along the road leading eastward from the junction of Guadalupe and Rincon Creeks. In the roadcuts the organic shales and siltstones form well-defined persistent beds up to 4 feet in thickness. Where fresh, they are light to dark gray and flecked with minute white spots, but they are mostly weathered to a grayish brown or chocolate color. They are fairly massive and break along irregular or conchoidal fractures as readily as along bedding planes. The larger mineral grains are of quartz, orthoclase, plagioclase, microcline, and a little calcite, but a large part of the rock is clay and organic matter. Foraminifera are abundant, and fish scales are not uncommon. The interbedded arkosic sandstone, occurring in beds of comparable thickness, is a fine- to medium-grained greenish-gray rock characterized by a relatively high percent of glauconite and calcite cement. A few of the thinner beds contain enough calcite to be termed "arenaceous limestone."

In the Blossom Hill area, and farther east along the north edge of Los Capitancillos Ridge, the upper part of the Temblor formation consists mainly of light-colored well-sorted medium-grained sandstone; but for about 4 miles eastward from a point a little west of Guadalupe Canyon, the formation includes a comparatively thin but mappable bed of dacitic tuff-breccia. (See pl. 1.) This bed deserves particular

attention because of the importance attributed it by Becker (1888, p. 314, 468), who believed that it was an intrusive dike, probably of late Pliocene age, and that it was the source of the solutions that deposited the quicksilver ore.

The dacitic tuff-breccia has a maximum thickness of about 40 feet north of the Senator mine, but it thins along its strike both eastward and westward to a thickness of only a few feet. It is more resistant to erosion than the Miocene sedimentary rocks, and along much of its length it forms an irregular scarp on the steep side of a hogback. Its outcrops are rugged and irregularly rounded, and they give rise to bouldery float that is strewn over the slope below. In general, they are mostly white and streaked or mottled with red and yellow iron stains; their surfaces are both pitted and embossed. In detail the tuff-breccia shows considerable variation from place to place, but it is everywhere fragmental. The fragments are mostly angular and less than 1 inch in diameter, but some are lenticular and of greater size; these are generally less than 2 inches long, but some are as much as 1 foot long. The lenticular fragments are oriented parallel to the bedding and are rudely banded parallel to their length; they are believed to be collapsed pumice. Most of the larger angular fragments are composed of volcanic rocks, but some of them, particularly in the lower part of the tuff-breccia, are sandstone and shale. The matrix material is so altered in most places that its original nature cannot be determined, but, largely because of the abundance of volcanic fragments in the rock, it is believed to be pyroclastic. If it is, the original tuffaceous material must have contained many small, whole crystals of plagioclase and some quartz, for locally, especially where the rock is silicified, the rock resembles a fine-grained dacitic lava. Alteration of the rock has everywhere been intense. The ferromagnesian minerals have been completely leached and locally replaced by jarosite; the feldspars in some areas were completely leached out, whereas in others they remained fresh and glassy; and the quartz generally escaped alteration. The alteration process was accompanied by the filling of veins with quartz, opal, and jarosite.

The tuff-breccia is believed to be a pyroclastic deposit rather than either a dike or a flow for the following reasons:

1. It contains angular fragments throughout.
2. It is underlain by somewhat tuffaceous sandstone, and locally grades upward through tuffaceous sandstone to normal sandstone of the Temblor formation.

3. There is no evidence of baking either above or below.
4. It is everywhere apparently conformable with the other sediments.

The most prominent mass of Miocene volcanic rocks forms Lone Hill an elliptical knoll rising 120 feet above the floor of the Santa Clara Valley about 4 miles northeast of Los Gatos. The hill has been regarded as a volcanic neck, but it is merely an erosional remnant of eruptive rock. It is underlain by three varieties of volcanic rock which cross the hill in irregular layers that strike slightly west of north and dip, in general, steeply eastward. The southwestern base of Lone Hill and a rise just south of it are underlain by altered well-bedded whitish rocks that are regarded as pyroclastic tuffs, though they differ little from the more tuffaceous varieties of shale in the Monterey. Lying unconformably on the pyroclastic rocks is a layer of perlitic dacite, which in some places is as much as 200 feet thick. Where fresh, the perlitic rock is light gray and exhibits a glassy matrix flecked with plagioclase phenocrysts, a few quartz crystals, and deformed cavities filled with secondary minerals. The plagioclase has cores of andesine and rims of albite-oligoclase. Stratigraphically above the perlite and underlying the greater part of the hill is a body of massive and flinty gray dacite. It is exposed in rather small blocky weathered outcrops that break along irregular, somewhat conchoidal fractures. Some of it is vesicular, and some exhibits irregular flow banding. The dacite contains varying proportions of small phenocrysts of quartz and glassy andesine, which are generally unoriented, and slightly larger dull-white fine-grained fragments that are probably tuff. Ferromagnesian minerals were originally present in small amount, but are completely replaced; the shapes of pseudomorphs indicate that the rock contained both a pyroxene and an amphibole. All the various kinds of volcanic rocks on Lone Hill are in most places extensively altered. They are in large part kaolinized and pyritized, and much of the more porous rock contains high-temperature forms of silica. Both cristobalite and tridymite occur so abundantly in the groundmass and in cavities as to have attracted the attention of mineralogists and mineral collectors.

The other smaller bodies of dacite shown on the map (pl. 1) are composed of similar rocks all greatly altered. Their occurrence along faults and as isolated bodies suggests that they are intrusive, but most of them are so brecciated and silicified that their original character is obliterated. The dacite that projects through the alluvium at the east end of the hill of Eocene rocks north of the Senator mine is of special

interest, because it locally contains cinnabar in sufficient quantity to be readily visible without the aid of a hand lens.

Monterey shale

The sedimentary rocks of the Monterey in the district conformably overlie the sedimentary and volcanic rocks of the Temblor formation. They consist largely of extremely fine grained dazzling-white siliceous rocks which are mostly diatomaceous, but near the base of the formation these are interbedded with fine- to medium-grained light-gray sandstone and massive white sandstone. The exposed thickness of the formation is 1,300 feet, but its top is nowhere exposed. The exact time range of the sedimentary rocks doubtless could be ascertained from their foraminiferal content, but such a study has not been made; the age of the formation is regarded as late Miocene only because most of the diatomaceous shale in the Coast Ranges was deposited at this time.

Between the Temblor and Monterey formations in part of the area is a transitional zone about 100 feet thick in which porcelanite and diatomaceous shale are intercalated with bentonitic shale, coarse-grained buff sandstone, and reddish conglomerate with pebbles up to 4 inches in diameter. The rocks of this zone generally do not crop out, but rather disintegrate to form a pale ocher-colored sandy soil containing diatomite fragments and rounded pebbles. They are well exposed at only one place in a cut on a road branching south from Shannon Road, about 2 miles east of Los Gatos. The bentonite exposed here is a homogeneous greenish-gray plastic clay occurring in beds up to 18 inches thick. Under the microscope no fragmental material or shards were found in the bentonite, but from its refractive index it is believed to be largely montmorillonite. The buff sandy layers average about 1 foot in thickness and are poorly consolidated; they contain conspicuous, though not abundant, small well-rounded pebbles of black chert. The conglomerate beds, also poorly consolidated, consist predominantly of cobbles of dark-brown medium-grained sandstone and blocky fragments of indurated shale. In other parts of the area the contact between the Temblor and Monterey formations coincides with the top of the tuff-breccia, and in still other places there is no gradation between arenaceous and siliceous sedimentary rocks.

The typical rocks of the Monterey are most extensive in the Blossom Hill area east of Los Gatos, where they underlie steep-sided rounded hills that are extensively planted in vineyards and fruit orchards. Although the siliceous shales are well exposed in many artificial cuts, they form few natural outcrops, because

they readily disintegrate to yield a light- to dark-gray porous soil containing only scattered fragments of rock. In good exposures the shales can commonly be seen to be rhythmically bedded in thin layers, averaging about 2 inches and locally exceeding 4 inches in thickness; but in places they form massive exposures several feet thick so dissected by closely spaced irregular fractures that it is difficult to distinguish any bedding. Where the shales are well bedded, however, the fractures are generally normal to the bedding planes and thus cause the rock to break out into rectangular blocks. Neither cherts, formed by extensive silicification of the siliceous shales, nor opaline concretions, both of which are common in other areas, are found in the Monterey in the New Almaden district.

The siliceous shales of the Monterey in the New Almaden district are light colored, porous, and punky to hard, depending on the amount of siliceous cement. In greater part they are finely laminated and correspond to the "porcelaneous shales" of Bramlette (1946, p. 15); the term "porcelanite" has been applied, however, to rocks that are thin bedded, but not conspicuously laminated (Taliaferro, 1934, p. 196). True diatomites, composed chiefly of the tests of diatoms, are uncommon in the New Almaden district. The most striking feature of the siliceous rocks is the dazzling-white to pale-cream color they assume on weathering. Their bedding planes, which are sharply defined and smooth, are flecked in places with fish scales, and in many places they show rings and bands of limonitic stain. The texture of the shales is much too fine to show individual grains under a hand lens, but in many specimens Foraminifera, or pores resulting from the removal of Foraminifera by weathering, are visible. Even in thin sections under the highest power objective, the groundmass of the rock looks like a fine cloudy mud; it consists chiefly of opal in the siliceous rocks and of clay in the more argillaceous shales. Scattered through this groundmass are angular fragments of quartz, small amounts of glauconite and zircon, and a few fragments of fine-grained siliceous rock. The fossils observed in the shales include numerous Foraminifera and diatoms, fish scales and bones, the thin-shelled *Pecten peckhami*, and a few large fragments of silicified vertebrate bones.

SANTA CLARA FORMATION

The Santa Clara Valley contains alluvium of at least two ages. The older alluvium is exposed mainly in the northwest corner of the New Almaden district, in and near Los Gatos, but small patches of it are scattered along the northern foothills of the Los

Capitancillos Ridge as far east as the mouth of Almaden Canyon. From the area around Los Gatos it may be traced northwestward into the Santa Cruz quadrangle, where it has been mapped as the Santa Clara formation (Branner and others, 1909, p. 6), and although the other scattered patches shown on the map of the New Almaden district may differ a bit in age, all probably were deposited within the depositional interval represented by the Santa Clara formation as mapped elsewhere. The formation has been dated as Pliocene and Pleistocene in age on the basis of a few fresh-water fossils (Branner and others, 1909, p. 6), some plant remains (Hannibal, 1911, p. 329-342), and a correlation with marine beds of the Merced formation lying south of San Francisco (Lawson, 1914, p. 14). Although no diagnostic fossils have been found in the formation in the New Almaden district, this age determination is accepted because it seems consistent with the local physiographic development of the landforms on the formation.

The Santa Clara formation in the New Almaden district consists largely of fine to very coarse alluvial material, deposited by streams that differed little from those now eroding the mountains that border the Santa Clara Valley. It is poorly sorted in most places and locally shows irregular bedding due to gullying. The finest material is a coarse silt, and the largest observed boulders are a little more than 2 feet long. In shape the pebbles and boulders are commonly more flat than spherical, and because they lie with their flat surfaces parallel to the bedding, they provide in many places the only means of estimating the attitude of the formation. The pebbles and boulders are of rocks found in the adjacent range, and although they are dominantly of the harder rocks, they include some pieces of soft siltstone. The formation contains boulders of silica-carbonate rock in several places, and on Blossom Hill, in an exposure almost 400 feet above the present valley floor, it also contains an appreciable amount of detrital cinnabar. Beds of light-brown limestone containing abundant fresh-water gastropods were found in the formation at a single locality, south of Los Gatos and half a mile north of St. Josephs Hill.

The formation as a whole is poorly exposed, except in roadcuts or streambanks, for it rapidly weathers to a reddish bouldery soil. The small patches of Santa Clara sediments lying on spurs of the Los Capitancillos Ridge are recognized only by the abundance of rounded boulders of the hardest rocks, such as diabase, gabbro, silica-carbonate rock, and chert, strewn over the surface. The attitude of the beds was measured accurately in only a few places, where the steepest recorded dip was 20°, and although in some

places outside the New Almaden district the formation is highly tilted, most of it within the district is believed to be tilted no more than a few degrees from its original attitude of deposition which, of course, was nowhere quite horizontal.

QUATERNARY ALLUVIUM

Quaternary alluvium covers the floor of Santa Clara Valley, and narrow tongues of it extend from the edge of the valley for several miles up the larger tributary canyons. The alluvium consists of silt, sand, and gravel, and contains pebbles and boulders of rocks evidently eroded from the nearby hills and mountains. As it forms the principal storage reservoir for the all-important ground water required for irrigation in the Santa Clara Valley, it has been extensively studied by W. O. Clark (1924). The reader desiring more details as to the thickness of the alluvium, the relative proportions of the various sizes of materials it contains, or its porosity or permeability is referred to Clark's report.

Terrace gravels only slightly older than those on the floor of Santa Clara Valley are perched on terraces along the lower courses of the larger canyons as high as 100 feet above the present canyon floor. These were mapped in places along the Guadalupe and Los Gatos Canyons, where they are fairly extensive, and similar terrace gravels were also noted in Alamitos, Cherry, and Llagas Canyons.

LANDSLIDES

More than 50 landslides are shown on the map of the New Almaden district, and many more were noted in the field but considered either too small or too shallow to be worth mapping. Most of the larger slides lie in a belt that strikes diagonally northwestward across the district, from the southeast corner to Blossom Hill. That so many landslides were mapped in this belt is partly because the belt includes the area that was mapped in greatest detail. But landslides are in fact especially numerous here, because the rocks in this belt were originally less massive, and are now more altered and sheared than those in other parts of the district.

The recognition of landslides is important in planning the location of adits, roads, or dams, because on slides there is always danger of renewed movement. Most of the slides in the district are easily recognized by some physiographic expression, such as cirquelike heads, hummocky surfaces, and distorted drainage; a few of the older ones, however, have long been stagnant and can best be distinguished by their abnormal

overlapping onto different kinds of rocks. If a slide has descended a canyon, as many have in this district, it is generally easy to recognize; where a canyon crosses a slide it is more sharply incised than elsewhere, and where a stream has passed around the toe of a slide, its channel is obviously bent out of its normal course.

The largest slides occupy nearly half a square mile, and from these there are all gradations down to small earth slumps. Their shapes are irregular, for many of them are composites of several parts which have slid at different times. The heads of the slides are commonly rounded and somewhat wider than their lower parts, but many of the more irregular ones have several heads and join downward to form a single mass.

Most of the larger slides are of the types classed as rockslides, consisting chiefly of bedrock and of débris-slides (Sharpe, 1938, p. 74, 76) composed largely of talus and soil. The distinction between these two types, however, must necessarily be rather arbitrary in areas underlain by highly broken or crushed rocks of the Franciscan group, because there is so little difference between the broken rock in place and the débris derived from it.

A good example of an earthflow, which moved more slowly than landslides normally do, was mapped topographically, on a scale of 200 feet to 1 inch, as a part of detailed mapping of the surface above the New Almaden mine. This flow is especially interesting because it originated in 1927 and is therefore little eroded; moreover, as the area had been accurately mapped before 1927, on the same large scale, by the mining company surveyors, the form of the surface before and after the movement can be closely compared. The change is illustrated by the profiles shown in figure 55 which indicate the supposed position of the sole of the slide. This sole is doubtless somewhat more irregular than shown, but the angle of its slope (14°) cannot be far from correct. This flow, like many slides in the area, shows many of the features generally associated with glaciers. Its head is cirquelike, and a basin near the head contains a small pond. The surface of the lower part is cut by many open cracks like the crevasses of a glacier, and along the lower margins in places there are low, linear mounds resembling lateral moraines. The surfaces of slippage that are exposed show striae indicating the direction of movement.

Some of the small slides shown on the map of the New Almaden mine area (pl. 3) originate in the large mine dumps, but as the waste rock moves, it generally drags along the upper 5 to 10 feet of the under-

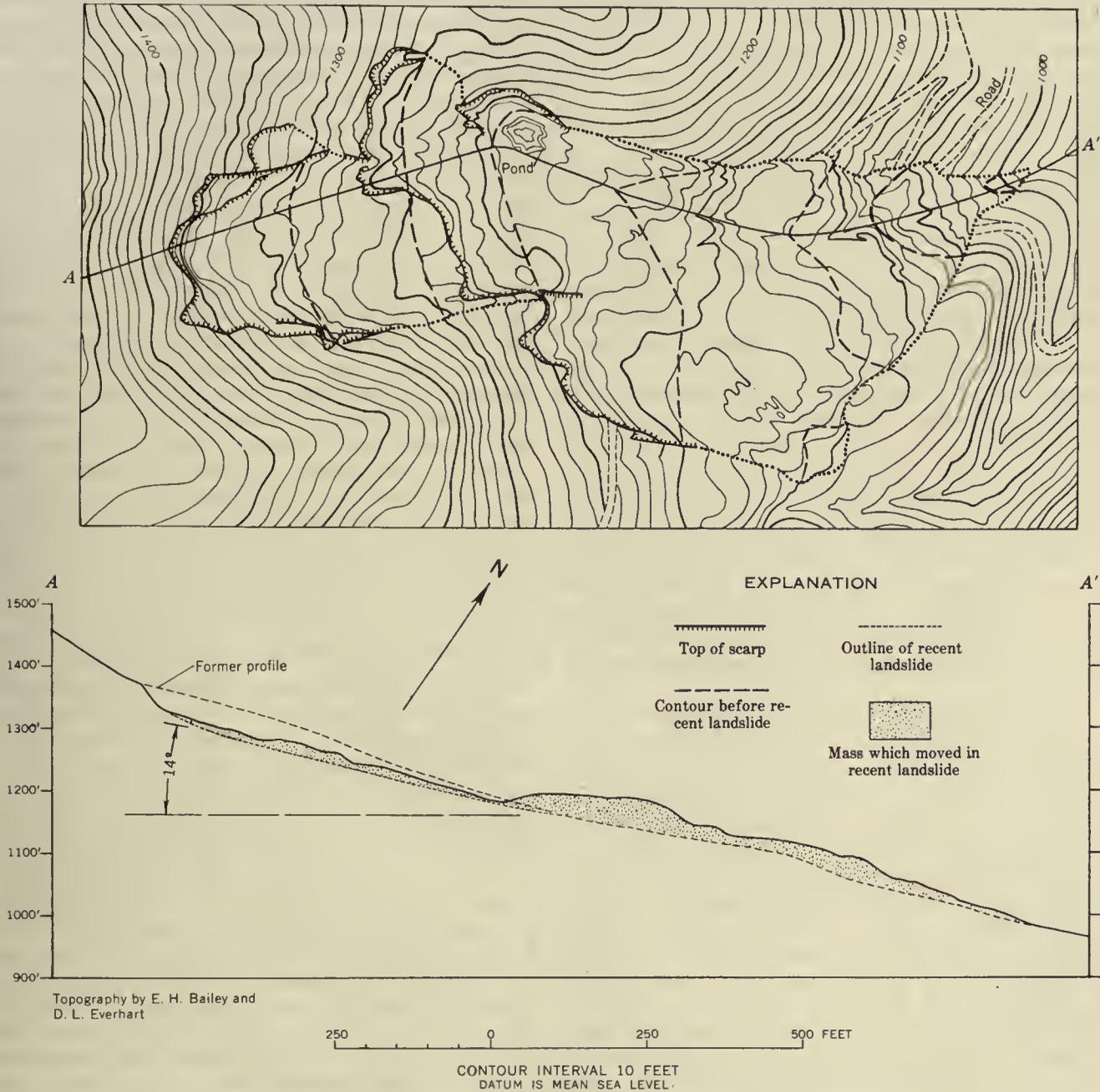


FIGURE 55.—Topographic map and section of landslide in the New Almaden mine area, 1946.

lying hillside. These slides, which were only a few years old when mapped, are much like rock streams or rock glaciers, having crenulated surfaces and very steep arcuate fronts. They move very slowly, apparently when saturated with water, by solifluction; in this climate freezing can play no part in their movement.

GEOLOGIC STRUCTURE

The geologic structure of the California Coast Ranges, amid which the New Almaden district lies, has been intensively studied so far as the post-Franciscan (post-Cenomanian) rocks and structures are concerned, by petroleum geologists and others, with the result that the geologic history of the region from

this time on is well known. Petroleum geologists, however, have a habit of classing the older rocks as granitic and metamorphic basement or Franciscan complex, and consider them only as much as seems required to determine possible oil-bearing areas and structures. What detailed knowledge there is of the older rocks of the Coast Ranges is largely a result of work by geologists connected with various universities or with State or Federal surveys engaged in the search for economic deposits commonly associated with the older rocks, notably the ores of quicksilver, chromium, and manganese.

In the New Almaden area the post-Franciscan rocks do not cover large areas, and important structures were developed before any younger rocks were deposited; many of the structural features, therefore, must be deduced from the attitudes and distribution of the rocks of the heterogeneous Franciscan group. When this has been done, it becomes clear that these older structures have affected profoundly the subsequent deformational pattern of the younger rocks in the district, and this also seems to be true in other parts of the Coast Ranges (Clark, B. L., 1932, p. 385-401). Consequently, the study of these older structures is of vital importance in fully understanding even the later structure and geologic history of the Coast Ranges.

A brief summary of the previous geologic studies of terrains underlain by rocks of the Franciscan group is desirable to orient the reader as to the present knowledge of these older structures. Such areas in the central Coast Ranges were studied largely from a lithologic standpoint near the turn of the century, and in the following decade the major geologic structures of limited areas were briefly described in three geologic folios of the U.S. Geological Survey (Fairbanks, 1904; Branner and others, 1909; Lawson, 1914). During the last 20 years much larger parts of the Coast Ranges have been ably studied by Taliaferro (1943a, b), of the University of California, and many students working under him, but although several excellent summary reports on this work have been published, much of the more detailed structure remains undescribed. A different approach to the structure of the Coast Ranges has been a synthesis of the available published data by such eminent students of the geology of the Coast Ranges as Willis (1927, p. 34-37; 1946, p. 1885-1886) and Reed (1933, p. 11-14, 27-59, 86-88). Some European geologists (Kober, 1925, p. 139-144) have compared the Franciscan sedimentation and deformation to that of major synclinal areas elsewhere in the world. As a result of all these varied ap-

proaches, as Taliaferro (1943b, p. 151) aptly points out, "Almost every assertion regarding the fundamental control of Coast Range structure has been met with a contradiction." Some geologists have emphasized the dominance of folding over faulting whereas others have believed that the Coast Ranges were comparable to the Alps in containing major overthrusts and "mobile belts". Some (Clark, B. L., 1930, p. 747-828; 1935, p. 1026-1034) have considered the Coast Ranges to be fault blocks which periodically move up or down, whereas others, though also believing them to be broken into blocks, considered the dominant movement along the bordering faults to be relative northwestward shifts of the blocks on the southwest side of each fault. Obviously, then, much remains to be done before the older structures of large parts of the California Coast Ranges are understood. The detailed mapping of the New Almaden district, according to the methods described, (p. 8-9) reveals structures that lead to a reasonable analysis for this limited area; but whether they are representative of typical structures of the Coast Ranges will not be known until the results of geologic study of areas of Franciscan rocks in a far larger part of the Coast Ranges have been published.

METHODS USED IN DETERMINING THE STRUCTURES

The difficulties encountered in finding, mapping, and explaining structures of the rocks of the Franciscan group are due partly to the generally poor exposures and partly to lithology and structure. Lithologically, the sequence of interbedded greenstones and feldspathic sedimentary rocks varies greatly from place to place, yet few individual beds or groups of beds possess distinctive features by which they can be correlated across even short intervals. Coupled with this is the general lack of fossils in the rocks. As a result, it is not generally possible to set up a "standard section" before completion of the areal mapping, nor can one rely on fossils for aid in correlation. These difficulties due to lithology and lack of fossils would not be so insurmountable were it not for the complications added by the way the Franciscan group has responded to deformation. The rocks have yielded by shattering, or by crumpling accompanied by extensive rock flowage, to such a degree that nearly every part of the group is broken and deformed. Consequently, an isolated exposure may show an attitude that departs widely from the attitude prevalent in the surrounding area, and one cannot rely on the significance of any local attitude observed in the field. Furthermore, the rocks have not developed cleavage or systematic linear elements by which one may determine the direction of

axial planes or plunges of folds. As an additional structural complication, most of the large faults that cut the rocks form wide shear zones that are not obvious in the field, and most of them strike nearly parallel to the bedding. Many of these faults are believed to have a large component of strike-slip displacement.

Some of the difficulties can be minimized by the tedious and time-consuming process of following out in detail all contacts between major types of rocks, and that was done in mapping the mineralized northeast half of the district; but even after the distribution of the greenstones and sediments was known, many important structures were not obvious. In attempting to further unravel the structure of the New Almaden district an additional refinement was made tentatively by distinguishing varieties of greenstone, such as tuff, breccia, pillow lava, and tachylitic rock, and also by trying to draw fine distinctions in the clastic sediments. We found that the greenstones could be fairly well divided into three groups—tachylitic rocks, mafic tuffs, and more massive lavas—but we were unable to make subdivisions of the clastic rocks that were persistent enough to aid in correlation. By means of this additional refinement two partial stratigraphic sections were recognized in the area. Only one of these was valid over a sufficiently large extent to be of much use. It consisted of feldspathic graywacke, tachylitic rocks, and thin discontinuous lenses of foraminiferal limestone, which, as they generally lay close to the tachylitic rocks, were believed to be at a single horizon rather than at several horizons. The distribution of these units which aided in understanding the structure is shown in figure 56. The other sequence, which consisted of tuff, graywacke, and massive lavas, was recognized only on Mine Hill, where it was useful in determining local structures of economic importance. The mapping of the distribution of these partial sections led to the delineation of some folds, several faults, and the major shear zone of the district, and when this had been done the structural pattern of the area was outlined. Other faults were then added on the basis of exposures of abnormally sheared rock, topographic expression, apparent linear features in the pattern of rock distribution or in the topography, and the alinement of serpentine bodies that appeared by their shapes to have been controlled by faults. The resultant map of the district we believe to be as reliable as the exposures allow, and although it may omit faults that strike virtually parallel to the bedding of the rocks of the Franciscan group, it probably depicts all the dominant structures of the district.

PRELIMINARY OUTLINE OF THE GEOLOGIC STRUCTURE

The geologic structure of the older rocks of the New Almaden district is so complex in detail that most exposures exhibit at least minor folds or faults. Despite this complexity, the larger lithologic units have retained considerable continuity, and the major structures are reasonably simple ones, which can be worked out with a fair degree of assurance. (See fig. 58.) All major structures have trends falling between west and north-northwest. The rocks of the Franciscan group in general strike about west-northwest in the southern two-thirds of the district and nearly east-west in the northern third; in much of the district they dip to the north. A major anticlinal fold trends west-northwest along Los Capitancillos Ridge and extends southwards to a point near the junction of Longwall Canyon and Llagas Creek; however, it is offset by several faults and so poorly represented by the attitudes of the rocks exposed at the surface that it might have remained undiscovered had we not had the benefit of the many exposures provided by the quicksilver mines.

The larger faults that traverse the Franciscan strata are nearly parallel to the strike of the strata but somewhat steeper in dip. The most remarkable of these is the Ben Trovato shear zone, which strikes west-northwest through the center of the district, attains a maximum width of 4,000 feet, and has an apparent offset of about 10 miles. From this zone, faults with thousands of feet of offset diverge northward, and others with large, but less positively known, offset diverge westward. Other faults that parallel the Ben Trovato zone, both to the north and south of it, have a strike-slip component of at least several hundred feet. In addition, there are many discontinuous and generally unmappable faults resulting from folding, crushing, or the intrusion of serpentine. All these structures are believed to have originated shortly after the deposition of the Franciscan rocks, but many have been modified by later movement. Probably all the larger faults originated in response to the same forces that produce right lateral displacement along the San Andreas fault, which is only a few miles southwest of the district. (See fig. 57.)

The serpentine associated with the Franciscan group is partly in sills and partly in steep tabular bodies along faults. The time of the intrusion of the serpentine to its present position is probably not the same for all of the masses. The sill-like bodies antedate most of the faulting, whereas those lying along faults were dragged or squeezed into their present

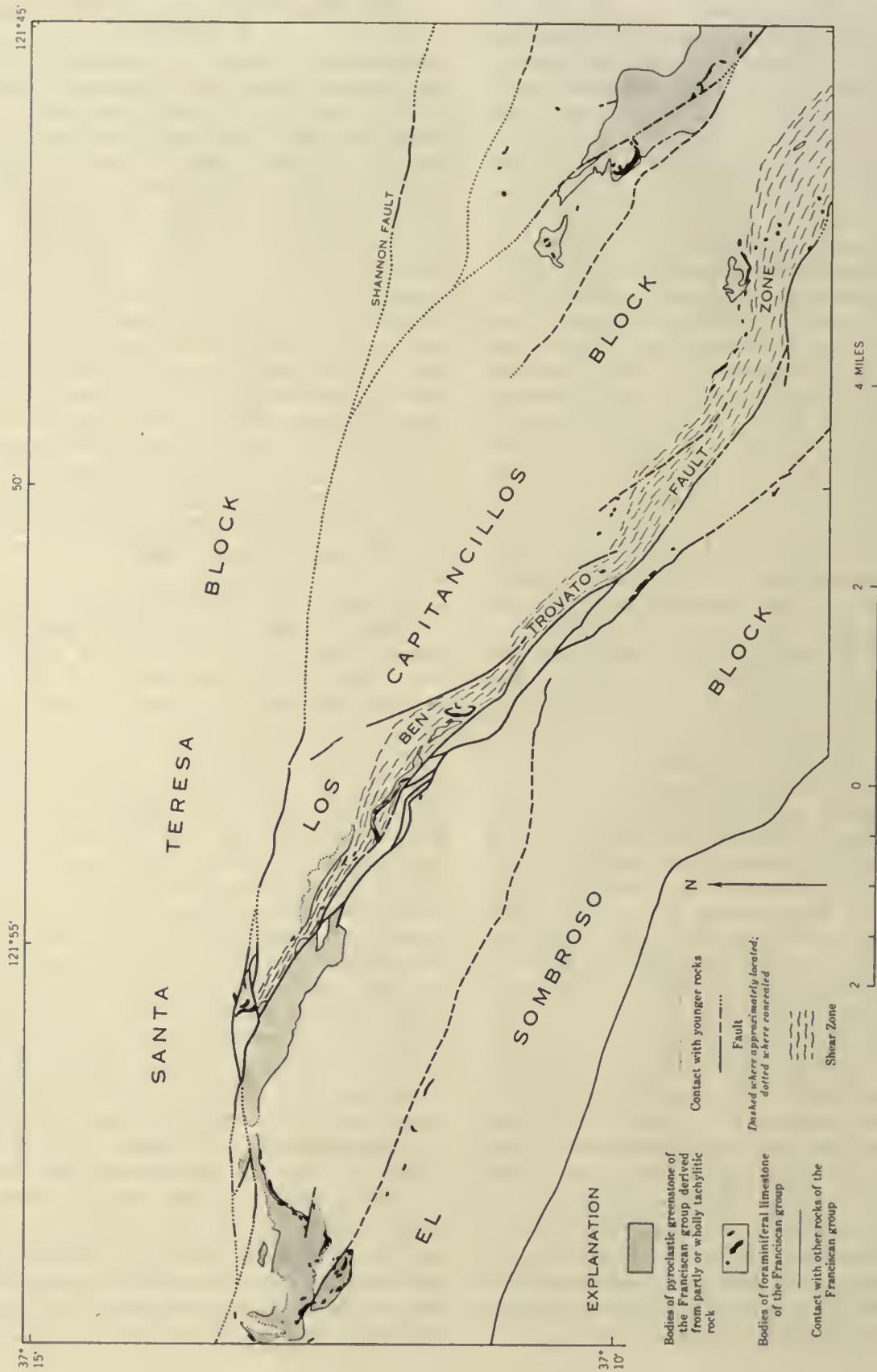


FIGURE 56.—Map showing distribution of Calera-type limestone and greenstone of the Franciscan group derived from tachylitic rocks.

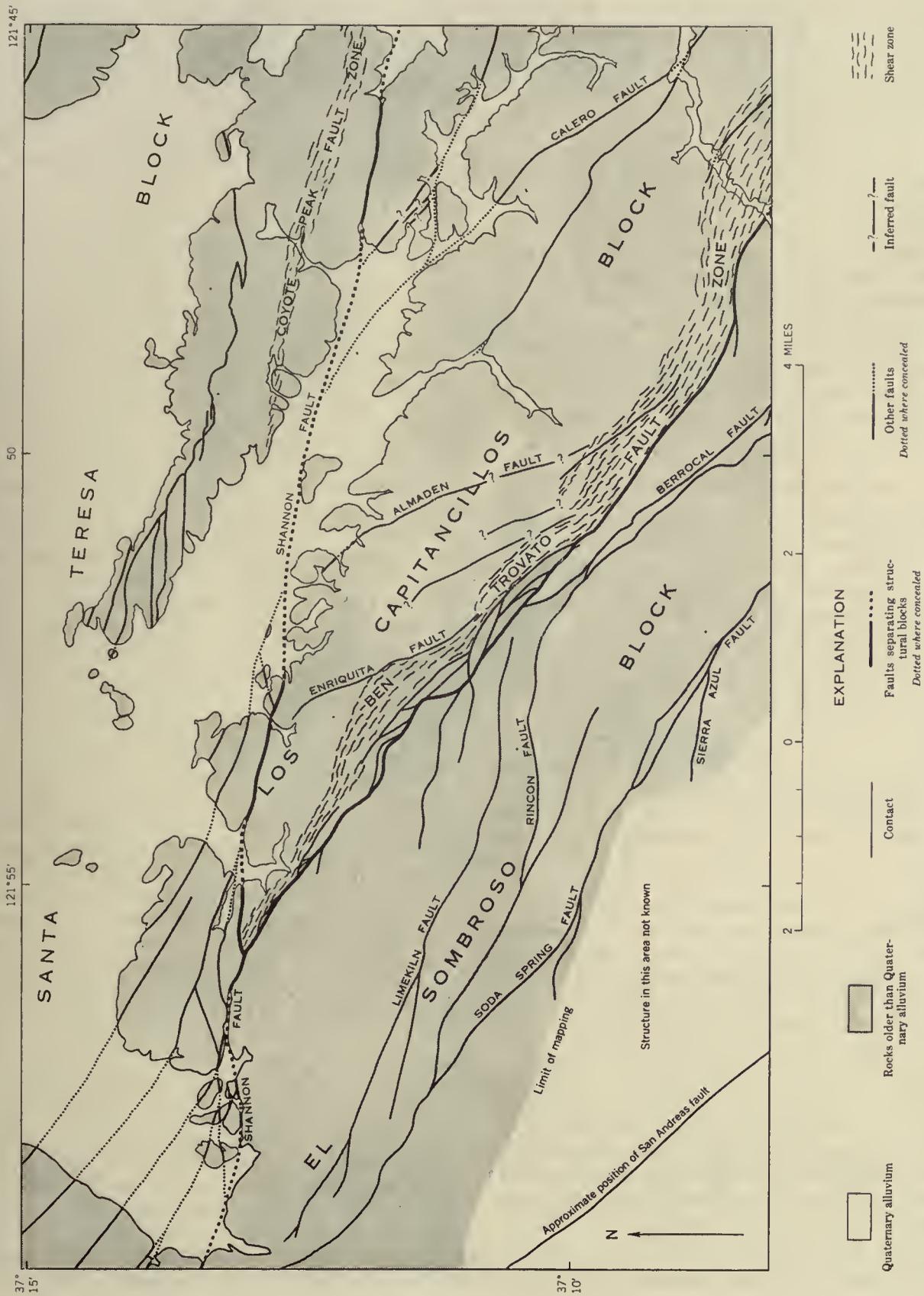


FIGURE 57.—Map showing structural blocks in the New Almaden district and the major faults in them.

position during movement of the faults. Most of the serpentine occupying a fault zone appears to have been emplaced before the deposition of the post-Franciscan rocks, but, locally, small masses have been squeezed into rocks that are clearly post-Franciscan.

Structures involving rocks younger than the Franciscan group include both faults and folds, and their positions and trends are governed largely by the structures previously developed in the rocks of the Franciscan group. Most of the folds are fairly open and strike nearly east. The most important of the faults following older structures are the Shannon fault, which separates the northern third of the district from the remainder, and a braid of more discontinuous faults, displacing Miocene rocks, along the southwestern border of the Ben Trovato shear zone. Comparatively young normal faults strike northwest across the displaced gravels of the Santa Clara formation in the northwest corner of the district.

MAJOR STRUCTURAL BLOCKS

For description, the New Almaden district may be divided into three major blocks separated by major faults as shown in figure 57, and each of these exhibits a different structural pattern (fig. 58). The northernmost, called the Santa Teresa block, has an indefinite northern limit covered by the alluvium of the Santa Clara Valley, but is bounded on the south by the Shannon fault, which trends a little south of east across the entire district. The middle, or Los Capitancillos block, lies south of the Shannon fault, and is separated from the southern, or El Sombroso block, by the Ben Trovato shear zone, which diverges from the Shannon fault in the Blossom Hill area and extends southeastward to the southeast corner of the district.

SANTA TERESA BLOCK

The northern, or Santa Teresa, block contains structures that strike generally eastward, but in its western part it is cut by faults that swing northwestward from the Shannon fault. The rocks exposed in this block range in age from the Upper Jurassic and Cretaceous rocks of the Franciscan group to the Recent alluvium filling the Santa Clara Valley. The alluvium, which itself is not deformed, covers the older structures in a large part of the block. The Pliocene and Pleistocene gravels of the Santa Clara formation exposed in the northwest corner of the district have been slightly deformed and are cut by normal faults that produced only minor topographic scarps and irregularities in the drainage pattern. The formations of Miocene, Eocene, and latest (?) Cretaceous age have been thrown into open eastward-trending folds, which are cut by

eastward-trending faults. The basement rocks of the Franciscan group, which are largely graywacke in this block, are poorly exposed, but the few attitudes that could be obtained indicate that they are plicated into folds with a similar strike. The rocks of the Franciscan group also are traversed by two eastward-trending shear zones intruded by thick masses of serpentine.

LOS CAPITANCILLOS BLOCK

The middle, or Los Capitancillos, block consists chiefly of folded interbedded sedimentary rocks and greenstones of the Franciscan group intruded by serpentine. The major anticline of the district follows the Los Capitancillos Ridge, but it is cut obliquely by several widely spaced faults which diverge northwestward from the Ben Trovato shear zone. (See fig. 57.) All these faults on which one can determine the displacement have a large strike-slip component, the west side moving northward. The westernmost fault, named the Enriquita fault, extends from the Ben Trovato shear zone to a zone of serpentine bodies believed to have been intruded along an old fault zone that has been followed fairly closely by the younger Shannon fault. The other faults are roughly parallel to the Enriquita; but as their courses are marked only in part by serpentine intrusions, they are harder to follow. The Almaden fault, for example, diverges southward from the precursor of the Shannon fault 7,000 feet east of the Enriquita fault. Its course near its northern end is indicated by offsets of the sedimentary rocks and greenstones of the Franciscan group, but on reaching the New Almaden mine area it becomes more nearly parallel to the strike of the older rocks and cannot be traced on the surface. It was, however, apparently reached by some of the underground workings of the New Almaden mine. Along its southward projection are intrusive bodies in line with it that may mark its continuation or be in shear zones parallel to it. Similarly in the area south and west of the apex of Mine Hill, the north-northwesterly alinement of bodies of serpentine and silica-carbonate rock suggest they were squeezed into, or dragged along, fractures parallel to the Enriquita and Almaden faults, but this cannot be demonstrated by offsets of the surround rocks. The easternmost parallel fault in this block, termed the "Calero fault," likewise probably diverges from the Shannon fault, though the point of junction is covered with alluvium. From the Calero fault branch two other faults, which are more nearly parallel to the Ben Trovato shear zone than the other oblique faults are. The Franciscan strata in the fault-bounded areas west of the Calero fault are variously deformed, but before the development of the oblique

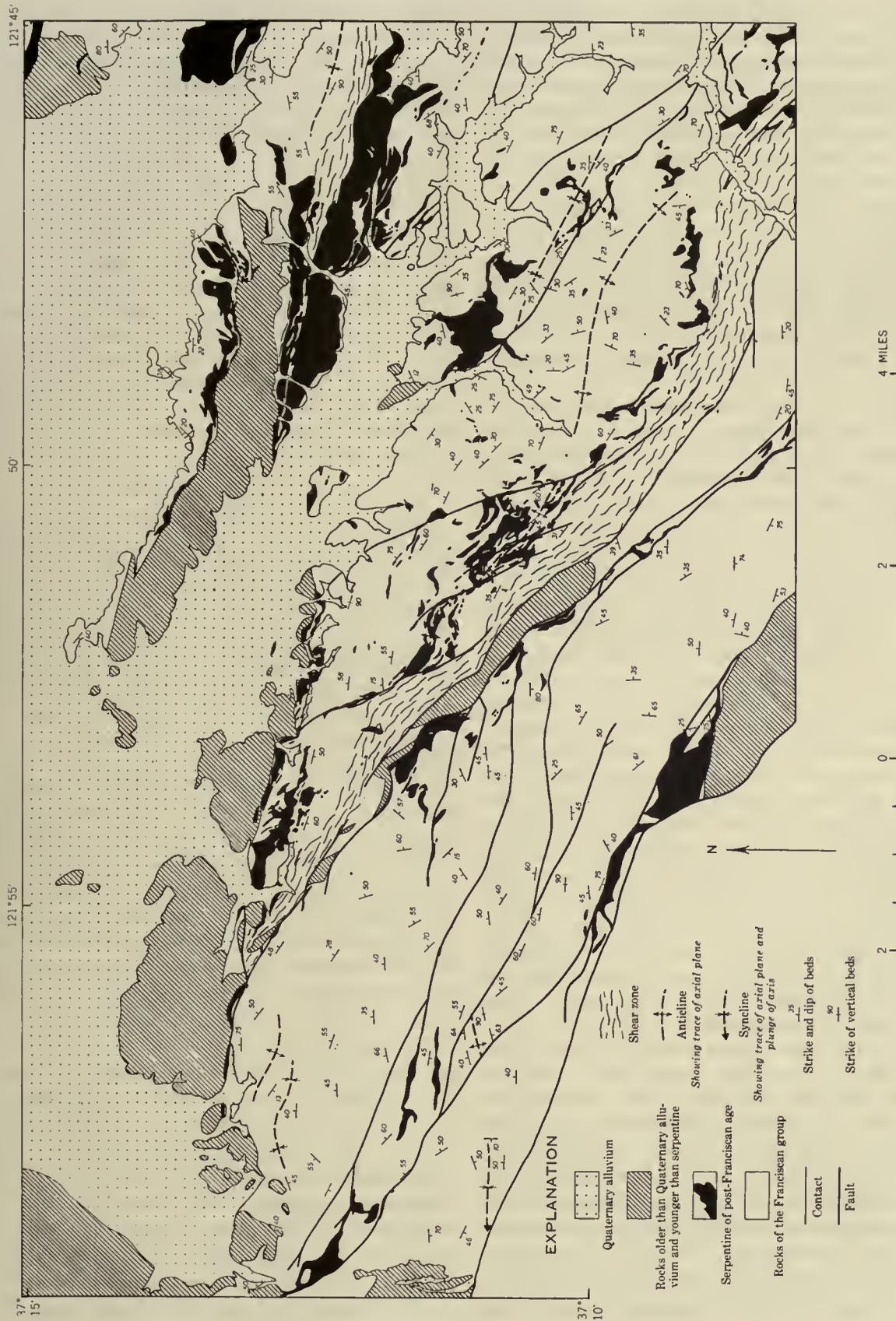


FIGURE 58.—Map showing the major structural features in the older rocks in the New Almaden district.

faults they were probably folded into a single anticline with a very steep southwest limb and a more gently inclined northeast limb. Subsequent deformation, largely caused by adjustment to movement along the various faults, has superimposed local plications upon the broad anticlinal structure, and in parts of the block there was extensive crushing, intricate folding, and rock flowage.

The tapering west end of the wedge-shaped Los Capitancillos block contains the Guadalupe and Senator mines, and local details of the geology are discussed in the descriptions of these mines. In general, the rocks in this area lie along the steep southwest-dipping southwest limb of the anticline, and have merely been compressed and steepened by later deformation.

The part of the Los Capitancillos block which lies between the Enriquita fault and the Almaden fault and its southward projection contains the New Almaden mine, together with several smaller mines. The geology adjacent to and in these mines is discussed in detail in the mine descriptions. Viewed broadly, the structure of this part is an anticline striking west-northwest, cut obliquely by faults that strike northwest and on which the dominant movement is strike slip. The middle part of the anticline contains many relatively thin sill-like bodies of serpentine, along the altered borders of which most of the ore bodies were found. The southwest limb of the anticline merges into the Ben Trovato shear zone, and it is probably cut, particularly on the southwest slope of Mine Hill, by several faults that diverge from the shear zone parallel to the Enriquita and Almaden faults. But as any such faults have been at least in part obliterated by serpentine and also subsequently deformed, their positions are so uncertain that no attempt has been made to show them on the accompanying maps. The northeast limb of the anticline is more regular, and is well marked by the outcrop of a thick sequence of predominantly tuffaceous greenstones extending from near the Almaden Dam to the junction of the Enriquita and Shannon faults.

The area lying between the Almaden fault and the southern branch of the Calero fault contains beds that formerly had relatively low dips to the north, but these beds have subsequently been so crumpled that the outcrop patterns of even the larger rock masses cannot be resolved into any conventional pattern of folds and faults. In this area particularly, rock flowage appears to have been an important factor in the deformation.

The rocks in the next sliver to the east are more orderly, and they are folded into recognizable anticlines and synclines of northwesterly trend. The

wedge-shaped area northeast of the Calero fault contains seemingly massive greenstone in its southern part, but along its northern border is an area of graywacke, chert, and limestone that is much crushed and broken. The sliver lying north of the northern split from the Calero fault is similarly sheared close to the fault, and near its west end the alignment of masses of serpentine and silica-carbonate rock parallel to the Calero fault suggests these are in parallel fractures. In general, however, the block retains such coherence that a relatively thin bed of greenstone tuff can be traced throughout the exposed length of the sliver.

In all the smaller units that make up the Los Capitancillos block, there are sizable masses of serpentine. Most of these are tabular bodies parallel to the bedding of the country rock and are sills, but also included are a few that have been described as lying along faults and were probably squeezed into their present position.

EL SOMBROSO BLOCK

The southern, or El Sombroso, block, which extends from the Ben Trovato shear zone southward beyond the limits of the district, consists mainly of Franciscan rocks; but bordering the shear zone on the north are unfaulted wedges of Miocene rocks, and along the south-central border of the district it includes the rocks of Late Cretaceous age in the Sierra Azul. The older rocks of the block generally strike west-northwest and dip to the north, though in several areas folds and minor irregularities result in their having other attitudes. Viewed broadly, however, the rocks show neither the extreme plication and crumpling nor the flowage that is characteristic of the middle, or Los Capitancillos, block. This more massive El Sombroso block is cut into elongate slivers by several major strike-slip faults, most of which trend west-northwest, nearly parallel to the strike of the Franciscan rocks; the Berrocal fault zone, however, diverges from the Ben Trovato shear zone in the central part of the district and extends southeastward for several miles, cutting a silver from the east end of the block.

The northernmost of the major west-northwest striking faults, termed the "Limekiln fault," extends from Los Gatos Canyon on the west to the Berrocal and Ben Trovato shear zones in the central part of the district. The Franciscan group to the north of the Limekiln fault consists of a thick sequence of massive feldspathic graywacke that dips northward and is overlain by tachylitic breccia and tuff, which in turn is overlain by a thin bed of foraminiferal limestone. The area is surprisingly regular in structure; road cuts and other good exposures exhibit minor shears

and folds especially near its western end, but the Franciscan rocks on the whole are less deformed here than in any other part of the district.

The Rincon fault is a little less than a mile south of the Limekiln fault and is nearly parallel to it for several miles, but to the east the Rincon swings south-eastward and becomes a part of the Berrocal fault zone. Two other faults split southward from the Rincon fault; the longest of these, the Soda Spring fault, joins the Sierra Azul fault in the south-central part of the district. The rocks of the Franciscan group within the silvers bounded by these faults are dominantly graywacke to the west and greenstone to the east. They dip generally northward, but locally, especially near the greenstone masses, they have erratic dips.

The southernmost fault, the Sierra Azul, which separates rocks of the Franciscan group from the Upper Cretaceous rocks of the Sierra Azul to the south, also trends west-northwestward. Although it has been mapped in the district for only a couple of miles, it is believed to be a major fault that extends along its projection both ways for several miles more.

Within El Sombroso block, characterized by faults trending about west-northwest, are several steep more or less tabular bodies of serpentine. These are believed to have been emplaced largely along faults or shear zones, although in places they obviously break across beds lying between the major faults.

FOLDS

FOLDS IN ROCKS OF THE FRANCISCAN GROUP

The folds and warps in rocks of the Franciscan group in the New Almaden district differ greatly in character. This is partly because they result from forces applied at different times since their deposition, and partly because of differences in the strength or competency of the various kinds of rocks involved. Extensive flowage of the shale and other fine-grained rocks accompanied by breaking of the more competent graywackes complicates the more detailed structure of many of the folds. The large folds are generally composite and contain smaller warps, folds, and faults superimposed on the broader structures; when viewed on a district-wide scale, however, they show a comparatively orderly though rather vague pattern. These large folds are believed to have resulted from regional forces. On the other hand, some of the small-scale folds might have been formed during the original deposition, others are related to movement along later faults or to local intrusions, and still others merely represent minor flexures on larger structures.

Folds formed during deposition

Folds that might have been formed at the time of deposition are found throughout the district, in at least three of the rock types of the Franciscan group. The most striking examples of these possibly preinduration folds are exhibited by some of the bedded chert bodies of the area. For example, a roadcut about half a mile northwest of Bald Mountain exposes the highly contorted chert shown in figure 17, which is well stratified in beds that are only locally as much as 8 inches thick; in these cherts there are intricate folds measuring less than 3 feet in any dimension, overturned and offset by small faults along their limbs. Such contortion seems to be restricted to the chert and not shared by the surrounding clastic sedimentary rocks; and furthermore, the relatively brittle chert has neither been crushed nor broken along the places of maximum deformation. This suggests that the crumpling occurred shortly after the original deposition of the chert and before it became hardened, though similar folds can also form without rupture under a thick cover. Similarly contorted well-bedded radiolarian chert may be seen in a cut along the Day tunnel road on Mine Hill a few hundred feet west of its junction with the main road to the mine camp; other excellent examples are observable underground in the Day tunnel of the New Almaden mine, between the portal and the cross cut to the Santa Rita shaft (pl. 6).

Other small folds probably contemporaneous with the formation of the rocks of the Franciscan group have been observed along the margins of exposures of pillow basalt throughout the district. These are only small puckers or plications, partly in the material that fills the interstices between the pillows of basalt and partly in the soft shales adjacent to them. Such folds doubtless resulted from the movement of the extruded lava against the soft muddy sediments; these folds, of course, do not indicate deformation during deposition. An example of such minor folds may be seen in the pillow lavas on Los Capitancillos Ridge, about 2,000 feet northwest of the northwest corner of the area shown on plate 3.

Local unconformities in the Franciscan group may indicate minor tilting at the time of deposition, but these are hard to detect in the field. The unconformities most commonly observed separate individual beds or series of beds in single isolated outcrops or in the walls of mine workings, but neither their extent nor the amount of tilting involved can generally be determined. No large-scale unconformities or channels that might indicate extensive deformation during the period of deposition were found.

Uplift during deposition may also be indicated by conglomerate beds that contain pebbles derived from erosion of other parts of the same formation. Elsewhere in the Franciscan rocks of the Coast Ranges there are beds of conglomerate or breccia that seem to demonstrate local uplift, erosion, and deposition (Taliaferro, 1943b, p. 140-143). In the New Almaden district, conglomerates are of rare occurrence in the Franciscan group, and those that have been found show by their general lack of pebbles of Franciscan rocks that they were not derived in any large part, if at all, from a reworking of deposits laid down in Franciscan time.

In summary, the evidence provided by the chert and the minor unconformities suggests a little warping during the deposition of the rocks of the Franciscan group, and the presence of extrusive lavas, which must have come from nearby vents even though none of these were found, also requires some crustal instability. However, no uncontestable evidence for deformation during deposition was found, and although the area of deposition must have been subsiding, it seems unlikely that it was being strongly deformed while the thick sequence of Franciscan rocks was being built up.

Folding after deposition

Folds in the rocks of the Franciscan group resulting from regional or local forces applied after the rocks were deposited have been formed at repeated intervals. The broader folds are comparatively normal, though complicated by superimposed structural features, but the character of the tighter or smaller folds depends largely upon the competence of the folded rock and the difference in competence of adjacent beds (figs. 59-61). Especially incompetent rocks are the shale, siltstone, greenstone tuff, and the closely associated, but slightly younger, serpentine involved in the later folding. Other rocks, including some of the graywacke, chert, limestone, and diabasic greenstone, are comparatively competent, and where they occur in large masses, they form rather cohesive units more susceptible to faulting than to small-scale folding. Where the more competent rocks are folded with interbedded incompetent rocks, they have commonly been broken into blocks which are embedded in a plastically deformed matrix. In such material the softer rocks are largely folded and show evidence of having flowed whereas the harder ones are faulted. Much of the Los Capitancillos block contains such material, and the rocks in the Ben Trovato fault zone and the alta bordering the serpentine provide outstanding examples.



FIGURE 59.—Plastically deformed and sheared rocks of the Franciscan group as exposed in workings of the New Almaden mine. White is tuffaceous greenstone, gray is chiefly graywacke, and black is siltstone and shale.



Parallel or isoclinal folds involving rocks of the Franciscan group and large enough to be major features are not a prevalent type of structure in the New Almaden district. One such well-defined major fold, however, is the irregular and crenulated anticline that underlies Los Capitancillos Ridge. Many of the data on the form of this anticline near Mine Hill are derived from the detailed maps of the New Almaden mine and cross sections prepared from these maps; the details of its structure as related to the ore bodies are discussed in the description of the mine, beginning on page 128. This anticline has a breadth from one flank to the other of about $1\frac{1}{2}$ miles, and its axis



FIGURE 60.—Interbedded graywacke and siltstone of the Franciscan group, showing typical irregularities due to rock flowage and minor faulting.



FIGURE 61.—Plastically deformed and faulted layer of greenstone (gr) in graywacke and siltstone. Photograph taken in the Cora Blanca part of the New Almaden mine. Note banded dolomite vein in lower right.

is traceable for several miles along the crest of the ridge. The southwest limb is clearly defined near the Guadalupe mine, where it dips 45° SW., but near the New Almaden mine, where it is closest to the Ben Trovato shear zone, this limb is partly obliterated by the development of parallel folds and faults. The northeast flank of the anticline dips about 50° NE. near the New Almaden mine, but is faulted off west of the Senator mine. The band of greenstone extend-

ing from the New Almaden Dam to the junction of the Enriquita and Shannon faults serves admirably to show both the general continuity and the detailed complexity of the fold along Los Capitancillos Ridge. The anticline probably also extends southwest of Almaden Canyon at least to Llagas Creek, for northwest of Llagas Creek the arcuate pattern of serpentine suggests a southeast plunging anticline. If this area is in gross structure an anticline, it must be highly deformed because neither the observed attitudes nor the pattern of rock distribution can be made to fit any reasonably simple structure.

In parts of the district where one does not have the advantage of three-dimensional observation afforded by mine workings, the character of folds too large to see in a single exposure is somewhat conjectural. Unless they involve distinctive lithologic units, such folds must be reconstructed from the attitudes plotted on the map, and attitudes observed locally in the rocks of the Franciscan group may or may not be truly representative. Therefore, the nature of the larger structures within the fault-bounded segments of the El Sombroso block, for example, could be variously interpreted. Most of the measured attitudes show northwesterly strikes and northeasterly dips, from which it may fairly be concluded that the entire block is tilted to the northeast. This general tilt, however, has minor folds superimposed upon it, as is shown by the regular divergence of closely spaced strike symbols in parts of the area. A few folds that show opposing dips, and are thus anticlines or synclines in the usual sense of the terms, may be demonstrated and are shown in figure 58. The best examples of these are a parallel anticline and syncline in the northwestern part of El Sombroso block. The axes of both, although sinuous, trend in an easterly direction. In the area to the south and east of these folds, the beds have a consistent east-west trend and northerly dip, but between the Guadalupe mine and El Sombroso the strike swings through northwest to north, and locally exhibit a northeast strike and southeast dip. Other folds of the same order of size may be inferred from available data near the southwest corner of the district in the rocks underlying a ridge to the north of Soda Spring Canyon about $2\frac{1}{2}$ or 3 miles upstream from Los Gatos Creek and also in the area north and northwest of Mount Umunhum. The axes of all these folds have a general easterly trend.

Smaller folds also due to regional forces are difficult to distinguish from structures that have resulted from the large-scale flowage of the rocks that is common in the district, particularly in the Los Capitancillos block. Some local undulatory folds measuring a few hun-

dreds of feet across are shown on the geology map of the district (pl. 1) and the more detailed geologic map of the New Almaden mine area (pl. 3). Where a large area is considered, folds of this magnitude seem to make no regular pattern, and no simple concept of folding seems to account satisfactorily for the position and attitude of such beds. They seem to represent yield to local stresses whose direction is diverted from the normal stress direction by the large difference in stress transmission of the competent and incompetent rocks.

Drag folds adjacent to faults occur throughout the district, but an entire fold can rarely be observed in a single outcrop. The presence of these folds is indicated on the map by the patterns showing the distribution of the rocks adjacent to faults, and some of the folds are best shown in cross sections. On the south side of the Soda Spring fault there are drag folds probably as much as 100 feet wide, as is shown on section A-A', plate 1. Another drag fold of comparable size is indicated by the surface trace of a cherty limestone bed adjacent to a minor fault in the deep canyon 1,250 feet southwest of the modern reduction plant on Mine Hill.

Another type of small fold in sedimentary rocks of the Franciscan group, apparently related to, and probably caused by, intrusions of serpentine, may be observed at a few places in the New Almaden mine adjacent to serpentine bodies. An easily accessible example of such crumpling can be seen in a short crosscut from the Day tunnel south of the Cable raise (pl. 6), where graywacke and shale are in contact with silica-carbonate rock derived from serpentine. Because the serpentine was intruded plastically, rather than as a peridotite magma, its contacts are not very different from faults, and the folds formed along them are similar to drag folds formed along faults.

FOLDS IN POST-FRANCISCAN ROCKS

Folds in the post-Franciscan rocks of the district are much more clearly defined, simple, and regular in shape than those in Franciscan rocks, and they are more readily worked out because of the more numerous outcrops and the greater consistency of observed attitudes (fig. 62). Most of the folds are large and open and have comparatively gentle dips on the limbs, although in exceptional places, along faults for example, the younger rocks are drag folded like those of the Franciscan group. The deformation of the post-Franciscan rocks has been accomplished by simple folding, unaccompanied by the extensive rock flowage that is so typical of the deformation of the rocks of the Franciscan group.

Upper Cretaceous rocks of the Sierra Azul

Folds in the Upper Cretaceous rocks of the Sierra Azul have been mapped in much less detail than those in any of the other post-Franciscan formations. To judge from the few dips observed, the beds along the divide near the south boundary of the district strike northward to northwestward and in general dip at moderate angles to the northeast, whereas in the eastern and western tributaries of Almaden Canyon, adjacent to the Sierra Azul fault, they strike northwest and dip southwest. As the attitudes in this unit are comparatively consistent over large areas, they probably indicate a broad synclinal structure.

Upper Cretaceous rocks of the Santa Teresa Hills

Folds in the Upper Cretaceous rocks of the Santa Teresa Hills are indicated by attitudes observed in the sandstone and by the surface traces of contacts between sandstone and shale. The large mass of these rocks in the Santa Teresa Hills is broadly folded into a syncline whose axis plunges to the west. The position of the axis of this fold is readily plotted through an area extending westward from the quarry near the west end of the hills to the place where it passes beneath the alluvium of Alamitos Creek, but east of the quarry the fold gets lost in poorly exposed shale. The flanks of this fold are cut off by parallel east-trending faults that lie about 1,500 feet apart, but the eastward extension of the south limb is indicated by the easterly strike and gentle northerly dips of the beds exposed in the fault-bounded blocks.

Eocene rocks

The broad syncline which involved the rocks of Late Cretaceous age in the Santa Teresa Hills is shared by the Eocene rocks, which overlie them with only a minor unconformity. Two smaller well-defined folds, a syncline and an anticline, lie near the crest of the ridge west of the Santa Teresa mine. Their axes, which are traceable for less than half a mile, trend northwestward, and their limbs have dips of less than 45°.

Miocene formations

The folds in the rocks of the Temblor and Monterey formations of Miocene age have been mapped in more detail than those in any of the other formations in the district, owing to the abundance of exposures, the distinctness of the bedding, and the presence of mappable stratigraphic units. These folds are regular and clearly defined, and are comparatively extensive, though many are cut off by faults. The most extensive is a syncline that makes up the central part of Blossom Hill and the hill north of the Senator mine. This fold trends eastward and is nearly symmetrical. The steepest dips

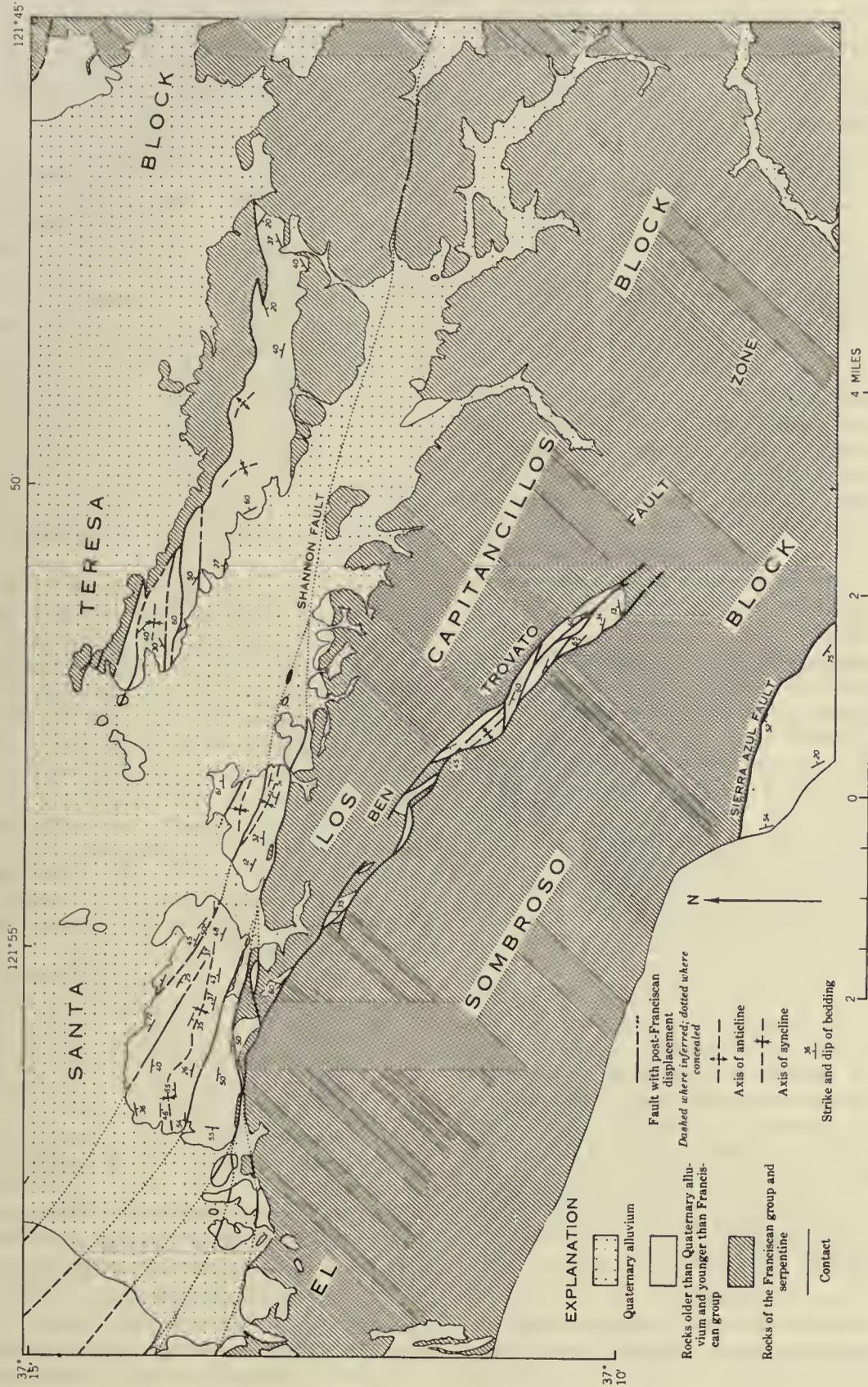


FIGURE 62.—Map showing the major structural features of the post-Franciscan rocks of the New Almaden district.

on its limbs do not exceed 60° , and are little steeper than dips near the trough. Other folds mapped in several of the smaller Miocene fault blocks of the district are similar, but some in the Berrocal fault zone are tighter. (See section B-B', pl. 1.)

Santa Clara formation

No folds, either small or large, have been observed in the Santa Clara formation, but at several places near faults these relatively young gravels appear to have been tilted. The greatest inclination was seen in the high terraces just south of Los Gatos, where dips as great as 18° were recorded.

FAULTS

The faults in the New Almaden district, like the folds, vary considerably in size and character; they include major and minor shear zones, strike-slip faults, normal and reverse faults, minor faults due to intrusions, and widely distributed but uniformly oriented tension fractures. Of these, only the shear zones, strike-slip faults, and tension fractures appear to have any relation to the development of the quicksilver ore deposits, and only the tension fractures are known to cut the ore bodies.

Only three periods of extensive faulting in the area can be demonstrated, but there may have been others. The oldest faulting is believed to have closely followed the deposition of the lower Upper Cretaceous (Cenomanian) Franciscan rocks, for it has affected the rocks of this group but not the Upper Cretaceous rocks of the Sierra Azul, which are believed to be somewhat younger. This faulting is characterized by the development of shear zones and faults with strike-slip movement. The youngest faulting, the normal faulting in the Santa Teresa block, offset the Santa Clara formation and therefore must be as recent as Pleistocene. The offsets of the Santa Clara formation, however, are apparently not so great as the offsets of the Miocene rocks in the Blossom Hills along the same and related faults, and this difference indicates an extensive period of faulting in early or middle Pliocene time. On some of the older faults also recurrent movement has obviously taken place, and has served to confuse the record of faulting in the area.

In the following paragraphs each type of fault is described, the available data on direction and amount of movement are recorded, and the evidence for the dating of each type is considered.

SHEAR ZONES

Two extensive zones of sheared, squeezed, and broken rocks are among the largest, yet least obvious, structural features in the district. Similar shear zones are

rather characteristic of the Franciscan group throughout the Coast Ranges of California, and have been described (Eckel and others, 1941, p. 533-535; and Bailey, 1946, p. 209-210) as occurring in several other widely separated quicksilver districts. In the New Almaden district the larger of these zones, named the Ben Trovato fault zone, extends from the extreme southeast corner of the district with a general trend of $N. 60^\circ W.$ through the heart of the area to Shannon Road, where it is cut off by a younger fault—a total distance of more than 11 miles. Its maximum width, as exposed in the southeastern part of the district, is about 4,500 feet, but to the northwest it is appreciably narrower. A second shear zone, named the Coyote Peak fault zone, extends $N. 75^\circ W.$ from the vicinity of Coyote Peak at the eastern edge of the district, for more than 4 miles; its west end is buried under the alluvium of Alamitos Creek. It attains its maximum width of about 2,000 feet just south of Coyote Peak. The dip of neither zone can be determined with certainty, but both appear to be nearly vertical.

The shear zones consist chiefly of a sheared matrix of the weaker clastic sedimentary rocks surrounding irregular inclusions of hard graywacke, greenstone, limestone, chert, and glaucophane-bearing metamorphic rocks (pl. 1). The inclusions are a few feet to 2,000 feet in greatest diameter, and in shape they range from equidimensional blocks to thin sinuous lenses. They commonly have slickensided surfaces, although internally many are little sheared or otherwise deformed. Outcrops in these zones consist largely of the isolated blocks, but in a few places the matrix is well exposed, notably along the sides of the Almaden Reservoir; in these exposures it is extremely sheared, plastically deformed, and tightly folded. The borders of the shear zones must necessarily be placed somewhat arbitrarily, as the highly deformed rocks grade imperceptibly into less deformed rocks of the Franciscan group. In many places the apparent margin is highly irregular, but the southwestern boundary of the Ben Trovato zone is sharp in part where formed by a post-Miocene fault. Serpentine has been intruded into the western part of the shear zone in the Santa Teresa Hills, but it is strangely scarce in the Ben Trovato zone.

The shear zones are marked by rather distinct vegetation and topography: in most places they underlie grasslands that extend over ridges and valleys, cutting a wide swath through the generally brushy terrain. In part of the area, as, for example, south of the Los Capitancillos Ridge, the path of the Ben Trovato zone is marked by longitudinal canyons, but else-

where it is not followed by the drainage. In detail, the topography along the shear zone tends to be irregular, with scattered knobs and knolls, these irregularities being largely the result of differences in resistance between the included rock masses and the sheared matrix. Landslides develop readily in the parts of shear zones underlain by matrix material containing a high proportion of shale.

The regional effect of the Ben Trovato fault zone is fairly well illustrated by the position of the limestone and tachylite key horizons in the Franciscan group. (See fig. 56.) The discontinuous limestone horizon trends irregularly from the western slope of St. Josephs Hill at the west edge of the district eastward and northeastward to Shannon Road, where it encounters the shear zone, within which it is represented only by fault-bounded blocks. In the central part of the district the limestone also occurs only in heterogeneously oriented blocks within the shear zone. Near the southeast corner of the district the limestone forms a nearly continuous ledge along the headwaters of Longwall Canyon on the north edge of the shear zone, but isolated boulders are found in the zone even farther to the southeast. Thus, only relatively short segments of the limestone stratum at either end of the district are unaffected by the shear zone.

To judge from the position of the limestone on opposite sides of the fault zone, the apparent horizontal offset is about 10 miles, the southwest side having moved northwest relative to the northeast side. The real offset, however, may not be so great, for the shear zone does not diverge greatly from the regional strike, and the limestone may have been folded into partial parallelism with the shear zone before the shearing took place. The tachylite which underlies the limestone is distributed similarly to the limestone and apparently was affected by the shearing in much the same way.

The northern shear zone, passing near Coyote Peak, does not cut any good horizon markers, and there seems to be no way of determining the direction and amount of movement along it.

Both fault zones must be post-Franciscan, for they involve all the rock types of the Franciscan group. The Ben Trovato fault zone is clearly older than middle Miocene, for it is unconformably overlain by rocks of the Monterey at its northwest end. The Coyote Peak fault zone trends west to an area underlain by the Upper Cretaceous rocks of the Santa Teresa Hill, but these rocks are not sheared and appear to overlie the shear zone unconformably. The shear zones are thus at least as old as the Upper Cretaceous rocks found in the Santa Teresa Hills, but

their age in relation to the Upper Cretaceous rocks of the Sierra Azul, which are probably a little older, cannot be determined directly because the shear zones nowhere border these rocks. Chiefly because the Franciscan rocks throughout the area are more sheared than are the Upper Cretaceous rocks of the Sierra Azul, we suspect that the major shear zones were first developed before the deposition of the Upper Cretaceous rocks of the Sierra Azul.

STRIKE-SLIP FAULTS

The New Almaden district contains at least six long faults that are parallel to the general strike of the beds that they traverse or intersect at low angles. The movement along these faults is believed to have been largely horizontal, and they differ from the previously described shear zones mainly in the narrowness of the band of rock effected by movement. Three of the faults, and some splits from them, are in the El Sombroso block, and three in the Los Capitancillos block. They involve only rocks of the Franciscan group.

The Soda Spring fault, in the El Sombroso block, extends for more than 8 miles across the southwest corner of the district. It trends about S. 60° E., nearly parallel with the Ben Trovato shear zone, from a point about 1 mile south of Los Gatos to a point in the middle fork of Almaden Canyon about 1¾ miles upstream from Twin Creeks. Its dip, as deduced from its slight swing toward the northeast in crossing canyons, is believed to be steep to the northeast. The fault does not cut any of the key horizons in Franciscan group, though it does appear to terminate several folds. The strongest evidence for its existence is its topographic expression: much of the middle and upper course of Soda Spring Canyon appears to follow the fault line and the saddle between Mount Umunhum and the backbone of Sierra Azul Ridge falls on it; also, the abnormally steep scarps to the northwest of Priest Rock and southeast of Mount Umunhum are apparently due to the presence of this fault. It is believed to be a right lateral fault because of the drag folding expressed by dips in the beds in the upper part of Almaden Canyon and Soda Spring Canyon.

A short fault branches from the Soda Spring fault 1 mile west of Mount Umunhum and extends generally N. 75° W. for about 1½ miles along the crest of the Sierra Azul. It separates greenstone from clastic sedimentary rocks, and is marked by minor irregularities in the topography and abrupt changes in the attitudes of the beds.

A very long strike-slip fault, named the Rincon fault, branches eastward from the Soda Spring fault on the north slope of Soda Spring Canyon about $1\frac{1}{2}$ miles upstream from the mouth. It trends about east-southeast to the saddle south of El Sombroso, and from there it extends more nearly due east for about 3 miles. It merges into the Berrocal fault zone about half a mile northeast of Bald Mountain. A branch of this fault continues on the east-southeast course from the ridge south of El Sombroso for more than 2 miles, and apparently dies out in a fold in the thick body of clastic sedimentary rocks underlying the upper course of Guadalupe Creek. The Rincon fault offsets basaltic greenstone at a very low angle to the strike, and both the main and the branch faults seem to cut off several folds. Both faults have rather striking topographic expression in some places, the best examples being unusual right-angle turns and abrupt changes in gradient in the upper tributaries of Soda Spring Canyon. The chief evidence for it being a right-lateral fault is the 1-mile offset of the greenstone northwest of Bald Mountain and its relation to other right-lateral faults.

Another major fault within the El Sombroso block, named the Limekiln fault, is roughly parallel to the Rincon fault and about half a mile north of it. Evidence for its existence is largely based on a straight-line offset of the limestone and tachylite horizons to the west, a straight-line contact between greenstone and clastic sedimentary rocks along its eastern part, and anomalies in the attitude of adjacent beds. Only here and there does this fault have any topographic expression. The displacement along the Limekiln fault is problematical. Because of its relation to the Ben Trovato shear zone and its near parallelism with the strike-slip Rincon fault, one is tempted to assume it has similar movement along it. If it has chiefly strike-slip movement, however, the displacement of the limestone and greenstone near the west edge of the district would indicate left-lateral movement, which is contrary to the movement along the other strike-slip faults. This apparent conflict may be the result of sizable dip-slip movement more than compensating the displacement due to strike-slip movement, for this fault does parallel others in the Blossom Hill area which have chiefly dip-slip movement. No uniform dip-slip movement, however, will account for the apparent offsets, and we are inclined to believe it really has a large component of left-lateral displacement.

The three strike-slip faults that cut the Los Capitancillos block strike more nearly northwest than those in the El Sombroso block and cut across the main folds at wider angles. The most westerly of these is the Enriquita fault, which trends about N.

30° W., on the average, from the Guadalupe Reservoir across Los Capitancillos Ridge to the canyon below the Senator mine. The north end of the Enriquita fault is complicated by a structural "knot" of serpentine and other rocks, but it is evidently cut off by the post-Miocene Shannon fault. Along much of its length the trace of the Enriquita is marked by slivers of serpentine believed to have been dragged along the fault, or squeezed into it, and judging by the dip of these masses the fault dips eastward at a moderately steep angle. The strike-slip offset along this fault is believed to be about 9,000 feet, the western side having moved northward. This estimate is based on the offset of the serpentine sills, of the greenstone body marking the south limb of the anticline, and of the northern limit of the Ben Trovato shear zone. The amount of dip-slip movement cannot be determined, but is believed to be small.

Parallel to the Enriquita fault and about $1\frac{1}{2}$ miles east of it is another strike-slip fault, the Almaden fault, which extends southward from the Shannon fault to the Mine Hill area. The apparent offset of this fault is best indicated just south of where it crosses a small tongue of alluvium on the border of the Santa Clara Valley; a greenstone band on the west side of the fault is here shifted 1,800 feet northward from its counterpart on the east side. Within the New Almaden mine area mapped in detail the fault could not be followed on the surface; however, it seems to have been exposed in some of the mine workings that are now inaccessible. On the ridge north of Deep Gulch, thin beds of chert on the east side of the fault as projected are folded in such a manner as to take up most of the strike-slip offset indicated along the traceable part of the fault.

Three branching strike-slip faults occur near the east edge of the district in the Los Capitancillos block. The largest of these, the Calero fault, is exposed in the south wall of Llagas Canyon at the edge of the district and trends N. 40° W. to and beyond Calero Dam, where it disappears beneath the valley alluvium. This fault is marked by a straight-line contact between tachylitic greenstone and graywacke a little southeast of the Calero Reservoir; it also appears to offset the limestone, and it has striking topographic expression in the upland area north of Llagas Creek, where it follows straight stream courses and passes through marked saddles in two ridge tops. The horizontal component of movement along it, as indicated by the offset of the limestone beds, is about 3,500 feet, with the southwest block shifted to the northwest relatively to the northeast block. No definite data on the vertical component of movement on the fault are ob-

tainable. About half a mile northwest of the Calero Dam the Calero fault sends off a branch that trends east-southeast along the northern edge of Calero Reservoir to the east edge of the district. The evidence for this fault is not strong, but part of its course is marked by straight canyons and part by a difference in the color of the residual soil on opposite sides. Still another branch goes northwestward from the Calero fault at Llagas Canyon, and may reach Almaden Canyon at the sharp bend 1 mile below the Hacienda. It is marked by lenticular bodies of serpentine and a little silica-carbonate rock.

The age of the strike-slip faults in the Los Capitancillos block is probably about the same as that of the shear zones and is definitely earlier than middle Miocene. The Enriquita fault and several parallel shorter faults appear to merge into the Ben Trovato fault zone, as though they were contemporaneous with movements along it, but they also seem to displace the northern margin of the shear zone. Some of the strike-slip faults cut serpentine, but others seem to have been intruded by serpentine. Locally, the apparent intrusion of serpentine into them can be interpreted as due to drag, but elsewhere, as in the southeastern part of the New Almaden mine area, this explanation seems less probable than simple intrusion. These bits of evidence, though inconclusive, suggest that the strike-slip faults of the Los Capitancillos block were formed before the end of the period of normal intrusion of serpentine, and soon after the initial development of the major shear zones, in Late Cretaceous time.

DIP-SLIP FAULTS

Faults with dip-slip movement are widely distributed through the district, and unlike the strike-slip faults, they cut all the rocks older than the Quaternary alluvium. These faults differ widely in amount and direction of movement; a few are reverse faults, but most of them are normal. The available evidence for dating them places the age of faulting only within broad limits; most of them, however, are later than late Miocene, and on a few there was recurrent movement in Pliocene time.

A post-Cretaceous reverse(?) fault near the south boundary of the district forms the contact between the Upper Cretaceous rock of the Sierra Azul and the Franciscan group and serpentine. This fault, which has been named the Sierra Azul fault, extends for a distance of about $2\frac{1}{2}$ miles from the slope east of the easternmost tributary of Almaden Canyon, and reaches the main crest of the Sierra Azul about 3,800 feet south of Mount Umunhum. Its general course is about west-northwest; its dip is to the northeast. The

fault cuts off structures in the two formations separated by it, but has little topographic expression. From the relative ages of the rocks that have been brought together by the fault, one can tell that the southwest block has been depressed relatively to the northeast block, which suggests it is a reverse fault, but the horizontal component of movement is not known.

The most extensive post-Cretaceous fault in the district is the Shannon fault, which trends a little north of west across the entire district and separates the Los Capitancillos block from the Santa Teresa block. This fault is covered at the east edge of the district by alluvium in a small embayment from the Santa Clara Valley; to the west it is exposed south of Coyote Peak, but again becomes buried under the alluvium of Alamitos Creek north of the Calero Dam; it emerges east of the Senator mine, crosses the hills north of the mine, and follows valleys down to Guadalupe Canyon; from Guadalupe Canyon it continues westward beyond the west boundary of the district. Several other faults diverge northward from the Shannon fault in the west half of the district, and west of the Guadalupe mine there is a mile-long interval wherein the Shannon fault gives way to a complex braid of faults.

The dip of the main Shannon fault, and that of most of its branches, is apparently steep to the north, and the movement is believed to be largely down the dip. Some of its smaller branches, however, seem to be reverse faults. The net downthrow to the north cannot be determined accurately, but in places it certainly amounts to several hundred feet. The faulting is believed to have occurred in the early or middle Pliocene time.

The Shannon fault and its branches are represented in the area west of Los Gatos Creek by five parallel faults of comparatively small displacement. These faults were mapped largely on the evidence afforded by straight-line stream valleys and other topographic anomalies, developed on a surface underlain by the gravels of the Santa Clara formation. They are obviously younger than the Pliocene and Pleistocene Santa Clara formation, which they offset, and older than the Quaternary alluvium filling the Santa Clara Valley. They strike about N. 50° W., and the one farthest north dips northeastward and is normal. The dips of the others were not observed, but on all of them the downthrow appears to be to the north, and they probably are all normal. Because of the relative recency of these faults and their small offsets, they are believed to represent minor recurrent movement along branches of the older Shannon fault.

The rocks underlying the western part of the Santa Teresa Hills, also, are divided into elongate blocks by parallel and anastomosing faults, which trend about east and have steep dips. The evidence for these faults is stratigraphic, for none of them have more than minor topographic expression. The amount of movement along them, if it is largely vertical, appears to be of the same magnitude as that along the Shannon branch faults of the Blossom Hill area, though the movement on the faults separating rocks of the Franciscan group from younger rocks could be greater. The faults on the Santa Teresa Hills cut no rocks younger than Eocene, and can therefore be dated only as post-Eocene, but their similarity to the Shannon faults makes it likely that they developed in early Pliocene time or shortly thereafter.

The braid of faults in the area just southwest of the Ben Trovato fault zone is so complex and contains so many short faults that they cannot all be described individually. Each involves rocks of Miocene and Franciscan age, or is traceable into a fault that does involve them, and all are proved by stratigraphic displacement as well as indicated by topographic expression. The faults appear to be steep, and both normal and reverse displacement of several hundred feet have been recognized in this area of elevated, depressed, and tilted blocks. The extension of this zone of faults southeast of the area underlain by the formations of Miocene age cannot be traced with certainty, because in the absence of younger rocks there is no way of separating post-Miocene faults from older ones. Topographic evidence and the arrangement of geologic contacts suggest, however, that the well-defined post-Miocene fault separating rocks of the Temblor formation from the Ben Trovato fault zone continues along the edge of the shear zone southwest of Mine Hill, and crosses the south boundary of the district in Llagas Canyon. Another fault that may be of about the same age extends southeast from Twin Creeks in Almaden Canyon to the edge of the district, and still another runs parallel to it about 1,000 feet farther southwest.

FAULTS DUE TO INTRUSION OF SERPENTINE

The development of the alta along contacts of the serpentine bodies as a result of their emplacement has been discussed on pages 18 and 19. The alta has been compared to a fault gouge, and the contacts along which it formed might all be regarded as faults, for they are surfaces dividing two rock masses that have moved relatively to each other (figs. 63, 64). These contacts, however, may also be regarded as intrusive, even though the serpentine at the time of intrusion



FIGURE 63.—Fairly regular contact between serpentine (now altered to silica-carbonate rock) below and alta above. Even though the alta resembles fault gouge, contacts of this type are shown as intrusive contacts on the maps accompanying this report, because the alta is believed due to intrusion rather than to later faulting.



FIGURE 64.—Irregular contact between serpentine, now converted to silica-carbonate rock (sc), and alta exposed in underground workings of the New Almaden mine.

was a plastic mass rather than a magma. On the maps and cross sections accompanying this report such contacts are shown as intrusive contacts unless there is evidence of postintrusive faulting along them.

Faults that differ in that they cut across the alta along the margins of some of the serpentine bodies are also thought to have resulted from forces created by the intrusions. These faults are largely normal, though a few are reverse, and the displacement along them generally does not exceed 10 feet. Their effect

has been to produce in some places a steplike intrusive contact, which partly parallels the shearing in the alta and partly follows these faults that run across the grain of the alta. The cross-cutting faults continue on into alta, but do not extend into the serpentine. In many places it appears likely that the wallrocks were fractured before the intrusion of the serpentine, and the intrusive was responsible only for differential movement along preexisting fractures.

Faults of this type are best observed at scattered localities in the underground workings of the New Almaden mine, where nearly complete exposure in three dimensions aids in determining their true relationships. Good examples may be noted in the northern part of the Harry area on the 600 and 700 levels, where step faulting has raised the alta side of the intrusive contact at intervals of a few feet, and developed mullions extending down the dip of the fault contact. Faults of this kind are also well exposed between the 600 and 700 levels in the New World stope, where the offsets exceed 10 feet in a few places, and in the Giant Powder and Ponce stopes of the Santa Rita area, where the normal faults may be seen to veer off from the silica-carbonate rock and die out in the Franciscan wallrocks.

TENSION FRACTURES

The thousands of tension fractures in the silica-carbonate rock of Los Capitancillos Ridge, and to a minor extent in similar rock in the Santa Teresa Hills, are small, but economically important structures in the New Almaden district. During the quicksilver mineralization they were open, but during the waning stages of mineralization they became filled with dolomite and quartz. They are generally no more than 1 or 2 inches wide, although a few are as much as 6 inches wide. Individual fractures generally extend less than a hundred feet along the contact between the silica-carbonate rock and the Franciscan rocks, and the distance to which they extend into the Franciscan rocks is generally much less. Although individual fractures are not very long, they are commonly grouped in swarms which may extend for hundreds of feet. The most striking feature of these fractures is their prevalent N. 30° E. strike and steep dip, which is maintained regardless of the attitude of the larger structural features in which they occur. The strikes recorded for thousands of these fractures in various parts of the district do indeed range from due north to N. 50° E., but a large proportion of them are between N. 25° E. and N. 35° E. The dips may be as low as 60° in either direction, but most are within 15° of vertical.

Nearly all the fractures are filled with vein material, which consists mostly of dolomite and quartz but locally contains pyrite, hydrocarbons, and cinnabar. Veins of this type are so prevalent throughout the silica-carbonate rock of Mine Hill that the early miners gave them a name, "hilos" (Spanish for threads, and comparable to our term "stringers"), and regarded them as guides to ore bodies or integral parts of them. These hilos in most places do not contain enough cinnabar to constitute ore, but the fractures were the principal channelways for the ore-forming solutions. Hilos are conspicuous in many of the accessible parts of the mines at New Almaden and are very numerous in part of the Guadalupe mine, particularly the Water tunnel stopes. Scattered hilos have also been observed in the silica-carbonate rock bodies of the Santa Teresa Hills, including those explored by the Santa Teresa and Bernal mines, but here they are somewhat less numerous and less uniform in attitude than in Los Capitancillos Ridge.

ORE DEPOSITS

The economically important ore deposits of the New Almaden district are those that contain quicksilver, but small amounts of ores of chromium, manganese, and copper, bearing no direct genetic relation to the quicksilver ores, have been noted. The recorded production of quicksilver from the district between the recognition of the quicksilver ores in 1845 and the end of 1945 was 1,137,727 flasks, with a value of about \$55,000,000. A few hundred pounds of chromium also has been produced, but only the quicksilver deposits have been fully studied, and they alone are comprehensively described in this report.

Even though the New Almaden district has yielded far more quicksilver than any other in the United States, in 1948, when the first draft of this report was written, the mines were inactive and many of the workings were inaccessible. Furthermore, in contrast to many other districts in the California Coast Ranges, this district did not respond to the stimulus of high prices during the two world wars by again reaching its former high level of production, although the mines were active during these periods. The study leading to this report indicates that, in spite of the large amount of exploration already done, the district should not be regarded as worked out, for undiscovered bodies of quicksilver ore probably remain along the mineralized belt. Because the history of the exploration and development of the individual mines has direct bearing on the possibility of recovering additional ore from them, pertinent historical facts have been included with the individual mine descrip-

tions. These supplement the comprehensive history of the New Almaden mines given on pages 176-195.

QUICKSILVER ORE BODIES

In the New Almaden district the mineralized area likely to contain ore bodies is relatively small, and during the past hundred years all the surficial exposures that appear to be mineralized have doubtless been thoroughly examined. Nevertheless, it is believed that the area still contains undiscovered subsurface ore bodies, which must be found by either actual mining or drilling. The prime purpose of this report is to call attention to the places where the chances for finding hidden ore bodies are best, in order that any additional expenditure of money and energy may have the best opportunity to revitalize the district and add to the meager domestic production of quicksilver.

To arrive at conclusions as to whether or not a district may contain hidden ore bodies, and, if so, where they are most likely to be found, and whether they can be expected to be worth the exploration cost necessary to find them, an ore geologist must pursue several lines of inquiry. In all of these, however, his most reliable guide is the ore bodies already found in the district under consideration or in similar districts. He studies the character of the previously discovered ore bodies to learn from their mineralogy and textures how they were deposited and to accumulate data leading to an understanding of the conditions that prevailed when they were formed. He also studies the geologic environment, or structural control, of the known ore bodies to learn what places were most favorable for the deposition of ore, and then prepares and studies maps of the entire district in order to locate other places where similar environmental conditions prevail. Such observations, however, are not sufficient in themselves to allow him to predict that areas with similar rocks and structures will contain ore bodies; he has also to consider several other more elusive problems. Such problems are—what medium transported the ore metal, what pathways did it follow, what was the temperature and pressure range over which it deposited the ore minerals, and at what depth were the ores deposited. The solution of these problems requires some knowledge of the time of mineralization. Finally, the geologist must collect information on the size and grade of the ore bodies already mined, in order to present data that will be helpful in judging whether the search for undiscovered ore bodies is justified by the expectable value of the ore that might be found.

The following pages, together with the maps, will

present as much of this information as is required to understand why we believe that certain areas may contain undiscovered subsurface ore bodies. Factual data pertaining to the ore bodies are presented first, interpretations follow, and the conclusions based on these data are given on pages 170-176. The factual data are presented in the following order: (1) Description of minerals, including ore minerals and others deposited with them; (2) the distribution of these minerals in the rock to form ore bodies, including size and grade of the ore bodies; and (3) the distribution of the ore bodies in the mining district, including a discussion of their lithologic and structural environment.

MINERALOGY

The mineralogy of the quicksilver ore deposits is comparatively simple. The only quicksilver-bearing mineral of real economic importance is cinnabar, though native mercury is found locally, and a little metacinnabar and tiemannite are said to have been found. Other sulfides that are closely related to the ore deposits include pyrite, stibnite, chalcopyrite, sphalerite, galena, and bornite, but of these only pyrite is common or widespread. Arsenopyrite, which was reported in 1854 (Blake, 1854, p. 438), has not been observed since and probably was erroneously identified. No marcasite has been found. The common nonmetallic gangue minerals, other than those present in the silica-carbonate rock formed before the quicksilver mineralization, are dolomite and quartz. Calcite is rare and possibly nowhere genetically related to the ore mineralization; chalcedony and opal are also uncommon. Single occurrences of apophyllite, gyrolite, pilinite, and barite have been noted. Hydrocarbons, both tars and oils, accompany the ores in many places, and in some places they appear to have been deposited contemporaneously with them. Secondary minerals deserving no further description, are various iron and manganese oxides, jarosite, epsomite, aragonite, and zaraitite.

ORE MINERALS

Cinnabar (HgS)

Cinnabar, the red mercuric sulfide, occurs most abundantly as fine-grained to microcrystalline aggregates replacing silica-carbonate rock, and it is less common in pore spaces in other kinds of rocks, and as open-space fillings in veins. Well-formed crystals of cinnabar are unusually rare in the New Almaden district, though small ones have been found in nearly all the mines. Isolated equant crystals from 1 to 2 mm in diameter have been formed in some places on the walls of fractures and in small vugs; these commonly have rhombohedrons and pinacoid as their dominant

forms, and many are two-fold twins. Such crystals were described by Melville and Lindgren (1890, p. 22). Needlelike crystals of cinnabar occur sparingly in some of the youngest dolomite veins. Most of the cinnabar, however, forms complex aggregates of minute crystals exhibiting a multitude of sparkling crystal faces and cleavage planes.

Interesting, but uncommon, are small hemispherical crystalline groups showing no apparent radial structure. These are believed by local miners to have formed directly from globules of native mercury, and all examples of these observed by the writers do appear to be accompanied by native mercury. Other hemispherical aggregates of pulverulent cinnabar, characterized by smooth surfaces, concentric banding, and an orange- to brick-red color, were found only locally in near-surface workings and may be of secondary origin.

Metacinnabar (HgS)

Metacinnabar, the black tetrahedral mercuric sulfide, was not found in the course of this study, though it has been said to occur in the district. It was first reported by Melville (1890, p. 293-296; 1891, p. 80-83), who gives an analysis of impure material and a list of interfacial angles measured on minute tapering conical crystals, cross sections of which are equilateral triangles. He assigned these crystals to the hexagonal system, and as his report fails to state their color, they may have been of a deep-colored variety of cinnabar. His original material is apparently no longer available for reinvestigation. Other metacinnabar specimens labelled "collected by F. L. Ransome from the lower levels of the New Almaden mine, definite point unknown" were loaned the writers by the U.S. National Museum; but as the specimens consist in part of a dense black silica-carbonate rock, which is not known to occur in the New Almaden mine, and as they contain a large amount of jarosite, which also is uncommon in the mine, it seems probable that the specimens are incorrectly labelled.

Metacinnabar is also reported in the bulletins on "Minerals of California" (Eakle, 1923, p. 94; and Pabst, 1938, p. 56) as occurring in both the New Almaden and Guadalupe mines, Melville's article being cited as authority. No specimens of metacinnabar from the district were found, however, in the museums of the California State Division of Mines, of Stanford University, of the University of California, or of the University of California at Los Angeles. The occurrence of metacinnabar in the district therefore needs to be verified, although there is no reason for believing that it could not occur there.

Mercury (Hg)

Native mercury did not occur in much of the ore in the district, though in some it occurred in considerable quantity. All the native mercury seen by the writers was accompanied by cinnabar. Most lay in fractures and vugs in silica-carbonate rock, but some of that in the Cora Blanca workings of the New Almaden mine was in greenstone tuff, and in the adjacent Harry workings it occurred in graywacke of the Franciscan group. Although native mercury is believed by some to be a supergene mineral, no relation between its abundance and depth is apparent in the New Almaden district. It was found near the surface in the opencuts developed at the New Almaden mine during World War II; but it was also found at a depth of about 500 feet in the same mine near the Santa Rita stope and in the Far West stope, and it was reported (Christy, 1879, p. 455) to have "run out of shattered alta" on the 1500 and 1600 levels in the Randol part of the mine. Specimens from the Guadalupe mine containing a little native mercury have been seen, but their exact source is unknown. No native mercury has been observed in ores from the Senator mine.

Tiemannite (HgSe)

Tiemannite, the gray mercuric selenide, is said to have been found in ores from the Guadalupe mine (Eakle, 1923, p. 64), but none was found in this study.

ACCOMPANYING SULFIDES

Pyrite (FeS₂)

Pyrite is generally scarce in the quicksilver ores of the district, and in none of them was it so abundant as to necessitate special precautions in furnacing. As pyrite is more widespread than cinnabar and is not particularly concentrated in or near the ore bodies, it cannot be used as a guide to ore. Many specimens of high-grade cinnabar ore contain no visible pyrite, but others equally rich contain several percent. Conversely, some barren silica-carbonate rock, especially the black chalcedonic variety common in the western part of the district, contains as much as 5 percent of pyrite. In some places the pyrite was deposited before the cinnabar; elsewhere it accompanies dolomite veins that were formed after the ore bodies. Some specimens from the Senator mine show alternations of pyrite and cinnabar in banded dolomite veins as is shown in figure 65. Other specimens from the same mine show cinnabar crystallizing selectively on pyrite, but such relationship is rare. Pyrite found near the surface is generally altered to hydrous iron oxides, but the major source of the iron stains in the ocherous



FIGURE 65.—Photomicrograph of section across banded dolomite vein containing some cinnabar, pyrite, and hematite. Such veins, which are a little younger than most of the quicksilver ores, were mined as ore in the Senator mine, but elsewhere in the district they contained too little cinnabar to be of commercial grade.

rock formed by the weathering of silica-carbonate rock is probably ferroan magnesite rather than pyrite.

Stibnite (Sb_2S_3)

Minute needles of stibnite occur sparingly in parts of the Senator and New Almaden mines. It is most abundant in the former, where it occurs in banded dolomite veins containing a little quartz, pyrite, and cinnabar. (See fig. 66.) Where both stibnite and cinnabar occur in a single vein, they alternate in thin layers but are not intermingled; although both minerals were deposited in the same period of mineralization, they were not strictly contemporaneous. In the New Almaden mine, stibnite was seen on the 800 level in two places—in the Day tunnel and in the Cora Blanca workings—and in both places it appears to have been deposited after the major period of cinnabar mineralization.

Sphalerite (ZnS)

The deep-brown or black ferroan variety of sphalerite known as “black jack” occurs in a few places in the New Almaden mine. Its dark color suggested that it might contain some mercury, but specimens subjected to the sensitive fluorescent screen test showed not even a trace. The sphalerite tested was found in irregular breccia veins on the 800 level, in a crosscut extending westward from the Day tunnel, about 3,000 feet from

the portal. It formed a coating on quartz, and was coated in turn with dolomite. Other accompanying minerals included galena and pyrite. No cinnabar was found in the vicinity, but throughout the mine this type of breccia vein generally is younger than the quicksilver ores. Silica-carbonate rock on the dump by the St. George shaft is traversed by quartz-dolomite veins containing sphalerite, galena, and chalcopyrite, and some of these cut cinnabar-quartz veins. The sphalerite, therefore, was probably all deposited after the main period of cinnabar deposition.

Galena (PbS)

Galena occurs with sphalerite in very small amount, and is likewise younger than the cinnabar ores.

Chalcopyrite ($CuFeS_2$)

Since chalcopyrite is associated with sphalerite and galena on the dump of the St. George shaft, it is also believed to have been deposited after the main period of cinnabar deposition.

Bornite (Cu_3FeS_4)

Bornite is indicated on one of the maps made by S. B. Christy as occurring on the 2100 level of the New Almaden mine a short distance south of the Buena Vista shaft. Although none has been seen by the writers, Mr. Christy's other statements have proved so reliable that this one is believed to be authentic.

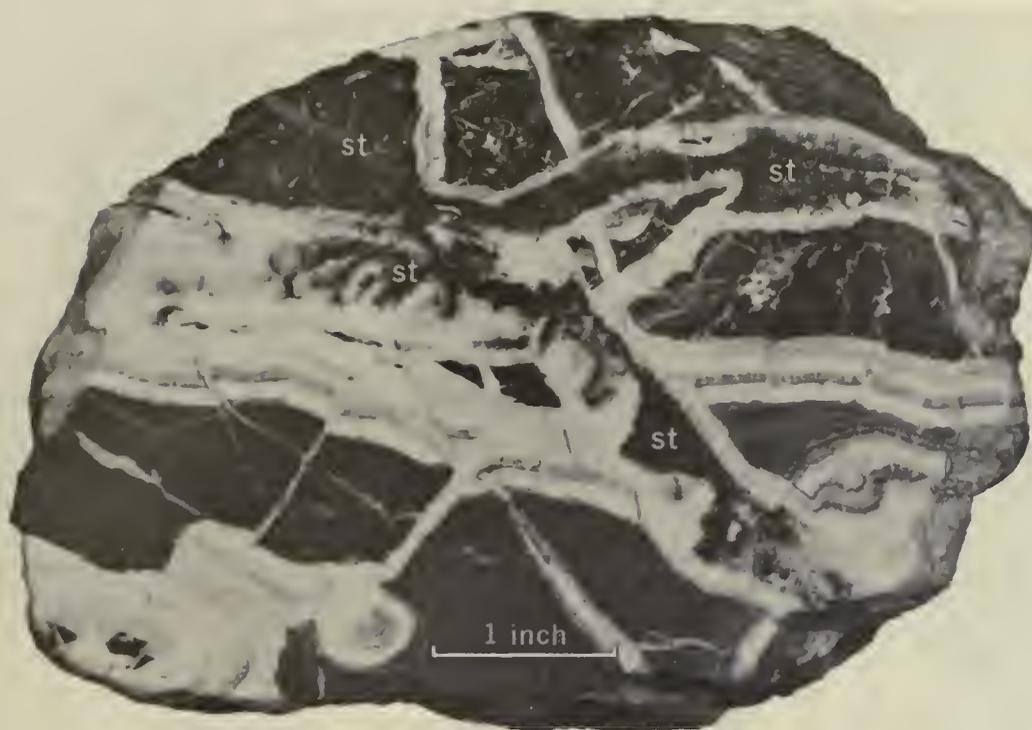


FIGURE 66.—Stibnite (st.) in dolomite vein cutting earlier dolomite veins. Senator mine dump.

Millerite (N1S)

Millerite is nowhere abundant in the district, but it is apparently widespread; it forms minute curved needlelike crystals and "hairs" in the silica-carbonate rock. It seems to be as abundant in places far removed from any cinnabar ores as in the ore bodies themselves, and is therefore thought to have formed during the conversion of serpentine to silica-carbonate rock rather than during the period of quicksilver mineralization.

GANGUE MINERALS

Dolomite [CaMg(CO₃)₂]

Dolomite is the most abundant vein-forming carbonate in the district, where it has at least four modes of occurrence worthy of description. In two of these it is closely related to the ore deposits and may contain cinnabar, whereas in the other two, which are of later origin, it is barren.

White dolomite accompanied by quartz forms the principal filling for the northeastward-trending veins, ½ to 2 inches thick, which occur as swarms in the silica-carbonate rock of most of the large ore bodies. These veins, or hilos, are generally composite and sharply bounded, and contain slivers of wallrock. Where the hilos traverse ore bodies, the included slivers are generally fragments of cinnabar ore, and

the hilos themselves may be veined or partly replaced by cinnabar. (See fig. 67.) Conversely, many hilos not adjacent to ore bodies contain virtually no cinnabar.

In some places both the silica-carbonate rock and the other rocks in the mineralized area are cut by prominent veins of northwesterly trend, which consist largely of white dolomite but locally contain some quartz. These veins are generally much thicker than the hilos; they range in thickness from a few inches to as much as several feet. Some of the largest and best exposed are shown on the geologic map of the New Almaden mine area. (See pl. 3.) Most of these veins are composite and show repeated filling, either simply by the layering of dolomite of different pale tints or by less obvious textural discontinuities. Some others, however, have been brecciated one or more times during their formation and show complex internal structures, resulting from filling along new fractures or coating of brecciated fragments. (See fig. 68.) In some places, as, for example, in the Senator mine, these thick northwest-trending veins contain enough cinnabar deposited intermittently with the dolomite to constitute ore, but in most places they are barren or contain only scattered needlelike crystals of cinnabar.



FIGURE 67.—Silica-carbonate rock cut by typical hilo, or quartz-dolomite vein. Vein walls and included silvers are partly replaced by cinnabar, although the vein itself is barren.

Other dolomite masses, formed relatively late in the period of mineralization in places where the silica-carbonate rock is brecciated, show all gradations between loosely cemented breccia to sharply bounded veins with only a small proportion of fragments. In most places the dolomite has partly replaced the fragments and the vein walls, so that it forms patches and discontinuous areas having a spotted appearance and very irregular margins. These breccia veins are not

known to contain cinnabar, but they locally contain sphalerite, galena, and chalcopyrite.

Lastly, dolomite forms fine-grained cavity fillings, with a faint banding that is horizontal or concave upward in some of the coarser vuggy dolomite veins. This material in most places closely resembles fine-grained limestone, and it is believed to have been deposited by nearly stagnant solutions.

The dolomite is widely varied in appearance: it shows differences in texture due to depositional factors and differences in color due to small amounts of compositional iron or included minute grains of other minerals. It is mostly snow white, but some of it is tan or buff. Some of the dolomite is colored pink by finely divided cinnabar, and some that contains stibnite needles is gray or black. Most of the dolomite has a bladed texture, but a great many of the veins contain vugs lined with curved crystals shaped like the blade of an axe.

The chemical composition of the dolomite from several kinds of veins is shown in table 15. These analyses indicate a slight decrease in the $\text{CaCO}_3/\text{MgCO}_3$ ratio through the long period of deposition, but they fail to show any significant difference between the dolomite of the barren veins and that of the veins containing either cinnabar or stibnite.

TABLE 15.—Composition and maximum indices of refraction of carbonates from the New Almaden district

[Analyses by Israel Warshaw; index determinations by J. J. Fahey, U.S. Geological Survey. All analyses based on portion of vein soluble in 1:1 HCl; total FeO, MgO, CaO, and MnO determined, calculated as carbonates, and recast to equal 100 percent]

	1	2	3	4	5	6	7
CaCO_3	55.2	52.8	54.4	53.8	54.0	54.9	46.6
MgCO_3	39.5	40.3	44.8	44.2	44.3	44.5	50.4
FeCO_3^*	5.1	6.5	.7	2.0	1.6	.6	2.9
MnCO_3.....	.2	.4	.1	.0	.1	.0	.1
CaCO_3	1.40	1.31	1.21	1.20	1.22	1.23	.92
MgCO_3							
Omega Index.....	1.674	1.684	n.d.	1.682	1.674	1.682	1.680

*All iron is not present as FeCO_3 , for 1, 2, and 3 contain small amounts of pyrite.

Arranged from 1 to 7 in probable order of deposition:

1. White fine-grained dolomite vein in altered tuff, pre-ore(?).
2. Pale honey-yellow coarsely bladed dolomite in thick vein, which in earliest part contained cinnabar.
3. Pale-tan medium-grained dolomite coating pyrite, which, in turn, coats a vein like 2.
4. Snow-white coarsely bladed dolomite coating 3.
5. Fine-grained white dolomite colored gray by minute needles of stibnite.
6. Snow-white very coarsely bladed dolomite vein.
7. Gray fine-grained horizontally banded dolomite deposited in vug in vein.

Magnesite (MgCO_3)

Magnesite is the dominant replacing carbonate in the silica-carbonate rock in the district, but so far as known it does not occur in any of the younger veins. If, as appears probable, the quicksilver ores were all deposited after the formation of the hilo fractures, the magnesite is all older than the quicksilver ores.

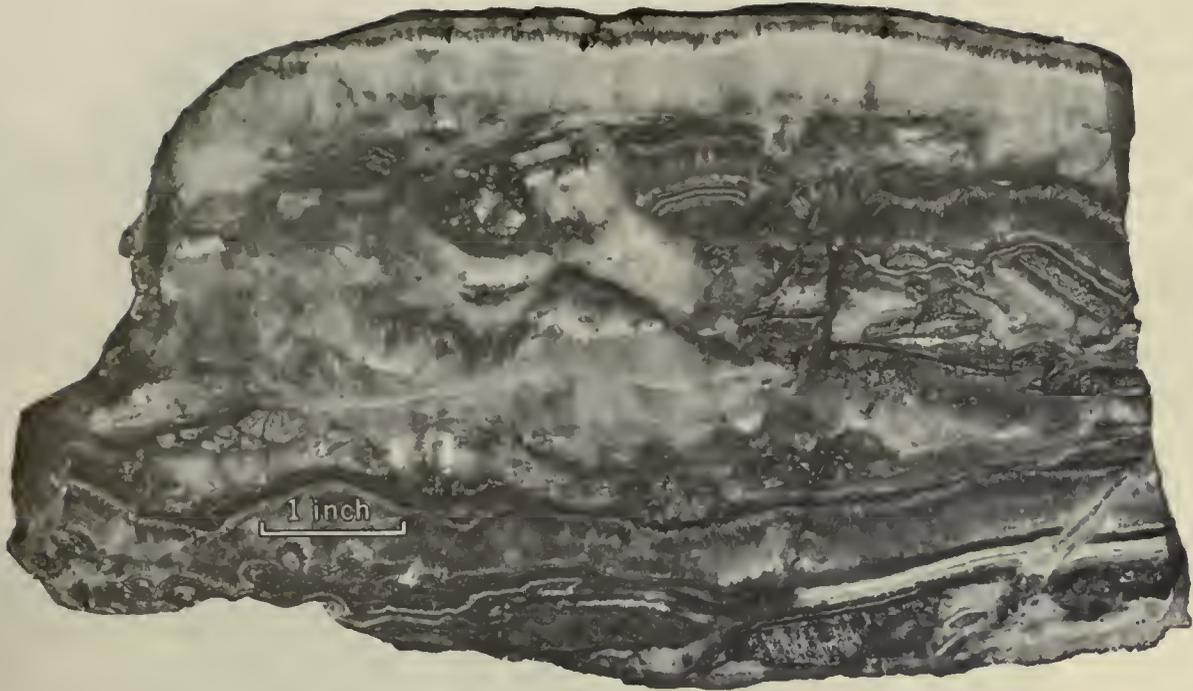


FIGURE 68.—Post-ore dolomite vein from Deep Gulch, New Almaden mine area, showing result of repeated brecciation and filling.

Calcite (CaCO_3)

Calcite occurs locally in small veins and irregular veinlets in many of the varied rocks of the Franciscan group; but since these veins are as abundant in places far removed from the mines as they are near the ore bodies, they probably are not genetically related to the mineralization that formed the quicksilver ores.

Quartz (SiO_2)

Quartz, though not so abundant as the carbonates, is as widely distributed. It is an original constituent of the silica-carbonate rock, has been deposited with cinnabar in the ores formed by replacement, locally replaces cinnabar in some of the richest ores, accompanies dolomite in the hilos, and occurs in small amount in the postmineral veins. It was thus deposited before, during, and after the main period of cinnabar deposition.

The quartz in the unmineralized silica-carbonate rock occurs partly in veins, but the greater part is in microcrystalline patches distributed throughout the rock. The vein quartz is readily recognized, for it is comparatively coarse-grained and clear to milky white in color; but the disseminated quartz cannot be recognized megascopically, except where it is especially abundant. In thin sections it appears as small irregular areas of minute interlocking anhedral grains scattered among larger areas of coarser-grained magnesite.

The quartz that was deposited with cinnabar in the

replacement of silica-carbonate rocks to form the richer ores is recognized by its distribution rather than its character, for it does not differ even in thin section from the quartz originally present in the unmineralized silica-carbonate rock. Occasionally one can see a somewhat wider zone of microcrystalline quartz extending along a replacement vein of cinnabar. And in some replacement ores quartz is present almost to the exclusion of all carbonates, so that quartz is known to have been introduced with the cinnabar even though no criteria by which it can be distinguished from the earlier quartz have been discovered.

The quartz that replaces some of the rich ores can be seen in thin section to occur chiefly in irregularly bulbous areas, imparting a worm-eaten appearance to an otherwise solid mass of cinnabar, and it forms isolated euhedral crystals in the cinnabar. The irregular areas of quartz show their relation to the cinnabar by their general shapes, and some of the euhedral crystals contain small inclusions of cinnabar and thin films of it extending along lines of growth.

The quartz in veins cutting the ores commonly exhibits in thin section a mosaic central part and a flamboyant border. In some places the quartz veins contain borders that appear, in plane-polarized light, to be colloform like chalcedony, but under crossed nicols these borders are seen to be recrystallized to quartz in optical continuity with adjacent grains of coarser quartz coating the colloform vein walls. Some spher-

ules of similar material replacing the cinnabar in the rich ores are likewise converted to radial groups of quartz.

The quartz in the late postmineral veins is generally somewhat clearer than the older quartz, and forms rather spectacular groups of stubby well-developed crystals in many of the vugs of the dolomite veins.

Chalcedony (SiO₂)

Chalcedony is rare in the ores in the New Almaden district. Some of the silicea deposited almost contemporaneously with the cinnabar doubtless was chalcedony originally, for it shows spherulitic and colloform textures, but nearly all of it has recrystallized to radial groups of flamboyant quartz.

Opal (SiO₂·nH₂O)

Opal is not a constituent of the silicea-carbonate rock or of the ores in this district. The only opal found during the study was in the Guadalupe mine, where it formed the filling in a late fracture.

Barite (BaSO₄)

Barite was found only as small euhedral crystals coating silicea-carbonate rock in the old dump near the Buena Vista shaft, and its relation to the ores is unknown.

Apophyllite [KFCa₄(Si₄O₁₂)₄·8H₂O]

Apophyllite crystals, saturated with hydrocarbons, are said to have been found in a vein in the New Almaden mine (Clarke, 1890, p. 22-23), but no details concerning their relation to the ores have been given. This occurrence was confirmed by the finding, in the new open-cut on Mine Hill, of a loose piece of silicea-carbonate rock containing a quartz vein studded with quartz pseudomorphs after apophyllite crystals.

Gyrolite (H₂Ca₂Si₂O₇·9H₂O)

Gyrolite was described by Clarke (1890, p. 23) as forming a fibrous layer between apophyllite crystals and wallrock in a specimen from the New Almaden mine.

Hydrocarbons (compounds of H and C)

Hydrocarbons, both tars and oils, are common in and near the ore bodies in the district, where they occur in thin quartz-dolomite veins. The prevalent variety is a deep-brown, nearly black, tar, which is hard enough to break under a sharp blow, but plastic enough to flow, at an extremely slow rate, down the walls of mine workings. All gradations from this dark tar to light-colored thin oils have been observed. In one unusual type of occurrence, hydrocarbons fill spherical shells of quartz, which are aggregated into what the writers have termed "froth-veins." (See fig. 69.) Such veins are interpreted as having formed

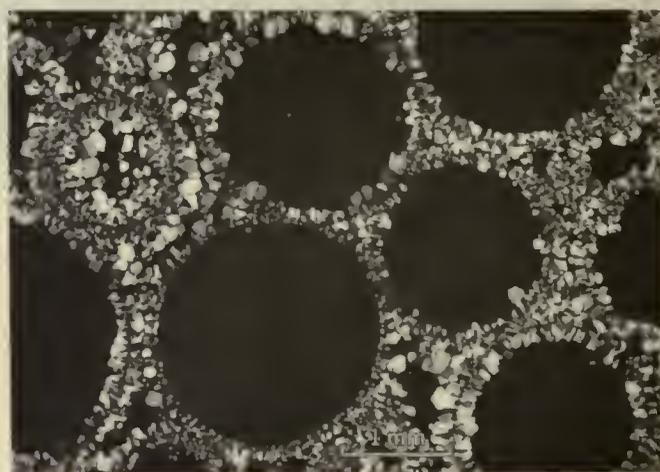
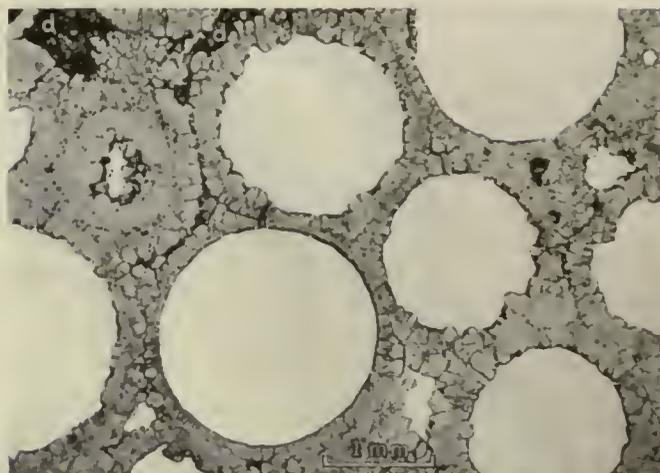


FIGURE 69.—Photomicrograph of section of "froth vein." These veins formed by crystallization of quartz at the interface between two immiscible liquids, one of which was a thin oil and the other a hydrous fluid like that which deposited the quicksilver ores. Upper, Plane light. Locally there were open spaces between the loosely packed quartz spheres, and in a few of these dolomite (d) was deposited. The thin black layer inside spheres is a carbon residue left when the specimen was roasted to remove the oil before thin sectioning. Lower, Crossed nicols. Note that each quartz shell is double owing to the quartz having grown both ways from the oil-water interface.

by quartz crystallizing first at the interface between droplets of oil and hydrous vein solutions, and then growing toward both the oil and the vein solution. The spaces between the two-layered shells in some of the veins are voids resulting from the incomplete filling of the vein. Another hydrocarbon encountered during development of the deep levels of the New Almaden mine is referred to in the surveyors' records as "inflammable gas"; this was doubtless chiefly methane.

CHARACTER OF THE ORES

The character of the ores is dependent upon the way the ore and gangue minerals that have been described are distributed through the mineralized rock; but because the distribution of the chief ore mineral, cinnabar,



FIGURE 70.—Polished specimen of rich ore from the New Almaden mine, showing cinnabar (gray) replacing silica-carbonate rock. Probably the nearly straight left edge resulted from the specimen breaking free along the margin of a quartz-dolomite bldo, for typically the cinnabar replacement extended outward from hilos for a distance of a few inches and terminated abruptly, as in this specimen.

bar, is of prime importance, the following discussion is largely confined to a description of its mode of occurrence. The greater part of the ore mined in the district is of primary origin, but one alluvial deposit containing transported ore has been mined. In this alluvial deposit the nuggets of ore are like the primary ore in all respects; thus, they require no further description.

The cinnabar ores in the New Almaden district were formed by both replacement and filling of open spaces, and, although the ore in some specimens and even in a few ore bodies was all formed by one of these processes, most of the ore bodies contain cinnabar deposited

in part by one process and in part by the other. Considering the district as a whole, however, far more cinnabar was deposited by replacement of the country rock than was deposited in open spaces.

Ore formed in silica-carbonate rock by replacement is the common variety in the district, but small quantities of ore formed by replacement of graywacke and shale of the Franciscan group have been mined. There is compelling evidence that these ores were formed by replacement. The nearly perfect preservation of rock textures by fine-grained cinnabar and the absence of distinct veins or veinlets of cinnabar both indicate replacement (figs. 70-72). Still more conclusive is the



FIGURE 71.—Large polished slab of ore from the New Almaden mine, showing cinnabar replacing silica-carbonate along a fracture which is no longer apparent. Neutral-gray band crossing the central part of the specimen longitudinally in cinnabar. Note the preservation of the serpentine texture in the silica-carbonate rock. Light patches resembling phenocrysts are replaced bastitic pseudomorphs; light-colored coarse transverse veins are largely magnesite that has replaced veins of chrysotile. U.S. National Museum specimen.

fact that most of this ore contains so much cinnabar that the possibility of it having been deposited in minute openings or fractures is untenable.

In the ores replacing silica-carbonate rock sheared textures inherited from sheared serpentine are generally pronounced, and in some ore that replaces silica-carbonate rock which has itself replaced relatively unshaped peridotite, relict bastitic pseudomorphs are easily recognized. The magnesite of the silica-carbonate rock is the most susceptible to replacement by cinnabar, and quartz is also extensively replaced, but the serpentine minerals seem to be resistant to replacement. Where the silica-carbonate rock contained veinlets or seams of serpentine minerals, these remain to mark the serpentine texture, even though most of the rock has been replaced by cinnabar. (See figs. 73-77.)

The formation of ore in silica-carbonate rock generally began with replacement along fractures, which in many places were later filled by quartz or dolomite to form hilos, and the ore extended out from these hilos for a distance of an inch to as much as a foot. The substitution was generally so complete that the ore contains from 35 to more than 90 percent cinnabar; only in zones less than half an inch wide between the rich ore and the barren silica-carbonate rock does the cinnabar content amount to only a few percent. Extensive ore bodies were formed where the feeding fractures were closely spaced, but in some places the replacement along even a single fracture was extensive enough to form a minable ore body. Because of the

sharp transition between ore and country rock, the ore bodies of the district differ from those in many California mines in two important respects: they are generally surrounded by rock containing only a trace of cinnabar rather than by submarginal ore, and they are exceptionally amenable to hand sorting.

Ore formed mainly by replacement of shale and graywacke was mined in the Yellow Kid workings in the southern part of the Harry area of the New Almaden mine, and it also constituted the ore bodies of the San Mateo mine. Very few specimens of such ore were available for study, and these showed only a few scattered crystals and patches of cinnabar. Most of the cinnabar in these specimens is judged from its distribution to have been deposited by replacement, but some cinnabar deposited in open spaces is also present.

Ore containing cinnabar deposited in open spaces is neither as abundant nor as rich in the New Almaden district, for the ore formed by replacement. Nevertheless, open-space filling forms a minor part of many of the ore bodies, and it apparently was dominant in the large ore bodies of the Senator mine and possibly in the near-surface ore mined from opencuts on Mine Hill during the period from 1941 to 1945. Most ore of this character was found in silica-carbonate rock or in veins cutting this rock, but some has been found in graywacke and shale of the Franciscan group. Although these ores all resulted from deposition of cinnabar in open spaces, they may be readily

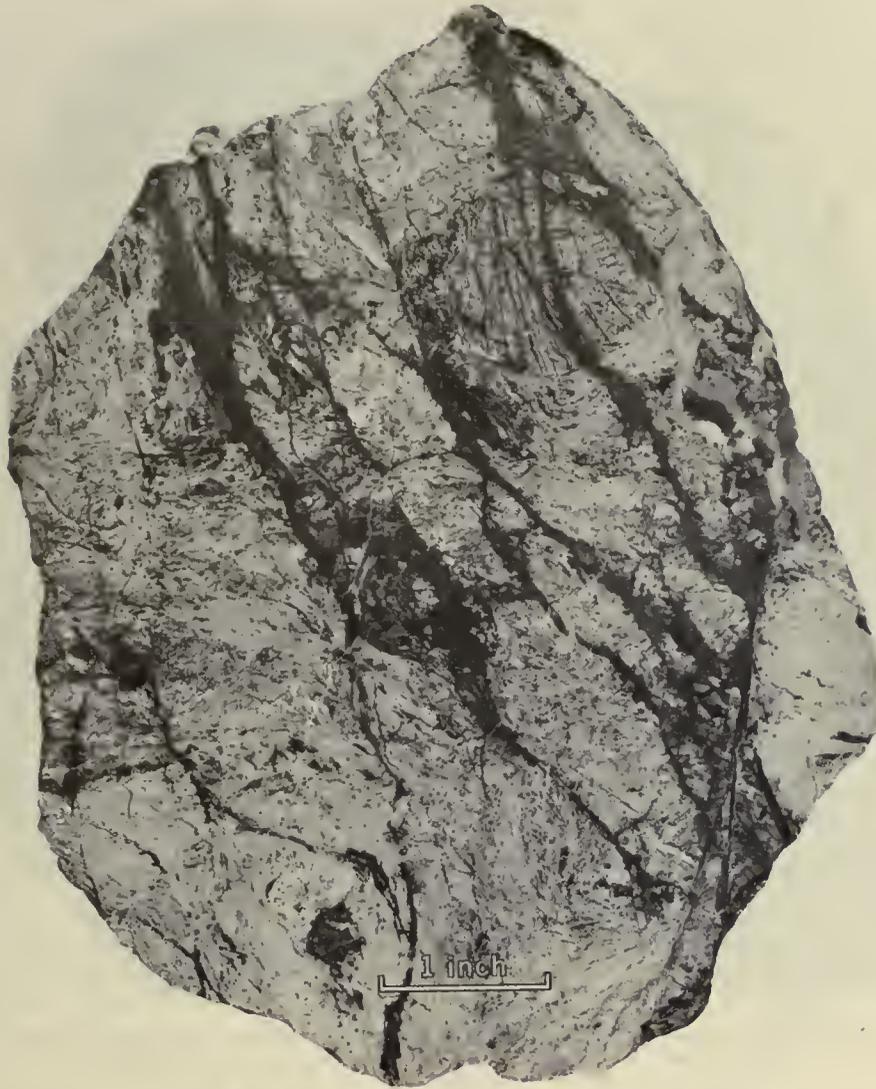


FIGURE 72.—Polished surface on ore specimen from Randol workings of the New Almaden mine. Dark veins are cinnabar with a little quartz; rest of specimen is silica-carbonate rock, which has replaced sheared serpentine that contained a few larger unsheared rounded fragments of serpentine. This specimen is unusual in that the cinnabar is largely confined to the veins, being disseminated out from them only enough to give the vein borders a fuzzy appearance. U.S. National Museum specimen.

divided for description into two groups, depending upon whether the cinnabar is accompanied by other minerals in veins or occurs unaccompanied in vugs.

The cinnabar in veins is generally accompanied by quartz or dolomite and takes a variety of forms. Some cinnabar is fine grained and is dispersed through the other vein minerals; some forms botryoidal clusters deposited along the vein walls or on previously deposited vein minerals, and this is generally itself encrusted; and some forms small crystals erratically distributed between the quartz spheres in the hydrocarbon-bearing "froth veins." Many of the veins that

contain disseminated cinnabar have irregular selvages in which cinnabar replaces the wallrock, and it is often difficult to tell just where replacement of wallrock stops and vein filling begins. In other veins, in which the cinnabar is separated from the wallrock by a layer of dolomite or quartz, the margins are sharp and are not replaced. Such veins, consisting largely of coarsely bladed dolomite, probably formed the greater part of the ore of the Senator mine, which averaged only about 10 pounds of quicksilver to the ton.

The cinnabar occurring by itself in vugs or open cracks is generally coarse grained, and as it does not



FIGURE 73.—Polished surface on rich ore formed by replacement of silica-carbonate rock, which, in turn, had replaced sheared serpentine. Neutral gray on left is cinnabar; rest is silica-carbonate rock.

completely fill the openings, it commonly shows crystal faces. How widespread this type of ore may have been is unknown; virtually none remains in the stope walls in the accessible parts of the mine, and, judging by museum specimens and the ores found on dumps and in the fill in stopes, it was probably rare.

In summary, the writers, who have seen none of the real ore bodies in the district, believe from a study of the available information that the phenomenally rich ore bodies were all composite—that cinnabar replaced silica-carbonate rock along closely spaced fractures, which later were filled with dolomite, quartz, and a little cinnabar. Possibly a few of the thinner and flatter blankets of ore are so little veined that they could properly be termed “replacement bodies”; other ore bodies of lower grade apparently contained only the late cinnabar-bearing veins and should be classed as fissure deposits.

SIZE OF THE ORE BODIES

The size of the ore bodies mined in the district varies between wide limits. Not only were large ore bodies followed from level to level, but it was customary also, because of the general richness of the ore, to mine out any small pockets or even single rich veins that were cut in mine development. Thus, only the upper limit to the size of the ore bodies deserves particular attention. The most extensive single concentration of ore found in the district was the North Randol ore body of the New Almaden mine. This had a strike width of about 200 feet and an average thickness of about 15 feet, and was mined down the dip for a distance of 1,300 feet; its total volume was therefore about 4,000,000 cubic feet. The great central ore bodies in the same mine—including the Santa Rita, North Ardilla, La Ventura, Sacramento, Buenos Ayres, and others—were so closely spaced along the

same geologic structure that they might be thought of as a single ore body with barren patches; if they are so grouped, the composite body was larger than the North Randol ore body.

In the Guadalupe mine the two ore bodies mined through the older workings, south of Guadalupe Creek, were considerably larger than any found in the newer part of the mine. They were mined in the Thayer and Dore labores ("labor" is Spanish for "stope"; plural, "labores") which measure 300 by 350 feet and 400 by 450 feet, respectively, and they are said by Wagoner⁷ to have had a thickness of about 25 feet. In the Senator mine the largest ore body had an average length of about 175 feet, an average width of perhaps 20 feet, and a pitch length of about 800 feet.

GRADE OF THE ORE BODIES

The average grade of the ore from a given ore body in the New Almaden district depends, as it does almost anywhere, upon how much of the lower grade or barren material surrounding or mixed with the rich ore was sent to the furnaces. As the ore bodies were at first mined very selectively, and at a later date had their margins stripped to such an extent that hardly any cinnabar can now be seen in some of the old stopes, it is possible to give information on both the average grade of the richest portions mined in the early days and the grade of the entire ore body. The richest ores ever mined from the New Almaden mine were taken out in its earliest days, and during the first 7 years of recorded production the annual average content of quicksilver determined by furnace recovery was always above 20 percent. To obtain such exceedingly rich ore required not only selective mining but extensive cobbing and hand sorting, so that the average for the ore bodies as a whole was much less than 20 percent; this figure does indicate, however, that the ores mined from near the surface of Mine Hill were extremely rich. Further indication of their richness is given by the nuggets mined from a placer deposit below the original outcrops of ore in the New Almaden mine area; these nuggets have an average cinnabar content of 75 percent, or about 65 percent quicksilver.

A somewhat closer indication of the average grade of the ore found in the large and exceptionally rich ore bodies is furnished by the Santa Rita ore body, which yielded 25,300 tons of ore averaging a little more than 10 percent of quicksilver. This ore body was reported to have been less rich than the North

Ardilla body which adjoined it, but for the latter no exact figures are available. Perhaps the best idea of the average overall grade of the New Almaden ore bodies can be obtained from the following figures. From the time that mining began in 1846 until the end of April 1896, when 942,447 flasks had been recovered, the average grade of all the ore treated had been 4.57 percent, or only a little less than 100 pounds of quicksilver to the ton. Subsequent mining of lower grade ores has diminished this figure somewhat, but probably the average grade of all the ore mined up to the end of 1948 is not below 4 percent.

To get an indication of the richness of the ore bodies in the New Almaden mine as compared with those of other quicksilver mines in California, we may compare the yield of quicksilver per linear foot of horizontal workings in this mine with that for some other California quicksilver mines. For the New Almaden mine this yield, based on the total extent of all horizontal workings including all the nonproductive adits, is 5.9 flasks, which is higher than that of any of the other mines, as shown in table 16.

TABLE 16.—Approximate yield of quicksilver per linear foot of workings in some California quicksilver mines

Mine	District	Production to the end of 1945	Flasks per linear foot
New Almaden.....	New Almaden.....	1,044,075	5.9
New Idria.....	New Idria.....	425,570	4.2
Oat Hill.....	Mayacmas.....	161,531	1.6(?)
Knoxville.....	Knoxville.....	120,094	5.5
Guadalupe.....	New Almaden.....	111,529	3.6
Oreat Western.....	Mayacmas.....	105,138	2.6
Oreat Eastern-Mount Jackson.....	Guerneville.....	58,467	4.1
Cloverdale.....	Mayacmas.....	17,914	1.8
Helen.....	do.....	16,463	1.3
Culver-Baer.....	do.....	12,134	1.4
Socrates.....	do.....	5,500	1.2

At the Guadalupe mine the ore bodies mined from the large stopes to the south of Guadalupe Creek are estimated by Wagoner⁸ to have averaged a little less than 5 percent quicksilver. The ore bodies of the Senator mine, exploited between 1910 and 1925, averaged only about 0.5 percent quicksilver.

The material taken from the opencuts of Mine Hill during World War II was even leaner, and yielded only a few pounds of quicksilver to the ton. Although it was profitably mined because of the prevailing high price of quicksilver, and hence was ore according to the usual definition, it contained only scattered cinnabar crystals and veinlets, and was not comparable to the material that constituted the true ore bodies of the New Almaden district.

⁷ Wagoner, Luther, 1881, Unpublished report on the Guadalupe mine.

⁸ Wagoner, Luther, 1881, op. cit.



FIGURE 74.—Extremely rich replacement ore from the New Inclined shaft area of the Guadalupe mine.

LOCALIZATION OF THE ORE BODIES

The ore bodies in the district are not distributed at random; most of them are in certain rocks and in certain structural environments. The following section discusses the influence of these controlling factors, which were responsible for the restricted distribution of the known ore bodies and which should be considered in seeking new ones.

LITHOLOGIC CONTROL

In the New Almaden district at least 99 percent of the quicksilver ores mined were in silica-carbonate rock. This rock contained not only the greatest number of ore bodies but also the largest and richest. Therefore, even though ore bodies have been found in other rocks in the district, exploration for new ore bodies in silica-carbonate rock is most likely to be rewarded. There are probably several reasons why the silica-carbonate rock was the most favorable for ore deposition. The rock is exceptionally brittle, and it generally forms a thin shell between incompetent serpentine and sheared rocks of the Franciscan group;

it was therefore the rock most likely to be fractured by even mild deformation. Hence it provided the channels for the migration of mineral solutions and openings for the deposition of ore minerals. And, because of its mineral content, it was especially susceptible to replacement by cinnabar-bearing solutions.

The small bodies of ore in other rocks of the district, however, are locally of economic importance as well as of scientific interest. Apart from silica-carbonate rock, only rocks of the Franciscan group and serpentine occur along the mineralized belt in the district; only these, therefore, have had a good opportunity to become mineralized. Graywacke and shale contained the ore bodies of the San Mateo mine, and also some of the ore mined in the Yellow Kid workings in the southern part of the Harry area of the New Almaden mine. Altered greenstone or tuff contained the ore mined in the upper Cora Blanca and Los Angeles workings of the New Almaden mine. Chert, which is the host rock for ore bodies elsewhere in the Coast Ranges (Bailey, 1946, p. 217, 219-



EXPLANATION

	
Pyrite	Dolomite vein
	
Silica-carbonate rock	Quartz vein with cinnabar
	
Cinnabar	Hole

FIGURE 75.—Key to minerals in figure 74.

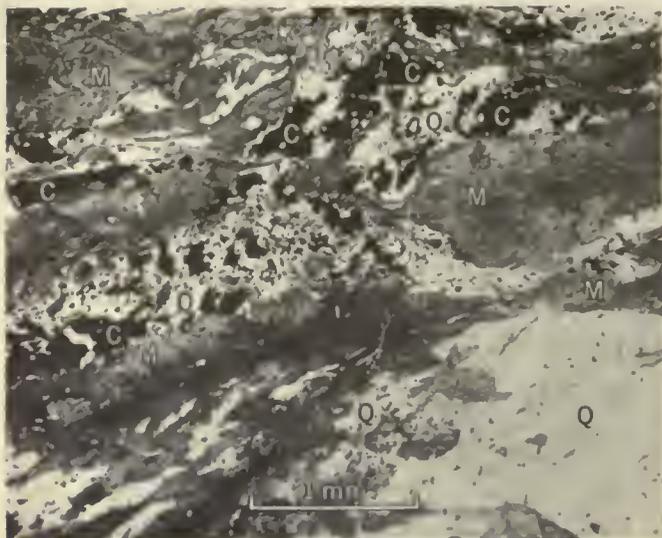


FIGURE 76.—Photomicrograph of rich ore formed by replacement of silica-carbonate rock by cinnabar. Light areas granular quartz (Q), gray areas magnetite (M), and dark areas cinnabar (C) with a little magnetite. The lensiform structure and the magnetite are inherited from sheared serpentine. Cinnabar has mainly replaced quartz, but its embayed boundaries suggest that in a late stage there was a little replacement of cinnabar by quartz.

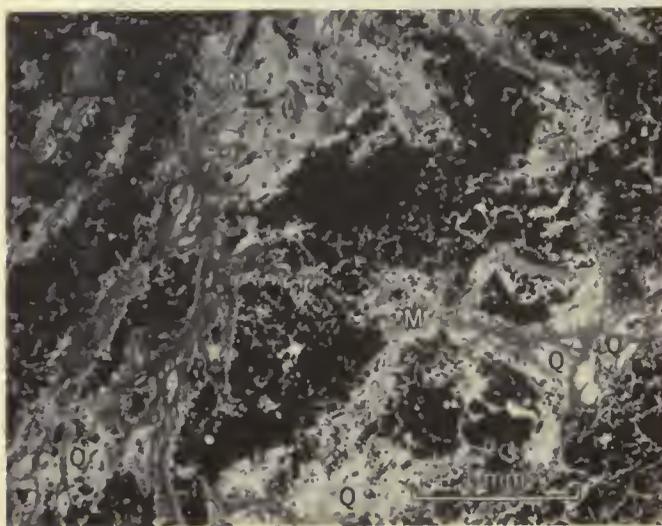


FIGURE 77.—Photomicrograph of high-grade ore formed by the replacement of silica-carbonate rock by cinnabar. Quartz (Q), magnetite (M), and black is chiefly cinnabar with a few small residual grains of magnetite. Although textures inherited from the sheared serpentine are still visible, there has been considerable migration and redeposition of the quartz and magnetite, and the magnetite-quartz ratio has been diminished. In places where the replacement is most advanced, the ore contains only cinnabar and quartz.

221), is nearly everywhere barren near ore bodies in this district; but in outcrops on the top of Church Hill, half a mile east-northeast of the summit of Mine Hill, it contains some cinnabar, though not enough to constitute ore. Unaltered serpentine contains a little

cinnabar about 70 feet east of the Santa Rita shaft on the 800, or Day tunnel, level, but this occurrence seems to be unique in the district.

An isolated occurrence of cinnabar in rocks younger than the Franciscan group, which aids in dating the mineralization period, was found on a low ridge 2 miles S. 43° E. of Lone Hill. Here cinnabar coats fractures in a silicified volcanic rock of late Miocene age, but it is so scarce in the surface exposures that any search for ore in this area would probably be fruitless.

STRUCTURAL CONTROL

The ore bodies in the silica-carbonate rock have in the aggregate an extremely small volume compared with the volume of silica-carbonate rock in the district; the ratio as observed in existing exposures is probably less than 1 to 1,000. Study of the structural setting of the ore bodies that have been found permits further limitation of the areas favorable for the finding of new ore bodies in this rock, and knowledge of this structural control of ore bodies is of the utmost importance in planning the search for ore. Insofar as quicksilver ore bodies are concerned, two radically different views have been held regarding the importance of structural controls. In the New Almaden district adherence to these views has in the past led either to disregarding favorable places where there might be ore bodies or to virtually useless prospecting in unfavorable places. The two prevalent views, which contradict each other, are: cinnabar ore occurs, like gold, "where you find it," and cinnabar ore occurs only in structural traps beneath cappings of shale, alta, or other relatively impervious rocks. There is some justification for each of these beliefs, but a thorough study of the district shows that the location of an ore body is likely to have been determined by several mappable, and for the most part predictable, structures that have operated together.

Hilo fractures

Most of the ore bodies in the silica-carbonate rock have been formed where the rock is traversed by swarms of closely spaced and steeply inclined narrow fractures, which, where filled with quartz-carbonate veins, are termed "hilos." These hilos appear to be about as abundant on upper borders of sills as on lower borders, but they are less common away from the borders. Almost everywhere in the district they trend between North-South and N. 40° E., regardless of the direction of the strike or the dip of the altered serpentine sill. The hilos are generally from 0.5 to 2 inches thick, being widest in the silica-carbonate rock near the alta contact. How far they extend from the

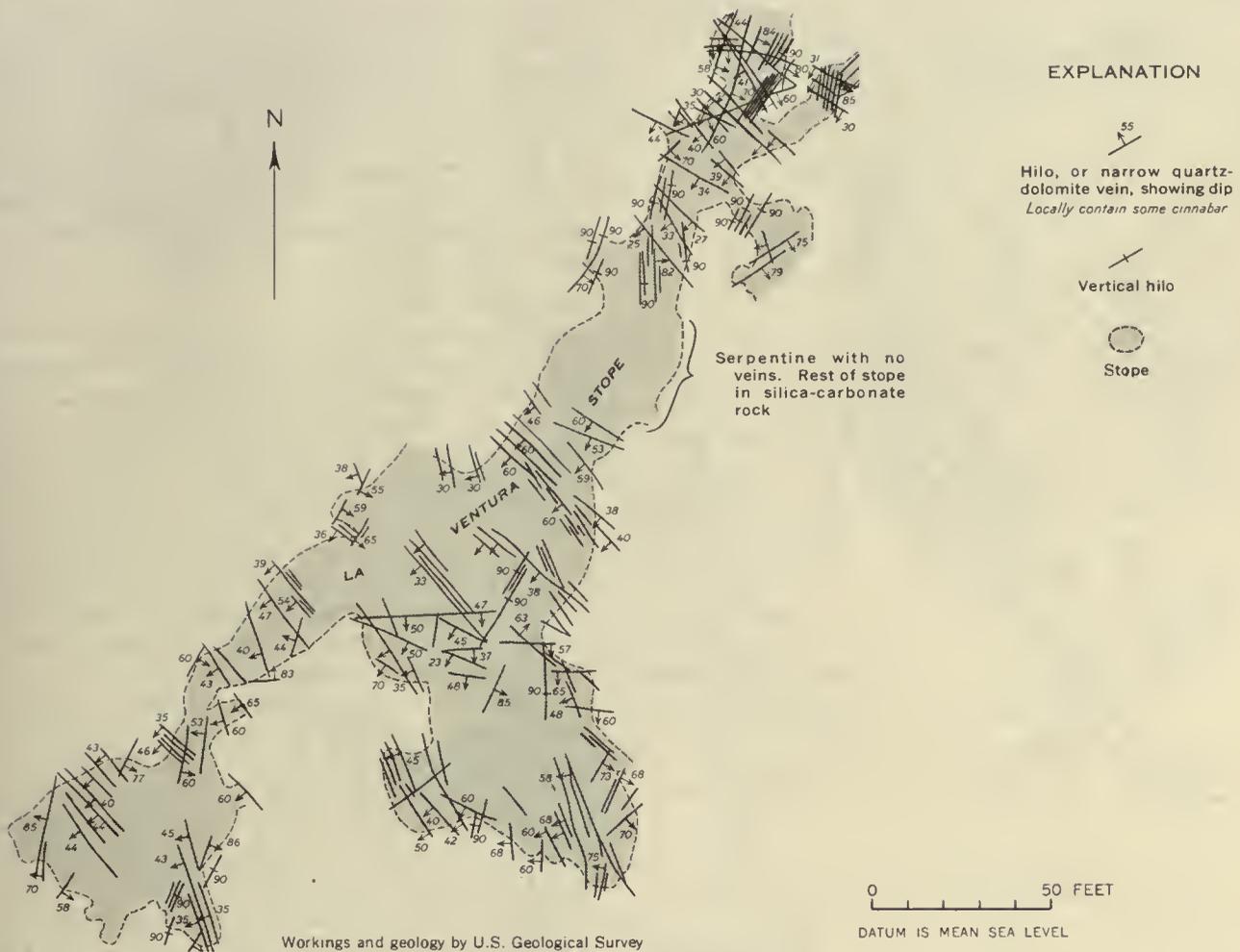


FIGURE 78.—Map of La Ventura stope of the New Almaden mine where the localization of the ore is unusual in that it is along northwest-trending fractures rather than along fractures with a northeast trend.

contact into the silica-carbonate rock can rarely be determined; but they generally taper gradually to beyond the limits of any ore, and in some places they extend at least a hundred feet from the contact. Their extent from the contact into rocks of the Franciscan group is more variable. In some places, especially where the rocks of the Franciscan group are hardened by alteration, the hilos penetrate, though with much diminished size, for a few feet into the country rock. In other places they terminate exactly at the contact. Exceptionally, as in the Water tunnel above the Cora Blanca workings of the New Almaden mine, more persistent veins with strikes similar to those of the hilos are found in the rocks of the Franciscan group at distances of several scores of feet from silica-carbonate rock, but in general the typical hilos are confined to the silica-carbonate rock near its contact with the rocks of the Franciscan group.

Similar steeply dipping quartz-carbonate veins that

strike N. 40°-50° W. are in a few places considerably more abundant than the typical northeast-striking hilos. They appear to represent a conjugate system related to the typical hilo fractures, rather than a local deviation from them, for they accompany, rather than take the place of, the normal hilos. In at least one stope—La Ventura (fig. 78)—this second system of fractures probably had an important part in localizing ore.

Swarms of hilo fractures were the dominant structural control for some ore bodies, particularly those along steep contacts, as in the Randol area of the New Almaden mine and in the central part of the Guadalupe mine. (See figs. 93, 89.) The fractures were also an important factor in the formation of many of the other ore bodies of the New Almaden mine, as is indicated by the elongation of many of the stopes parallel to the trend of the hilos. (See fig. 79 and pl. 4.) It should be emphasized, however,

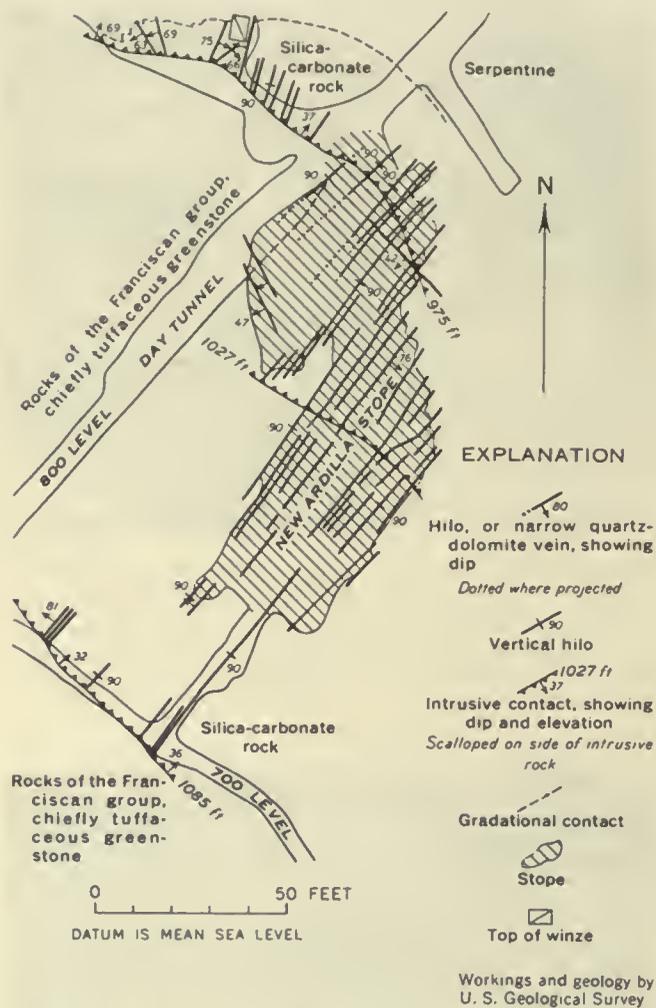


FIGURE 79.—Map of the New Ardilla stope of the New Almaden mine showing the localization of ore along a swarm of hilos cutting silica-carbonate rock formed on the lower side of a serpentine sill.

that in some other parts of the mines where hilos are very abundant (fig. 80), no ore has been found, and that in some rich ore bodies, such as those of the Cora Blanca workings of the New Almaden mine, hilos were apparently scarce.

Proximity to contact

Most of the ore bodies that have been found in silica-carbonate rock extended either to the contact with the rocks of the Franciscan group or to within a few feet of it, and the ore was generally richest near the contact. From the contact the ore may extend into the silica-carbonate rock for only a fraction of a foot or for more than 20 feet, but as the ore generally grades almost imperceptibly into barren rock, its limit is economic. As is shown on some of the maps accompanying this report, the ore occupies in some places the full thickness of the silica-carbonate rock,

but in most places it is not nearly so thick. The close relation between ore and contact prevails nearly everywhere, regardless of whether the contact is nearly flat or steeply inclined, and regardless of whether the silica-carbonate rock lies above or below the rocks of the Franciscan group. Examples of ore bodies lying along both upper and lower margins of the carbonated serpentine sills are described in following sections of this report.

Shape of the contact

Many of the ore bodies in the silica-carbonate rock were apparently localized along parts of the contact that are so shaped as to retard and concentrate the ore-forming solutions rising from greater depths. Shapes that have been effective include domes, terraces, and rooflike structures with either flat or rather steeply plunging ridge lines. Structural controls appear to be most effective on contacts with dips of less than 45°. Along steeper contacts, as in the North Randol workings of the New Almaden mine and in the Senator mine, their influence is overshadowed by that of swarms of fractures.

In addition to these major structures of the intrusive contact, other smaller structures locally assume importance in affecting the size of ore bodies formed. Some of the serpentine bodies are bordered by many thin apophyses, which branch at low angles from the main intrusive and are separated from it by septa of Franciscan rocks only a few feet thick. These thin tongues of serpentine increase the ore possibilities in a block of ground in two ways. First, within a narrow zone along the border of the main intrusive body they may increase the area of the contacts along which ore can form, and thus increase the thickness of minable ore. Second, where they branch and taper upward from the main sill, their enclosed extremities form natural traps for rising ore solutions.

The structures described as aiding in the localization of ore bodies are not all equally important, and some, especially those due to branching apophyses, are difficult to predict in advance of mining. Nevertheless, a mine operator who pays attention to geologic structure has a far better chance of finding ore, and of staying with it when he has found it, than one who does not. Some examples will now be given of ore bodies found in various structural environments.

EXAMPLES OF ORE CONTROL

Ore bodies beneath alta

Most of the ore bodies in the New Almaden district lie in silica-carbonate rock close beneath a "capping" of alta. Ore bodies so situated include (a) all those in the New Almaden mine that lie on the upper mar-

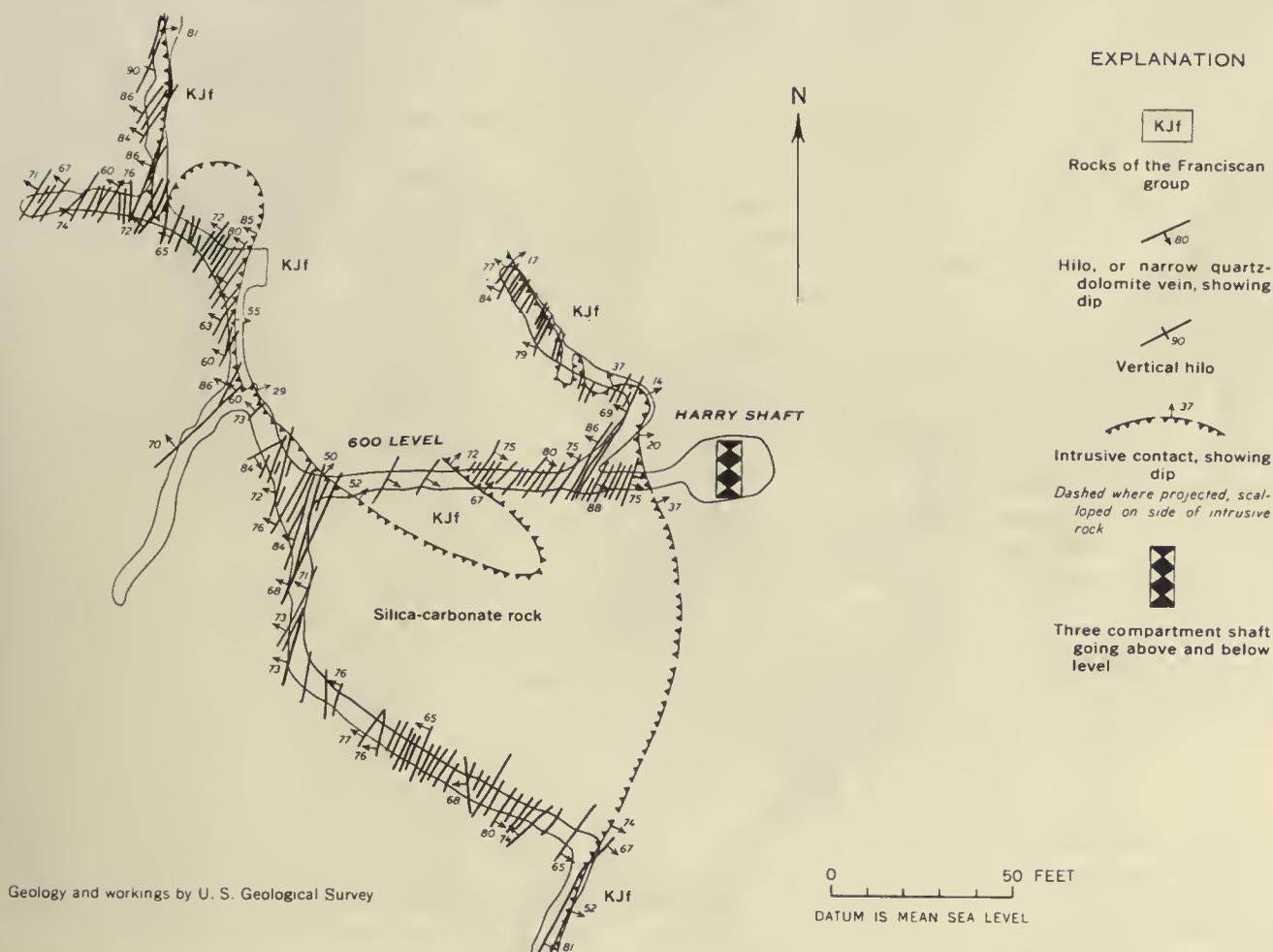


FIGURE 80.—Map of a part of the 600 level of the Harry workings of the New Almaden mine showing an area of unmineralized silica-carbonate rock containing swarms of hilos adjacent to an intrusive contact.

gin of the extensive serpentine sill shown by contours in figure 81, (b) the ore bodies of the older part of the Guadalupe mine (pls. 14, 15), and (c) the ore bodies of the No. 3 vein in the Senator mine (pl. 14, section B-B'). Many of these are localized by various factors at particular places along the contact, some chiefly by the intersection of swarms of hilos, a few chiefly by the shape of the contact, and many others apparently by a combination of the two. Ore bodies localized by the intersection of hilos with steep contacts are exemplified by the North and South Randol ore bodies of the New Almaden mine (pl. 4 and fig. 93) and the ore bodies of the Senator mine (pls. 14, 15). Those controlled by the favorable shape of the contact appear to develop largely where the contact is relatively flat, for example, in the domal structures of the Velasco, Upper Pruyn, and Machine stopes of the New Almaden mine (fig. 82). Ore bodies lo-

calized along the crest of an inclined anticlinal arch either with or without hilo fractures include the Santa Rita, Santa Rita West, Victoria, Giant Powder and Ponce, and the lower New World ore bodies (figs. 83, 84). The Harry ore body was localized along a relatively flat terrace on an inclined contact, but its geologic setting is further complicated by several overlying thin sills, which also are mineralized.

Ore bodies with alta above and below

A few of the ore bodies were localized in silica-carbonate rock that replaced thin sill-like apophyses of serpentine that diverged from larger masses. Where such a body lay close to an ore body along the margin of the larger mass, the ore in both the apophysis and the main mass was mined in a single stope. One such composite body is the previously mentioned central part of the Harry ore body in the New Almaden mine. Where ore bodies were found in apophyses

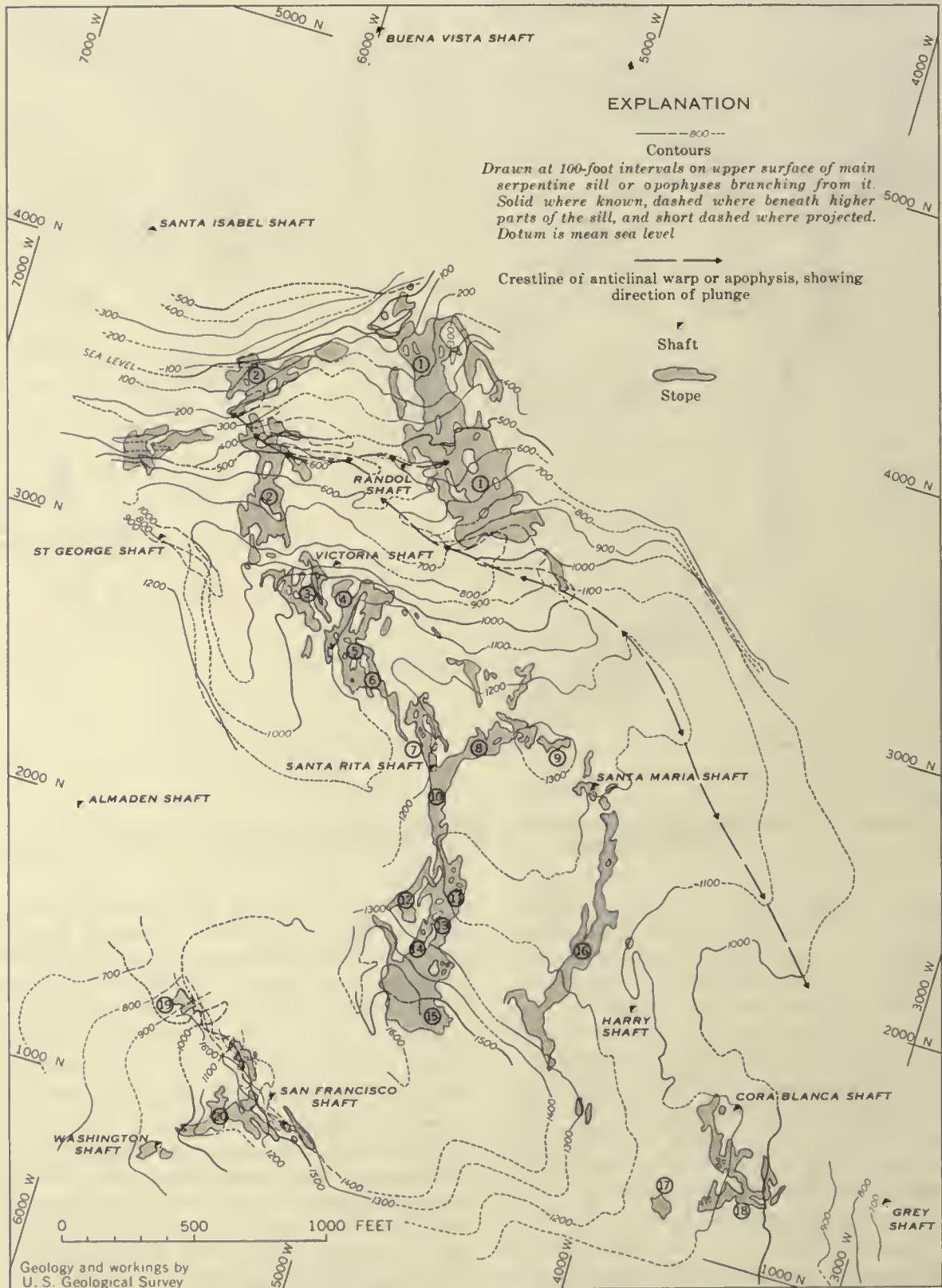


FIGURE 81.—Map showing distribution of stopes along the upper surface of the main serpentine sill in the New Almaden mine.

- | | | | | |
|-------------------|--------------------|-------------------|------------------|-----------------|
| 1. North Randol | 5. Ponce | 9. Velasco | 13. La Ardilla | 17. Machine |
| 2. South Randol | 6. Giant Powder | 10. Santa Rita | 14. Dios Te Gula | 18. Cora Blanca |
| 3. Victoria | 7. Santa Rita West | 11. North Ardilla | 15. El Collegio | 19. Curasco |
| 4. New Santa Rita | 8. Santa Rita East | 12. Far West | 16. Harry | 20. New World |

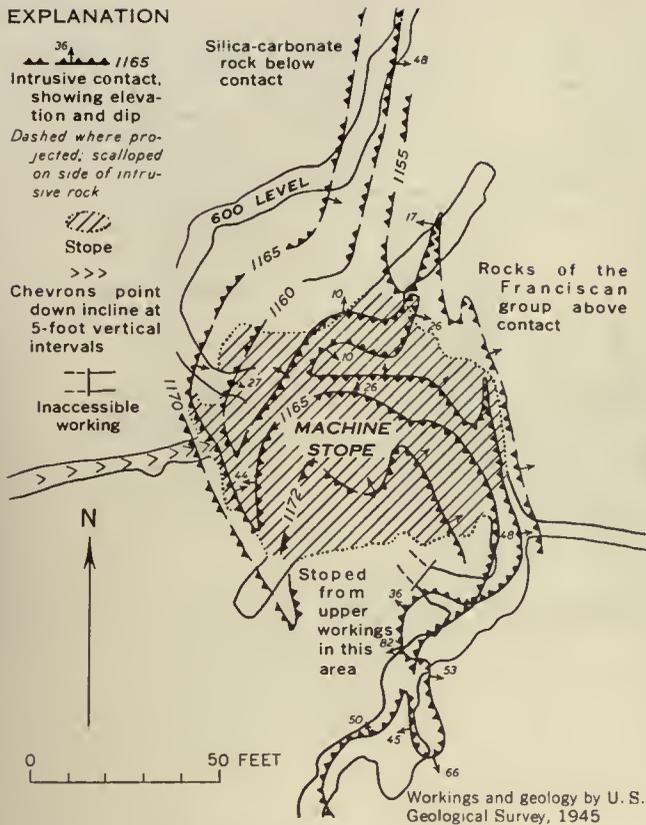


FIGURE 82.—Map showing the localization of the Machine stope ore body of the New Almaden mine beneath a small dome or “hlistor” on the upper contact of an intrusive sill. The shape of the intrusive contact is indicated by structural contours drawn on its surface.

more widely separated from the main intrusive mass, they were mined in individual stopes. As the apophyses are generally thin, they were in many places mineralized across their entire thickness, and the resultant ore bodies lay both above and below alta walls. In the extreme case they formed in small pods of silica-carbonate rock only a few feet long, isolated from the main intrusive body by the shearing that accompanied the intrusion. These thin ore bodies in apophyses were common in the San Francisco area of the New Almaden mine; a particularly good example was the ore body mined in the Warren stopes (fig. 85).

Ore bodies lying above alta

Several ore bodies in the New Almaden district lie close to the lower contact of serpentine masses and above, rather than below, the alta. Although this type of occurrence was recognized in the early days of mining, it seems to have been almost disregarded in the subsequent development of the New Almaden

mine, and most of the ore bodies so situated were found accidentally in workings driven for other purposes. The ore bodies above alta are similar in most respects to those beneath alta: in both cases the ore is richest and most abundant close to the contact, hilo fractures are important in localizing the ore, and the same structures that result in the localization of ore beneath alta are effective even where the relative position of the rocks is reversed.

An ore body localized above a dome-shaped contact was mined in the southeastern part of La Ventura stope of the New Almaden mine (fig. 86). Ore bodies found along the crest of an inclined arch structure include those in the Curasco and the New Ardilla stopes, although in mining the latter, the trend of the hilos rather than the apex of the arch appears to have been followed upward. (See figs. 87, 79.) Other ore bodies found in silica-carbonate rock above alta in the New Almaden mine include those taken from the Far West, Santa Rosa, and El Collegio stopes (fig. 88), from the San Pedro, America, and 400 level San Francisco stopes, and from the small stope near the portal of the Juan Vega tunnel. The Mason stope in the Guadalupe mine and the ore bodies in the No. 2 vein of the Senator mine are similarly situated.

Ore bodies not near alta

A few of the ore bodies found in the district appear to be in the middle of carbonatized serpentine sills and to bear no relation to any known contact. The ore body mined in the Moreno and Water stopes of the central part of the Guadalupe mine appears to be surrounded by silica-carbonate rock and to owe its localization entirely to the abundance of hilos. (See fig. 89.) Another such ore body may have been the one mined from the main stopes of the Enriquita mine, although here the geology is not well known and the ore may possibly have been localized along a thin septum of alta separating two parallel sills of serpentine.

Ore bodies in rocks of the Franciscan group

Only a few small ore bodies have been found in rocks of the Franciscan group. These include the ore bodies of the San Mateo mine, which consist of veinlets and irregular replacement bodies of cinnabar in altered graywacke, and those of the upper Cora Blanca and Los Angeles workings of the New Almaden mine, which consist of veinlets in altered tuff. Because of their low grade, these ore bodies have mostly been mined in highly irregular workings by selective gouging of individual veins or swarms of closely spaced veinlets. (See fig. 90.)



Workings and geology by U. S. Geological Survey, 1945

FIGURE 83.—Map showing the localization of the New World stope ore body of the New Almaden mine beneath a plunging inverted trough on the surface of an intrusive sill. The shape of the intrusive contact is indicated by structural contours drawn on its surface.

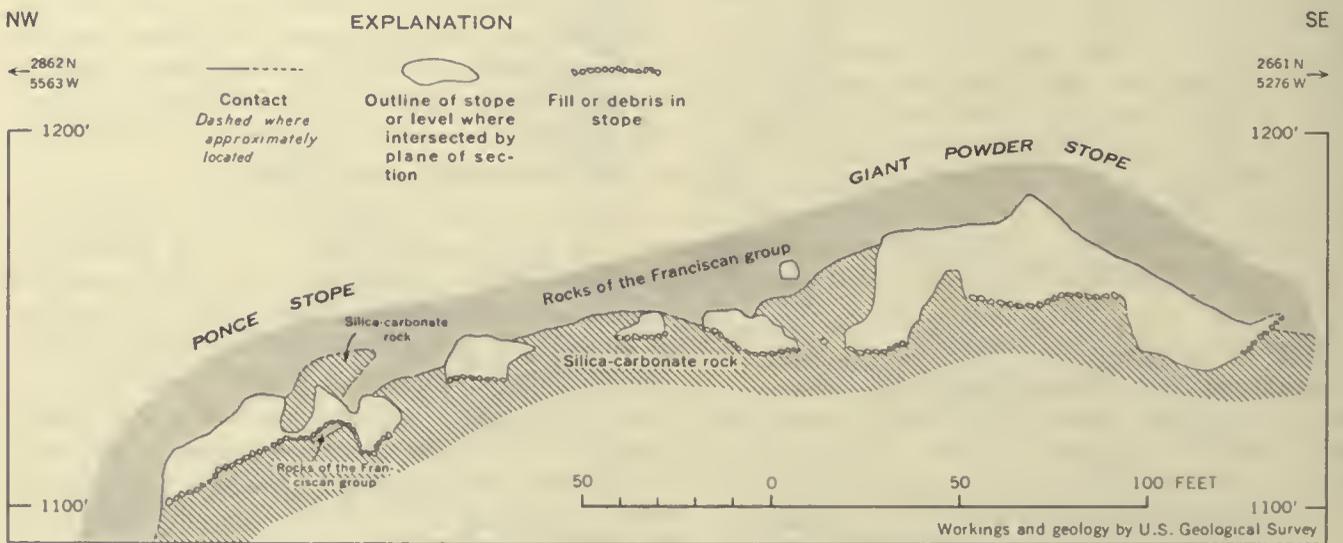


FIGURE 84.—Cross section through the Giant Powder-Ponce stope area of the New Almaden mine showing the localization of ore in an antinodal warp on the upper surface of a sill of serpentine, which is here altered to silica-carbonate rock.

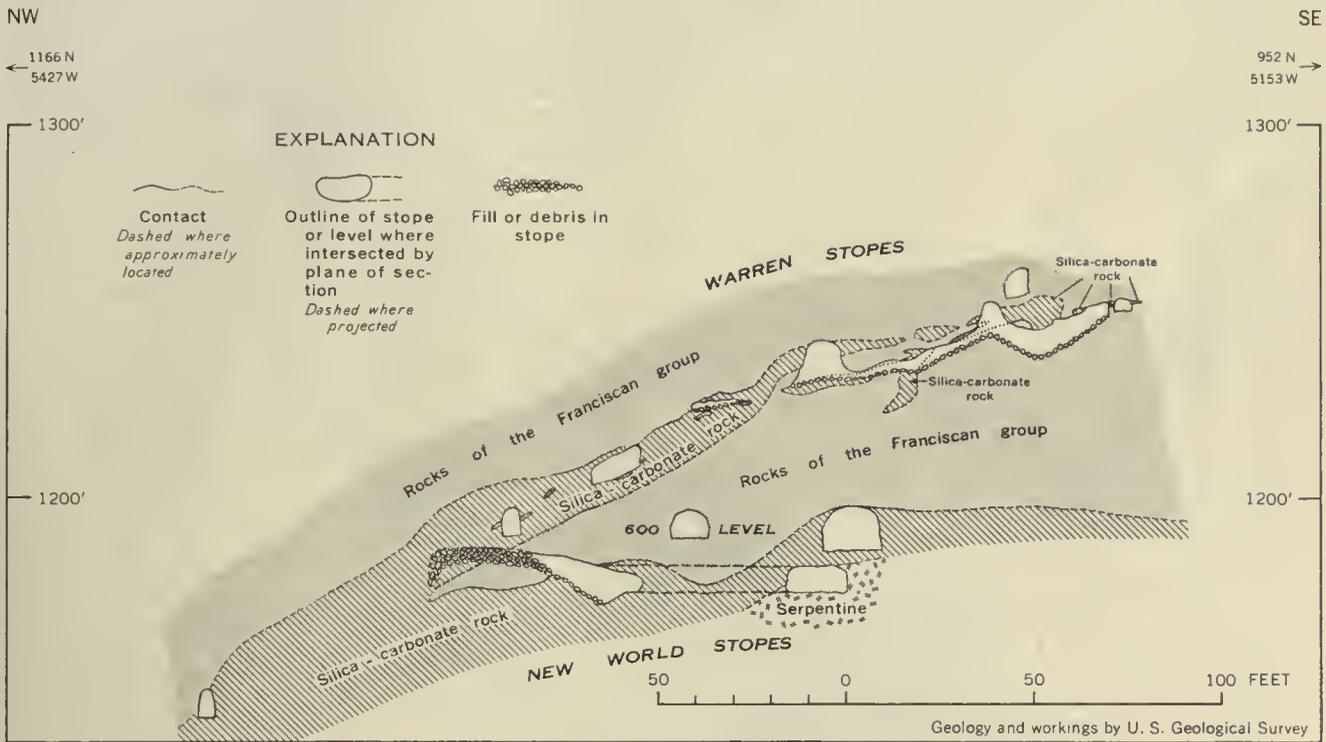


FIGURE 85.—Cross section through the Warren stopes of the New Almaden mine showing ore bodies formed in a thin apophysis diverging upward from a large intrusive sill.

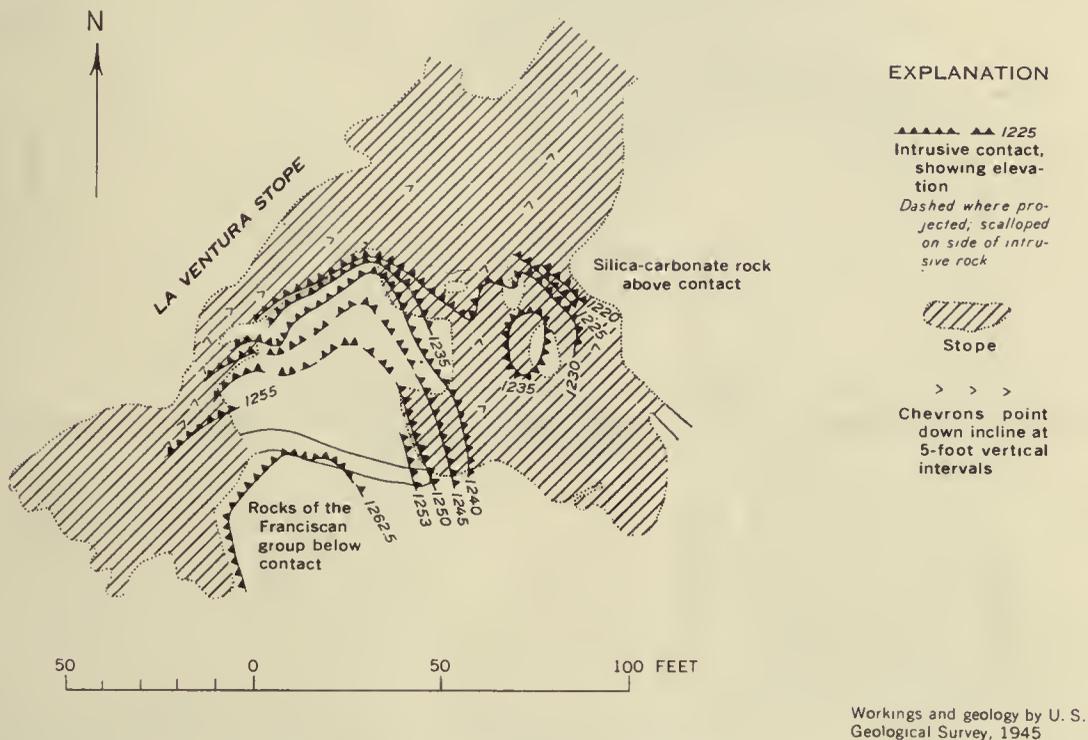
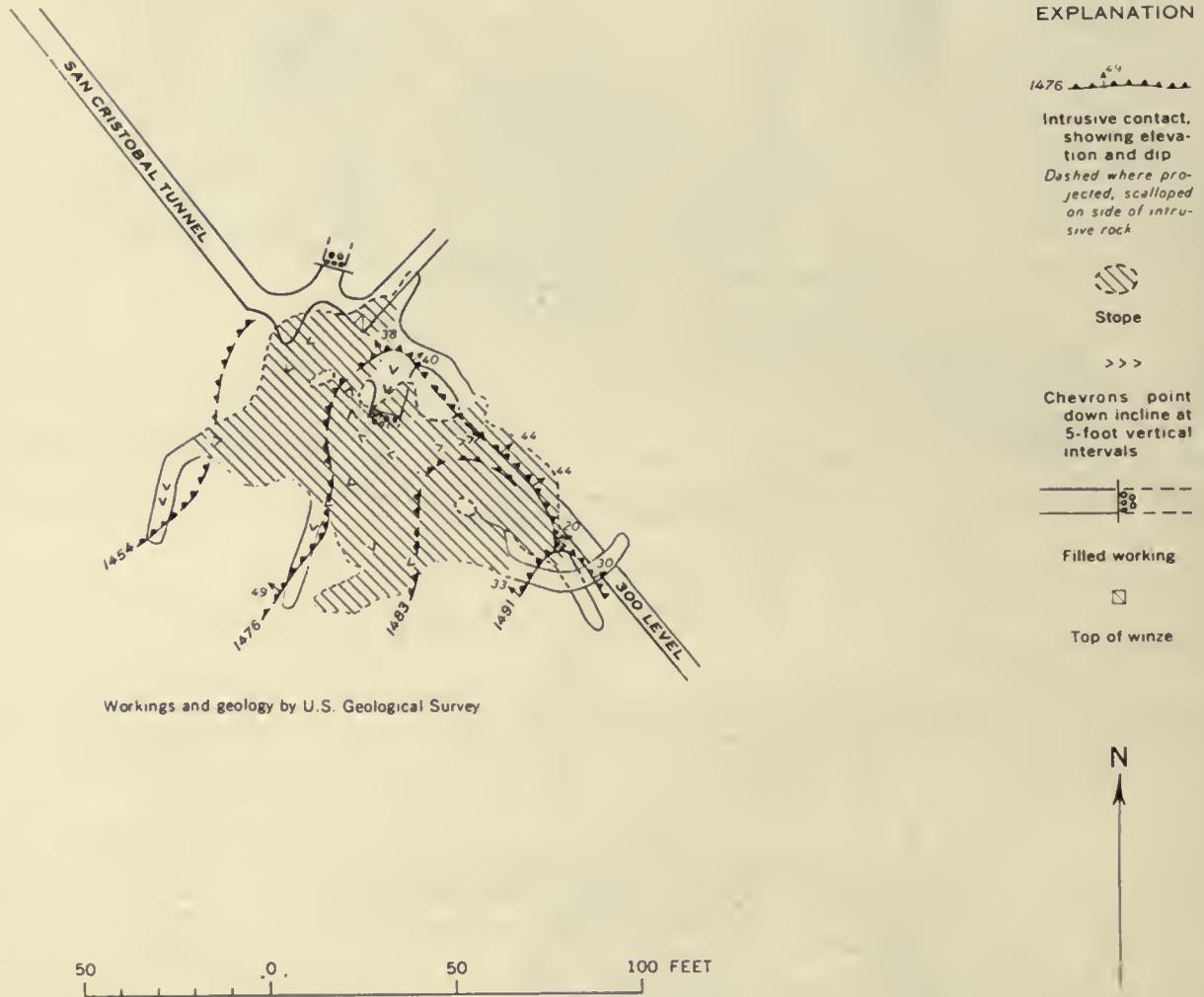
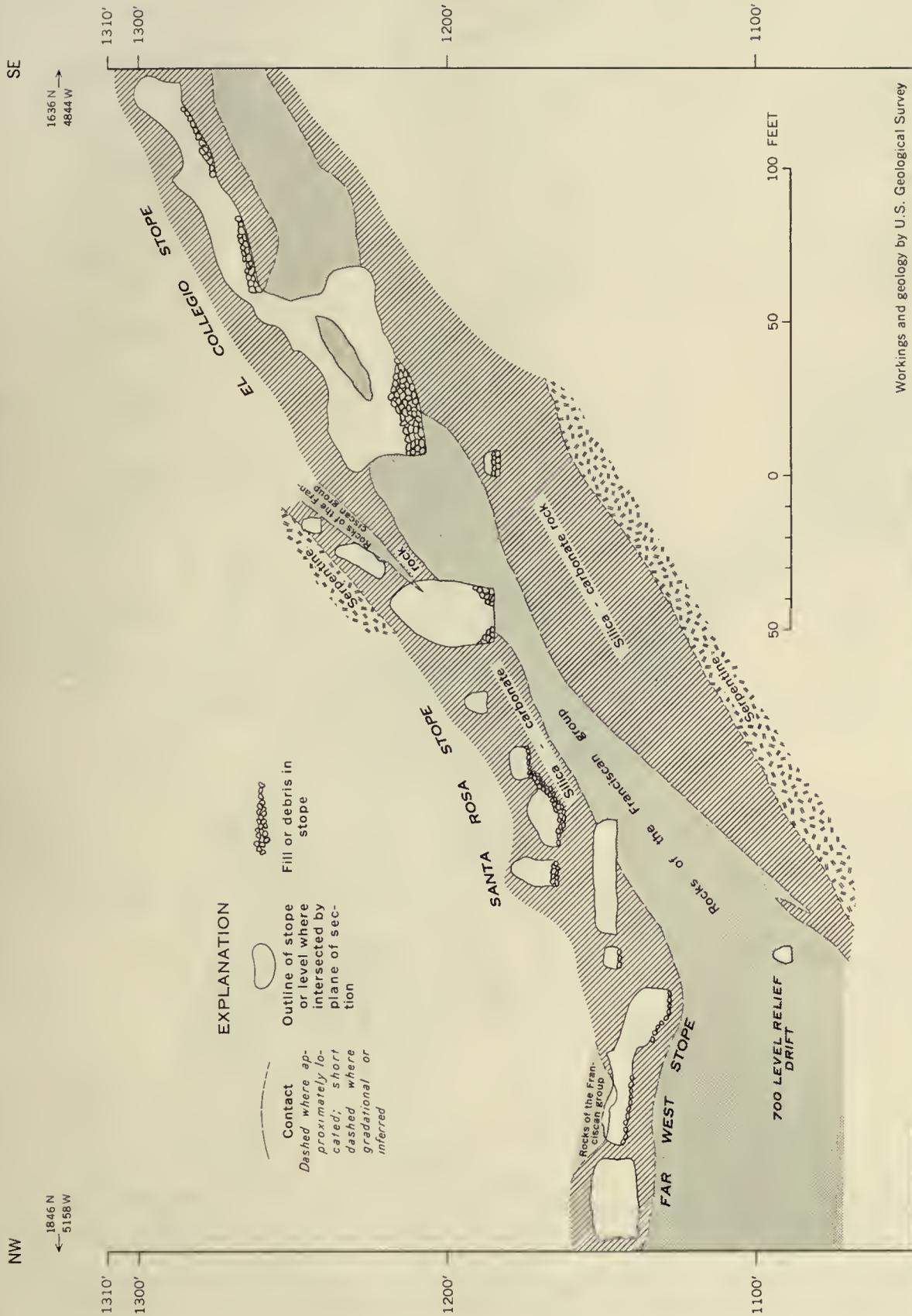


FIGURE 86.—Map of La Ventura stope area of the New Almaden mine showing localization of ore bodies in silica-carbonate rock along the lower contact of an intrusive sill.



Workings and geology by U.S. Geological Survey

FIGURE 87.—Map of the Curasco stope area of the New Almaden mine showing localization of ore along the lower side of a sill where it forms a plunging inverted trough.

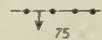


Workings and geology by U.S. Geological Survey

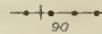
FIGURE 88.—Cross section through the Far West, Santa Rosa, and El Colegio stope area of the New Almaden mine showing ore bodies localized in silica-carbonate rock near the lower contact of an intrusive sill of serpentine.

EXPLANATION

All workings in silica-carbonate rock



Hilo, or narrow quartz-dolomite vein, showing dip



Vertical hilo
Dashed where projected



Top of near-vertical scarp
>>>

Chevrons point down in-
cline at 5-foot vertical
intervals



Head of raise or winze



Stope



Altitude of point on floor
Datum is mean sea level



Fill or debris along margin
of stope

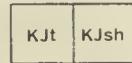


By E. H. Bailey and D. L. Everhart, 1947

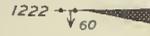
FIGURE 89.—Map of the Moreno and Water stope area of the Guadalupe mine where ore bodies were formed along hils that are not near intrusive contacts.

CORA BLANCA PORTAL
Altitude 1191.2 feet

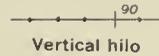
EXPLANATION



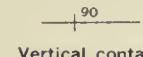
Tuffaceous greenstone of the Franciscan group, KJt; shale of the Franciscan group, KJsh



Hilo, or quartz-dolomite vein, showing elevation and dip
Locally contain cinnabar



Contact, showing elevation and dip
Dashed where indefinite



Fault, showing elevation and dip
Dashed where indefinite



Top of vertical or near vertical wall

Chevrons point down incline at 5-foot vertical intervals

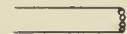
Head of raise or winze

Foot of raise or winze

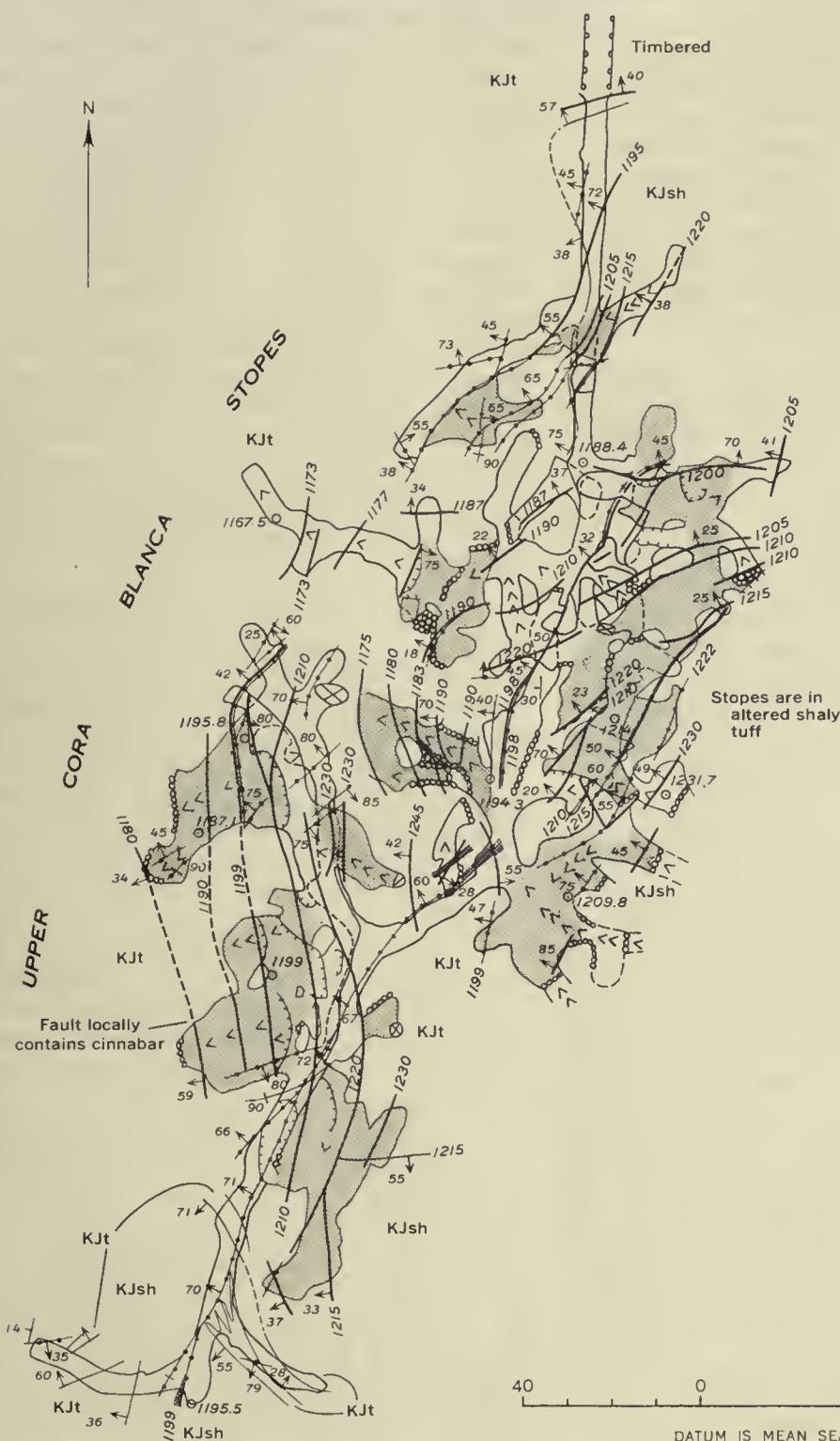


Slope

Altitude of point in floor



Backfilling in workings



DATUM IS MEAN SEA LEVEL

By E. H. Bailey and D. L. Everhart

FIGURE 90.—Map showing the upper stopes and workings of the Cora Blanca area of the New Almaden mine where the ore occurred in veins and in fault gouge in tuff. The map also shows the difficulty of mapping closely spaced overlapping inclined workings, and how the veins and faults were mapped by means of contours drawn wherever exposures were continuous enough to provide control.

GENESIS

AGE OF THE QUICKSILVER ORES

If it be assumed that the quicksilver was all deposited during one period of mineralization, that period fell between the late Miocene and the Pliocene and Pleistocene. This age assignment agrees with others that have been made for quicksilver mineralization in the California Coast Ranges (Ransome and Kellogg, 1939, p. 365; Eckel and others, 1941, p. 544; Bailey and Myers, 1942, p. 420; Yates and Hilpert, 1945, p. 23; and Yates and Hilpert, 1946, p. 252), although at Sulphur Bank (Everhart, 1946, p. 139-140) the deposition of quicksilver has persisted until Recent time.

The quicksilver ores cannot have been formed later than the perched gravel lying on the north slope of Blossom Hill, 6,000 feet S. 20° E. of the Union School, for this gravel contains detrital cinnabar. The gravel, which is one of several isolated remnants of an old stream deposit, lies at an altitude of 700 feet above sea level, or about 400 feet above the floor of the adjacent Santa Clara Valley, and it has been correlated with the rather heterogeneous assemblage of marine and continental sediments that constitutes the Santa Clara formation. In view of the physiographic changes and the amount of erosion since the deposition of the stream gravel, this formation must be at least as old as earliest Pleistocene and is probably Pliocene.

The quicksilver ores cannot be older than the silicified volcanic rock of middle or late Miocene age cropping out on a small knoll 2.0 miles S. 43° E. of Lone Hill, for this rock is cut by quartz veins containing cinnabar. Indirect supporting evidence is given by dolomite veins which cut rocks of late Miocene age on the north slope of the ridge by the Guadalupe mine. These veins do not contain cinnabar, but similar veins in the Guadalupe mine are so closely related to the ores that they are believed to represent the last stages of the mineralization. Additional evidence that the mineralization is later than late Miocene is based on the fact that the cinnabar occurs along sharply defined fractures in the silica-carbonate rock, the age of which is believed to be later than late Miocene. A secondary line of evidence indicating that the quicksilver ores were deposited fairly recently is the general lack of faulting of either the silica-carbonate rock or the ore bodies observed in the mines.

CHARACTER OF THE MINERALIZING AGENTS

From the relations of ore bodies to structural features, we conclude that the ore-forming agent traveled upward, chiefly along zones of open fractures, especially those which were later filled to form hilos. It

also tended to follow contacts between silica-carbonate rock and rocks of the Franciscan group, and it appears to have been retarded and spread out beneath domal and troughlike structures. It was not confined, however, to open fractures, for it also penetrated the seemingly unfractured part of the silica-carbonate rock bordering the fractures for distances of several inches to a foot, depositing cinnabar and some quartz, and simultaneously dissolving other substances, chiefly magnesium carbonate. Considering the large amount of material deposited, and the equally large amount taken into solution, the mineralizing agent must have been a fluid rather than a gas.

The nature of the ore-forming fluid can be inferred only from the minerals that it deposited or took into solution. The most effective solvents of mercurial salts and silica are alkaline solutions, from which cinnabar can be deposited directly, and, as such solutions are also capable of dissolving magnesium carbonate, the ore-forming fluid may have been an alkaline hydrous solution.

DEPTH OF DEPOSITION OF THE QUICKSILVER ORES

Quicksilver deposits are classed as epithermal (Lindgren, 1933, p. 469), meaning they are deposited at relatively shallow depths. As the New Almaden mine is the deepest quicksilver mine in the world, it offers an unparalleled opportunity to estimate the vertical range through which quicksilver ore bodies may form; and, if the amount of erosion since their deposition can be established, it provides an opportunity to establish the maximum depth at which they are known to have formed.

The deepest workings in the New Almaden mine are on the 2450 level, which is 643 feet below sea level, and geologic reports contain many statements to the effect that ore was found at this depth. There is no record in the company surveyors' notes, however, to show that cinnabar was found on this level or on either the 2300 or 2200 level. The deepest opening reported to contain ore is a shallow winze sunk from the 2100 level, which lies 275 feet below sea level. As good ore is reported to have cropped out on the apex of Mine Hill at an altitude of 1,750 feet, the vertical range through which the cinnabar ores of the district as a whole were deposited was at least 2,025 feet. But the 2100 level lies only 1,275 feet below the ground surface just overhead, and ore found in a crosscut south of the Randol shaft of the New Almaden mine on the 1800 level actually lies deeper below the present overlying surface, which is 1,430 feet above it.

To estimate the maximum depth and vertical range

of the ore at the time of its deposition, we would have to estimate how much erosion there has been since then, and it will be hard to make satisfactory estimates of that until the late Tertiary and Quaternary history of the southern San Francisco Bay region has been more carefully worked out. The depth of erosion since middle-Pliocene time we estimate on the basis of what is known of the late history of the San Francisco Bay area to be between a few hundred and a thousand feet, and to assume an intermediate value of 600 feet, which is small as compared to the total depth of deposition, will not introduce a very serious error. We do not know, indeed, how close to this surface the highest ores were deposited, but the occurrence of detrital cinnabar in (late Pliocene or early Pleistocene) gravels that are nearly as old as the ores (post-Miocene) indicates that the cinnabar ores extended nearly to the surface and may have reached it. Therefore we may conclude that the quicksilver ores in the New Almaden district were deposited through a vertical range extending at least from within a few hundred feet of the surface down to a depth of 2,600 feet below the surface.

The question naturally arises why the ores did not form at still greater depths—whether it was because of unfavorable structures or because the temperatures and pressures were too great. The question cannot be answered with certainty, because the surveyors' records show little of the character or occurrence of the ore in the North and South Randol ore bodies, which were in the deepest part of the New Almaden mine. Beneath the North Randol ore bodies the structural conditions for deposition along the ore-localizing contact were less favorable than where the ores of those bodies were formed, for there the contact is steep and locally even overturned; but beneath the South Randol ore body there appears to be no special change in the attitude of the contact. The shell of silica-carbonate rock persisted with about the same thickness to the deepest levels, but the ore bodies apparently became thinner with increased depth. It therefore seems probable, as both the North and South Randol ore bodies died out at about the same level, that the temperature-pressure limits for cinnabar deposition had been reached. It is noteworthy that the ore bodies of the three largest mines in the district all died out downward at about the same level—in the Senator mine at 500 feet below sea level, in the Guadalupe mine at 400 feet, and in the New Almaden mine at 300 feet below sea level.

PRESSURE AND TEMPERATURE OF ORE DEPOSITION

The range of temperature and pressure through which the ores were deposited can be estimated ap-

proximately if certain assumptions that seem to be justified by the available facts are made. These are—

1. The ores were deposited through a vertical range extending from near the original surface to 2,600 feet below it.
2. The ores were deposited from water solutions which were nowhere above their boiling point for the prevailing pressure.
3. The channel ways for these solutions were sufficiently open for the system to be considered as one under hydrostatic rather than lithostatic pressure.

The evidence for the first of these assumptions has been given. The evidence for the second is twofold. The fact that the ores were formed by replacement, a process that entailed the removal of large amounts of material as well as the deposition of cinnabar, indicates the presence of a liquid phase; and replacement by cinnabar just beneath the alta in structural domes indicates the absence of a vapor phase, which, if present, would fill the structural highs and keep out the ore-depositing liquid. The validity of the third assumption—that of an open hydrostatic system—is questionable, but it is indicated by the openness of the channel ways and the quantity of cinnabar deposited, which in turn seems to require the availability of large amounts of ore-forming solution.

If these assumptions are correct, the maximum pressure possible would be the hydrostatic pressure of a column of fluid, largely water, 2,600 feet high. The pressure at its base would be a little below 1,000 pounds to the square inch.

The temperature range in which the ores were deposited cannot be directly determined from any of the contained minerals, but it was doubtless low as compared with the temperature of deposition of most hypogene ores or magmatic solutions. Lindgren has estimated the temperature of formation of quicksilver deposits as between 50° and 200°C. (1933, p. 212).

The maximum temperature allowed by the above assumptions would be the boiling point of water under the pressure equivalent of a 2,600-foot column of water, or about 280°C. Although the inclusion of dissolved salts and gases would modify this temperature somewhat, they tend to compensate each other and probably would produce no significant change. This provides a maximum temperature for a static system, but it may be considerably greater than the temperature in the flowing system believed to have deposited the New Almaden ores. For boiling not to occur at higher levels if the water at depth is near its boiling point, the water must move upward so slowly that

heat lost to the walls is large enough to counteract the lowering of the boiling point due to decreased pressures at higher levels. Because of the low heat conductivity of rocks, the rate of flow would have to be exceedingly slow to satisfy this condition.

Some idea of the quantity of water required to deposit the cinnabar, and hence the rate of flow, may be obtained by considering the quantity of mercury deposited, the length of time available for its deposition, and the quantity of mercury in the ore-forming solution. The minimum quantity deposited is fairly well known, the time can probably be estimated within reasonable limits, but much uncertainty exists regarding the concentration of the ore solution. A theoretical concentration can be calculated by assuming a solution with pH and sulfur content comparable to thermal spring water and saturated with HgS. A slightly alkaline solution containing 0.01 mole dissolved sulfur at about 150°C could contain 2×10^{-9} g Hg per liter, according to the data given by Krauskopf (1951, p. 501-504). For this solution to deposit mercury equal to that recovered at New Almaden (3×10^{10} g) in a period equal to all Pliocene time (11 million yr) requires a rate of flow of about 1 million gpm (gallons per minute). This rate is doubtless excessive, but it suggests a very open system, which in turn requires that the water at a depth of 2,600 feet be much cooler than 280°C or else extensive boiling should have occurred at higher levels. In contrast to the theoretical data, unduplicated analyses⁹ of waters closely associated with mercury deposits, collected at Skaggs Springs, Steamboat Springs, Elgin Spring, and a drill hole at Sulphur Bank, show mercury concentrations of about 1×10^{-4} g per liter. If this concentration is used in the calculation, the flow amounts to only 10 gpm. This is so slow that cooling by wallrock conduction probably is large enough to prevent the rising water from boiling even though it is everywhere near its boiling point. Until better data on the solubility of HgS in natural waters is available, we must conclude that the maximum temperature may have been 280°C, although calculations based on the solubility of HgS in slightly alkaline solutions suggests that this may be too high by 100° or more.

An approximation of the minimum temperature that may have existed at a depth of 2,600 feet can be obtained by considering the temperature gradient. The gradient was doubtless somewhat greater than the present gradient in the Coast Ranges of California, and we may safely assume it was no less than 1.5°C per 100 feet. Assuming an average surface

temperature of 25°C, this would give a minimal temperature of 64°C at a depth of 2,600 feet.

If all the ores formed at the same temperature, it would lie between 64° and 280°C, but temperatures of deposition were surely greater at depth than at the surface. Considering the data available at New Almaden, it appears that Lindgren's estimate of 50°C to 200°C is reasonable, but the upper limit may be a little too high.

RELATION TO INTRUSIVE ROCKS

The space relations between the ores and the intrusive rocks in the district have led to several widely held misconceptions. Because of the general proximity of quicksilver ores to serpentine, not only in this district but elsewhere in the California Coast Ranges, it was widely believed at one time that there was some genetic relation between the serpentine and the ore-forming fluid. Becker (1888, p. 117-138), believed that the serpentine was not igneous, but was formed by metamorphism of rocks of the Franciscan group—a belief that compelled him to ascribe some other origin to the ore fluid. After it became established that the serpentine bodies are of magmatic origin, the idea that the ore fluid was related to the ultramafic magma again sprang up. Now, once again, after repeated demonstration in many parts of the Coast Ranges that the serpentine is much older than the ore bodies, this conception has largely been abandoned.

The reported occurrences of dikes of basalt or diorite in quicksilver districts in the Coast Ranges has been cited as evidence of the derivation of the ore-forming fluid from mafic magma. Schuette (1931, p. 411) stated, referring to the New Almaden mine, "Thus a deep-seated magma is indicated as the original source and this view is strengthened by * * * the occurrence of diorite dikes in the mine." The only rock in the New Almaden mine that might be termed diorite is some of the greenstone, and as this is clearly a part of the Franciscan group of Mesozoic age, the ore-forming fluids of late Tertiary age cannot be in any way related to it.

The relation between the felsic igneous rocks exposed on the hill north of the Senator mine and the ore-forming fluid was emphasized by Becker. He believed that this pyroclastic bed, interlayered with sedimentary rocks of late Miocene age, was an intrusive dike occupying a fissure and genetically related to the ores, for he states, "Only one occurrence of rhyolite is known in the whole area * * * This is a dike at New Almaden (Becker, 1888, p. 156), and further, "This fissure was probably formed at the time of the rhyolite eruption, to which I also ascribe the genesis of the ores (Becker, 1888, p. 463). As the ores

⁹ Unpublished analyses made by Buckman Laboratories, Inc., Tenn.

are somewhat younger than the period of igneous activity represented by this bed, and as cinnabar is found in fractures in similar rock to the north, the genetic relation between the ores and the igneous activity is not so clear as Becker would have one believe. The ore-forming fluid obviously rose from a deep-seated source, and possibly this source was the same magma chamber in which the magma previously formed, but such a relationship is not proved by the available evidence.

RELATION TO MINERAL SPRINGS

The association, and supposed genetic relationship, between quicksilver ore and hot springs has been emphasized in textbooks on ore deposits; but so far as we know there are no hot springs in or near the New Almaden district. Mine surveyors' records, moreover, contain no mention of hot waters, or even of excessive heat in the deeper parts of the New Almaden mine, though they repeatedly observed the abundance of gases. Cold springs, on the other hand, giving off abundant carbon dioxide are found in at least three places in the area. One of these, near the mouth of Soda Spring Canyon on the west edge of the district, is far removed from any known ore deposit. The other two are close to Mine Hill. Near the junction of Deep Gulch and Almaden Canyon is a mineral spring whose water, naturally charged with carbon dioxide, was at one time bottled and sold as "Almaden Vichy water" (Hanks and Irelan, 1888, p. 73); and when a pit dug for mining cinnabar nuggets in this area became filled with water, gases bubbled to the surface in several places. There are other mineral springs in the vicinity of the Soda Springs tunnel, south of the Enriquita mine, and here the springs have built up a thin but striking accumulation of calcium carbonate tufa. A similar area of tufa lies about a mile southwest of the summit of Mine Hill, but no active springs were noted in it.

In the deeper workings of the New Almaden mine carbon dioxide was encountered in such abundance that it drove the miners from the working face many times, and in some of the deepest levels it is reported to have been under sufficient pressure to have "burst the face out." It was so abundant in the 1400-level crosscut driven from near the bottom of the Santa Isabel shaft toward the American mine that when the crosscut was abandoned it was bulkheaded, and the gas was piped to the surface, compressed into metal containers, and sold for commercial use. These mineral springs and the continued evolution of carbon dioxide gas may all be attributed to the last dying stages of the magmatic activity in the district.

SUMMARY OF ORIGIN OF THE QUICKSILVER ORE BODIES

The quicksilver ore bodies of the New Almaden district are believed to have formed during the Pliocene epoch. They resulted mainly from the replacement of silica-carbonate rock by cinnabar, but in minor part from replacement of other rocks and the filling of open space by cinnabar or quartz-dolomite veins containing cinnabar. The cinnabar was deposited in the silica-carbonate rock from rising alkaline hydrous solutions following fracture zones, which in most places are best developed near the contacts between the silica-carbonate rock and rocks of the Franciscan group. The richest ore bodies resulted from spreading out and slowing down of these solutions in structural traps formed by a capping of the relatively impervious *alta*, but some fairly good ones were formed under *alta* along steep contacts where *hilo* fractures were abundant. Some ore bodies, moreover, were formed above *alta* rather than below it. The depth of deposition extended from near the surface to about 2,600 feet, and the temperature range through which the ores were deposited can be no greater than 25° to 280°C and is more likely to be from 50° to 150°C. Erosion of the primary ore and redeposition has resulted in the formation of an unusual placer deposit in Almaden Canyon about a mile downstream from the surface exposure of the ore. The various stages of rock alteration, mineralization, erosion, and redeposition that resulted in the primary and placer ores are summarized on plate 2.

OTHER METALLIC DEPOSITS

COPPER

A gossan zone containing oxidized copper minerals has been prospected on the northeast slope of Fern Peak, at an altitude of 1,050 feet and about 0.7 mile S. 15° E. of the Hacienda. The gossan, which is only about 8 feet wide, crops out between serpentine and greenstone of the Franciscan group and consists largely of ochreous rock cut by veinlets of pyrite-bearing sugary and vuggy quartz. The rock contains some scattered crystals of cuprite, and is locally veined and coated with thin crusts of malachite.

Two shafts, one now filled and the other now inaccessible but open for at least 75 feet, were sunk many years ago in the gossan zone, and 500 feet southwest of the shafts are 3 caved adits driven to explore the zone at depth. These adits all begin in serpentine, but the lowest, which is apparently the longest, had some oxidized copper ore on its dump, indicating that it reached the gossan zone. We have no knowledge either of the history of these very old inaccessible workings or of what they revealed. Probably the metal sought was copper, but the gossan may also con-

tain some gold. The rock seen in the outcrops and on the dumps shows far too little copper deposition to be rated as copper ore.

CHROMITE

Chromite occurs sparingly in small lenses and irregular stringers in the serpentine of the New Almaden district. These bodies measure only a few inches in length, and are generally widely spaced. Typical examples are well exposed in the serpentine near the foot of the cable raise which goes up from a branch of the 800 level Day tunnel in the New Almaden mine (pl. 6). At the surface in a few nearly flat areas the serpentine containing widely scattered chromite lenses has weathered and been eroded, leaving a natural concentration of the resistant heavy chromite in the thin residual soil.

Short adits have been driven into the serpentine in search of chromite ore at two places in the district, but none of these revealed more than a few scattered pods. One of these places is close to the end of the east branch of the road leading from Guadalupe Canyon toward El Sombroso; the other is in the Santa Teresa Hills, near the narrow saddle three-fourths of a mile south of Coyote Peak. From the surface in the latter area one carload of ore was collected and shipped during World War I. In a third area, 8,000 feet east of the Senator mine at the northern base of Los Capitancillos Ridge, many pieces of massive chromite float, the largest nearly 1 foot in diameter, have been piled along fence lines, and it seems likely that some chromite ore was collected here also during World War I.

MANGANESE

Manganese-bearing chert lenses of the Franciscan group have been prospected by means of a few shallow cuts near the top of Fern Peak, 1 mile S. 40° E. of the Hacienda and also on a spur extending from Fern Peak, 0.35 mile S. 75° E. of the Hacienda. In each of these places the manganese minerals are of supergene origin; they consist of psilomelane, pyrolusite, and the more nondescript material generally called wad. These minerals fill cracks in the chert to form irregular veins, and locally they form small pods of nodular ore. Although selected specimens rich enough to constitute manganese ore can be collected at both places, in neither does there appear to be any chance of obtaining more than a few sacks of usable ore.

NONMETALLIC MINERAL RESOURCES

BUILDING STONE

The sandstone of Late Cretaceous age in the Santa Teresa Hills has been quarried in several places on

the southwest flank of the hills for use as a building stone. Seven of the larger quarries are indicated on plate 1, but all of these, and some smaller ones not shown, appear to have been abandoned many years before 1948. The quarries were first opened in 1866 (Irelan, 1888, p. 546-547) and were intermittently operated at least until 1906. During this period they supplied the building stone for several well-known public buildings in San Francisco and San Jose and for all the older buildings of Stanford University.

This sandstone was particularly desirable as building stone for several reasons. Its color where unweathered is gray, but, owing to the great depth of oxidation in the area, most of the rock that has been quarried had an attractive buff color. Of particular importance, especially in the days of ornately carved buildings, was the fact that the sandstone when first quarried was soft and easily carved but became harder on exposure to the air (Forstner and others, 1906, p. 134). One unfavorable feature of the sandstone is its tendency to crumble on repeated wetting and drying. This is especially well displayed by many of the sandstone columns around the quadrangle of Stanford University; in places as much as an inch of rock has crumbled off the lower parts of these columns, which have been exposed to water sprinklers, whereas the higher parts of the columns, which remained dry, are so little eroded that they still clearly show the marks of the stonemasons' tools. For further statistical data bearing on the suitability of this sandstone as a building stone, the reader is referred to the work by Forstner and other (1906).

The cavernous-weathered silica-carbonate rock of the New Almaden district is sold locally for decorative use in gardens. Fresh serpentine, limestone of the Franciscan group, and siliceous shale of the Monterey have also been used for ornamental rock walls in and around Los Gatos and San Jose.

LIMESTONE

Limestone of the Franciscan group was quarried before 1900 in several places in the area and converted in nearby kilns to lime. The more productive quarries were those of the Guadalupe Lime Co. about a mile southeast of the Guadalupe quicksilver mine, the Old Douglass Ranch quarries (Logan, 1947, p. 312) south of Los Gatos in the NW $\frac{1}{4}$ sec. 27, T. 8 S., R. 1 W., and the quarries on the north slope of Linekiln Canyon. The largest of these, the Guadalupe Lime Co. quarry, was first opened in 1864 (Irelan, 1888, p. 544) and remained in operation for more than 20 years. The limestone, which contained many lenses of chert, was apparently hand sorted at the quarry and trans-

ported to the kiln in Guadalupe Canyon by a gravity pulley. It was fired in a conical kiln said to have been 100 feet in diameter at the base and 60 feet high; a single charge yielded 160 barrels of lime and required $4\frac{1}{2}$ cords of wood for its firing. Part of the lime so produced was sufficiently pure to be used in sugar refining, and doubtless a part was used at the mines in the recovery of quicksilver.

Cement is being made from limestone of the Franciscan group at the quarry of the Permanente Cement Co., only a few miles north of the New Almaden district. The limestone of like age in the district is apparently similar and in places even purer, but occurs in smaller bodies. Because of the general scarcity of limestone in the region, at some time in the future limestone may be quarried from some of the larger lenses in the New Almaden district for use in the manufacture of cement.

Eocene limestone has been quarried from time to time since 1915 (Huguenin and Costello, 1921, p. 185) from a small quarry 1,000 feet southeast of the Bernal mine in the Santa Teresa Hills. It is reported (Logan, 1947, p. 311) to have been used chiefly for fertilizer in recent years, but in 1917 it was quarried for use in sugar refining. An analysis of this limestone follows (Huguenin and Costello, 1921, p. 185).

Analysis of Eocene limestone from Santa Teresa Hills
[Analyst unknown]

SiO ₂ -----	2.50
Al ₂ O ₃ -----	11.24
Fe ₂ O ₃ -----	2.90
MgO -----	1.55
CaCO ₃ -----	80.81
Total -----	99.00

SERPENTINE

Serpentine has been quarried in the New Almaden district about 12,000 feet northeast of the apex of Mine Hill for use in the manufacture of fused phosphate fertilizer. In 1947 the Permanente Metals Corp. trucked 10,000 tons of serpentine from this quarry to its plant at Permanente, Calif., where the serpentine was charged into an electric furnace with a fixed proportion of phosphate rock from Idaho, and the mixture then melted, tapped, and quenched. The resultant material, which was guaranteed to contain 18 percent of available P₂O₅, was sold as a phosphate fertilizer. The quarry site was selected primarily because of its accessibility, but the magnesia-silica ratio of the serpentine body there is slightly greater than the average for the other serpentine masses in the district. In 1948, the magnesian phosphate fertilizer was no longer being made, and the quarry was not being used.

GRAVEL, SAND, AND LOAM

Aggregate materials and loam are quarried by two companies from the bed of Los Gatos Creek in sec. 16, T. 8 S., R. 1 W., in the northwest corner of the district. The gravel and sand are used locally for concrete, septic tanks, and road metal. The loam, which is taken from the northernmost deposit, is in demand on the San Francisco Peninsula for use as foundation material for lawns and gardens.

The northern deposit is owned by W. R. Burchell, of San Jose, Calif., and operated under the name of the Los Gatos Sand and Gravel Co. Mr. Burchell has quarried in the area since 1926, at which time he bought the property from the Tiffany Bros. Gravel Co. In 1936 the Vasona percolation dam was built just downstream from his plant, and the damming of flood-stage waters resulted in the accumulation of a 10-foot layer of gravel, sand, and loam in the following 4 years. This material, particularly the fine loam that contains abundant decayed plant fragments, has furnished the bulk of the production of gravel and sand in recent years.

The southern deposit has been operated since 1947 by the Los Gatos Aggregate and Materials Co., owned by A. Johnson and Glenn Reinhart of Los Gatos. They own 13 acres of ground, 7 of which contain workable gravel to a depth of 30 feet, and lease 10 acres from the town of Los Gatos.

ROAD METAL

Chert of the Franciscan group has been quarried for road metal at the northern base of the Santa Teresa Hills, west-northwest of the Santa Teresa mine. The chert in this area required no crushing, because of its rhythmic bedding and the abundance of fractures at right angles to the bedding. Only a small amount of it has been quarried here for local use, but elsewhere in the California Coast Ranges chert has been used rather extensively because it makes a virtually indestructible road surface.

Burned mercury ore, usually referred to as "calcines," from the old Hacienda, has been used in surfacing the roads in the New Almaden mine area. This material, which tends to cement itself on repeated wettings, forms road surfaces that are hard and well drained but somewhat dusty when dry.

MINES

The principal mines of the New Almaden district lie along the 5-mile stretch of Los Capitancillos Ridge between Almaden Canyon on the southeast and Guadalupe Canyon on the northwest. The west end of the mineralized zone is a part of the Guadalupe mine

property; all the rest of the ridge is in the extensive New Almaden mine property. The latter contains not only the famous New Almaden mine at its eastern end, but also half a dozen other mines, which are included under the collective term "New Almaden Mines." The district also includes a second mineralized belt lying along the north slope of the Santa Teresa Hills and containing two small mines with relatively insignificant production.

NEW ALMADEN MINES

The New Almaden mine property, owned in 1948 by Richard H. L. Sexton and Eric H. L. Sexton, of Philadelphia, Pa., includes, from east to west, the New Almaden, America, Providencia, Enriquita, San Antonio, San Mateo, and Senator mines. This property was originally part of several Spanish land grants, and consequently, although it is more extensive than most mining properties, it is not subdivided into mining claims. It originally included 8,580 acres, or more than 13 square miles, but has been reduced by the sale of nonmineralized portions to less than half that size. About 3,361 acres lying along Los Capitanillos Ridge contain all the mines. A smaller separate acreage lying on the steep north slope of the Sierra Azul was formerly used as a source of mine timber and wood for the reduction furnaces, but it is now valuable as a source of water.

The hundred-year history of the New Almaden Mines is treated at length in the historical section beginning on page 176. A brief summary statement indicating the past production and present status of mines follows.

The value of the cinnabar-bearing quicksilver ores cropping out on Mine Hill was first recognized in 1845, and the development of the New Almaden mine was begun immediately thereafter. During the next 50 years enough ore was found beneath Mine Hill to make the New Almaden one of the world's great quicksilver mines. By 1905, however, the ore bodies had largely been exhausted. Since then, only small-scale attempts to find new ore bodies underground in the mine have been made; but production has been continued, at a low and declining rate, by the reworking of old dumps and the stripping of submarginal ore from the walls and floors of old stopes. During World War II production was temporarily increased by large-scale surface mining of low-grade ore. The other mines on the New Almaden property were also partly developed before 1870, but, because of the abundance of ore in the Mine Hill area, they remained little exploited until production from the New Almaden mine began to decline, when they were reopened. This re-

vival of the so-called outside mines resulted in a significant production from the Senator mine, but the others yielded little ore. The outside mines were not reopened during World War II, and they remain largely inaccessible. By 1948 the part of the New Almaden mine that had been reopened during the wartime boom had also again become largely inaccessible.

The total production of all the New Almaden mines to the end of 1945 was 1,046,198 flasks of quicksilver. Of this total, 93 percent was recovered before 1900, and more than 95 percent came from the famous New Almaden mine proper. The decline of the production of the mines and the decrease in grade of the ore treated are shown graphically in figure 91.

NEW ALMADEN MINE

The New Almaden mine proper includes the integrated workings and unconnected exploratory adits underlying an area of about 1½ square miles on Mine Hill. (See pl. 3.) In altitude these workings, as shown by plate 4, range from about 1,750 feet above sea level to 643 feet below sea level, and thus span a greater vertical interval than those of any other quicksilver mine in the world. In the aggregate length of its horizontal workings, which is approximately 33 miles though it is commonly reported to be several times as great, the mine probably holds first place among the world's quicksilver mines.

The top of Mine Hill (1,750 feet above sea level before mining began) was the datum for all the older maps, and levels were designated in hundreds of feet below this point. The major adits lie on the 800 level, and the deeper workings, extending down to 1,600 feet below this level, could be reached only through shafts. Some of these were internal, but 13 surface shafts, of which the deepest is 1,519 feet deep, surround the apex of the hill. Most of the workings above the 850 level, or about 40 percent of the total, were accessible during the examination leading to this report.

The surface geology of the area underlain by the New Almaden mine is shown on plates 5-10. In the latter the geology for the workings above plate 3, and the geology exposed on the levels as shown on the 850 level was reduced, and, in places, generalized from maps originally made by Survey geologists at a scale of 40 feet = 1 inch. The geology shown on the lower levels was plotted from records of company surveyors or from unpublished maps by S. B. Christy.

Even a cursory inspection of these maps and the sections shown on plate 11 will show that the geology is complex, and the subsurface geology could not have been even approximated from the surface exposures.

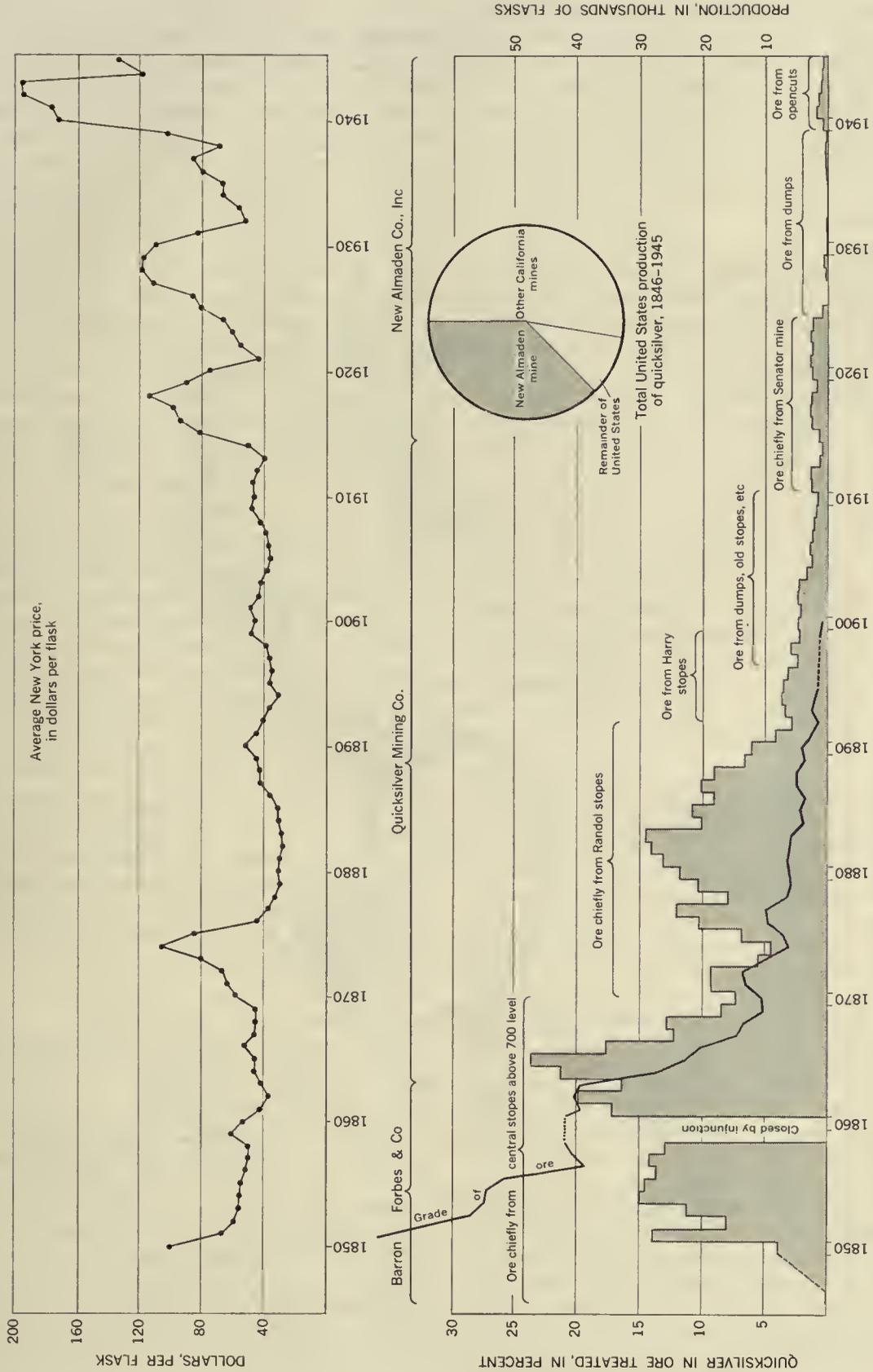


Figure 91.—Graph showing production of the New Almaden mines, 1847-1945 inclusive.

Because of this fact, the detailed geology of the New Almaden mine as a whole cannot readily be described. Therefore the various parts of the mine are described separately, and the major emphasis has been placed on the ore-controlling subsurface structures exposed along the underground workings. A brief preview of the main structural features, however, may help the reader to visualize the relation of the various parts to the complete structure.

The rocks in the mine area are those of the Franciscan group, serpentine, and silica-carbonate rock. These have a general northwesterly strike and form an anticline in the area explored by most of the workings. The crest of the anticline passes just south of the highest part of Mine Hill, and its limbs dip somewhat more steeply than the general slope of the topography. The distribution of the serpentine in the anticline can best be seen in the cross sections on plate 11. These show that there are two thick sills of serpentine on the north limb of the anticline, but that beneath the summit of Mine Hill these are merged, forming a central mass of serpentine which extends to the surface. On the north limb there are also several thinner sills above the two thick ones; these extend northward from the central mass and taper out downward. On the south limb of the anticline only one thick sill extends from the central mass, forming a continuation of the lower of the two main sills on the north limb, but above it are many thin subparallel sills.

Most of the ore bodies mined lay on the north limb of the anticline, along the top of the uppermost of the two thick sills. The shape of the top of this sill is shown by subsurface contours in figure 81, which also shows the relation of the mineralized areas to the minor structural irregularities in this surface. Other ore bodies lay close to the junction of the two main sills, some of them on the lower margin of the upper sill and some on the upper margin of the sill beneath. Also on the north limb of the anticline some of the smaller apophyses lying above the two principal sills contained small but rich ore bodies. On the south limb of the anticline, ore was found on the top side of the extension of the lower sill and also along several thin short apophyses that extended outward from the central serpentine mass nearer the surface.

In the following description of the New Almaden mine, the workings are subdivided into units, or "areas," each containing closely related ore bodies that were found and mined at about the same time. Ore was first discovered close to the apex of Mine Hill, near the center of the area that was subsequently explored, and the first thing that the miners did was to

follow this ore downward. Then, from time to time, prospects were begun in adjacent areas, and generally those that revealed ore were ultimately connected with the ever-expanding central workings. In the early days, however, many groups of workings, being in isolated ore bodies, constituted separate mines and were known under separate names, which were those first applied to the original unconsolidated prospects. These groups are, in the order in which they will be discussed, the Cora Blanca, Harry, Velasco, Central stope, Victoria, North Randol, South Randol, San Francisco, Santa Mariana, and San Pedro-Almaden; their relative positions are shown in figure 92. For each there will be given a description of the workings, a brief history of the development and production, an account of the local geology, a discussion of the peculiarities of the local ore controls, and suggestion for further development.

CORA BLANCA AREA

Location and extent of workings

The Cora Blanca area contains the southeasternmost group of workings in the New Almaden mine, originally developed as an independent mine known as La Cora Blanca. The workings underlie an area in the upper part of Deep Gulch where the general surface altitude is about 1,200 feet above sea level. The principal drifts and crosscuts lie between 700 and 1,200 feet above sea level, and their aggregate length is about 10,000 feet. (See pl. 4.) They were formerly reached through the Deep Gulch, Faull, Cora Blanca, and Water adits and through the Grey and Cora Blanca shafts, but in 1948 the Cora Blanca adit provided the only access. A second group of near-surface workings and an open-cut lying above some of the Cora Blanca workings, known locally as the Los Angeles workings, are considered here as a part of the Cora Blanca workings, with which they are closely related.

History and production

Mining in the Cora Blanca area appears to have begun in 1864, on thin veins of cinnabar found in altered tuff of the Franciscan group. These veins, though small, were fairly continuous, and, after they had been followed downward for a short distance, the Deep Gulch tunnel was driven from Deep Gulch to cut under them at a depth of less than 200 feet. This tunnel penetrated little ore, and in 1868, after the mine had yielded about 2,700 flasks of quicksilver, it was virtually abandoned. In October 1873 the Cora Blanca shaft was begun, and unexpectedly it struck rich ore at a depth of about 50 feet. The Deep Gulch tunnel was thereupon extended to connect with the shaft, and the

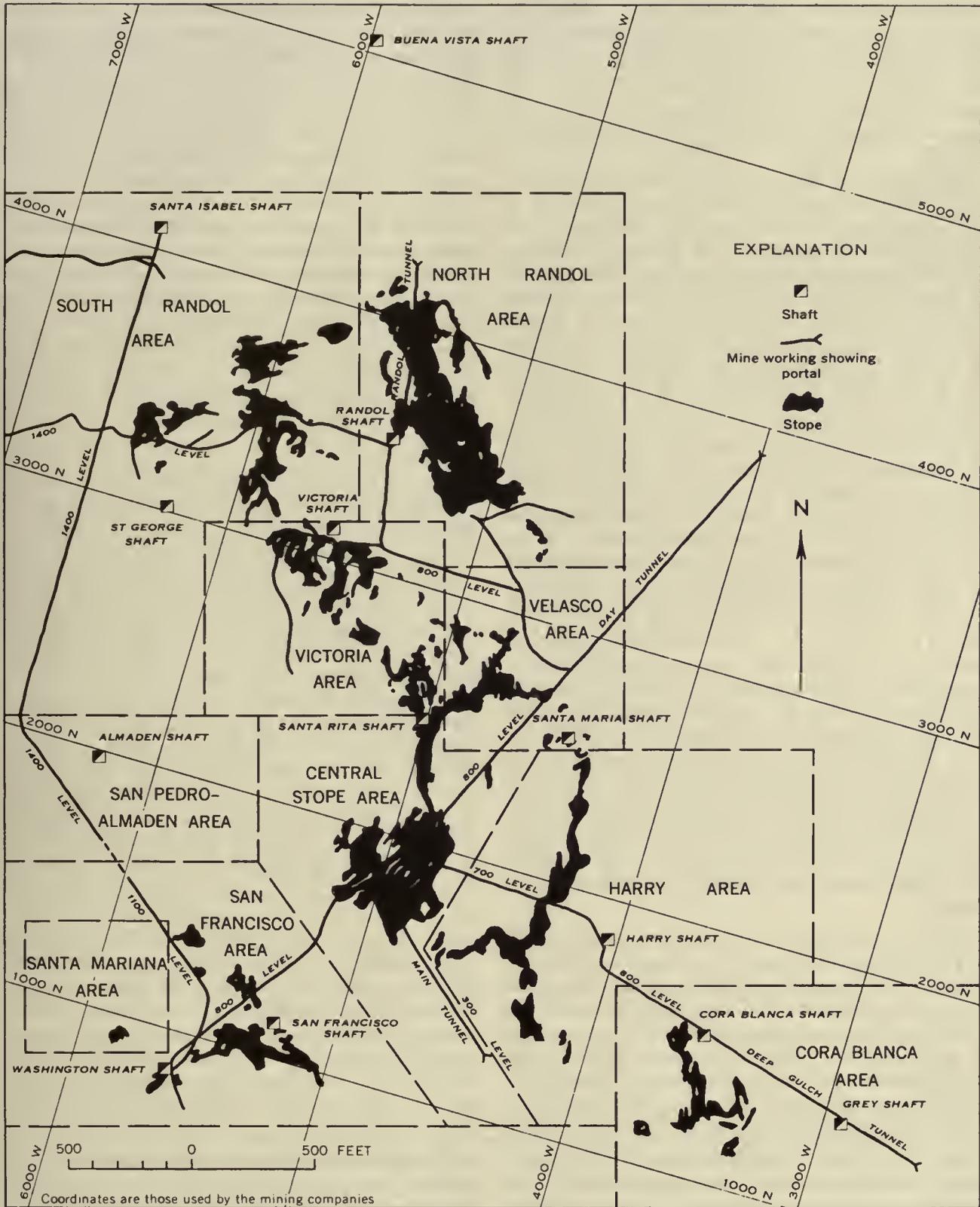


FIGURE 92.—Index map of the New Almaden mine area showing parts of the mine described as separate units in the text.

ore was followed downward and explored laterally between the 600 and 800 levels. In 1875 the Grey shaft was sunk, on the line of the Deep Gulch tunnel, and by 1878 drifts on the 900, 1000, and 1100 levels had explored the contact down the plunge of the ore body found on the higher levels, but without revealing any ore.

Meanwhile an 8- by 8-foot adit, known as the Hacienda tunnel or Bottom tunnel, had been started in 1867 from a point in Almaden Canyon about 0.3 mile upstream from the furnaces at the Hacienda. (See fig. 87.) This adit was intended to provide drainage for the entire hill to the 1200 level and to afford underground transport to the furnaces. Only 6 months after it was begun it had been abandoned as too costly, but in 1874, upon the discovery of the rich Cora Blanca ore bodies, the driving of the tunnel was resumed in order to drain the area and explore it at depth. During the next 5 years the Hacienda tunnel was alternately extended and abandoned until, 2,800 feet from its portal, it intersected the contact that at higher levels formed the back of the Cora Blanca ore bodies. Then, as no ore had yet been found in the Cora Blanca mine below the 850 level, the tunnel was abandoned without ever having served any useful purpose. By the end of 1879 the Cora Blanca ore bodies between the 600 and 800 levels had been virtually exhausted; the mine had then produced 7,500 flasks, recovered from ore averaging 4.5 percent quicksilver. All production from the Cora Blanca mine since 1880 has been accomplished by gouging thin veins in the upper levels, removing fill from stopes, reworking old dumps, and mining low-grade ore in the Los Angeles opencut. The production from these later operations is not recorded separately from that of the New Almaden mine as a whole, but it probably did not equal the recorded early production from the high-grade ore.

Geology

The most important structural feature explored by the Cora Blanca workings is the upper surface of a serpentine body overlain by rocks of the Franciscan group, which in this area are largely mafic tuffs. (See pl. 12.) Although only rocks of the Franciscan group are exposed at the surface, the serpentine body is so well delineated by mine workings that it is known to be a continuation of the sill that contains the Harry, Velasco, and Randol stopes to the northwest. (See fig. 81.) The rocks of the Franciscan group are poorly exposed on the surface and considerably faulted in the upper levels of the mine, but they apparently strike northwestward and dip southwest, and are probably overturned. In the accessible lower levels of the mine

these rocks have a general northerly strike and easterly dip, although in places they exhibit radically different attitudes. The upper surface of the underlying serpentine is irregular, but is broadly conformable with the bedding of the adjacent Franciscan rocks. The lower surface of the serpentine has not been reached by any of the Cora Blanca workings, but north and west of the Cora Blanca area the serpentine forms a sill-like body with a thickness of more than 400 feet. A part of the upper surface of the sill bulges outward to form broad ridges and domes which have been important in localizing ore bodies, and in some places apophyses and thin outlying sills extend above its main hanging-wall contact. Beneath this contact in most places the serpentine has been hydrothermally altered to silica-carbonate rock, some of which is as much as 50 feet thick, and most of the apophyses and outlying sills have been similarly altered.

Ore bodies

The ore bodies mined in the Cora Blanca area were alike in that they all contained cinnabar as the only ore mineral, but the cinnabar in altered tuff was differently distributed than that in the silica-carbonate rock beneath. The ore bodies mined from the upper levels of the Cora Blanca mine, and from the Los Angeles opencut and connected shallow workings, consisted of either single veins or a few parallel veins, generally less than half an inch thick, in altered mafic tuff. Some of the veins contained only cinnabar, but many contained dolomite gangue, and some also contained quartz and hydrocarbons. Most of the veins followed faults of small displacement striking a few degrees east of north. In the highest workings the veins dip steeply to the west, but near the underlying sill they steepen to vertical and then roll to dip eastward and join the serpentine contact at a low angle. The tuff bordering the veins is bleached and partly converted to kaolinite-halloysite, and around one of the small stopes it is extensively carbonatized. Most of the veins lie directly above known ore bodies in silica-carbonate rock and represent "leakages"; as yet, however, no ore bodies have been found below the cinnabar veins mined in the southern part of the Los Angeles workings.

The more productive of the ore bodies in the Cora Blanca area were those formed in the silica-carbonate rock just below the upper contact of the sill. The only large body of this type was mined in a nearly continuous stope extending upward from the 850 level to a point above the 600 level. Between the 700 and 750 levels, the stope branches to follow two diverging ore shoots; the northern shoot extends upward along

a bearing of a few degrees west of north to a point above the 600 level, and the other shoot extends west updip about half as far. As this body has been completely mined out, little is known of the character of the ore; a few narrow dolomite-quartz veins, or hilos, penetrate the walls of the exhausted stopes, but it seems likely that the ore occurred largely as a blanket, in which cinnabar filled small fractures and also extensively replaced the silica-carbonate rock. The localization of the shoots appears to have been controlled by the shape of the hanging-wall contact, for the stopes follow slight flexures nearly up the easterly dip of the contact to above the 600 level. There the contact rolls through a horizontal attitude to a westerly dip, causing the flexures to become domes.

An unusual feature, not found in other accessible parts of the New Almaden mine, is the extensive development of a dolomite vein almost, but not exactly, along the upper contact of the silica-carbonate rock. This vein, which in places is more than 3 feet thick, locally formed the back of several of the stopes between the 600 and 800 levels, but it probably follows a postore fracture. Below the 800 level it grades in places to a coarse dolomite-cemented breccia containing fragments of silica-carbonate rock, some of which are largely replaced by cinnabar whereas others are completely unmineralized. This mixture of mineralized and unmineralized fragments is interpreted to mean that the breccia and vein are younger than the quicksilver mineralization. As the vein is straighter, in both strike and dip, than the intrusive contact and was taken as the hanging wall in mining, it seems likely that in some places ore lying between the vein and the overlying contact may have been missed. The southern stope above the 700 level might be cited as such a place, but, as the thickness between the vein and the contact is small, no large amount of ore can be expected to lie above the vein in this area.

Suggestions for further development

The compact area containing the Cora Blanca mine appears to have been rather thoroughly explored. The main ore shoots were bottomed, and extensive deeper exploration along the ore-controlling contacts indicates that for several hundred feet down their projected plunge there are no new shoots. To the north of the well-explored area, however, some ore may have been overlooked. The northernmost opening near the 600 level, known as the Water tunnel, exposed two conspicuous northeast-trending zones of carbonate veins, and the westernmost of these contains some fair showings of cinnabar. These may represent "leakage" above an ore body, as less conspicuous veins in other

parts of the Cora Blanca area are believed to do, so that exploration of the silica-carbonate rock lying directly underneath appears to offer promise of finding ore.

HARRY AREA

Location and extent of workings

The Harry area, which contains the workings of the "Harry mine," extends from near the Santa Maria shaft southward to include the Yellow Kid opencut on the east slope of Mine Hill. (See fig. 92 and pl. 3.) Its principal drifts and crosscuts lie between the 800 and 400 levels and are about 13,000 feet in aggregate length. Access to the levels was formerly gained mainly through the Santa Maria and Harry shafts and through the Harry, Yellow Kid, and Buzztail adits; the workings are also connected on the 600 and 800 levels with the Cora Blanca workings to the east, and on the 700 level with the central stope area of the New Almaden mine to the west. The principal stopes in the northern part of the workings lie between the 700 and 600 levels, those in the central part lie between the 600 and 500 levels, and those in the southern part extend from the 500 level to the surface. When the workings were being mapped for this report, the 2 shafts, though partly open, could not be descended, and the 800 level could not be reached.

History and production

The Harry ore bodies were not discovered until 1893, although they lay between the great central ore bodies discovered in the early days of mining and the Cora Blanca ore bodies, which had been known since 1873. In 1892, when the known ore bodies of the New Almaden mine were nearing exhaustion and funds for development were at a minimum, a new small two-compartment shaft, known as the Santa Maria, was begun just west of the main camp to explore the area surrounding the old rich Velasco ore bodies. Early in 1893, while probing on the 600 level for the downward continuation of these ore bodies, the miners cut the north end of the extensive Harry ore body, and, owing to the urgent need for additional ore, the new find was quickly developed. When the extent of this ore body had been determined, the Harry shaft was sunk in order to remove the ores more economically. Production began virtually with the new discovery, and the Harry stopes furnished the major source of newly mined ore in the New Almaden mine for about 6 years. When the ore body was nearing exhaustion, the near-surface ores of the Buzztail and Yellow Kid areas, to the south of the main Harry ore body, were discovered, and these extended the productive life of the Harry area for several years more.

Between 1893 and 1905 the Harry area yielded about 25,000 flasks of quicksilver from 150,000 tons of ore averaging about 0.6 percent of quicksilver. Since 1905 some of the Harry dumps have been reworked, and the low-grade ore overlying the Yellow Kid workings has been removed by open-cut mining. How much quicksilver was recovered in this way cannot be determined from the available records, but the amount was probably not more than 5,000 flasks and may have been much less.

Geology

Most of the underground workings in the Harry area follow an intrusive contact between the upper surface of a serpentine sill of unknown thickness and the rocks of the Franciscan group. The Franciscan rocks from the surface to within about 70 feet of the contact are largely greenstones, with tuff predominating, but those bordering the sill are mostly graywacke and siltstone with minor intercalated lenses of mafic tuffs. The sedimentary rocks, in general, strike nearly north and dip about 35° E. The serpentine sill is the same one that contains the Velasco and Randol ore bodies to the northwest and the Cora Blanca ore bodies to the southeast. It has the same general attitude, but its upper surface is diversified by terraces, domal structures, and thin sill-like apophyses which were of importance in localizing the various ore bodies. The upper part of the sill and the overlying thin apophyses are nearly everywhere altered to silica-carbonate rock, which in this area had a thickness of from 20 to a little more than 50 feet.

The thick east-dipping dolomite vein conspicuous in the Cora Blanca area had a somewhat different counterpart in the Harry workings. A north-trending zone of breccia of silica-carbonate rock cemented with vuggy dolomite is followed by the easternmost workings on the Harry 550 level; this breccia extends downward and northward to the 600 level, where it is exposed near the Harry shaft and for about 400 feet farther north. The breccia zone, which is up to 3 feet wide, seems to be genetically related to the thick vein of banded dolomite in the Cora Blanca workings, but differs from it in that its dolomite cement contains hydrocarbons and a little cinnabar.

Ore bodies

The principal ore bodies were formed in silica-carbonate rock close to the overlying sedimentary rocks of the Franciscan group. The principal ore mineral was cinnabar; but native mercury was abundant enough in the silica-carbonate rocks on the 600 level at 2360 N. and 4270 W. to have been hazardous to the miners, and it was also noted in the graywacke

on the 550 level near the south end of the Harry stope. As the ore has all been mined, its character can only be inferred. The margins of the stopes contain innumerable thin steep north-trending hilos; in places these contain some cinnabar, and the silica-carbonate rock alongside them is locally replaced by cinnabar. Judging by these exposures, one may conclude that the main ore bodies consisted of concentrations of cinnabar both in the veins and in the adjacent wallrock. It should be emphasized, however, that in many parts of the Harry area where the hilos are exceedingly abundant there is virtually no cinnabar. This condition is found east of the Harry stope between the 550 and 700 levels (fig. 80). As is shown in the following descriptions of the individual ore bodies, the structural relations and shape of the intrusive contact was as important in the localization of the ore as the abundance of the hilos.

The large ore body mined in the Harry stope was 800 feet long, about 45 feet in average width, and had an average thickness of about 15 feet. Its north end was about 100 feet southeast of the Santa Maria shaft, and from there in plan it extended nearly straight along a bearing of S. 20° W. From its north end above the 600 level it extended downward to the 600 level, and south of its intersection with that level its plunge reversed, so that it rose at a low angle nearly to the 500 level. (See pl. 12.) Here the ore body divided, one part of it extending westward to the 500 West Harry stope and the other part southeastward to the Yellow Kid and Buzztail areas. The localization of the Harry ore body was affected along a structural terrace on the east-dipping upper surface of the serpentine sill, and it was widest in those places where there were small domes or gently plunging flexures on the nearly level part of the terrace. The aggregate thickness of the ore body was also influenced by thin sill-like apophyses overlying the main intrusive contact, for, where these were most numerous, the stope attains its greatest depth. This occurrence of similarly favorable places for ore deposition beneath several different septa of *alta* resulted in the formation of several thin superimposed ore bodies, but, as the entire mass of ore and *alta* was mined together, the superimposed ores are here treated as part of a single ore body.

Other less extensive ore bodies include the one mined at the south end of the 600 level in the Machine stope, and another mined on the 700 level 100 feet east of the Harry shaft. (See fig. 82 and pl. 5.) The Machine stope ore body was localized beneath a small domal structure on the intrusive contact, and like the Harry ore body it was composite, owing to

the mineralization of thin overlying sills. The reason for the localization of the other small ore body on the 700 level is not apparent.

Suggestions for further development

Most of the part of the Harry area lying either adjacent to the main stopes or down the dip of the intrusive contact beneath them appears to have been adequately explored. One small part of this contact, however, between the Machine stope and the Yellow Kid workings, remains unexplored, though its relatively low angle of dip above the 600 level should have encouraged some further prospecting. Areas lying to the west, northeast, and south of the explored part of the Harry area appear promising for the development of new ore bodies, but, as a discussion of these outlying areas involves the geology of surrounding parts of the mine, suggestions for their development are placed in the section of this report that deals with the outlook of the district (p. 170-176).

VELASCO AREA

Location and extent of workings

The Velasco area, northwest of the Harry area (fig. 92), is named after the old Velasco mine, which was developed in the earliest days of mining on Mine Hill. Its main underground workings are a relatively compact group of adits, drifts, and stopes, which extend north and west from the vicinity of the Santa Maria shaft for about 500 feet and go down about 300 feet from the surface, or about to the 600 level of the New Almaden mine. Practically all these workings were inaccessible when the study for this report was made. Before 1865 the workings were reached through the Road tunnel and the Upper and Lower Velasco tunnels, but after 1875 the deeper Great Eastern tunnel was used, and after 1892 some of the deeper levels were reached through the Santa Maria shaft. The Velasco workings were connected with the workings of the central stope area to the west on the 600 level by an incline from the Great Eastern tunnel and by various stopes; they also were connected with the Harry workings to the south by the Santa Maria shaft and several winzes from nearby levels. (See pl. 4.)

The maps of the Velasco workings included with this report are less complete and more confusing than those of most of the other workings of the New Almaden mine. Many of the levels were driven from old adits whose portals are caved and cannot be accurately located, and they lie at irregular elevations that do not coincide with the levels used in much of the rest of the mine. Furthermore, as the workings were virtually all inaccessible, those shown on the maps (pls.

4-10) are copied from the old company maps. These are believed to be fairly accurate in plan, but they do not give many exact elevations. Since the old company maps were prepared, the area has been reexplored and mined, and some of the more recent workings that were never surveyed are known to be missing from the maps included with this report. The Velasco workings shown on the maps are about 10,000 feet in aggregate length, and those not shown perhaps as much as 1,000 feet.

History and production

Ore is said to have cropped out at the surface in this area, and during the very early development of the New Almaden property, it was followed downward in an isolated group of workings known as the Velasco mine. Early records are too fragmentary and incomplete to give a detailed history of the subsequent development of the mine or an accurate record of its production. By 1864, however, the Upper and Lower Velasco tunnels and the Road tunnel apparently were serving as haulageways for ores that were being removed in large quantity. In 1865 the daily yield was reported as 7 tons of "very rich" ore, at a time when the ore from the New Almaden mined averaged 12.4 percent quicksilver, and in order to explore the area at greater depth the Great Eastern tunnel was driven and connected with the existing workings. During 1866 and 1867 production from the area dwindled rapidly, and apparently there was almost none in 1868 and 1869. Between 1870 and 1874, however, some new ore shoots probably were found, for during this period a production of about 5,000 flasks was obtained. Thereafter, production declined rapidly, and by 1877, the area, which had yielded about 25,000 flasks of quicksilver, was thought to be exhausted. With the sinking of the Santa Maria shaft in 1892 some of the workings were reopened, but no significant production seems to have come from the Velasco workings at this time. In 1908 and 1909, when ore was desperately needed to maintain the operation of the New Almaden mine, the old Mine Hill open-cut, east of the Santa Rita shaft, was excavated to remove the low-grade ore left above the older Velasco workings, several adits were driven below to find any remaining stope fill and pillars, and the dumps at the mouths of the Bush and Great Eastern tunnels were reworked. These operations, which apparently were the last undertaken in the Velasco area, probably yielded between 2,000 and 3,000 flasks of quicksilver.

Geology

The rocks penetrated by the Velasco workings consist in part of the extension of the greenstone tuffs of

the Franciscan group and the underlying serpentine sill explored by the Harry workings to the southeast and the Randol workings to the north. In addition, a higher sill, lying nearly parallel to the surface and in most places extending down to a depth of less than 100 feet, is explored by some of the higher adits. The lower margin of the upper sill is altered to silica-carbonate rock and contained some scattered ore, but the larger, more productive Velasco ore bodies were found in the upper margin of the underlying sill, which is even more extensively altered to silica-carbonate rock. (See section C-C', pl. 11.)

Ore bodies

The character of the ore in the Velasco ore bodies must largely be conjectured, but if the ore bodies averaged more than 15 percent quicksilver, as reported, the cinnabar cannot all have been in hilos; some of it must have replaced the silica-carbonate rock. In places where the ore bodies were small the cinnabar is said to have formed "small seams making up against the alta"; but where the bodies were larger it "extended back into the 'vein' [silica-carbonate rock]." Little is really known regarding the structural environment and control of the ore bodies. For example, detailed information about the geology of the small but very rich ore body lying at an altitude of 1,430 feet and mined through the Robles and Upper Velasco tunnels is lacking, although, judging from what can be seen on the surface, it lay in silica-carbonate rock above the upper contact of the upper sill. The more important of the ore bodies mined in the Theatre and Velasco stopes and extending southwest to the Santa Rita East stope lay in silica-carbonate rock along the crest of a domal structure on the upper surface of the main serpentine sill. Although it is possible to contour the general upper limit of the serpentine (fig. 81), the contact must be exceedingly complex in detail with several apophyses and included wedges and septa of rocks of the Franciscan group. The irregularities of the contacts in this area are indicated in an annual report of the Quicksilver Mining Co. for 1866, which describes the Velasco ore bodies as "extremely irregular in their mode of occurrence, being in some instances contorted to a degree to defy the most scrutinizing investigation"; and this irregularity seems to be reflected by the exploratory workings, which apparently do not follow the contacts in this area as faithfully as in most other parts of the New Almaden mine.

Suggestions for further development

The Velasco area seems to have been thoroughly explored, and no further exploration to find new ore

shoots in the area seems to be justified. However, as most of the workings have been inaccessible for many years, lessees might find considerably more ore suitable for retort operation remaining in the Velasco stopes than in other parts of the New Almaden mine that have been repeatedly opened during the last 40 years.

CENTRAL STOPE AREA

Location and extent of workings

The term "central stope area" is applied to that part of Mine Hill which was explored by a compact group of workings clustered around the internal main shaft (pl. 5) directly under the highest part of the hill; it also includes the Santa Rita stope, which extends northward from the cluster, and the northern part of the Day tunnel, which served as a haulageway. (See fig. 92.) The central cluster of workings honeycombs the hill from the surface down to the 600 level, and on this level the Santa Rita stope extends northward, following a nearly flat contact to and beyond the Santa Rita shaft. The Day tunnel, which is on the 800 level and whose portal is about 1,700 feet northeast of the Santa Rita shaft, extends beneath the central cluster of stopes and continues southwestward to connect with workings in the San Francisco area. From it branch off various crosscuts, one of which connects with the Santa Rita shaft. The two deepest workings in the area are the 900-level drift from the bottom of the Santa Rita shaft, and a short drift from the bottom of a winze that lies at the intersection of the Day tunnel and the crosscut to the Santa Rita shaft. Two access adits on the 300 level formerly served as haulageways. One of these, called the Main tunnel, is 800 feet long and has its portal southeast of the area, and from it the important internal Main shaft extended down to the 600 level. The other access adit was the Juan Vega tunnel, whose portal is about 1,000 feet north of the stope area. The area also contains many other levels driven as haulageways or for exploration, and the combined length of all the level workings is about 25,000 feet. (See pl. 4.)

History and production

The history of production from the central stope workings begins in 1846, with the first mining of the ores exposed on the surface of Mine Hill, and extends through 1945. Most of the ore, however, was taken out before 1870, and subsequent operations have consisted largely in stripping the walls of old stopes and removing stope fill. Although the total production from this comparatively small area cannot be exactly determined, it is known to exceed 500,000 flasks (19,000 tons) of quicksilver. To follow in de-

tail the various developments during the history of the mining of this, the greatest concentration of quicksilver ore on the North American continent, is obviously impossible, and only the more significant facts are touched upon.

Mining was begun almost immediately after the first recognition of cinnabar on Mine Hill, but during the first few years it was conducted in a very erratic fashion. In 1850, however, when the persistence of the ores had been proved, the Main tunnel was begun in an attempt to systematize the mining, and from it the Main shaft was sunk a few years later. The intricate and erratic workings above the tunnel are thus described in the annual report of the New Almaden Mining Co. for 1865:

The upper or old mine of Almaden continues to yield good ore from pillars and hilos left unworked from the early days of the mine. No description is possible of all this extent of ground from the level of the Main Planilla up to the flagstaff on the summit of Mine Hill. It is one mass of ruins with tunnels everywhere buried up, pillars crushed to pieces, and chambers caved in.

Obviously no complete maps of these early workings were made, but maps of some parts, which perhaps were reopened older workings, were available to the writers and have been incorporated in the accompanying maps of the mine.

By 1857, when the ore had been followed to a depth of 500 feet, the Day tunnel on the 800 level was begun, largely in order to drain the upper levels. In 1858, when the tunnel had been driven only 508 feet, the mine was closed by an injunction, and work was not resumed until the winter of 1861. In August 1862, the tunnel unexpectedly penetrated the ores that were subsequently mined from the New Ardilla stope, and in August 1864 a connection was made with the Junction shaft sunk from the 600 level. Up to this time the ore was all taken out through the 300-level Main tunnel, and even after the Day tunnel had been connected with the workings, little ore was hauled through it until 1870, because of the difficulty of transporting the ore from its portal to the furnaces at the Hacienda.

Meanwhile, in the mineralized area above the Day tunnel, hilos had been followed from one ore body to the next, and in 1865 the rich North Ardilla ore body, which yielded a 7-months' supply of ore, was struck. Next came the discovery of the great Santa Rita ore body, which in 5 years yielded 70,000 flasks of quicksilver. Up to 1870, when J. B. Randol took charge of the mining, the ores of the central stope area had yielded the major part of the 535,000 flasks that the mine had produced. Most of the stopes, however, were believed to be mined out, and there was little ore in sight. Thin veinlets were therefore followed

northward, and these led to the ore bodies of the Victoria area, described on pages 135-136.

In December 1884, the Santa Rita shaft was begun in order to search for ore bodies above and below the Santa Rita ore body. By 1886 it had reached the 800 level and was connected with the Day tunnel; in the following year it reached the 900 level, and crosscuts were driven from it toward the downward continuation of the New Ardilla ore body. These workings failed to reveal any ore, and the shaft was allowed to cave. In 1940 and 1941 it was reopened by C. N. Schuette to the 800 level, but in 1948 it had again caved from the 300 level to the surface and for an unknown distance upward from the 800 level.

In another attempt to find a downward continuation of the New Ardilla ore body, a winze was sunk in 1898 from a point 1,560 feet in from the portal of the Day tunnel, and at the same time some ore was underhanded in a winze from the 800 level nearby. It soon became obvious that this winze would never strike the continuation of the ore body, and a second winze, which was known, like the first, as the New Ardilla sink (winze), was started from the Santa Rita shaft crosscut. This winze was sunk to a depth of 150 feet, and short drifts were run along a contact near its bottom, but only a small amount of ore was found. In 1901 the New Ardilla sink was abandoned, and it quickly filled with water.

Again and again since 1870, lessees and company miners have returned to the huge cavern of the central stope area to recover ore left in the walls or fill, but no major attempt had been made to find new ore bodies in the area or along its margins. How much quicksilver was recovered by these sniping operations is unknown, but it may have been considerable because very little ore remains in the stope walls and floors.

Geology

The central stope workings penetrated rocks of the Franciscan group, and sills of serpentine whose margins were nearly everywhere altered to silica-carbonate rock. These dip northward, in general, at moderate angles, though locally there are radical departures from this attitude. In the southern part of the area one continuous mass of serpentine extends from the surface down to below the 800 level, but farther north it divides into several distinct and somewhat irregular sills. (See section *C-C'*, pl. 11.) The ore bodies lie along the margins of some of these sills, and where they are numerous the sills can be outlined with considerable accuracy. But the sills that are cut only by a few workings or a single crosscut cannot be projected

with any certainty, for they may change markedly in strike, dip, or thickness within a very short distance. Consequently, the larger sills, which contain most of the ore bodies, can be described in some detail, but others cannot.

Three thin north-dipping sills are cut by the 300-level Juan Vega tunnel, but only the lower side of the northernmost of these is mineralized. Another, lying only a short distance below the 300 level, contained the Pruyn ore body. Below these thin sills lies the extensive sill which to the north contained the Victoria and the North and South Randol ore bodies, and to the east the Velasco and Harry ore bodies; this sill also contained many of the largest ore bodies of the central stope area. Its general shape is shown by contours drawn on its upper surface (fig. 81 and sections *B-B'* and *C-C'* of pl. 11). The thickness of the sill where it diverges from the more massive serpentine body to the south is about 200 feet, though in places this thickness includes some pods of Franciscan rocks. In the vicinity of the Junction shaft (pl. 6) to the north it is only 50 feet thick, but only a little farther north, near the Santa Rita shaft, it attains a thickness of about 300 feet, which it maintains as it dips downward to pass under the Randol ore bodies. Beneath this economically important sill is still another, which is penetrated by the southern part of the Day tunnel. The thickness of this sill is uncertain, because its base has not been reached at any place near the central stope area, but it is believed to be somewhat thinner than the other large sill. These 2 major sills merge east of the New Ardilla stope on the 800 level, below the Santa Rosa stope at about the 600 level, and below El Collegio stope near the 500 level.

The Day tunnel, on the 800 level, affords a good opportunity to see both of these sills. The upper surface of the higher sill is cut about 500 feet from the portal—because of timbering the exact distance is not known—and here the sill is said to have had a very thin selvage of silica-carbonate rock. At 1,610 feet the tunnel ran into silica-carbonate rock, through which it was continued for 30 feet to the lower edge of the higher sill. The tunnel then continued through 700 feet of tuffaceous greenstone of the Franciscan group to the upper contact of the lower sill. The tunnel went through either silica-carbonate rock or serpentine for the next 900 feet to the point where it again passed into graywacke lying above the main San Francisco area sill. (See pl. 6 and section *C-C'*, pl. 11.)

Ore bodies

The ore bodies mined throughout the central stope workings were among the richest ever found in the mine, but in general character they resembled those found in the rest of the mine. They all occurred in silica-carbonate rock close to its contact with rocks of the Franciscan group. Some of the richest bodies lay on the upper borders of sills, but others that were highly productive were on the lower surfaces of sills, just above their contacts with rocks of the Franciscan group. In many of the stopes hilos trending north-eastward were prominent, but in others the most prominent veins ran northwest, and in still others only a few veins were present. Mineralization consisted mainly in replacement of the silica-carbonate rock and the filling of open spaces by cinnabar, but in at least one place some native mercury was found.

The upper margin of the large sill that contained the Randol ore bodies to the north also contained the richest and largest ore bodies in the central stope area. Along a gentle arch in the upper part of this sill were distributed the Santa Rita, North Ardilla, and part of the Ventura ore bodies, and the ore body mined in the 400-level stope was formed where the contact steepens to nearly vertical in the southern part of the area. The lower part of this sill in the same general area contained the Far West, Marysville, Sacramento, Buenos Ayres, La Ardilla, and El Collegio ore bodies (pl. 4), all lying just above a wedge of rocks of the Franciscan group. Down the dip of this contact to the north lay the New Ardilla ore body, the top of which was just below the 700 level and the bottom a few tens of feet below the 800 level. Beneath the wedge of rocks of the Franciscan group lies the large sill penetrated by the southern part of the Day tunnel. Although the upper margin of this sill was extensively converted to silica-carbonate rock, no ore bodies have been found along it except in a small area underlying El Collegio stope. (See section *C-C'*, pl. 11.)

Suggestions for further development

This central part of the New Almaden mine was developed at a time when ore was plentiful, and the rich ore bodies were found chiefly by following the narrow hilos northward from one ore body to the next. Considering the richness of the great masses of ore taken from this area, considerably more lateral exploration toward the Harry area or toward the unexplored area to the west seems to be justified, but the complexity of the geology is such that favorable structures for ore localization cannot be predicted far in advance of mining.

VICTORIA AREA

Location and extent of workings

The Victoria area of the New Almaden mine lies north of the central stope area. (See fig. 92.) It is explored by a group of levels that lie between the Santa Rita, Victoria, and St. George shafts and extend from an altitude of about 1,200 feet (600 level) down to about 900 feet (900 level). Also included in the area are the Victoria, Ossuna, Santa Anna, Oregon, New Santa Rita West, Ponce, Giant Powder, and Santa Rita West stopes. (See fig. 81 and pl. 4.) This part of the mine was developed chiefly as a northward extension of the workings of the central stope area, and it was first mined through drifts on the 600 and 700 levels and from the Day tunnel on the 800 level. Later the workings of the Victoria area became accessible through crosscuts on the 800 and 900 levels from the Randol shaft, and still later they could most easily be reached through the Victoria shaft. This shaft was open when this study was being made, but the manway had been destroyed by caving. The only parts of the Victoria area that were reached were the 700-level Relief drift (pl. 5) from the central stope area and the connected Giant Powder and Ponce stopes, but a miner who went down the unsafe shaft in 1947 reported that most of the workings were in silica-carbonate rock and still open. The total extent of the levels in the area is a little more than 1 mile, but almost as extensive are the various nearly level pathways that serve as levels through the old stopes. (See pl. 4.)

History and production

The largest ore bodies developed by the Victoria workings were discovered and mined between 1871 and 1874, and they probably supplied the ore for most of the 57,268 flasks yielded during that period by the New Almaden mine. In 1874, when the ore bodies of the Victoria area were thought to be largely depleted, the South Randol ore bodies were found, and apparently the Victoria workings were not kept open for long after this new supply of ore became available. In April 1891, however, when the Randol ore bodies had been largely mined out, the Victoria shaft was sunk to provide access to the old Victoria workings, which could no longer be reached through the crosscuts from the Randol shaft. This new shaft was rapidly sunk to the 900 level, and connections were run on the 800 and 900 levels to the old Victoria workings. This development resulted in the taking out of some old stope fill and some new ore, but in 1895 the shaft was closed down to reduce expenses. Seven years later, when little accessible ore was available elsewhere in the mine, the shaft was reopened, new

workings were run on the 800, 900, and 1000 levels, and again minable ore was obtained. Also at this time, in order to move the ore more easily from the stopes to the furnace, the 800-level crosscut from the Day tunnel was reopened. In 1906 the area was again considered to have been exhausted and was again abandoned. Since then at various times lessees have repaired the shaft and have obtained an unknown amount of ore from the old stopes. Records of production for these various periods of intermittent work are fragmentary, but the writers estimate that no less than 60,000 flasks in all has been recovered from the ores of the Victoria area.

Geology

The geology of the Victoria area cannot be described in detail, for very few of the workings were open when the mine was mapped by the U.S. Geological Survey and most of them are too old to have been comprehensively described by the company surveyors. Nevertheless, because the geology to the north and south is well known, it is possible to deduce with considerable confidence the broad features of the geology of the Victoria area from the distribution of the stopes and other workings. These follow the upper surface of the serpentine sill that contained the Randol ore bodies to the north and the Santa Rita ore body to the south. In the Victoria area the upper surface of the sill is arched into a gentle anticline striking N. 55° W. and plunging about 20° NW. (figs. 93, 81; pls. 5, 6, and sections A-A' and C-C', pl. 11). Below an altitude of about 1,000 feet the northern flank of the anticline is sharply flexed to a much steeper dip along a line that trends nearly parallel to its axis. The geologic setting, however, is complicated by at least one, and probably two, thin sills above the main contact. Their presence is indicated by the overlapping of stopes and drifts, particularly in the northwestern part of the area (pl. 4), but no evidence is available to indicate where these thin sills diverge from the main sill. Everywhere in the Victoria area the apophyses and the upper margin of the main sill are apparently converted to silica-carbonate rock. Judging by the distribution and height of the stopes, the shell of silica-carbonate rock along the main serpentine body is at least 30 feet in average thickness, and it may be much thicker.

Ore bodies

Most of the ore bodies in the Victoria area appear to have lain close beneath the upper surface of the main sill, along the flatter part of the anticlinal arch, though some ore bodies which overlap these were apparently in thin sills overlying the main one. Ex-

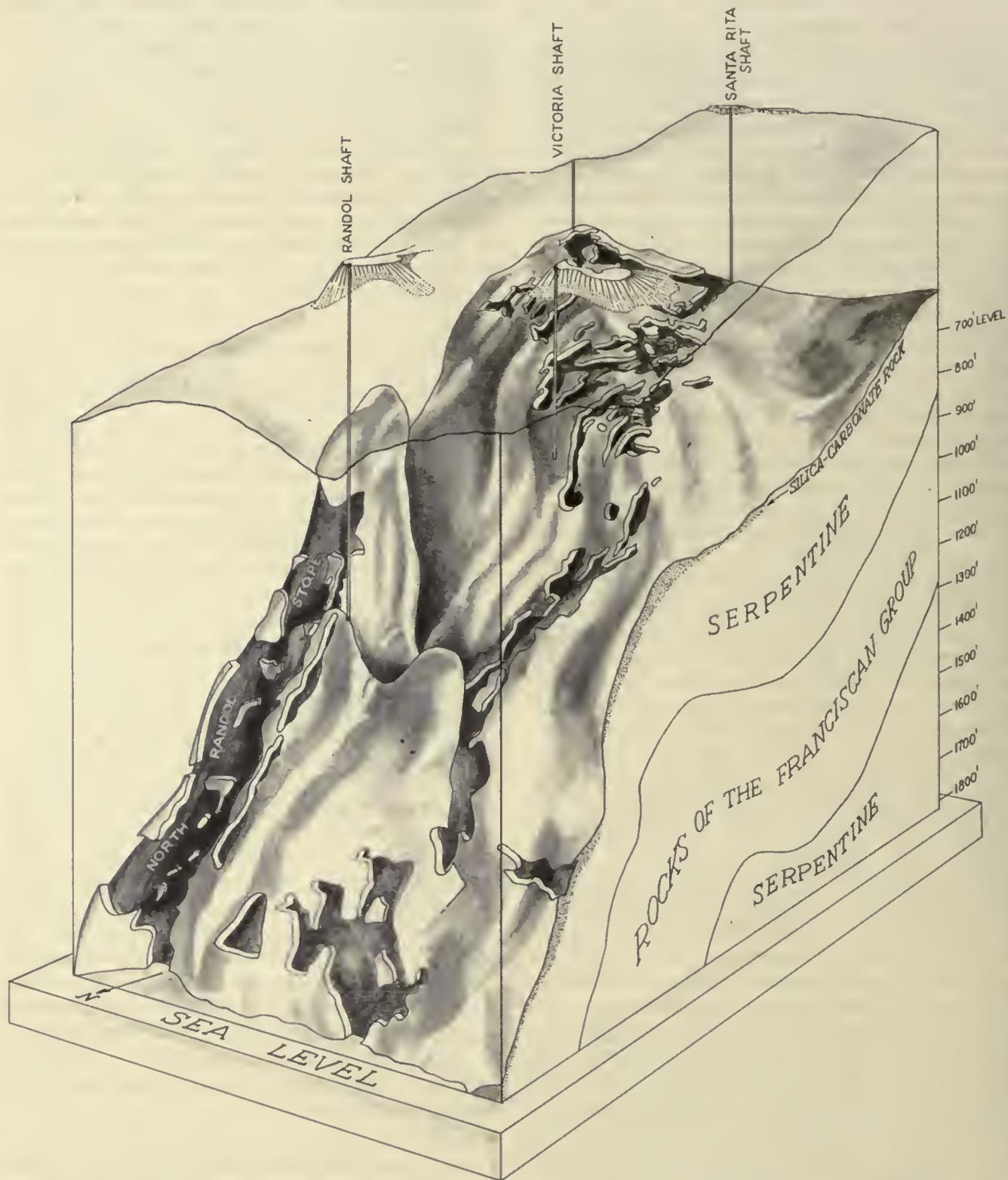


FIGURE 93.—Perspective drawing of a model showing the relation of the Randol and Victoria stopes to the upper surface of the upper serpentine sill in the New Almaden mine.

cept for the Giant Powder-Ponce ore body, the ore bodies were mined in stopes that trend N. 15°–20° E., and it can be safely assumed that the ores were localized along swarms of hilos, which have this general trend throughout the mine. The ore body mined in the Giant Powder-Ponce stope, which was accessible in 1945, lay along a relatively flat part of the west flank of the extension of the anticline (pl. 5 and fig. 81), and even though the importance of the hilos is not so obvious from the outlines of the stopes, the hilos were found to be especially abundant in this area. It is surprising that, although some exploration has been done at the crest of the anticline to the northeast of the Giant Powder stope along the projection of the hilos exposed in the stope, no ore has been found there. (See pl. 4.)

Suggestions for further development

The margins of the sills in the area appear to have been so completely explored that no sizable ore body is likely to have remained unnoticed. Inasmuch as the area has been reworked several times, it seems improbable that any very rich stope fill has been overlooked. We feel, therefore, that even though this part of the New Almaden mine could easily be made accessible for mining it offers little incentive for further development.

NORTH RANDOL AREA

Location and extent of workings

The North Randol area surrounds what is known as the North Randol ore body, which was the largest single ore body developed in the New Almaden mine. (See fig. 92.) This body trended a little west of north, one end of it being about 450 feet southeast of the Randol shaft and the other about 600 feet north of it. From its apex near the 800 level it plunged downward at an angle of about 50° to and below the 1800 level (pl. 4 and fig. 93). Access to the ore body was afforded mainly by the Randol shaft, from which levels extended at 100-foot intervals between the 800 and 1800 levels; and at greater depth the area was explored down to the 2300 level by similarly spaced workings connecting with the Santa Isabel and Buena Vista shafts. In this area the deepest workings in the New Almaden mine, reached through the underground Church shaft, were driven on the 2450 level (643 feet below sea level) to search for the downward extension of the North Randol ores. Ore was trammed from the Randol shaft at the 800 level to the surface through the Randol tunnel, and at times some ore was also taken out by a rather devious route connecting with the 800-level Day tunnel. Several exploratory workings that furnish geologic information in otherwise unexplored areas are of special interest. These in-

clude the 1100-level east drift, which reached a point 3,300 feet southeast of the shaft, the 1500-level crosscut extending 1,900 feet north of the Randol shaft, and the 1800-level crosscut extending 1,100 feet south of the shaft. (See pl. 4.) The aggregate length of the workings in the North Randol area is more than 5 miles.

History and production

The development of the North Randol area began in June 1871 with the sinking of the two-compartment Randol shaft, which was absurdly inadequate in size, being only 4 by 9 feet. At that time the ore bodies of the central area had been followed northward and downward to such a depth that the ore had to be back-packed up to the 800 level and then trammed along a circuitous route to reach the surface at the mouth of the Day tunnel. The new Randol shaft was intended to facilitate the handling of this ore lying to the northwest and to explore its downward continuation. For this purpose it was poorly located, but later, when the North Randol ore body was found it proved to be very advantageously placed. Because of the primitive methods used in sinking the shaft, it had reached a depth of only 383 feet by the end of 1871, and in 1872 it was sunk only 132 feet farther; in this year drifts were being run, also, to the south and southwest to tap the ore bodies on the 800 and 900 levels. During the next 5 years the shaft was slowly deepened, and ore bodies lying to the west were sought and found on several levels; however, little exploration was done in other directions from the shaft. In 1877, 6 years after the shaft was started, it struck "vein-rock" (silica-carbonate rock) at a depth of only a little more than 700 feet, and a small amount of development work on the 1200 level tapped the North Randol ore body. (See section *B-B'*, pl. 11.) Further exploration revealed that this hitherto unknown ore body was very extensive, and it lay close enough to the shaft to be readily mined from the 800 level down to the 1800 level. By the end of 1880 most of the North Randol ore body had been blocked out and was being mined. In July 1882, in an attempt to explore the North Randol area at still greater depth and also to overcome the hoisting problem that resulted from the small size of the Randol shaft, the large three-compartment Buena Vista shaft was begun, about 1,600 feet north of the Randol shaft. Workings driven southward from the Buena Vista shaft explored the ore-bearing structures at various levels down to the 2300, but they revealed virtually no minable ore. As a result, the magnificent and costly Buena Vista shaft, which was sunk in 3½ years to a depth of almost 1,400 feet, was never used for anything but exploration and pumping.

In 1893 it was abandoned and the lower Randol workings were allowed to fill with water.

Failing to find new ore bodies at depth, the management explored the North Randol area laterally to the east on the 1100 level in 1888 and 1889, to the south on the 1800 level in 1889, and to the north on the 1500 level in 1890. This development work revealed some cinnabar but no ore, and in 1892, owing to the exhaustion of the deeper ore bodies, the Randol shaft was hoisting ore from the upper levels during only one shift a day. In January 1896, when the Randol shaft needed retimbering from the 1000 to the 1400 level, it was closed down completely, and the workings below the 800 level were allowed to fill with water. Since that date the shaft has never been reopened, and the North Randol workings and ore bodies have been completely inaccessible.

The amount of quicksilver obtained from the huge North Randol ore body cannot be accurately determined from the available records, but from 1879 to 1895 inclusive this single ore body probably yielded nearly 200,000 flasks of quicksilver from ores averaging more than 2 percent quicksilver. At various times since the closing of the shaft attempts have been made to recover quicksilver from the dump at the mouth of the Randol tunnel, but the total amount recovered has been insignificant compared with the earlier production.

Geology

Most of the North Randol workings extend along the upper contact of the same serpentine sill that contained the Cora Blanca, Harry, and Velasco ore bodies, and the great central ore bodies of the New Almaden mine. The general strike of the sill in this area is about east-west, and the average dip about 50° N. This attitude persists westward into the South Randol area, but east of the North Randol stope and below the 800 level the sill swings abruptly southeastward and steepens to nearly vertical. This sharp flexure, as shown by the abrupt change in direction of several of the lower levels near their eastern ends, may be the result of the sill being offset by a steep fault. Above the 650 level the sill arches over into the broad dome of the Velasco area, below the 1900 level it steepens to vertical, and at greater depth it is overturned and dips steeply to the south.

The upper surface of the sill is highly irregular; it has sharp rolls in both strike and dip, and two thin finlike apophyses rise from it. One of these apophyses branches from the main sill along a line extending between a point above the middle course of the Great Eastern tunnel and a point southeast of the Randol shaft on the 1200 level. The other, which assumes

much greater importance in the discussion of the South Randol ore bodies, branches from the first near the 1000 level, and is separated from the main sill by a narrow wedge of graywacke down to a point about midway between the Randol and Santa Isabel shafts on the 1800 level. These relations are shown in figure 81, which is a map showing contours drawn on the upper surface of the sill, and perhaps are even better shown in figure 93. The serpentine making up these narrow apophyses, and also that along the periphery of the main sill, was nearly everywhere converted by hydrothermal solutions to silica-carbonate rock, which is the host for the ore. The thickness of the shell of silica-carbonate rock is ascertainable in only a few places, but it apparently reaches a maximum of about 40 feet in the upper levels and is somewhat thinner in the lower levels.

The rocks above the sill and its apophyses are dominantly clastic sedimentary rocks of the Franciscan group. On the north 1500 level, however, a thin sill of serpentine with some barren silica-carbonate rock was cut 350 feet above the sill, and 30 feet higher was a layer of greenstone 120 feet thick. The main sill is a little more than 350 feet thick where penetrated by the Randol shaft, and according to surveyors' records no silica-carbonate rock was found along its lower border at this point. It is separated from another thick sill lying below it by about 350 feet of clastic sedimentary rocks and greenstone. This lower sill is totally unexplored between the 1800 level and the Day tunnel (800 level), but it was prospected for a short distance on the 1800 level south, where it had a thin shell of silica-carbonate rock. According to the surveyors' records the silica-carbonate rocks were traversed at this point by "stringers of calcite containing traces of cinnabar." (See section *B-B'*, pl. 11.)

Ore bodies

As the North Randol workings have been totally inaccessible for more than 50 years, all information about the ore bodies must either be gleaned from sketchy reports of geologists and surveyors who observed them or else be inferred from the shapes and positions of the workings shown on the old company maps. The plan of the ore body mined in the great North Randol stope is known with certainty, but its third dimension is less well known. The stope's length is about 1,300 feet and its average width about 200 feet; its height apparently varied from 25 feet in the upper levels to less than 10 feet in the lower levels. The single ore body mined from it must have been remarkably persistent, for only a few pillars were left in spite of the fact that the ground was exceptionally "heavy," requiring huge, costly timbers to support the



FIGURE 94.—Tramming on the 1500 level in the North Randol area of the New Almaden mine in middle 1880's. From L. E. Bullmore collection.

backs of the large open chambers. (See fig. 94.)

The ore mineral was chiefly cinnabar, though some native mercury was found below the 1800 level. The cinnabar occurred in and along hilos, which trended nearly due north through the silica-carbonate rock formed along the upper edge of the serpentine sill and its upward-branching fin. The hilos were several inches wide, and most persistent near the sharply defined and locally 'slickensided' upper contact; they pinched and died out toward the serpentine footwall. The ore is said to have been richest where the hilos were most closely spaced. The average quicksilver content of all the ore furnaced was about 2 percent, and a rough comparison of the records of tonnage that went to the furnace with the volume of the stope, indicates that most of the rock taken out was furnaced.

The ore of the huge North Randol ore body appears to have been localized mainly by the thin parallel hilos, which here trend nearly down the dip of the contact. (See fig. 95.) The lower part of the ore body occupied a trough, in contrast to much of the

ore in the mine, which is localized in arches or flats. So far as can be deduced from available information, the stopes were as wide and their ores as rich on steep parts of the contact as on parts with lower dips, which is another unusual feature. Little ore was found, however, below the 1900 level, where the sill is very steep or overturned. (See section *B-B'*, pl. 11.)

Suggestions for further development

Since the North Randol area appears to have been so thoroughly explored in all directions that any continuation of the ore body can hardly have been missed, no further exploration in the area seems warranted. The Randol shaft, on the other hand, was closed down at a time when the ore had to average more than 1 percent to yield a profit, and it is likely that a large tonnage of ore containing several pounds of quicksilver to the ton remains in the stope walls or in fill. Whether or not it can be profitably mined, now that the workings are inaccessible and probably caved, depends on mining costs and the prevailing price of quicksilver.



FIGURE 95.—Stope on the 1500 level in the Randol part of the New Almaden mine. Note the numerous narrow steep veins, known to the miners as "hilos," in the silica-carbonate rock of the working face. These were followed as a guide to ore. Also note the size of the timbers necessary to hold up the back of stope after the removal of the silica-carbonate rock ore.

SOUTH RANDOL AREA

Location and extent of workings

The South Randol area includes the three principal South Randol ore bodies and outlying exploratory drifts and crosscuts near them. (See fig. 92.) Most of the workings of the area lie west of the Randol shaft, south of the Santa Isabel shaft, and north of the St. George shaft, and they are fairly evenly spaced, at intervals of about 100 feet, from the 1000 level down to the 2300 level. The workings are connected on most of the levels with the North Randol workings to the east, and they also connect through raises with the workings of the Victoria area to the south. Most of the ore taken from the stopes was hoisted in the Randol shaft to the 800 level and trammed from there through the Randol tunnel to the surface, but some ore from the deeper stopes was hoisted through the Santa Isabel shaft, and a little through the St. George shaft.

The South Randol workings include two long exploratory crosscuts on the 1400 level. One of these extends south from the Santa Isabel shaft for half a mile and connects with the 1100 level from the Washington shaft through a long incline. The other

branches from the first at a point 150 feet south of the Santa Isabel shaft and extends westward for 580 feet, then runs southwestward toward the America shaft for 1,400 feet. (See pl. 4.) Including these long crosscuts, the total length of the South Randol workings is about 6 miles.

History and production

The development of the South Randol area may be said to have begun with the sinking of the Randol shaft in 1871. At that time the ore bodies of the central stope area had been followed northward and downward into bodies lying below the 800 level, and the ores were being removed by tramping through the long, circuitous route by way of the Day tunnel. The new shaft was intended to provide access to these workings and to explore the area at greater depth, but by the end of 1872, when connections had been driven from the shaft to the stope area on the 900 and 1000 levels, the ore bodies were apparently dying out downward. By 1874 the production of the mine had fallen to its lowest level since the first year of recorded production some 24 years earlier. In the same year the 1100 west crosscut struck the "vein" (silica-carbonate

rock) and a sudden inflow of water flooded the lower 80 feet of the shaft. This difficulty was quickly overcome, however, and drifting along the contact soon revealed a new body of ore 250 feet wide. During the next 5 years this body, known as the No. 2 South Randol ore body, was followed down the dip for about 600 feet to the 1500 level, and it furnished the bulk of the 83,159 flasks recovered during that period. In 1877, when the ore had been found to extend downward, the Santa Isabel shaft was started, some 1,300 feet northwest of the Randol shaft, to explore the area at greater depths. Early in 1879, a crosscut was extended on the 1700 level from the Randol shaft toward the Santa Isabel shaft. Some disappointment was felt when this crosscut had been driven through solid serpentine far beyond the projected position of the overlying ore body. Late in the year, however, this crosscut finally reached silica-carbonate rock that contained a substantial amount of cinnabar and native mercury, and drifting soon revealed a new ore body with a strike width of about 300 feet. During the following 5 years the ore was followed from the 1700 level up to the 1450, and down about to the 2000, which lies some 200 feet below sea level. As it was developed, this new ore body was found to lie in a narrow offshoot from the main sill, which contained the other South Randol ore body, and crosscuts were driven northward from the higher levels to reach the upward extension of the new ore body. (See pls. 5-10, and fig. 93.) In 1885, after this new ore body had yielded more than 75,000 flasks of quicksilver and was nearly exhausted, a connection between the Santa Isabel and Washington shafts was started on the 1400 level to explore the entire western part of the hill at that level. In the following year a drift from this crosscut, running along the contact toward the old depleted ore bodies, struck an entirely new ore body lying west of the old South Randol stopes. Exploration westward from the Randol shaft on several levels proved that the new ore body was exceptionally wide, but extended only from the 1550 level to the 1200 level. It was mined largely through the St. George shaft, which was sunk in 1886 and 1887, and by 1889 it was fairly well mined out, after having yielded about 30,000 flasks of quicksilver. Meanwhile, in 1885, an attempt was made to extend a drift on the 1400 level from near the Santa Isabel shaft to the bottom of the America shaft, which was then being sunk. This work was diligently pursued, in spite of difficulties caused by repeated floodings, huge quantities of carbon dioxide, and caving ground, until June 1888, when the America shaft caved and the drift was abandoned 475 feet short of its goal.

After the Randol shaft was abandoned in 1896, access to the stopes above the 1000 level could be gained through the Victoria shaft. Since then some ore and stope fill have been taken from these high-level stopes at various times, but production from them has been very small.

Geology

The same serpentine sill along whose upper surface most of the large ore bodies of the New Almaden mine were found is also the host for the South Randol ore bodies. (See fig. 81.) In most of the South Randol area the sill strikes nearly east-west and dips between 55° - 65° N. Above the 800 level, however, it flattens abruptly to form the arch containing the Victoria and Santa Rita West stopes, and along the southwest side of the arch a large troughlike depression extends northward past the St. George shaft. Near this shaft the west limb of the trough steepens to nearly vertical, and close to the surface, where it is cut by the shaft, it is overturned to a steep westerly dip. Several thin finlike apophyses project upward from the main serpentine sill in the South Randol area. One of these that contained ore extends from just above the 1600 level to the 1200 level, and is separated from the main sill by a narrow wedge of graywacke, the keel of which plunges westward at about 45° . Below the 1900 level, downdip from this apophysis, is a second thin fin which apparently extends downward at least to the 2300 level. A third apophysis, which lies above the main sill in the vicinity of the westernmost of the South Randol ore bodies, extends downward from about the 1450 level, but not enough information is available to outline it fully. These intricacies of the upper surface of the serpentine are shown by contours in figure 81, by cross section *C-C'*, plate 11, and by a drawing of a model in figure 93.

The thickness of the sill can be determined in only a few places. The serpentine sill is about 350 feet thick in the eastern part of the area, where it is crossed by the Randol shaft. West of the St. George shaft the long 1400-level crosscut penetrated only 60 feet of serpentine, but as a body of serpentine some 550 feet across horizontally was cut 150 feet farther south, it is likely that this thin body was merely another offshoot branching westward from the main sill. On the same level a thousand feet farther west the sill was penetrated for 500 feet.

The rocks above the sill are largely sedimentary rocks of the Franciscan group, but, as is revealed by the workings on the 1400 level near the Santa Isabel shaft, a few other thin sills, which are partly rimmed by silica-carbonate rock, lie above those more fully explored by the workings in the South Randol area.

The rocks beneath the main sill are not well enough exposed by the workings of the area to justify any statement concerning their distribution or structure.

Ore bodies

Three major ore bodies and several smaller satellite bodies were mined in the South Randol area. They have been inaccessible for more than half a century, but the little available information about them suggests that they were similar in character to the other ore bodies of the New Almaden mine. The principal ore mineral was cinnabar, though an isolated occurrence of native mercury accompanying cinnabar on the 1700 level is reported. The ore minerals occurred in and along steep hilos which trend nearly north through the silica-carbonate rock. The most extensive ore shoot plunges northward, parallel to the hilos and almost exactly down the dip of the upper surface of the serpentine sill, from about the 1000 level to the 1600 level, or about 900 feet. (See pl. 4.) No exact information as to how far the ore extended back from the contact is available, but probably the distance varied between 5 and 15 feet. A second large irregular ore shoot was found on the upper surface of a thin finlike serpentine body which lapped over the shoot just described. It extended down the dip from about the 1450 level to the 2000 level; it had a maximum strike length of about 300 feet on the 1700 level, but tapered rather abruptly above and below. Apparently both of these ore shoots were localized by a single set of fractures, which were later filled to form the hilos. Another ore body lying farther west along the upper surface of the main sill had a strike width of 300 feet on the 1500 level, and it extended from the 1200 to the 1550 levels, having a dip length of about 350 feet.

SAN FRANCISCO AREA

Location and extent of workings

The San Francisco area includes surface cuts, underground levels, and stopes clustered about the San Francisco and Washington shafts, which are high on the south slope of Mine Hill. (See fig. 92 and pl. 3.) The large surface cut, which is known as the San Francisco open-cut, was made during World War II. Its upper end, from near the top of the hill, is 1,725 feet above sea level; its lower end is at an altitude of 1,500 feet, equivalent to the underground 300 level. The principal underground workings, which are much older, extend from the 300 level down to the 1100 level, but the stopes extend only to the 900 level.

The San Francisco workings are somewhat isolated from the rest of the New Almaden mine and were developed largely through separate adits and shafts, but for better ventilation and economy in handling

ore they were ultimately connected with the central stope area of the mine on four levels. (See pl. 4.) Access to the San Francisco workings could formerly be gained through several high-level adits on the south slope of Mine Hill, through the 300-level San Cristobal tunnel from the north slope of Mine Hill, through the Main tunnel on the east slope, and through the San Francisco and Washington shafts. In 1944, when the workings were mapped by R. R. Compton, G. Donald Eberlein, G. W. Walker, and A. C. Waters, the only means of entrance were the San Cristobal tunnel, the 600 level Santa Rosa drift (pl. 10), and the 800 level Day tunnel from the central stope area. All the workings below the 800 level were flooded, and some others were largely inaccessible, so that only a little more than half of the 20,000 feet of level workings in the area could be studied. Nevertheless, at least parts of nearly all the stopes were accessible for study, and, with the aid of the records of the company surveyors, an adequate conception of the unusually complicated geology of the area is believed to have been obtained.

History and production

Ore is reported to have first been found in the San Francisco area in the "Upper San Francisco tunnel" in 1864. It seems likely, however, that this exploratory tunnel was aimed at deeper exploration beneath unrecorded surface ores that were removed at an earlier date. With the discovery of ore in the upper tunnel, an adit known as the "Lower San Francisco tunnel" was soon begun, and by 1866 the San Francisco branch from the Main tunnel was driven to connect with the San Francisco workings. (See section C-C', pl. 11.) Production from this "outside mine" reached a yearly peak of more than 2,000 tons of "average grade ore" in 1867, and in 1868 the internal San Francisco shaft was put down from the level of the Main tunnel (300 level) to connect with the Santa Rosa drift from the central stope area of the New Almaden mine. The ore bodies that had been found on the 300 and 400 levels were not large, but were rich enough to encourage further development. In 1871 the Warren stope ore body was found near the 500 level, and by the end of 1873, after 9,197 tons of good ore had been mined from the Warren and higher stopes, the mine seemed to be nearly exhausted.

In June 1874 the extensive New World ore bodies (fig. 81) were found near the 600 level. During the next 4 years these were followed downward to and below the 800 level, and the Day tunnel, on the 800 level, was extended to serve this part of the mine. To search for the continuation of the New World ores at greater depths the Garfield (Washington) shaft

was started in November 1881. From the first the miners felt it was cursed with bad luck, for it was repeatedly caved, flooded, or beheaded by landslides; but by August 1883 it had been sunk below the 900 level and had passed through a little ore. In June 1884 the Garfield shaft was renamed the Washington shaft, with elaborate ceremony, in the hope of lifting the curse, but its bad luck persisted. By January 1885 the shaft had been sunk below the 1100 level, and a connection was made, in August 1885 through a long drift and incline, with the 1400-level crosscut from the Santa Isabel shaft. Prospecting in the lower levels continued for the next few years without results, and in September 1890 the Washington shaft was closed down.

In that same year, however, an attempt was made to recover more ore from the abandoned upper stopes and to explore laterally from them. For this purpose the San Francisco branch from the Main tunnel was reopened, and the internal San Francisco shaft was extended from the 300 level up to the surface and provided with a hoist. Some ore was recovered near the upper level by this new work, but no sizable new ore bodies were found. In 1899 the Washington shaft was again reopened, only to be almost completely obliterated by another landslide in June 1901. The San Francisco shaft remained passable for many years, but with the excavation of the large San Francisco opencuts in 1944 and 1945 it was covered over and probably largely filled. The surface operations during World War II yielded ore at the prevailing high price for quicksilver, but no ore bodies comparable in grade to those mined underground were struck. In 1948 some ore was being taken by H. F. Austin from adits driven into the opencut area. The entire production from the ores of the San Francisco area cannot be computed from the available records, but it is estimated to have been about 50,000 flasks.

Geology

The rocks explored by the San Francisco workings are serpentine, the silica-carbonate rock derived from it, and various sedimentary rocks and greenstones of the Franciscan group. The serpentine forms the southern continuation of the two sills explored in the rest of the New Almaden mine, which in this area are apparently joined to form a single mass. (See section *C-C'*, pl. 11.) In general the contact between the serpentine and the country rock from the surface down to the 600 level strikes about N. 35° W. and stands nearly vertical. In detail, however, it is extremely complex: many sill-like apophyses, ranging in thickness from a hundred feet to less than a foot, branch southward and downward from it, following rather

closely the southward dip of the beds of the rocks of the Franciscan group. In many places along the contact, also, there are small pods and lenses of carbonatized serpentine entirely isolated in the bordering alta. Locally the serpentine and the shaly alta interpenetrate in so complex a fashion that it would not be possible to tell from the field relations which rock was intruded into the other. A very unusual complication in this area is the presence of faults of a few feet displacement that are later than the silica-carbonate rock. These complexities in the details of the geology have made the area a difficult one in which to carry on exploration and development work.

Below the 600 level the roughly vertical but highly complex intrusive contact gives way to an arching contact dipping gently southwestward, formed by the extension of a single thick sill beyond the general limit of the intrusive contact in the higher levels. (See fig. 81 and pl. 12.) Exploration below the 800 level was nearly all directed toward searching for ore along the upper margin of this sill, which therefore is fairly well outlined by workings down to the 1100 level. The sill extends westward below the south end of the 1400 level driven from the Santa Isabel shaft, but farther south it must pinch out at a higher level, for it was not struck by the south crosscut on the 1000 level. The arched lower contact of the sill was cut on the 1100, 1000, and 900 levels, but as it was not cut on the 800 level it is believed to reach the highest point on its arch not far below that level. (See section *C-C'*, pl. 11.)

Ore bodies

Most of the ore bodies mined in the San Francisco area were small, but the largest, the New World ore body (fig. 81), was comparable in size to some of those in the central stope area. It extended down below the 850 level and up to about the 600 level; it had a maximum plunge length of about 500 feet, an average strike width of less than 100 feet, and a thickness of 10 to 20 feet. It lay mostly along the upper margin of the thick sill that extended southwestward beyond the general limits of the intrusive contact above, but some ore lay in a higher sill which extended out over the lower ore body. (See section *C-C'*, pl. 11.) A third sill, only 6 feet thick, contained near the 600 level a small but rich extension of the New World ore body. The ore apparently was localized by a sharp roll in the contact of the larger sill, which formed a well-defined inclined inverted trough, and the overlying thinner sill apparently had a similar shape. The ore lay just beneath the alta hanging walls, and extended along numerous hilos that had a strike of N. 30°-50° E.

The smaller ore bodies mined from the jagged intrusive contact above the 600 level included, in ascending order, the Warren, Arcial, 500-level, 400-level, Curasco, and Manilla ore bodies. The first two of these were in well-defined thin apophyses that appear to have been mineralized throughout, the 400-level and Curasco ore bodies were on the lower contacts of branching apophyses, and the other smaller ore bodies were found in silica-carbonate rock near the junctions of adjacent apophyses. The scattered occurrence of ore bodies along this irregular contact on both upper and lower sides of apophyses made prospecting difficult, as is emphasized in the following quotation from the company superintendent's report of 1885:

The peculiarity of this portion of the mine even in the rich upper works of the San Francisco and New World is that the ore masses are capriciously distributed, and do not have connecting links. Some of the ore chambers like the New World, found when almost all hope was abandoned, are rich and extensive and others again are nothing but mere pockets. Difficulty of prospecting in this portion of the mine is vastly increased from the fact that the faithful guide, the black alta hanging wall so reliable and comparatively uniform in the main "New Almaden" and "Randol ore territory" is in this section as fickle and uncertain as the ore chambers themselves, sometimes not occurring at all on the hanging wall and at others abruptly ceasing and giving place to serpentine.

SANTA MARIANA AREA

Location and extent of workings

The Santa Mariana area includes the scattered surface cuts, shallow adits, and connected workings that explore a body of serpentine and silica-carbonate rock lying along and near the crest of Mine Hill between the Washington shaft and the San Pedro workings (pl. 3 and fig. 92). The many opencuts are all small and appear to have been excavated by hand in the early days of mining on the hill. The underground workings, which lie at and above the 200 level, consist mainly of 3 adits totaling only a little more than 2,000 feet in length on the company maps and known as the Lower Santa Mariana, Upper Santa Mariana (or Carler), and the Mariana Road (or Upper Mariana No. 2) tunnels. The Lower and Upper Santa Mariana tunnels were driven from the south side of the hill and the Mariana Road tunnel from the north side. (See pl. 4.) Several other adits were driven in this area, but they are not plotted on any available maps and apparently failed to develop any ore. During this study only the surface cuts and a part of the Mariana Road tunnel were accessible; information on the rest of the other underground workings is therefore based on company maps and surveyors' records.

History and production

All that is known of the early history of mining in the Santa Mariana area is that in 1864, 10 tons of ore was mined from some workings in the area, that by 1871 about 218 tons had been mined, and that in 1888 and 1889 another 557 tons was mined. The main period of production, however, was brought about by the reopening and extension of the three principal adits, which began in 1897. For the period 1898-1902 the recorded yield of ore was 9,725 tons. In 1897, also, the small Santa Mariana shaft was put down, some 800 feet west of the Lower Mariana tunnel, to a depth of 62 feet. Company records indicate that in the following years several new adits were driven to prospect the area further, but some of these workings can no longer be identified. The Refanni tunnel, on the "southwest side of the hill," was driven in 1898; the Chabolla tunnel, "200 feet west of the Lower Santa Mariana," and the Bernal tunnel, on the "north side of the hill," in 1899; the Payson tunnel, "on the southwest slope," in 1900; and the Tank tunnel, "near the Lower Santa Mariana," in 1901. All of these, however, were abandoned after a few months, and none contributed to the production of the area. Virtually no mining has been carried on in the area since 1902, although several unsuccessful exploratory trenches were dug in 1941 and 1942.

No figures showing the amount of quicksilver produced from the Santa Mariana area are available, for its ores apparently were mixed with those from other parts of the New Almaden mine. Any estimate of its production, therefore, depends largely on the assumed grade of the ore. If the ore from this area during each of its productive years was of the same grade as the average ore furnaced at New Almaden during the same years, the production of the Santa Mariana area was somewhat more than 2,600 flasks; but because of the ready accessibility of the area it is likely that ores of lower than average grade were mined, in which case the production was less.

Geology

The principal geologic feature of the Santa Mariana area is a tabular intrusive body of serpentine partly replaced by silica-carbonate rock, which forms a southeastward extension of the body explored by the San Pedro workings. (See pl. 3.) On the surface the general trend of this tabular body across the top of the ridge is N. 32° W.; underground its strike, as delineated by both sides of the body on two levels, is about N. 20° W. The dip can be determined only down to the 200 level, but the contacts on the two sides in the Upper and Lower Santa Mariana tunnels lie directly below those on the surface, indicating that

here the contact is vertical. The maximum width of the body on the surface is about 220 feet, and on the Upper Santa Mariana tunnel level it appears to be only about 160 feet. From the relations of the serpentine bodies exposed on the crest and south slope of Mine Hill, and from the known extent of the nearby serpentine mass in the underground workings of the San Francisco-Washington area, it is concluded that the serpentine bodies explored in the two areas are not connected.

Silica-carbonate rock has replaced the serpentine at almost every place where it is exposed on the surface, though a narrow core of serpentine is preserved at the road just northwest of the Washington shaft. Underground only the margins appear to have been converted to silica-carbonate rock, for considerable serpentine was encountered in crosscuts traversing the inner part of the mass.

Ore bodies

The ore in the Santa Mariana area was irregularly scattered, for the cinnabar occurred in small veinlets distributed irregularly through the silica-carbonate rock. Cinnabar seen in the Mariana Road tunnel was associated with veinlets of quartz and dolomite, but these were too small and irregular to be typical hilos, and the mineralization at that place was not obviously related to any contact. On the other hand the one mapped stope in the workings, which is in the southeastern part of the Upper Santa Mariana tunnel level, was apparently near the northeast contact of the serpentine, which suggests that the contact may there have had a part in localizing its ore. (See pl. 5.) Elsewhere small raises and winzes, in some of which small ore shoots were mined, appear to have been driven along contacts.

Suggestions for further development

Judging from the general distribution of the workings in and along the serpentine, it would seem that the Santa Mariana area has been fairly well prospected down to the 200 level. As a 200-foot interval of unexplored ground lies between the lowest Santa Mariana workings and the 400 level extending northwest from the Washington shaft, and as the closest workings below that are on the 800 level, some additional exploration beneath the Santa Mariana tunnels may be justified. Another possibility is a stripping operation on the large surface area of silica-carbonate rock, but the work done here in 1941 and 1942 indicates that the quicksilver content of this rock is too low to make such an operation pay, except when the value of quicksilver is exceptionally high.

SAN PEDRO-ALMADEN AREA

Location and extent of workings

The San Pedro-Almaden area contains a group of surface and underground workings on the north slope of Mine Hill, near the crest of the ridge and about midway between the America and San Francisco shafts. (See pl. 3 and fig. 92.) The San Pedro workings comprise an opencut and several relatively short adits; the adits are about 1,000 feet in aggregate length as shown on available maps, though company records give their extent in 1865 as 1,608 feet. The Almaden shaft is a few hundred feet northeast of these workings, and the levels from it, which in part extend under the San Pedro workings, are known as the Almaden workings. The 500 level from the shaft contains about 1,400 feet of workings, the 600 level about 1,200 feet, and the 700 level about 300 feet. (See pl. 4.) The 1400-level crosscut from the Santa Isabel shaft to the Washington incline passes 700 feet directly below the deepest Almaden workings, but as the geology exposed in the crosscut cannot be projected with assurance across this 700-foot gap, the 1400 level is not further considered with the San Pedro-Almaden area.

History and production

The ores of the San Pedro area were exposed at the surface, and they probably were mined from opencuts, at least intermittently, between the early 1850's and 1865. Available records indicate that both the San Pedro and the nearby San Ramon tunnels were begun in 1865, and from then until 1874 ore was mined from this area at the rate of less than 200 tons per year. After a 10-year period of inactivity small amounts of ore were recovered between 1884 and 1893. The total recorded production of the San Pedro workings was about 1,000 tons of ore, which probably yielded some 1,500 flasks of quicksilver. During World War II the outcrops were mined with a power shovel and yielded 2.68 pounds of mercury per ton. With the postwar price decline the ore became too lean to make continued operation profitable.

The Almaden shaft was begun in August 1888, and ore was mined from the shaft on the three levels until January 1891. Although hilos containing cinnabar were cut on both the 500 and 600 levels (pls. 9, 10), they were not sufficiently numerous to form minable ore at a time when the price of quicksilver was only \$45 a flask, and the only recorded production through the shaft was 3 tons of "fair ore."

Geology

The San Pedro-Almaden workings explore a serpentine sill of northwesterly strike which seems to be an

offshoot from the lower part of the larger sill containing the Randol ore bodies to the north. Near the crest of the ridge the sill is nearly flat; but in the vicinity of the San Pedro workings it dips about 40° NE., and it has about the same dip where it is cut by the levels from the Almaden shaft. Between the San Pedro and Almaden workings it either steepens to nearly vertical or has a jagged surface resulting from the protrusion of apophyses. (See section A-A', pl. 11.) The lower margin of the sill is extensively altered to silica-carbonate rock, which is about 40 feet thick in the upper workings and more than 100 feet thick on the lower levels. The upper part of the sill is likewise altered to silica-carbonate rock near the surface.

Ore bodies

The only real ore body found in the area was developed through the San Pedro adits. It was comparatively small and lay in the silica-carbonate rock along the lower margin of the sill. The stoped area is bordered by rock containing a few well-developed hilos and scattered irregular quartz-carbonate veins. Except for a local flattening of the contact, no structural reason for the localization of the ore is apparent.

Suggestions for further development

The extensive workings on the upper levels in the area have probably exhausted the possibilities for finding additional ore there, but cinnabar is reliably reported to have been found on the 500 and 600 levels along the lower margin of the sill. At a time when the price of quicksilver is high this deeper material might perhaps be profitably mined. An inclined shaft going down the dip of the contact seems to offer the best means for reaching the ore, as it would also explore the interval between the lowest San Pedro and the highest Almaden workings.

AMERICA MINE

Location and extent of workings

The America mine lies close to the top of Los Capitanillos Ridge, a little more than 3,000 feet west of the Randol shaft on Mine Hill. (See pl. 3.) It is the nearest to the New Almaden mine of the so-called outside mines, and at one time an unsuccessful attempt was made to reach it by extending a crosscut from the New Almaden mine. The workings, which were almost entirely inaccessible in 1948, include an old shaft 216 feet deep, adits and connected drifts, known as the Upper and Lower America workings, on the 300 and 500 levels, and extensive drifts from the 700-foot America shaft on the 600 and 700 levels. The total length of the level workings is a little more than a mile. (See pls. 4, 13.)

History and production

The early history of the American mine is known only from fragmentary records. One early company report mentions that between September 1863 and July 1866 the mine was worked through the old shaft and the Upper and Lower America tunnels, and that stopes developed from each of these levels yielded about 1,000 flasks of quicksilver from 1,037 tons of hand-sorted ore. After 1866 the America mine was apparently abandoned until 1885, when the upper levels were reopened and a decision was made to attempt to develop the America workings into a large mine. The proposed program involved the sinking of the America shaft to a depth of 1,100 feet and the driving of a 2,000-foot crosscut on the 1400 level from near the Santa Isabel shaft. The America shaft was begun in October 1885, and at about the same time the long crosscut was started from near the Santa Isabel shaft. When the America shaft reached the level of the Lower America tunnel, a crosscut was driven to reach this adit, which had been simultaneously reopened from the portal. The level was also extended east of the shaft for 450 feet, where it reached apparently barren silica-carbonate rock. When the shaft had been deepened another hundred feet, the 600 level was driven westward to tap an ore body mined in the old stopes above, but although ore was found on the level, only a small amount of raising showed that the old stope extended downward virtually to the 600 level. In March 1887 a 700 level was driven westward from the America shaft, and a connection between the 600 and 700 levels tested the downward extent of the ore body. Ore was cut in the first 35 feet of a winze from the 600 level, and a short drift along the contact 80 feet below the level also was reported to have been run in "fair-grade ore."

Meanwhile the shaft was being deepened under considerable difficulty, owing to the large amount of water pouring into it, and in February 1888, at a depth of 701 feet, the shaft struck "boulders of silica-carbonate rock" and an inflow of water that the pumps were unable to keep pace with. The sinking of the shaft was temporarily abandoned, and although new pumps capable of pumping 50,000 gpd (gallons per day) were installed, the water continued to rise in the shaft, causing it to cave from the bottom upward. In June 1888, when the shaft had caved to within 20 feet of the 600 level, it was closed down, and the long crosscut from the Santa Isabel shaft, which had been driven through heavy and gassy ground to within 475 feet of the projected bottom of the shaft, was abandoned.

During the revival of the America mine between 1885 and 1888, about 500 flasks of quicksilver was recovered from ore mined chiefly above the 600 level.

The ore lying between the 600 and 700 levels was apparently never mined, and since 1888 several unsuccessful attempts have been made to gain access to this ore through either the old stopes or the Lower America tunnel. In 1943 a small quantity of low-grade ore was mined in an opencut lying above the old stopes, and in 1947, when the Upper America tunnel was again reopened, a little ore was recovered from a thin seam about 190 feet from the portal. In 1948 the mine was abandoned and the Upper America tunnel caved. The total production of the America mine resulting from all these ventures is probably less than 2,000 flasks of quicksilver.

Geology

The America area contains a serpentine sill intrusive into the rocks of the Franciscan group, which in this area are chiefly greenstone tuffs but include a small amount of amphibolite and clastic sedimentary rocks. Most of the ore found in the America mine came from the lower side of this sill, which is relatively thin and has largely been converted to silica-carbonate rock. The sill is folded with the rocks of the Franciscan group to such a degree that its contacts are too irregular to be projected with any certainty, but it may be an extension of the sill cut in the southern part of the 1400 level southwest of the Santa Isabel shaft in the New Almaden mine. Its course on the surface near the mine workings cannot be traced, for the area in which it might be expected to crop out is largely covered by dumps. Underground, however, the lower surface of the sill, along which the ore was localized, can be fairly well delineated from an area above the Upper America tunnel to a little below the 600 level. In the upper levels the sill strikes east and dips about 50° N.; on the 600 level its dip is about the same but the contact is more sinuous, striking northwestward where it is mineralized and northeastward elsewhere. Little is known of the upper surface of the sill, but the sill is more than 60 feet thick on the upper levels and only about 30 feet thick on the 700 level. (See pl. 13.)

Elsewhere in the America mine there are other bodies of silica-carbonate rock, which apparently contain only insignificant amounts of cinnabar. These include a thin sill that borders the opencut on the west, a sill crossed by the upper part of the America shaft, and a lens of silica-carbonate rock penetrated on the 500 level about 450 feet east of the America shaft.

Ore bodies

The America mine appears to have contained only one ore body, although existing maps are so poor,

especially with regard to elevations, that the true position of the old stopes is uncertain. The cross section *A-A'* on plate 13 was constructed on the assumption that all the stopes extended along a single contact—the lower side of the main serpentine sill. If that is correct, the ore body has been mined to the 600 level, or for at least 250 feet down the dip of the sill. The average width of the stope was about 30 feet, but no information on the thickness of the ore body is available.

Even less is recorded about the character of the ore, but specimens gleaned from the dumps are much like specimens from the New Almaden mine. Although the stope extends somewhat more nearly east-west than most of the narrow quartz-carbonate veins or hilos found on Mine Hill, the abundance of veins in the rock on the dump suggests that the ore body follows a swarm of such hilos down the dip of the contact. The small quantity of low-grade ore mined from above the Upper America tunnel in 1947, however, bore no relation to any hilos; it consisted of irregular cinnabar-bearing veinlets and a few scattered crystals of cinnabar in silica-carbonate rock lying beneath a thin septum of greenstone tuff.

Suggestions for further development

The lower part of the main ore body is reliably reported to have been left unmined below the 600 level, although a winze proved that it continued down for at least another 80 feet. This unmined ore probably has about the same tenor in cinnabar as the mined ore on the upper levels—about 2 percent. It could probably be reached most cheaply by sinking an inclined shaft down the plunge of the ore body, for past experience has shown that reopening any of the caved adits would be a costly procedure. Ore was also found in “boulders” of silica-carbonate rock at the bottom of the America shaft, but it appears unlikely that exploration at depth will be worth the cost of sinking a new shaft in the foreseeable future.

PROVIDENCIA MINE

Location and extent of workings

The Providencia mine, which is one of the smaller “outside” mines on the New Almaden property, lies on the south slope of Los Capitancillos Ridge, between the America and Enriquita mines and about 8,000 feet northwest of the summit of Mine Hill. (See pl. 1.) The principal workings consist of more than a dozen shore adits penetrating a body of silica-carbonate rock between 1,000 and 1,120 feet above sea level; one other longer adit, known as the Lower Providencia tunnel, extends under these workings

155 feet below. The aggregate length of all the known workings is only a little more than 2,000 feet.

In this same general area are other workings which may conveniently be discussed with the Providencia mine, though they are actually separate prospects. These include the Soda Springs tunnel (1,000 feet west of the Lower Providencia), the Yellow Kid Jr. workings (southeast of the Lower Providencia tunnel), and the Prospect shaft No. 2 (1,900 feet east of the Lower Providencia tunnel).

History and production

The Providencia upper workings are said to have yielded "several thousand cargas [1 carga = 300 pounds] of superior ore," which was treated in the Enriquita furnace during the period 1861-63. In 1864 the Lower Providencia tunnel was driven to explore beneath the upper levels, but it failed to reveal any ore and probably never even reached the downward projection of the ore-controlling structures. During the next several years some additional ore was found in small pockets in the upper workings, but when the Enriquita mine closed down in the late 1870's activity at the Providencia mine also came to a stop.

In 1882, however, the Providencia ledge was prospected farther east; the Prospect shaft No. 2 was sunk to a depth of 202 feet, and from its bottom a drift was extended along the ledge for 300 feet and a crosscut run north "through the ledge for over 100 feet." This work disclosed some cinnabar but no ore. In the following year the Soda Springs tunnel, to the south, whose portal was near an active spring depositing tufa, was driven 217 feet but struck no ore. Nine years later, in 1898, the Yellow Kid Jr. prospects southeast of the Lower Providencia tunnel yielded 170 tons of high-grade ore, but other adits driven nearby apparently were unproductive. In 1909, in an attempt to revive the Providencia mine, the Lower Providencia tunnel was extended 213 feet to serpentine, but, as a drift for 80 feet extending along the contact traversed only barren silica-carbonate rock, the project was abandoned. In 1942 some bulldozer work was done on the surface, but again no ore bodies were discovered.

The total production of the Providencia mine cannot be determined from available records, but it probably is less than 2,000 flasks of quicksilver.

Geology

The upper workings of the Providencia mine explore a conspicuous ledge of silica-carbonate rock that strikes nearly east-west. (See pl. 1.) This ledge dips 45°-60° N. where exposed in the Upper Provi-

dencia tunnel, but farther east, at the Prospect shaft No. 2, it stands nearly vertical or dips steeply south. It is on the south, or lower, side of a serpentine sill, which at the Enriquita mine to the west is mineralized along its north, or upper, contact. A second body of silica-carbonate rock is cut near the portal of the Lower Providencia tunnel, and its extension to the southeast probably contained the ore bodies of the Yellow Kid Jr. workings. This body dips about 40° S. where it is cut in the tunnel.

Ore bodies

Little is known regarding the occurrence of the small high-grade pods of ore found in the area. Some ore was seen in the Upper Providencia tunnel just above the north-dipping footwall contact of the silica-carbonate rock, and ore removed from an open-cut above apparently also lay above the footwall. If the area just above this footwall contact is the most favorable place for deposition of ore in the Providencia mine area, many of the upper adits, which began above the footwall, failed to test the best possibilities of the area.

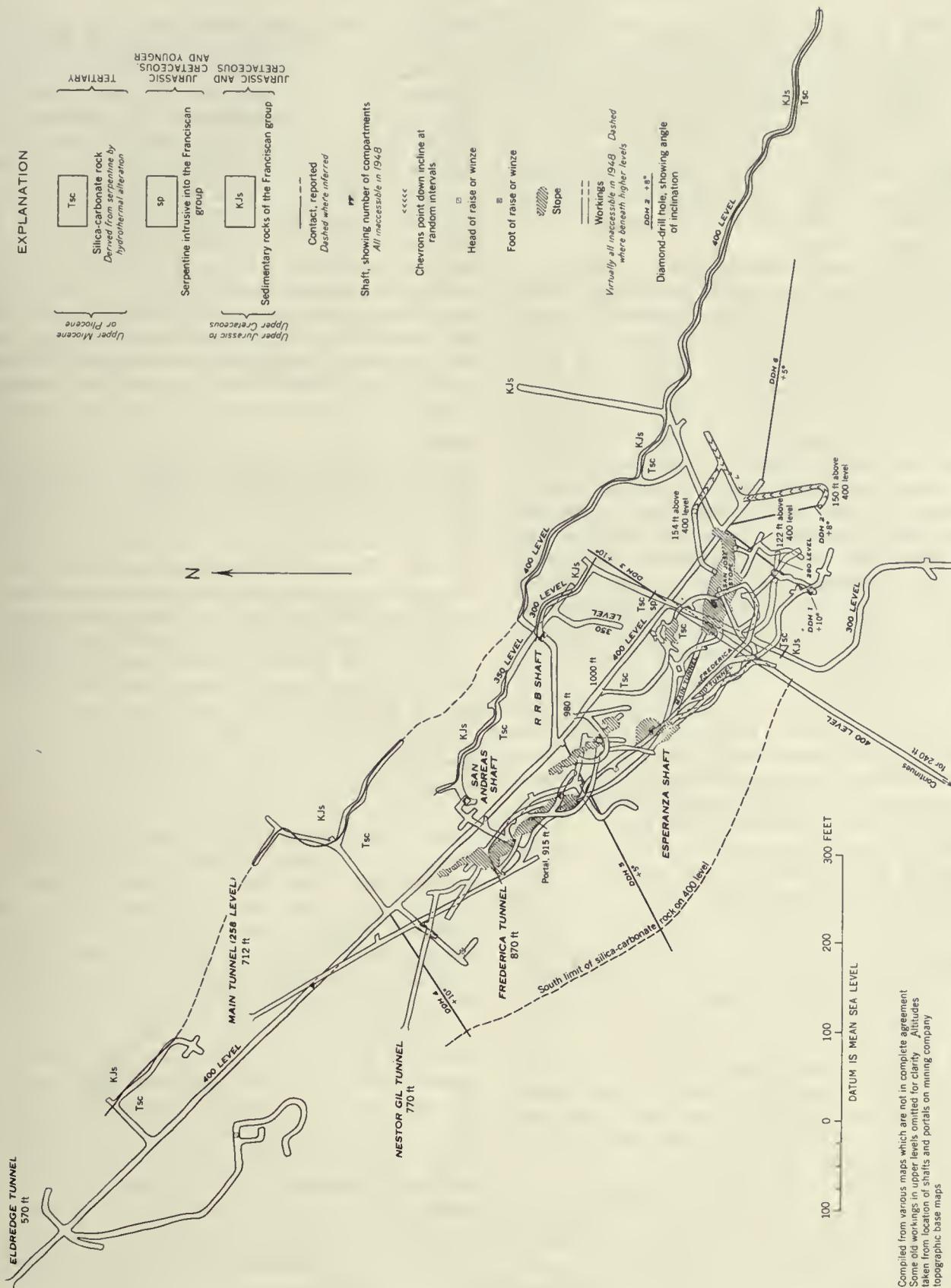
ENRIQUITA MINE

Location and extent of workings

The Enriquita mine, which was the second most productive of the "outside" mines on the New Almaden property, lies about 2 miles northwest of Mine Hill, on the steep south slope of Los Capitanillos Ridge. The workings extend from close to the top of the ridge down to the Eldredge tunnel, which is so close to the level of Guadalupe Creek that it is periodically flooded by waters impounded behind the Guadalupe Dam. These workings were virtually all inaccessible when this study was made, but according to available maps they consist mainly of more than 9,000 feet of drifts and crosscuts distributed on at least ten irregularly spaced levels. (See fig. 96.) These were formerly reached through 3 principal shafts and 6 adits, of which the lowest and longest is the Eldredge tunnel. This adit and the connected drifts and crosscuts were driven primarily to explore beneath old stopes mined out before 1865, and they constitute nearly half of the level workings of the mine. Most of the higher levels are older, and their position and extent are known only from several old tracings which do not entirely agree. On the map accompanying this report (fig. 96) a few of the shorter levels of unrecorded altitude have been omitted for simplification.

History and production

The Enriquita mine was first worked in 1859, and it is said to have yielded 10,571 flasks in the next 4



EXPLANATION

- Tsc
Silica-carbonate rock
*Derived from serpentine by
hydrothermal alteration*
 - sp
Serpentine intrusive into the Franciscan
group
 - KJs
Sedimentary rocks of the Franciscan group
- Upper Miocene
or Pliocene
- JURASSIC AND
CRETACEOUS
AND YOUNGER
- TERTIARY

- Contact, reported
Dashed where inferred
- |||||
Shaft, showing number of compartments
All inaccessible in 1948
- <<<<<<
Chevrons point down incline at
random intervals
- Head of raise or winze
- Foot of raise or winze
- ▨
Slope
- Workings
*Virtually all inaccessible in 1948. Dashed
where beneath higher levels*
- DDM 2 +8°
Diamond-drill hole, showing angle
of inclination

FIGURE 96.—Geologic map of the Enriquita mine.

Compiled from various maps which are not in complete agreement
Some old workings in upper levels omitted for clarity. Altitudes
taken from location of shafts and portals on mining company
topographic base maps

years, from ores that probably averaged more than 5 percent quicksilver. During this early period the ores were obtained from stopes reached through the Main, Nestor Gil, Frederica and higher adits; the connecting San Andreas and Esperanza shafts served largely for ventilation. The ores were treated in a nearby furnace with a reported capacity of "2,500 flasks per month," but unless a large amount of production remains unrecorded the furnace was seldom operated at full capacity.

In 1863, in order to prospect for downward extensions of the ore bodies found in the upper levels, the Eldredge tunnel was begun some 130 feet below the lowest level then existing. By 1875 this tunnel had been driven at a high cost, through hard silica-carbonate rock for 875 feet, but it failed to reach any ore. Other reasons combined with this to bring operations at the Enriquita to a standstill. First, the operators of the New Almaden mine had great difficulty in preventing the theft of quicksilver that was recovered at the Enriquita mine, in these early days, because of the remoteness of this mine from the main camp; second, the discovery of large ore bodies in the Randol area of the New Almaden mine left little incentive to develop any of the "outside" mines. Consequently, after 1875 the Enriquita mine lay idle until the known ore bodies of the New Almaden mine were virtually exhausted.

In 1892, when there was an urgent need to find new ore on the New Almaden property little capital was available for exploration; but the old Enriquita mine appeared to offer more promise than most other parts of the property, and a new attempt to find the continuation of the old ore shoots was begun. As the old furnace near the Enriquita mine had been destroyed, it was decided to treat the ore at the Hacienda (pl. 1.), to which the ore could be taken most cheaply by hoisting it through a new shaft from the lower levels of the Enriquita mine to a road on Los Capitancillos Ridge. A shaft, called the R. R. B., was accordingly put down and connected with the Eldredge tunnel. Exploratory work was done on the tunnel level and on the 300 and 350 levels above, but no new ore was found—even the attempt to find the old stope proved unsuccessful. In 1896 the development was stopped for lack of funds, but in 1900–1902 and in 1909–10 other apparently unsuccessful attempts to find the old stope were made.

Finally, in 1923, a raise put up from the end of the Eldredge tunnel found the old stope, but apparently little fill or new ore was taken from it because of the low price of quicksilver. The following year some drilling was done in the mine, which revealed some

cinnabar but no ore of sufficient extent to repay the cost of mining it. Between 1927 and 1935 little mining was done, even though nearly all the workings remained open; some quicksilver was recovered, however, from ore on the old dumps. In 1935 the Guadalupe Dam was built, and with the subsequent floodings the low-level tunnel caved near its portal. The widening of a road from the dam to the top of Mine Hill resulted, moreover, in the caving of the R. R. B. shaft. In 1942 the old dumps, which were found to average 4 pounds of quicksilver to the ton, were hauled to the modern furnace on Mine Hill. In 1948 the mine was idle and largely inaccessible. It had yielded more than 10,000 flasks of quicksilver before 1865, but since then, despite repeated attempts to revive it, the mine seems to have produced only a few hundred flasks of quicksilver, recovered from ore in the old dumps.

Geology

Little detailed geologic information about this largely inaccessible mine is available, but because of the apparent simplicity of the structure the limited data give a general idea of the geologic setting of the ores. The mine is close to the northern margin of a sill of serpentine that appears on the surface to be 800 feet thick. (See pl. 1.) The northern contact dips steeply north, and the southern contact where exposed in the workings of the nearby Providencia mine dips steeply south. The sill occupies the axial part of the anticline that contains the ore bodies of the main New Almaden mine. In the Enriquita area, however, the fold is tight, nearly isoclinal, and we do not know whether the sill itself is isoclinally folded or intruded after the folding.

Both to the north and south of the main sill are thinner satellite sills, which are largely converted to silica-carbonate rock. The deep-level Eldredge tunnel begins in one of these thin sills north of the main serpentine mass, and most of the workings are reported to be in hard silica-carbonate rock. Several crosscuts to the north reach the alta hanging wall; diamond-drill holes and the long 400-level crosscut to the southwest reach an alta footwall. (See fig. 96.) According to the available records the sill is completely converted to silica-carbonate rock on the Eldredge tunnel level, but on the 300 level above it contains a medial core of serpentine. Unfortunately the ore bodies are all above the levels for which some geologic information is available, and projecting the known geology upward would indicate that they are in the central part of the sill rather than adjacent to a contact, as is more usual in the district. It seems likely that they lie along included septa of Franciscan

rocks that are so thin they are not indicated in the notes and maps available to us.

Ore bodies

The ores of the Enriquita mine are similar to those of the nearby New Almaden mine, in that they contain cinnabar both replacing silica-carbonate rock and filling open fractures. Two large ore bodies and several smaller ones extended through the central part of the altered sill forming a gentle arch 550 feet long and from 15 to 40 feet wide. This arch has an altitude of less than 750 feet in the northwestern part of the mine, rises to 980 feet in the central part, and sinks to 700 feet in the southern part. In all probability, however, the ore bodies did not lie along a single structure; as they are near the middle of the sill, it is likely that they bordered several steeply dipping septa of sedimentary rock. Their trend is such as to indicate that they are unrelated to the hilos, which, according to Christy¹⁰ "cross the silica-carbonate rock of the Eldredge tunnel in a nearly north and south direction."

Suggestions for further development

The Enriquita mine does not thoroughly explore the carbonatized sill below the Main tunnel level, except along the northern margin on the 400 level; but until

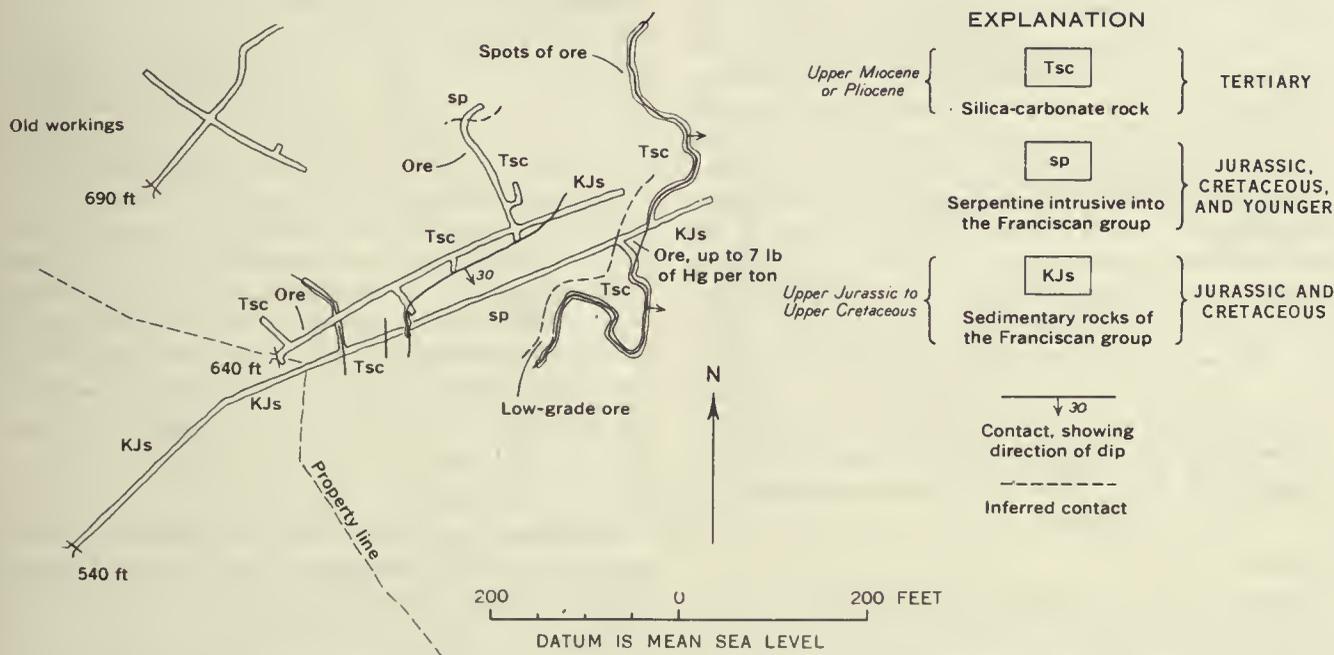
¹⁰ Christy, S. B., 1889, Unpublished report to the Quicksilver Mining Co.

the geology is more precisely known it will not be possible to judge whether more ore is likely to be found in the mine. Because of the unusually steep slope of the surface, together with the availability of the Eldredge tunnel and the many reported occurrences of veinlets of cinnabar, especially along the northern contact, the mine might have considerable promise for low-cost mining of low-grade ore if a furnace were built near its portal.

SAN ANTONIO MINE

Location and extent of workings

The San Antonio mine lies on the south slope of the Los Capitancillos Ridge, a few hundred feet upstream from the Guadalupe Dam and about 2,000 feet northwest of the Enriquita mine. (See pl. 1.) The lowest workings, which are not far above the floor of Guadalupe Canyon, are flooded with water impounded by the dam, and they lie in part under land that is no longer a part of the New Almaden property. The more recent workings consist of two adits, known as the Upper and Lower San Antonio tunnels, driven northward into the ridge; a somewhat older short adit lies higher up the ridge. (See fig. 97.) Still older workings are said to have been driven in the very early days, but if they exist they are caved, and in 1948 they could not be found. As they apparently were never mapped, we have no information about their location or extent.



All workings and notes from mining company records

FIGURE 97.—Geologic map of the more recent workings of the San Antonio mine.

History and production

The San Antonio mine was worked at least as early as 1848 (U.S. Supreme Court, 1857, p. 47, 53), and it produced some quicksilver in 1849. Very little else is known of its early history. It is reported in company records to have yielded "much good ore before 1865," but this is perhaps erroneous. In 1908 and 1909, when the management of the New Almaden mine was attempting to develop ore in several of the "outside" mines, a lower tunnel was cleared out and several hundred feet of new workings were driven from it. This work apparently failed to expose any ore, and the mine was soon abandoned. In 1915, under W. H. Landers, the two more extensive adits shown on the accompanying map (fig. 97), were driven in order to develop some ore found by a lessee during the previous year. Development was handicapped by shortage of miners, mining equipment, and funds, but was carried on at a relatively slow pace until Landers resigned in April 1917. Some ore was revealed by this work, and, to avoid the long haul to the New Almaden furnaces at the Hacienda, plans were made to either install a concentrator at the mine or haul its ores through the 260 level Senator tunnel to the Senator furnaces. Apparently a little ore was actually mined and hauled to the New Almaden furnaces, but neither of the other plans was ever carried out.

Geology

A comparatively thin tabular body of serpentine, together with bordering graywacke and shale of the Franciscan group, are explored by the more recent workings of the San Antonio mine. The serpentine body is well exposed on the surface, where it trends N. 20° W. from Guadalupe Creek to the crest of Los Capitancillos Ridge; its dip, in the few places where it can be determined, is consistently at low angles to the northeast. For much of its exposed length it has been converted to silica-carbonate rock, though above the uppermost mine workings its lower side is unaltered. In the mine workings it has a core of serpentine, with a shell of silica-carbonate rock along both sides. (See fig. 97.) A second, less extensive, body of silica-carbonate rock overlies the more conspicuous one from the crest of the ridge down about half way to the canyon floor. This body has been explored by a few shallow workings.

Ore bodies

Very little ore has been mined from the more recent workings, but according to company records almost all the silica-carbonate rock penetrated by the two adits driven in 1915-17 was "low-grade ore." The best ore was said to have been found along the upper side of

the sill-like body, but the silica-carbonate rock along the lower side also is said to have contained some ore on the lower level. The "low-grade ore" in the upper adit was reported to contain more than 3 pounds of quicksilver to the ton, and the records say, regarding the place in the lower adit where the 2 crosscuts branch to the north and south, "daily samples are being taken here and we have some returns as high as 0.35 per cent."

Suggestions for further development

No high-grade ore bodies have been found in the workings driven during the last 50 years, and it seems unlikely that the records of "rich ore" mined in the early days are authentic. However, if most of the silica-carbonate rock penetrated by the recent workings contains as much as the reported 3 pounds of quicksilver to the ton, the mine could be worked at a profit during times of high prices of quicksilver such as prevailed during World War II, provided a furnace were installed nearby.

SAN MATEO MINE**Location and extent of workings**

The San Mateo mine, which is one of the small "outside" mines on the New Almaden property, is near the base of the south slope of Los Capitancillos Ridge, just below the Guadalupe Dam. (See pl. 1.) The distribution of the more recent workings of the mine is shown in figure 98, but the positions of the older workings, driven in the 1860's and 1870's, are not indicated because accurate maps showing these workings are not available. Probably most of these lost workings were in the vicinity of the ones shown on the map, and certainly the position of one of the very old stopes is indicated on the map by a surface depression lying between the main adits. The ore bodies found in the mine were scattered within an area about 175 feet in diameter, and according to an old cross section they were mined through a vertical interval of at least 120 feet. Access to the larger stopes was first gained through an adit driven northward for a little less than 300 feet, and after this adit was caved the same area was reached through an adit driven eastward for 450 feet.

History and production

The small San Mateo mine has attracted so little interest that only fragments of its past history are available. The date of its discovery is unknown, but the mine is reported to have yielded some "rich ore" in the 1860's and 15 tons of ore in the 1870's. From 1890 to 1901, under C. C. Derby, part of the workings shown in figure 98 were driven, and in the first of

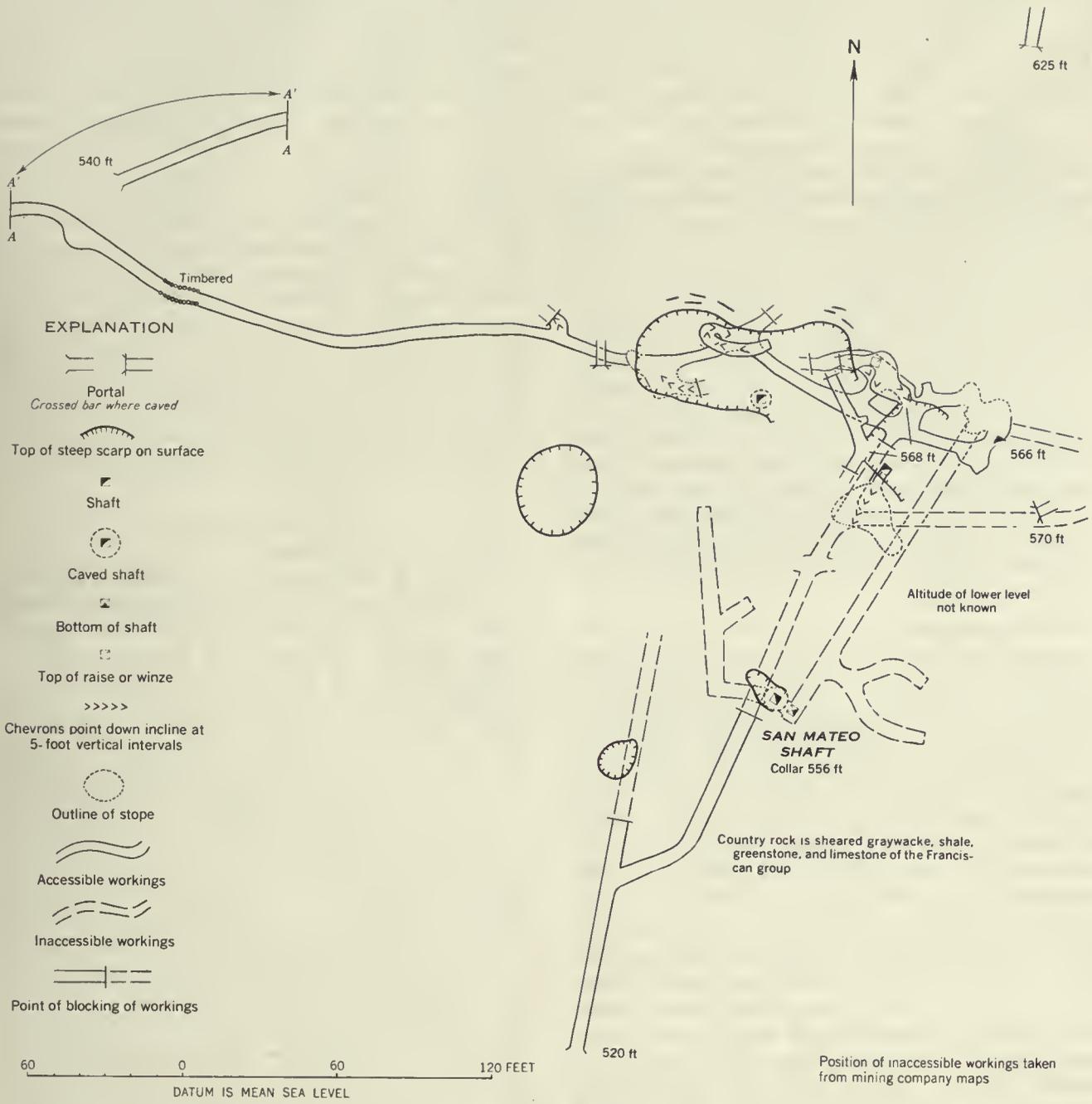


FIGURE 98.—Map of the San Mateo mine.

these years "rich ore" is said to have been hauled to the Hacienda furnaces (pl. 1). The average quicksilver content of the ore treated in the New Almaden furnaces in 1899 was about 1 percent, and the ore from the San Mateo mine must have been considerably richer to have justified the long haul to the furnaces. After 1901 the mine was apparently abandoned until 1908, when the lower adit was reopened, but after new workings of considerable extent had been run without finding ore it was again abandoned.

Between 1915 and 1917, under Landers' supervision, the old adit was reopened and several small ore bodies were found. The ore from these was apparently piled at the portal with the intent of hauling it through the 260-level Senator tunnel to the Senator furnace, but eventually this ore also was hauled around to the Hacienda furnace. In 1917, when Landers left, the mine was abandoned. During the period between 1935 and 1940 the long adit from the west was driven by P. S. Schneider and associates, and some ore was burned in a retort constructed near its portal. Since 1940 the mine had not been worked, though the most recent tunnel is still open and some cinnabar is visible. No accurate production records for the San Mateo mine are available, but it seems likely that at least 1,000 flasks has been recovered from its small but rich ore bodies.

Geology and ore bodies

The San Mateo mine is unique in the district in that its ores and all its workings lie in rocks of the Franciscan group. These rocks are dominantly graywacke and shale, but they include a little greenstone, and in the easternmost accessible workings some black limestone. The rocks are in great part highly sheared parallel to their bedding planes, which dip northwest, and in places they resemble *alta* because of the intercalation of layers and pods of greenstone. They are cut by many steep faults, of which the most conspicuous strike N. 55° W. and dip steeply northeast. Along the faults, and locally elsewhere, some of the rocks are silicified and others are argillized. The principal ore bodies lay along the northwest-trending faults. The cinnabar was partly disseminated as small crystals, but part of it occurred in irregular minute veinlets, most of which were in graywacke but some of which were in other types of rock. Narrow veinlets of dolomite accompany the ore, and considerable pyrite is disseminated in the rocks or forms small euhedral crystals in vugs.

Suggestions for further development

The ores of the San Mateo mine were in rocks of the Franciscan group rather than in silica-carbonate

rock like nearly all the other ore bodies in the district, and it may be for this reason that the mine does not seem to have been developed to as great an extent as most of the other productive workings in the district. Judging by the occurrence of large and valuable ore bodies in sandstone of the Franciscan group elsewhere in the Coast Ranges, as, for example, at Oat Hill (Yates and Hilpert, 1946, p. 260-265), this fact alone should not discourage further development. Because of the topographic position of the mine, exploration at depth would have to be carried on by means of drifts from a shaft, which should be located in the midst of the mineralized areas. It would be reasonable to expect that ore bodies of the type already mined would be found along the downward extension of the favorable northwest-trending faults. By comparing the ores with those in rocks of the Franciscan group above the main ore bodies of the Cora Blanca workings in the New Almaden mine, one might infer that there is mineralized silica-carbonate rock below the San Mateo ore bodies, but the lack of any nearby outcrops of silica-carbonate rock or serpentine argues against this speculation.

SENATOR MINE

Location and extent of workings

The Senator mine has been the most productive of the "outside" mines on the New Almaden property, and the only one extensively exploited since the turn of the century. The mine area extends across Los Capitancillos Ridge 3½ miles northwest of Mine Hill (sec. 29, T. 8 S., R. 1 E.), and to the west it adjoins the Guadalupe mine property. (See pls. 1, 14.) The workings, which were totally inaccessible in 1947, are on 15 main levels and are about 21,000 feet in aggregate length. (See pl. 15.) They underlie an area measuring about 2,000 by 1,200 feet, and they explore a vertical interval of about 1,290 feet, from the surface at the crest of the ridge to about 600 feet below sea level. The highest extensive level in the mine, the 100 level, is reached through an isolated adit driven southwest from the northeast slope of the ridge near the Guadalupe property line. The 260 level, which is the most extensive, is in part a real tunnel, with portals on both sides of the ridge; it is reached by the Nones shaft, which extends downward 256 feet from the ridge top. This shaft is also connected with the 125 and 225 levels. Two internal shafts, known as the Working shaft (Old Vertical winze) and the Senator incline, were sunk from the 260 level. The two-compartment Working shaft, which is the older, extended about 263 feet to the 500 level; the Senator incline, which served as the main hoisting shaft of the mine, was sunk 886 feet at an

inclination of about 60° to the 1000 level. From the 1000 level to the 1300 level a two-compartment winze extended downward at an angle of 57°. The stopes in the mine follow the footwall and hanging-wall contacts of a southwest-dipping sill of serpentinite, partly replaced by silica-carbonate rock. The footwall stopes extend downward discontinuously from the 100 level to the 1000 level. The hanging-wall stopes, which lie between the 260 level and the 1200 level, are even less continuous.

History and production

Ore was first found in the Senator mine area (then known as El Senator prospect) near the crest of the north slope of the ridge at some time before 1863, for in that year the mine was reported¹¹ to have already yielded some 60 tons of good ore. In 1863 a new adit, driven to a point 120 feet below the ore-bearing outcrop, also reached ore, but it was abandoned without further mining because of its remoteness from the reduction plant in Almaden Canyon. During the next 46 years the prospect was mined off and on and yielded a small amount of ore. Available records mention a period of activity in 1872 and 1873 that resulted in several hundred feet of drifting and the recovery of at least 6 tons of "fine ore."¹² Further prospecting in 1898 and 1899 developed a little ore in about 1,000 feet of new workings, but the mine was abandoned in 1900.

Systematic development of the Senator mine, which resulted in the recovery of more than 20,000 flasks of quicksilver during the following 16 years, began in October 1909, when E. J. Furst, then superintendent of the New Almaden mine, turned to the Senator mine in the hope of developing some ore to supply the New Almaden furnaces. This hope probably was aroused by a new discovery of ore at the Guadalupe mine, within 600 feet of the New Almaden property. Under the direction of John Drew, who remained in charge of actual prospecting and mining during most of the life of the Senator mine, development was started by trenching the outcrops of silica-carbonate rock at the top of the ridge. Low-grade ore was discovered, and the sinking of the Nones shaft in the trenched area was begun on December 8, 1909. By the end of the following March, much of the 125 level had been driven and ore had been found in its southwestern part. Under the direction of two other superintendents of the New Almaden mining property, development of the Senator workings to the 400 level con-

tinued until 1912. During this period the ore, which was hauled 7 miles to the Hacienda at the foot of Mine Hill for furnacing, averaged 0.75 to 1.0 percent quicksilver and is reported to have yielded about 3,500 flasks. In 1912 the operating company went into bankruptcy and the Senator mine was closed down. By 1915, Mr. George Sexton had obtained a 25-year lease on the New Almaden property and appointed W. H. Landers as general manager.

With the beginning of Landers' management in June 1915, the Senator mine was reopened, an extensive development program was begun, and a modern reduction plant was installed near the north portal of the 260 level to eliminate the long haul to the Hacienda. This reduction plant included the first Herreshoff furnace and electrolytic dust collector ever used in the recovery of quicksilver (fig. 99), and almost from the first it proved to be efficient. After 2 years of successful management Landers was succeeded by Mr. Edmund Juessen, who continued the development of the mine and also added a little-needed 60-ton Scott furnace to supplement the Herreshoff. The Scott was used only 3 weeks, for in May 1919 a wooden ore bin on top of it caught fire and ignited the rest of the reduction plant. Mining nevertheless continued with few interruptions between 1915 and 1926, when the mine was last closed down. During this period the workings were developed to the 1300 level, as shown on plates 15 and 18, but as the sinking of the deep inclines failed to keep pace with the removal of ore, much of the ore was underhanded. The fairly high rate of production maintained from 1915 to the end of 1923 diminished in the next 2 years, and early in 1924 the ore bodies were virtually exhausted. The company then did 1,870 feet of exploratory diamond drilling from the 300, 400, 500, 1000, 1100, and 1200 levels, but failed to find new ore shoots, and on March 11, 1926, the Senator mine was closed down. The record of its production is confused by the inclusion of ore mined at the New Almaden mine, but the total production probably was a little more than 20,000 flasks.

Since 1926 lessees have reworked the dumps, hand sorting the coarser material and using various concentrating devices to recover the fine cinnabar, but the amount of quicksilver they have been able to retort from this concentrated ore has been small. In the summer of 1948 the old Herreshoff furnace was demolished, principally for scrap iron and usable brick, but some of the bricks from the lower part of the furnace lining were found to contain enough quicksilver to justify treating them in a retort.

¹¹ Hawley, C. D., 1864, Unpublished private report on the New Almaden mines prepared for the Quicksilver Mining Co., November.

¹² Schuette, C. N., 1935, Unpublished private report on the New Almaden mine prepared for the Quicksilver Mining Co.



FIGURE 99.—Ruins of the mercury reduction plant at the Senator mine in 1947 shortly before it was dismantled. On right, brick Scott furnace; on left, rusted cylindrical structure is the first Herreshoff furnace used in reduction of quicksilver ore, and, barely visible behind it, is the top of a concrete structure which was the first Cottrell dust precipitator used as a quicksilver plant.

Geology

The following description of the geology of the Senator mine is based on geologic observations made at the surface by our party, geologic maps of parts of the 100 and 125 levels by L. S. Hilpert and G. D. Eberlein, geologic data and mine maps included in a private report by J. H. Farrell¹³ dated October 1923, and the company surveyors' records and superintendents' reports. It was necessary to rely on second-hand sources of information about the geology of the workings, which were all inaccessible during our field investigation. Although these sources are somewhat contradictory in minor details, they agree fairly well in all major features and lead to a structural interpretation believed to be sufficiently accurate to explain the distribution of the ore.

Most of the workings of the Senator mine are in clastic sedimentary rocks of the Franciscan group and three sill-like serpentine bodies with borders of silica-carbonate rock, although the 260 level, which extends far to the southwest of the other workings,

¹³ Farrell, J. H., 1923, Unpublished private report on the Senator mine, October.

also penetrates greenstone tuff of the Franciscan group and another major body of serpentine. (See pls. 16-18.) The only sill that is economically important is the third in order of position from northeast to southwest. The structures of the rocks of the Franciscan group is not fully understood, for no reliable indications of bedding have been observed on the surface and only a few attitudes are recorded on the available mine maps. In general, however, the strike of the beds is N. 50°-80° W. and their dip is 40°-75° SW. The four serpentine bodies which crop out in the area and which are explored underground were injected approximately along the bedding planes of the rocks of the Franciscan group, although some tongues and apophyses break across the beds. As in other parts of the district, these serpentine bodies are enveloped in *alta*.

The most northeasterly of the intrusive bodies is narrow, discontinuously exposed, and of no economic importance. (See pl. 14.) It crops out as a small lens of serpentine extending 1,000 feet northwestward from a point 150 feet N. 35° E. of the portal of the 100 level. Underground it is cut only on the 260

level, about 480 feet from the portal. Although large parts of this sill have been converted to silica-carbonate rock, no ore has been found in it.

The next serpentine sill to the southwest is a comparatively large body, which is barren of ore in the Senator mine, though it contains small ore bodies in the Guadalupe mine. This sill extends northwestward from the Senator mine across the Guadalupe mine property and reaches the canyon of Guadalupe Creek at Shannon Road; it also extends eastward from the mine for about 1,500 feet along the ridge. Within the Senator mine area the sill trends from the Guadalupe property line about S. 55° E., following the crest of the ridge to a point 400 feet southeast of the Nones shaft, beyond which it trends nearly east. Its general dip is about 50° SW., though along certain flexures its dip may vary as much as 25° from that figure. The serpentine body appears to pinch out completely at depth. Its thickness is greatest at the surface, where it has an outcrop width of 270 feet, but on the 260 level it is only 80 feet in horizontal width and its contacts converge downward. The deepest level at which the width of this body is known is the 500 level, where a nearly horizontal diamond-drill hole passed through it within an interval of 100 feet, and a crosscut on the 800 level extends northward beneath the body without striking either serpentine or silica-carbonate rock. These facts, taken together, indicate that the body pinches out a little below the 600 level, and this conclusion is further strengthened by the fact that the northwestward extension of the same body in the Guadalupe mine also appears to pinch out at a slightly lower level (pls. 16-18). The northeast or footwall margin of this serpentine body has been partly altered to a shell of silica-carbonate rock, which the miners refer to as the "No. 1 vein" (pl. 14, section B-B'). It crops out about 400 feet northeast of the Nones shaft, is exposed underground on the 260 level just north of the shaft, and probably is cut on the 125 level about 200 feet from the portal. Although this shell of silica-carbonate rock has been but little explored on the surface and underground, it appears to be barren. The southwest or hanging-wall border of the serpentine body is virtually unaltered except for thin selvages of silica-carbonate rock, penetrated by diamond-drill holes from the 400 and 500 levels.

The third serpentine body in the Senator mine (going southwestward) is important economically, for it is almost completely sheathed with silica-carbonate rock, and this sheath contains all the productive ore shoots that have been found in the mine. (See section B-B', pl. 14.) This body strikes N. 60° W. and

extends as a fairly regular sill from the deepest part of the mine nearly to the surface. At the surface, however, its presence is indicated only by three thin elongate bodies of silica-carbonate rock and serpentine cropping out in the vicinity of the Nones shaft. Underground, where every level in the mine explores this body, its width is well known to the 1000 level, and in the deeper levels its contacts can be inferred from the position of the workings. It is discontinuously exposed at the surface, but in the mine it is nearly 200 feet wide between the 500 and 800 levels, and below the 800 it tapers downward. Wherever it is exposed by the mine workings the serpentine has been extensively altered to silica-carbonate rock all along its periphery, but serpentine cores are preserved between the 125 and 300 levels and between the 400 and 800 levels.

The most southwesterly of the serpentine bodies in the Senator mine area crops out as bulbous body measuring 1200 by 750 feet, and extends northwestward into the Guadalupe property (pl. 14). It is bordered everywhere except on the north by greenstone tuff or by amphibolite derived from tuff. In general it is not altered to silica-carbonate rock, though a few small outlying bodies of that rock crop out within a 300-foot marginal zone to the south. The general dip of the serpentine body can be roughly inferred from the dips of the shear planes within the serpentine; these average about 60° to 65° SW., being steeper than the known dips of the extension of the body in the Guadalupe area. This inference regarding the dip cannot be confirmed by information gained from the records of the driving of the 260-level tunnel; for the records indicate merely that much of the rock along the course of the tunnel was serpentine and *alta*, without giving any exact locations for the contacts. The part of the tunnel lying within 300 feet of the southern portal is reported to have been in "vein" (silica-carbonate rock), but this is probably the downward extension of one of the small masses exposed on the surface.

Ore bodies

The descriptions of the ore bodies included in the following paragraphs are necessarily based on observations of others, including John Drew, who served as foreman of the Senator mine during most of its period of large production. Consequently, although the size, shape, distribution, and general grade of the ore bodies are well known, their geologic character and occurrence are partly inferred.

The ore bodies of the Senator mine were comparable to those of the New Almaden mine in size, but their

average quicksilver content was only about 0.5 percent, as compared with averages of from 1 to more than 10 percent in the New Almaden bodies. Some of the Senator ore was like that taken from the New Almaden mine in having been formed by the replacement of silica-carbonate rock along hilo fractures. Where replacement was extensive the ore is said to have been almost pure cinnabar, and one body of this extremely rich ore found below the 500 level measured 9 by 12 feet in plan and extended 30 feet down the dip. Judging from the dump material and the average grade of the furnace feed, the ore formed by replacement was less abundant than ores formed by the intermittent encrustation of cinnabar during the growth of layered dolomite veins. These veins, which ranged in width up to 14 inches, may be exceptionally large hilos, but they more closely resemble the large northwest-trending veins of the New Almaden mine, which only very locally contain cinnabar, and which, as far as is known, were nowhere mined as ore in the New Almaden mine. It appears likely that the difference in grade between the ores of the two mines results from this difference in the character of most of the ore.

The two main ore shoots of the mine lay in silica-carbonate rock on each side of a serpentine sill, and both sides plunged S. 20° to 30° E. The ore bodies in these shoots had similar horizontal dimensions; most had stope lengths of less than 200 feet, though on the 500 level the footwall stope is nearly 300 feet long. They varied in width from a few feet to as much as 30 feet in exceptional places, the average width being about 15 feet. The mass of silica-carbonate rock on the northeast or footwall side of the serpentine was known to the miners as the "No. 2 vein," and that on the southwest or hanging-wall side as the "No. 3 vein." In vertical dimension the ore bodies in the No. 2 vein were the more extensive, for they cropped out at the surface near the Nones shaft and have been mined to a varying extent on all the levels down to the 1200. The ore bodies in the hanging-wall, or No. 3 vein, have been mined only between the 260 and 1200 levels. No stopes were developed on the 1300 level, and rumors concerning the occurrence of ore on that level are contradictory. Since the geology of that part of the mine can only be inferred, we do not know whether the ore shoots were bottomed or whether they were of such low grade as not to be worth mining. The exploration done in the area appears, however, to have been properly directed to meet the downward projection of the ore bodies found on higher levels.

Suggestions for further development

The geology and history of the Senator mine, so far as they are known, indicate that the ore bodies found were fully exploited and that little marginal ore or stope fill remains in the mine. However, because of the strict economy practiced during much of its development, little lateral exploration was done except on the 260 and 1000 levels, and on the deeper levels where the contacts were followed in driving from the inclined winzes to the ore bodies. It is therefore possible that other ore bodies may lie close to workings and yet have escaped discovery. If so, there is no way of accurately predicting the location of such bodies from the limited geologic data available.

On the other hand, we can suggest a few places where one might mine submarginal ore at times when prices were abnormally high. These are (1) near the surface west of the Nones shaft, along the upward continuation of the ore shoots mined at depth; (2) near the south portal of the 260 level in the small body of silica-carbonate rock reported in the company records to have contained some cinnabar; and (3) below the known ore bodies on the 1300 level or deeper. The first two of these places are readily accessible from the surface and may easily be tested, but the last would be hard to reach because of caving, and probably would not be worth testing unless the mine were also reopened for further lateral exploration on the intermediate levels.

GUADALUPE MINE

The Guadalupe quicksilver mine is in the valley of Guadalupe Creek and along the adjacent Los Capitancillos Ridge in the west-central part of the New Almaden district. The property, which includes about 1,800 acres in the northeastern part of sec. 30, T. 8 S., R. 1 E., Mount Diablo base and meridian, is owned jointly by the estate of Mrs. J. S. Gregory, the law firm of Young, Hudson, and Rabinowitz of San Francisco, and the law firm of McKee, Tashiera, and Wahrhaftig of Oakland. In 1948 it contained several dwellings and a modern reduction plant with a rotary furnace having a daily capacity of 60 to 80 tons.

The total recorded production of the Guadalupe mine to the end of 1947 is 92,623 flasks. If we add the 20,000 flasks reported to have been produced between 1854 and 1875 (Bradley, 1918, p. 156-157) but not recorded, the total claimed production comes to more than 112,600 flasks, and places the Guadalupe mine sixth among California quicksilver mines. Like many other old quicksilver mines in the Coast Ranges,

it has been operated intermittently, and it yielded two-thirds of its entire output during the the second of its four main periods of production. (See table 17.)

TABLE 17.—*Annual production of the Guadalupe mine, Santa Clara County, Calif.*

Period of productivity	Year	Flasks of quicksilver
First.....	1846-1874.....	20,000, estimated
	1875.....	3,342
	1876.....	7,381
	1877.....	6,241
	1878.....	9,072
Second, 1875-85.....	1879.....	15,540
	1880.....	6,670
	1881.....	5,228
	1882.....	1,138
	1883.....	84
	1884.....	1,179
	1885.....	35
	1901.....	960
	1902.....	764
	1903.....	800
	1904.....	609
	1905.....	300
	1906.....	311
	1907.....	208
	1908.....	191
	1909.....	1,552
	1910.....	2,400
Third, 1901-22.....	1911.....	5,000
	1912.....	6,100
	1913.....	2,400
	1914.....	1,413
	1915.....	2,910
	1916.....	1,679
	1917.....	3,100
	1918.....	1,476
	1919.....	616
	1920.....	342
	1921.....	35
	1922.....	48
	1930.....	6
	1931.....	—
	1932.....	47
1933.....	8	
1934.....	14	
1935.....	—	
1936.....	52	
1937.....	65	
Fourth, 1930-47.....	1938.....	50
	1939.....	120
	1940.....	262
	1941.....	210
	1942.....	188
	1943.....	267
	1944.....	411
	1945.....	705
	1946.....	965
	1947.....	129
Total recorded production 1875-1947.....		92,623
Total production 1846-1947.....		112,623

known of the early development of the mine except that at some time before September 1850 an adit had been driven; a property conveyance of that date refers to the mine entrance as an established landmark (U.S. Supreme Court, 1857). After September 1850, when California was admitted into the Union, the ownership of the mine property, claimed by several groups on the basis of Spanish land grants, was tested by a series of lawsuits, which resulted in the awarding of the property first to one and then to another mining company. In 1854 the mine was being worked by the Santa Clara Mining Association of Baltimore, Md.,¹⁴ and the same company continued to work it until 1875. No complete production records for this period are known, though records of the California State Division of Mines (Ransome and Kellogg, 1939, p. 360) credit the mine with a production of 1,175 flasks in 1857 and 1,654 flasks in 1866. These figures, however, probably represent productive peaks, for the total estimated production during the period from 1850 to 1875 was only 20,000 flasks.

In 1875 the Santa Clara Mining Association was thoroughly reorganized and began a \$750,000 development program, which included the erection of 4 new Scott furnaces of 50 tons daily capacity, surface improvements, and extensive underground exploration. From then until 1884 the Guadalupe mine was in its hey-day; in 1879 it reached an alltime peak production of 15,540 flasks, only 4,974 flasks less than that of its neighbor, the New Almaden mine. Much of the large income resulting from this production seems to have been put back into development, for during this 9-year period the Old Mine south of Guadalupe Creek was fully developed, and north of the creek the Old Hill and Moreno areas were explored. Large-scale operation in the Old Mine virtually ceased late in 1882, though the mine was again worked during a 7-month period in 1884, when 1,353 flasks of quicksilver was extracted from ore taken from the old stopes. With the decrease in the price of quicksilver after 1880 to around \$30 a flask, this latest operation did not prove profitable; the production of the entire mine fell rapidly, and in 1886 the mine was closed down. A 14-year period of idleness accompanied by litigation followed, and the title passed first to the Coleman estate and later to James Coleman.

Late in the fall of 1889 a working lease and option with a sale price of \$250,000 were given to Hugh C. Davey and William Spiers, who early in 1900 formed the Century Mining Co. This company remodelled the furnaces to obtain a capacity of 80 tons of fine

¹⁴ Gould, H. W., 1925, Unpublished private report on the Guadalupe mine, November.

History and production

The early history of the Guadalupe mine is scantily recorded, and the available records are somewhat contradictory. The ore deposits were probably first recognized by Josiah Belden, who is said (Irelan, 1888, p. 542) to have encountered cinnabar-painted Indians along Guadalupe Creek in 1846. Little is

ore and 40 tons of coarse ore per day, began unwatering the old mine through the Engine shaft, and resumed mining on a modest scale. In 1906 the company was reorganized under the name of the New Guadalupe Mining Co., with Davey as president, and within 2 years it brought the productive rate of the mine up to a relatively high level that was maintained until 1918. During this period the New, or Guadalupe, Inclined shaft was sunk and workings were driven from it, the Old Hill mine and neighboring areas were further developed, and the north slope of Los Capitancillos Ridge was explored for the first time by several adits and pits. While all this development was under way on the ridge, an attempt was being made to unwater the old mine south of the creek; but it proceeded slowly because of the copious seepage from Guadalupe Creek. To overcome this difficulty, the company in 1917 lined the creek bed with a concrete flume 740 feet long and 55 feet wide, and with side walls 9 feet high. In 1920, however, when the mine was unwatered only to the No. 7 level and the stopes were still inaccessible, the pumps failed, and unwatering of the old mine was abandoned. In 1922 the entire mine was closed down after a third period of activity had yielded 33,214 flasks. During the inactive period which followed, the title first passed to Mrs. J. S. Gregory by legal action, and then in 1927 it became the property of Albert and Frank Golden. In 1930 a little quicksilver was recovered through retorts by a lessee, Hernandez, from a cleanup of the Scott furnaces.

In 1935 the Laco Mining Co., composed of H. N. Mason, George F. Kirk, and others, obtained a lease from the Golden brothers, and after building a small retort it began the fourth period of production from the mine by reworking some of the old dumps. When in 1937 the Golden brothers lost a lawsuit to Mrs. J. S. Gregory, the Laco Mining Co. obtained a lease from her. They then constructed four additional two-pipe retorts near the Guadalupe incline shaft, and in 1943 installed the modern reduction plant. In the same year the discovery of a new body of ore at the surface between the new plant and the Guadalupe Inclined shaft led to openpit operations, which yielded most of the ore furnaced during the next 4 years; some additional ore was obtained, however, from the upper workings connected with the shaft, from the Kelly and New Prospect areas near the crest of the ridge, and from the old dumps. In 1947 the Laco Mining Co. gave up its lease, after having recovered only 3,499 flasks during its 12-year period of operation, and in 1948 the mine was again idle.

A comparison of the mine's annual production with the annual price of quicksilver indicates that the more significant peaks in production have resulted largely from favorable conditions within the mine rather than from increases in the price of quicksilver. The greatest period of production, however, from 1875 to 1881, apparently was terminated by an abrupt decrease in price before 1880. The second productive peak, in 1912, was brought about by the discovery of new ore deposits, though production during the latter part of this period may have been stimulated by the price rise during World War I. The comparable increase in the value of quicksilver during World War II gave rise to only a relatively small annual production, which, however, was several times that of the years between the wars.

Mine workings

The workings of the Guadalupe mine consist of about 30,000 feet of level workings, 5 main shafts, more than a dozen stopes, and several thousand square feet of openpits that lie within an area of a little more than a quarter of a square mile. (See pl. 15.) The mine is sharply divided into two parts—a compact older group of underground workings lying mainly south of Guadalupe Creek and known as the Old Mine, and the newer more scattered workings underlying Los Capitancillos Ridge north of the creek.

The older part of the mine was inaccessible when the field investigation leading to this report was made. It was originally developed through 5 vertical shafts and 1 inclined shaft, all put down near Guadalupe Creek. The largest of these was the three-compartment vertical Engine shaft, sunk from a terrace 30 feet above the creek to a depth of 620 feet, where it bottomed on the No. 6 level. From this level an inclined winze extended to a depth of about 830 feet below the creek bed, or 464 feet below sea level, to the No. 10 level, the deepest in the mine. The other vertical shafts, known as the Maryland shafts Nos. 1 and 2, the Virginia shaft, and the Lamb shaft, connected the extremities of some of the upper drifts with the surface. The collar of the Old Inclined shaft was on the north bank of the creek near the bridge, and its bottom on the No. 2 level nearly 300 feet southwest of the collar and 280 feet lower. The level workings from these shafts total about 13,000 feet in length and consist of 14 main levels, although only the lower 11 of these are numbered. The vertical intervals between levels do not exceed 100 feet, and some are considerably less. As shown on the old company maps and cross sections nearly all the levels

are connected by stopes. (See pl. 15 and section A-A', pl. 14.)

In the newer parts of the mine there are 17,000 feet of underground workings, widely distributed beneath the crest and southern slope of Los Capitancillos Ridge. (See pls. 14, 15.) Most of the workings lying more than 300 feet above sea level were accessible when this study was made, but most of those below that level were inaccessible. In 1942, however, when the pumps were working in the Guadalupe Inclined shaft, a Survey field party was able to reach the 200 level, which is only 235 feet above sea level. Most of the newer workings were reached through adits, but four important levels and connected stopes were accessible only through the New Guadalupe Inclined shaft. The collar of this shaft is 504 feet above sea level, and it bottoms on the 300 level at an altitude of about 90 feet. The most extensive workings from it are on the 100 level; these extend 600 feet southwest from the shaft to reach the surface near the camp, and 1,300 feet northeast to points under the New Prospect tunnel area. Most of the other adits lie between 420 and 530 feet above sea level and were driven northeastward into the ridge along a zone extending 1,000 feet northwest of the shaft, but a small group of adits were driven southward into the north slope of the ridge at altitudes of 600 to 670 feet.

Other important parts of the newer mine workings are the open pits, which are clustered in two areas. One area, which extends northwestward from the modern reduction plant for about 1,200 feet, includes at its southeastern end the pit from which the greater part of the ore mined in recent years was taken. This pit, which is about 220 feet long, 60 feet wide, and 60 feet deep in its deepest part, is connected by a raise with the 100 level from the New Guadalupe Inclined shaft. The other cluster of pits lies on the north slope of Los Capitancillos Ridge near its crest and extends for about 800 feet parallel to the trend of the ridge. Most of the pits in this area are shallow bulldozer cuts, but the two known as the Kelly cuts are larger. The western one of these is 125 feet in diameter and 25 feet deep, whereas the other is only 80 feet in diameter but nearly 60 feet deep on its upslope side. One other large pit, known as the Office Mine pit, lies outside the two main areas of opencuts, between the reduction plant and the bridge across Guadalupe Creek.

Geology

The dominant geologic feature of the Guadalupe mine area is a complex composite serpentine body, which is intrusive into deformed clastic sedimentary

rocks and greenstones of the Franciscan group. The general strike of this irregular intrusive body is N. 55° W., roughly conformable with the strike of the rocks of the Franciscan group (pl. 14), and its southwesterly dip of 35°-50° also is probably parallel to that of these rocks. (See pl. 14.) The intrusive body is therefore roughly sill-like, but in its surface exposure it is split lengthwise by two narrow highly irregular but roughly wedge-shaped septa of graywacke, which nearly converge in the area northwest of the New Guadalupe Inclined shaft. The eastern septum, which extends beyond the Senator mine, does not dip gently southwestward with the sill, but appears to extend downward almost vertically, thus separating a rootless northern serpentine body from a more sill-like southern body. The marginal parts of this complex serpentine body, which have been hydrothermally converted to silica-carbonate rock, have contained most of the ore. A little additional ore, however, was obtained from a landslide of brecciated silica-carbonate rock near the crest of the ridge.

The southern part of the intrusive body crops out as a band of serpentine and silica-carbonate rock that extends through the camp area along the southwest base of Los Capitancillos Ridge and slants upslope to the southeast. Underground these rocks were extensively explored by the now inaccessible workings of the old mine. (See pls. 16-18.) The upper surface of the serpentine body is fairly well delineated by the workings of the old mine that apparently followed it, but the position of the lower surface is known in only a few places. In general, however, the body is a sill about 500 feet thick with extensive shells of silica-carbonate rock along both sides. The character of the silica-carbonate rock formed along different parts of the intrusive mass in the mine area varies from place to place, even though the serpentine shows no apparent variation, being all sheared and bouldery. The silica-carbonate rock formed along both borders of the southern serpentine mass contains a relatively high proportion of carbonate, and is cut by a large number of steep northeastward-trending carbonate-quartz veins or hilos. These hilos, which are exceptionally abundant where the northern and southern serpentine masses coalesce, were of great importance in localizing ore bodies, though in some places the localization was also affected by rolls and irregularities in the shape of the hanging-wall contact. (See fig. 89.)

The northern part of the composite intrusive body crops out along the crest and upper southwestern slope of the ridge from a place beyond the northwest corner of the Guadalupe mine area to the Senator mine area. (See pl. 14.) The extent of this northern body at

depth can be determined only as far down as the 200 level; here the body appears to be much narrower than at the surface, and in the central part, at least, of the mine area it apparently pinches out completely near the 300 level. To the southeast, in the Senator mine, the extension of the same serpentine body also pinches out, at a slightly lower level. The entire northwestern part of the serpentine body is altered to silica-carbonate rock, and so are parts of the margins of the rest of the mass. The silica-carbonate rock along the southern margin is rich in carbonate like that along the southern part of the entire intrusive complex; but that along the northern margin is generally hard and flinty, apparently contains little carbonate, and is cut by only a few thin carbonate veins. In general this siliceous type of silica-carbonate rock seems to be unfavorable for ore deposition, though a few small ore bodies have been found in it at depth.

A landslide, containing brecciated silica-carbonate rock, that lies near the crest of the ridge requires more lengthy description, not because of its economic importance, which is small, but because it contains some unusual conglomerates and breccias not found elsewhere and not previously described in this report. The breccia, which covers an area of about 360,000 square feet, is explored by the Kelly workings, the New Prospect tunnels, and other shallow cuts. On the surface it is similar in general appearance to some of the blocky outcrops of silica-carbonate rocks found elsewhere in the district, but in cuts and underground workings where it is better exposed it is clearly seen to have a different structure. It is made up of fragments that are angular to subangular and range in diameter from several feet to a small fraction of an inch, with all sizes about equally well represented. There is no matrix, for the smaller fragments are packed in solidly between the nearly equidimensional larger blocks. Scattered through this breccia are a few carbonate veins filling straight fractures; and carbonate fills irregular cracks and cavities between the angular fragments.

A second unusual rock in the area is another type of breccia, similar in texture to that just described but of different composition. It was observed only in the New Prospect tunnels, where it consists of angular fragments of graywacke and shale of the Franciscan group embedded in a matrix of buff to light-brown clay. The largest fragments do not exceed 18 inches greatest diameter, and most are no more than a few inches long.

A third unusual lithologic unit is an unconsolidated pebble conglomerate believed to be of late Tertiary age. This rock is well exposed in only two places,

both near the north edge of the area. The first is at the portal of the middle New Prospect tunnel, where it forms a 2-foot bed overlying arkose of the Franciscan group and overlain by highly sheared weathered serpentine. For at least 300 feet west and north of the adit, scattered pebbles from the conglomerate may be found on the surface close to the serpentine contact, but there are no real outcrops in this area. The second place is in the Kelly tunnel, 800 feet northwest of the New Prospect tunnels, where a 5- to 6-foot bed of the conglomerate lies above greenstone and below silica-carbonate rock, from which it is separated by a low-angle shear. The conglomerate has a sandy matrix and contains a mixture of pebbles and cobbles of graywacke, siltstone, greenstone, and chert of the Franciscan group, considerable serpentine, and a few well-rounded pebbles of soft ocherous sandstone similar to the Upper Cretaceous sandstone of the Santa Teresa Hills. It is poorly bedded, and in the only two exposures it has widely different attitudes. We believe it to be of late Tertiary age, but on no more definite evidence than its unconsolidated character and its geologic occurrence.

The origin and structural relations of these unusual units could not be determined with certainty from their limited exposures. In general the breccias, as exposed in the adits, dip gently southwestward into the ridge, and at some places in the New Prospect tunnels they are overlain by rocks of the Franciscan group. Diamond-drill holes extending downward from the crest of the ridge in the Kelly area have reached the base of the brecciated silica-carbonate rock, and they indicate that it forms a flat-lying roughly lenticular body having a maximum thickness of about 75 feet. The character of the material and its general distribution suggest that it may be a remnant of a late Tertiary(?) landslide which migrated from the southwest when the ridge was somewhat higher and overlapped a late Tertiary terrace deposit.

Ore bodies

The chief ore mineral of the Guadalupe mine is cinnabar, though a little native mercury was found on the No. 8 level of the Old Mine and possibly elsewhere. In character and occurrence the ores were like those in the other large mines in the district: the cinnabar was deposited in and beside hilos cutting through silica-carbonate rock, and was especially abundant where the hilos were closely spaced or were near the intrusive contacts. The grade of the ore probably varied considerably, even within a few inches, and since hand sorting in the early days resulted in the discarding of rock that in more recent

years would have been furnaced, it is not possible to judge closely the relative quality of the ore bodies found in the various parts of the mine. It is evident, however, that the ore bodies, though they would be considered rich at present, were not quite so rich as those of the New Almaden mine. According to available records, the richest ore in the Guadalupe area was found in the Old Mine, where large ore bodies yielded from 2 to 5 percent mercury. Other large ore bodies found adjacent to the New Guadalupe Inclined shaft averaged from 6 to 12 pounds of mercury per ton, and the surface pit above some of these yielded, in recent years, about 6 pounds of mercury per ton. The brecciated silica-carbonate rock near the top of the ridge included 5-inch pieces of ore containing as much as 40 percent quicksilver, but the average grade of the ore mined from the breccia was probably not more than 1 percent.

The ore bodies fall naturally into four groups lying in different structural environments, and these groups will be discussed in turn. The structures and the workings that explore them are (1) the hanging-wall side of the southern serpentine body, explored by the workings of the Old Mine; (2) the area of coalescence of the two serpentine bodies, explored chiefly by the levels from the New Guadalupe Inclined shaft and the adits to the northwest; (3) the footwall of the northern part of the serpentine, explored chiefly by the northern parts of the 100, 200, and 300 levels from the New Guadalupe Inclined shaft and the East Hill-top workings; and (4) the landslide area, explored by the New Prospect and Kelly workings.

The largest and richest ore bodies in the Guadalupe mine were those lying along the hanging wall of the southern intrusive mass, explored by the Old Mine workings. These lay close to the intrusive contact, in a continuous shell of silica-carbonate rock which in places is at least 150 feet thick, and they extended along the strike, according to the memory of one miner,¹⁵ beyond the limits of all the levels. The greater part of the ore came from two great stopes or labors—the Thayer Labor and the Dore Labor. The Thayer Labor plunges from the No. 11½ level west of the Engine shaft S. 30° E. to a place on the No. 6 level east of the shaft. Below the No. 6 level ore bodies were mined in several small stopes, but at the No. 7 level these merge into the Dore Labor, which continues down nearly to the No. 9 level, still plunging southeastward but becoming much flatter. The southernmost part of this stope is shown only vaguely

on available maps, but it appears to lie a little higher than the flat part to the north. In the uppermost part of the mine above the 1½ level the ore bodies were scattered and were mined in several small stopes adjacent to the Old Inclined shaft.

The reason for the localization of the ore bodies in this part of the mine are obscure because of the inaccessibility of the workings, but some interpretations may be made on the basis of the positions of these workings. The major ore bodies appear to have lain along the hanging wall of the serpentine sill just northeast of its intersection with a steeply dipping contact, which may or may not be a fault, separating greenstone from graywacke. This contact strikes nearly northwest rather than west like the upper surface of the sill, and its intersection with the south-dipping sill results in the N. 30° W. elongation of the ore bodies. The position of this contact from the No. 1½ level to the No. 6 level is indicated by abrupt northward swings in the western parts of the levels, bringing the lower levels beneath the upper levels. In the deeper workings, it is suggested by short branching drifts from the main workings on the No. 7, 9, and 10 levels and by the southwestern margin of the Dore Labor. The nature of the contact is not known, but if it is a fault separating greenstone from graywacke, as seems likely, it is so poorly exposed on the surface that it was nowhere recognized there as a fault. However, the fact that the graywacke, which has a wide surface exposure, gives way at depth to greenstone as the hanging wall for the ore bodies lends support to the fault hypothesis. A further structural control for the ore body mined in the Thayer Labor may have been effected by the slight bowing of the contact, as indicated by the position of the No. 2, 3, 4, 5, and 6 levels, and at greater depth by a structural nose near the No. 8 level, though on this level the apparently irregular shape of the serpentine cannot be deduced with certainty from the position of the workings. The bottoming of the ore above the No. 9 level nearly coincided, according to reports, with the change of the hanging wall from greenstone to what was known by the miners as the "lime ledge," which was limestone of the Franciscan group. However, a change in the shape of the intrusive body may have been more effective than a change in the wallrock in preventing the deposition of cinnabar.

The ore bodies in the area of coalescence of the two parts of the serpentine body, explored by workings from the New Guadalupe Inclined shaft and the adits to the northwest, were neither as large nor as rich as those of the old mine. They lay in silica-carbonate rock derived from the serpentine between the ends of the

¹⁵ Conversation with Mr. Alberto Garcia of Gilroy, California, who was employed at the Guadalupe mine during the period 1876-86.

two septa of graywacke and along other small inclusions of rocks of the Franciscan group, and, consequently, they were not localized along an extensive hanging wall or footwall. In the Mason stope and the pit above, however, a relatively thin inclusion of country rock acted as a footwall, and in the Water, Moreno, and McGurk stopes there are isolated exposures of *alta*. The ore bodies appear to have been formed in the silica-carbonate rocks at places where steep northeastward-trending hilos are abundant, and they were richest where the hilos are closely spaced. The mineralized zone, though it extended along the surface for a distance of 1,200 feet, has been followed downward for only about 200 feet. The deepest ore body yet found along this zone extended up from the intersection of the New Guadalupe Inclined shaft with the 150 level, but the rest of the mineralized zone has not been extensively explored even down to this relatively shallow depth.

The ore bodies in the silica-carbonate rock that borders the northern or lower contact of the northern part of the serpentine have been mined in stopes from the 100, 200, and 300 levels by way of the New Guadalupe Inclined shaft and in the East Hilltop workings. These bodies were small, erratically distributed, and about as rich as the ore bodies mined near the shaft. The largest was mined in the No. 2 stope, which extended from near the surface at the Air shaft down almost to the 100 level. It lay in silica-carbonate rock more than 50 feet from the contact, under a shear that dipped northward toward the south-dipping footwall, and the inaccessible stope on the 300 level appears to have been similarly situated. In contrast, one small body of ore was found right against the footwall contact below the 100 level, close to the downward continuation of the No. 2 stope. Hilos were abundant in all these ore bodies, and they may have been important in localizing the ore, although this silica-carbonate body is so little explored that hilos may, for all we know, be as abundant elsewhere. The silica-carbonate rock containing the ore bodies was of the carbonate-rich variety, which contains ore elsewhere in the mine, but where the extension of the same body of silica-carbonate rock reaches the surface it is of the silica-rich variety, which is apparently unfavorable for ore deposition. At depth extensions of this footwall mass of silica-carbonate rock may well contain undiscovered ore bodies. Those that have been discovered were found largely by chance, for even the largest of them was not extensive and was not localized along the footwall contact; a systematic search for additional ore bodies near this

contact, therefore, would probably entail prohibitive expense.

The ore mined from the landslide of silica-carbonate rock breccia in the Kelly workings and in the shallow pits to the southwest was unique in the district. It contained small angular pieces of very rich ore scattered through a breccia that consisted mainly of barren silica-carbonate rock, and in places the interstices in the breccia contained native mercury. The fragments of ore were not equally distributed through the breccia, but were concentrated in certain parts that were several tens of feet in length. According to G. F. Kirk (oral communication, 1947), one of the operators, these rich parts were marked by thin films of a yellow mineral, apparently a solid hydrocarbon, that was used as a guide to the ore concentrations. One of these concentrations, mined in a glory hole 28 feet in diameter and 18 feet deep lying above the Upper Kelly workings, averaged between 1 and 2 percent quicksilver. The average quicksilver content of the entire breccia mass, however, as determined by samples taken by the U.S. Bureau of Mines (Bedford and Ricker, 1950, p. 6, 7-9), is between 2 and 3 pounds per ton.

Suggestions for further development

Further development of the Guadalupe mine might be directed toward finding new ore bodies and recovering quicksilver from stope fill or dumps.

The most favorable area for the discovery of new ore bodies lies beneath the old stopes and cuts extending northwest from the New Guadalupe Inclined shaft below an altitude of 400 feet. This area, as yet almost unexplored, may reasonably be expected to contain ore bodies localized along swarms of hilos. Judging by the positions of the ore bodies already found, near the surface new ore bodies are most likely to be in the silica-carbonate mass tens of feet from the contact, and at greater depth they would probably dip southward along the footwall of the southern part of the serpentine. In two other places on the surface near the New Guadalupe Inclined shaft small quantities of ore could probably be obtained with little effort. The first of these is an extension of the ore mined in the large pit east of the shaft, where ore on and behind the north wall has been left because of the hazard involved in attempting to remove it from the base of the overhanging cliff. The other place offering promise is in the mass of silica-carbonate rock extending under the modern furnace building; this rock is reported to contain some cinnabar near the surface but remains unexplored. Still other places where ore might be developed are (1)

above the No. 1½ level of the Old Mine, up the plunge of the ore body mined in the Thayer Labor, and (2) beneath a point 100 feet southwest of the East Hilltop workings, where there appears to be an arch in the footwall contact.

Some stope fill and low-grade ore probably remain in the Old Mine in the Thayer and Dore Labores. These were reworked for the last time in 1884, and the material then taken out failed to yield a profit with quicksilver priced at about \$30 per flask. At times of high prices this material might possibly be mined at a profit, especially if the old dumps and the silica-carbonate rock breccia on the crest of the hill were also utilized to support a large-scale low-cost furnace operation.

SANTA TERESA MINE

The Santa Teresa mine is near the crest of the north slope of the Santa Teresa Hills, close to the 957-foot summit and about 3.5 miles N. 30° E. of the summit of Mine Hill. (See fig. 2.) It is one of the two small mines developed many years ago on the mineralized belt lying north of the main ore zone on Los Capitancillos Ridge. As it has been inactive for more than a score of years, it is virtually inaccessible, and its present ownership is not known.

The mine was active and apparently had been developed nearly to its present state when it was examined by Forstner (1903, p. 186-187) in 1902. His report includes a sketch map, which shows 3 main adits within a vertical interval of about 300 feet and 2 connecting shafts. The aggregate length of these workings is reported to be about 2,000 feet.

A lens of silica-carbonate rock is explored by the various workings of the mine. At the surface the lens is separated by a septum of sediments from a larger body of serpentine to the north, but underground it apparently forms the southern border of the serpentine. The lens dips steeply northward, and is at least 90 feet thick where it is explored on the intermediate level. It is described by Forstner as being cut by many quartz-carbonate veins that contain numerous vugs, and doubtless the ore occurred in and along these veins.

The property was equipped in 1903 with a 40-ton Scott furnace (Bradley, 1918, p. 167), and in that year the property had a recorded production of 9 flasks of quicksilver. No other production is recorded, and further exploration seems unwarranted.

BERNAL MINE

The Bernal mine is at an altitude of about 600 feet on the north slope of the Santa Teresa Hills, about

1 mile east of the Santa Teresa mine. (See fig. 2.) Its production is not recorded, and its present ownership is not known.

The mine is an old one, for Forstner (1903, p. 171-172) described most of its workings in 1902. These workings consist of 2 shafts, reported to be 65 and 20 feet deep, a 215-foot adit driven nearly 200 feet below, and another driven somewhat more recently to a point about 10 feet under the bottom of the shallower shaft. Very little is known of the early history of the mine, but probably a small amount of quicksilver was recovered from its ores by the early operations. In 1942, 4 drill holes, none of them more than 200 feet long, were put down from the surface into the ground below the shafts. In 1946 the shallower adit was extended to the area below the shaft, and a retort was installed at its portal. In 1947 the mine was idle, and no quicksilver appears to have been recovered in the retort.

The shafts explore a very thin nearly vertical lens of silica-carbonate rock which is crossed by several north-trending 1-inch veins of quartz and dolomite. Some of the veins exposed in the shallower shaft contain showy patches of cinnabar, which if present in quantity would form good retort ore. These veins, however, are thin and barren where they are cut in the adit below the shaft, so that further development is probably not worth while.

PLACER CINNABAR DEPOSIT

A remarkable placer deposit (Bailey and Everhart, 1947, p. 77-79) containing detrital nuggets of cinnabar was found just north of the dump of burnt ore at the Hacienda, where Deep Gulch joins Almaden Canyon. The deposit was accidentally discovered by H. F. Austin while he was sinking a shaft to bedrock to search for native mercury, which commonly leaked downward from the old brick Scott furnaces and came to rest on the bedrock. With a few associates he worked the placer deposit from the fall of 1945 to the winter of 1947, recovering about 600 flasks of quicksilver.

The stream gravel of the area averages about 20 feet in thickness and is composed of 2 layers, which can be distinguished by their color and pebble content. The upper layer, which is in places as much as 15 feet thick, has a yellowish cast due to iron staining, and as it contains many boulders from Upper Cretaceous conglomerates of the Sierra Azul washed down from the upper parts of Almaden Canyon, it is believed to have been derived almost entirely from the Almaden Canyon drainage area. The lower layer of gravel, which contains almost all the nuggets, is blue-

gray, lacks the conglomerate boulders, and apparently was derived from the Deep Gulch drainage area. The cinnabar nuggets were concentrated in the lower few feet of this gravel and were most abundant just above the bedrock.

The cinnabar nuggets are of exceptional size and purity. The largest one recovered was nearly as large as a man's head, nuggets with a maximum diameter of 3 inches were not uncommon, and probably the majority were between $\frac{1}{2}$ and $1\frac{1}{2}$ inches in diameter. Very little of the cinnabar would be classed as "fines." Nearly all the nuggets were at least subrounded, and most were well rounded, although they tended to be somewhat flat. The content of cinnabar was amazingly high. Many of the nuggets appeared to contain more than 90 percent cinnabar, and their average content, as determined by retort recovery, was about 75 percent cinnabar.

The original source of the cinnabar must have been the outcrops near the summit of Mine Hill. The apparent reason for the concentration of the nuggets at the junction of the 2 canyons is the difference in the carrying capacity between the stream flowing down Deep Gulch, with a gradient of 1,000 feet per mile, and that in Almaden Canyon, with a gradient of only 50 feet per mile. The marked absence of "fines" in the deposit indicates that the fines were washed on down Almaden Canyon, and minute grains of cinnabar can be panned from the stream gravels at least as far downstream as the junction of Guadalupe and Alamitos Creeks, about 7 miles below the placer deposit.

The gravel deposit was mined by dragline, which loaded the productive gravels directly into trucks. These moved the material a few hundred yards to a washing plant consisting of a 4-foot by 24-foot trommel, a jig, and a sorting belt. The muddy gravel was slowly fed into the trommel, where it was washed by a copious spray of water. The washed material more than an inch in size was fed onto a sorting belt, from which a few men, usually two, picked the bright-red nuggets. The finer material was passed through a jig that recovered the pieces down to about one-eighth of an inch in diameter. The nuggets and finer concentrates were treated in a D-retort, and because of the high grade of the ore it was found necessary to add about 60 pounds of lime to each charge to oxidize the large amount of sulfur.

The placer deposit appears to have been mined nearly to exhaustion up Deep Gulch, though other small pockets of nuggets are known to remain in places farther up the gulch where there is a sharp change in gradient. The extent of the deposit down-

stream cannot be determined accurately. The operator stopped mining in that direction as soon as the work failed to be profitable, but he believed that he had then lost the main channel. As the size of the nuggets had not materially decreased down to the point where he quit, either the channel was wider there than upstream, so that the nuggets were less concentrated, or else the gradient of the bedrock was slightly steeper, so that many nuggets travelled beyond that point. In either case, there can be little doubt that the stream gravels in Almaden Canyon below Deep Gulch still contain a large amount of alluvial cinnabar. The nuggets cannot be expected to be as concentrated as at the mouth of Deep Gulch, but if local concentrations, due to changes of gradient or to a bend in the stream—as at the point of emergence of the canyon onto the valley floor—can be found they might be mined at a profit during times of high quicksilver prices.

FUTURE PRODUCTION

The outlook for additional production of quicksilver from the New Almaden district must be considered to be poor if predictions are based on the present showings or the record of diminishing production. But from a geologic viewpoint, the outlook is promising. Whether or not the district is again brought up to a high level of production will depend upon several factors, among which are the enterprise of the operators of the mines and the capital available for exploration, the price of quicksilver, and the validity of our conclusion that the district yet contains undiscovered ore bodies.

Continuation of the practice of the past 40 years whereby attempts are made to take ore from the mines without new exploration, and especially without well-planned exploration on a sound geologic basis, may be expected to yield only a very small amount of quicksilver, except possibly during short periods when the price of quicksilver is abnormally high. Conversely, if the mines are developed by a well-planned exploration program enough new ore bodies may be found to bring the mines back to a state of uninterrupted operation and to maintain production at a moderately high level for many years.

The operation of the mines, of course, depends directly on the price of quicksilver as compared with operating costs. The price of quicksilver had fluctuated about 300 percent in the 10 years that preceded the preparation of this report, and when the first draft of this report was written (1948) it was at the low level of about \$70 per flask. If price index is taken into account, this is nearly the equivalent of the lowest price obtained during any part of the 100

years of production in the district. Even at such a price, however, ore bodies similar to those that have been mined in the past could be profitably mined under present conditions, because technologic advancements have appreciably increased mining efficiency and lowered reduction costs. The average ore taken from the New Almaden mine contained about 1 flask of quicksilver per ton, or 4.0 percent, and the ore from the Guadalupe mine was nearly as rich. Even with quicksilver priced at only \$70 per flask and mining and reduction costs normal, 1 percent ore can be mined and furnaced at a profit; and if large ore bodies equal in grade to those that have been mined can be found the margin of profit would allow considerable expenditure for further exploration.

It also seems reasonable to expect that the price of quicksilver will increase to its former high level at some future date, owing either to the unavailability of quicksilver from outside the United States or to legislation. At such a time some of the submarginal ore and dump material in the district could be treated, even without spending money on further development or exploration of the mines. In this way the district can produce a small amount of quicksilver at times of high prices with relatively small expenditure or risk. But the district is believed to be equally capable of yielding much larger returns on the greater expenditure and risk involved in seeking new ore bodies. Some places known or reported to contain submarginal ore that could be mined at times of high prices for quicksilver will now be pointed out, and an attempt will then be made to show where new ore bodies might be found along totally unexplored structures or along unexplored parts of structures that contained ore elsewhere.

SUBMARGINAL ORE

Known submarginal ore in the New Almaden district consists of low-grade ore in place, stope fill, and old dumps containing large tonnages of material rejected in the days of plenty. During World War II, when quicksilver prices were high, such material provided a considerable part of the district's production. At the New Almaden mine nearly all the known accessible stope fill and dump material containing more than 2 pounds of quicksilver per ton was utilized, and, at the Guadalupe mine, dumps sampled by the U.S. Bureau of Mines (Bedford and Ricker, 1950, p. 5-9) provided part of the ore treated in the rotary furnace.

Even larger amounts of stope fill and low-grade ore in place are believed to remain in the now inaccessible parts of the mines. This belief is based on the written records of the mine superintendents or the known

cutoff limit at the time when stopes became inaccessible. In general, however, this low-grade material is so situated that it cannot be profitably removed, except during a protracted period of exceptionally high prices for quicksilver.

Sampling of the landslide mass of silica-carbonate rock breccia near the Kelly cuts of the Guadalupe mine (pl. 14) is reported (Bedford and Ricker, 1950, p. 5-9) by the U.S. Bureau of Mines to have indicated 34,400 tons of ore containing 2.33 pounds of quicksilver per ton, on the conservative assumption that the deposit is only 10 feet deep. This is equivalent to a little more than 1,000 flasks of quicksilver. Some of the richest ore in this landslide was taken out, however, after the sampling was done. Sampling of most of the dumps in the Guadalupe area indicated 56,480 tons of ore containing 2.26 pounds of quicksilver per ton, equivalent to 1,680 flasks of quicksilver. Some rock impregnated with mercury is also known to remain beneath the old brick furnaces on the Guadalupe property, but its grade and quantity are not known. The Thayer and Dore Labores in the old Guadalupe mine were last reworked in 1884 and doubtless contain stope fill that could now be profitably treated, but to gain access to this material and mine it would be very costly.

The possibilities for finding submarginal ore in the various "outside" mines of the New Almaden property may be briefly considered from west to east. The Senator mine dumps have been partly reworked by lessees making use of screens and hand sorting, but this material appears to be too low in grade to be considered even as submarginal ore. No other readily accessible submarginal ore in the Senator mine area is known. The San Antonio mine was reported by one of the early mine superintendents to contain a large block of "low grade ore," but according to C. N. Schuette, who has examined this mine in recent years, this material is of too low grade to be of value in the foreseeable future. The Enriquita mine dumps have been largely reworked and probably contain little of value; it is reported, however, that the old stopes lying above the Eldredge tunnel (fig. 96) may contain good furnace ore.

In the New Almaden mine area most of the dumps containing more than 2 pounds of quicksilver per ton have already been reworked, though some parts of the large dumps at the portals of the Day and Randol tunnels may have been missed. Some low-grade ore in place may yet be obtained from the big surface cuts to the south of Mine Hill, where the recent operation was abandoned largely because of the drop in the price of quicksilver; and some could probably be

stripped from the Santa Mariana body of silica-carbonate rock (pl. 3 and fig. 92), though its average grade is not precisely known. The other bodies of silica-carbonate rock exposed at the surface in the New Almaden mine area are thought to be either too lean, too small, or too unfavorably situated to supply submarginal ore that might be mined by power shovel.

Underground in the New Almaden mine submarginal ore could doubtless be obtained in several places, but the old workings are so badly caved that more or less extensive development work would be required to reach them. In the area south of the Almaden shaft "low-grade ore" was reported to have been found on the 500 and 600 levels in 1890, when the average grade of ore being furnaced was about 2 percent quicksilver, and this ore was never mined. The Randol stopes below the 1000 level became inaccessible at a time when 1-percent ore was considered economic, and doubtless these extensive stopes contain a large tonnage of ore containing several pounds of quicksilver per ton. The stopes in the rich Velasco area have been inaccessible for such a long time that not even rumors of what was left behind can now be heard. This area may contain a sizable quantity of submarginal ore, but it appears to offer even greater promise of containing a small amount of rich ore that should prove suitable for retort operation.

HIGH-GRADE ORE

The search for high-grade ore in the New Almaden district can be directed toward finding extensions of known ore bodies or satellite bodies lying near known bodies and on the same structures; or search may be directed to the finding of wholly new ore bodies in hitherto unexplored places that satisfy the conditions described on pages 108-112, as having been effective in localizing the known ore bodies. For reasons now to be explained, the chances of finding rich ore by following either of the first two methods seem to be less favorable than the chances of finding new ore bodies not closely related to those now known.

EXTENSIONS OF KNOWN ORE BODIES

In general, the ore bodies of the district have been so sharply limited and so thoroughly exploited that the possibility of finding extensions of known ore bodies is rather remote. Some exceptions, however, occur in a few places where the trend of an ore body was not apparent, or where the ore became inaccessible before it could be completely mined out. An example of unperceived change of trend may be afforded by the New Ardilla stope of the New Almaden mine (fig. 79 and pl. 4) in which the extension of an

ore body was looked for unsuccessfully along the intersection of a contact with a group of hilos; this ore body may change trend slightly to follow a roll in the contact that strikes more easterly than do the hilos. An example of the second condition, that of known ore left unmined because it suddenly became inaccessible, is provided by the America mine, where an ore body that was reported to extend downward below the 600 level was left unmined when the America shaft caved.

SATELLITE ORE BODIES

The chances of finding satellite ore bodies near others that have already been mined out are not particularly good, because most of the contacts thought to be favorable for the localization of ore in the mines have been explored beyond the limits of the known ore bodies. It was a general practice, however, where the contacts were not followed by exploratory drifts, to look for new ore bodies by following along the intersection of a contact and hilos, and many new ore bodies were found in this way in the central stope area in the New Almaden mine. But there was little exploration along the contacts at right angles to the trend of the hilos, which raises the question whether some satellite ore bodies lying parallel to those that have been mined may not have been missed. At any rate, the amount of exploration at right angles to the hilos in this area is far less than would seem justified by its fabulous concentration of cinnabar. In the Guadalupe mine, the importance of the hilos north-west of the New Guadalupe Inclined shaft apparently was not realized, for they have not been followed downward as far as they should have been. Also, in the San Mateo mine, where there is no silica-carbonate rock and no well-defined contacts or veins to guide exploration, the downward extent of the ore zone does not seem to have been thoroughly prospected.

POSSIBLE NEW ORE BODIES

The possibilities for finding isolated new ore bodies in places of favorable environment appear to be best in the area already explored by the workings of the New Almaden mine. This is due partly to the fact that all three dimensions of the structures involved are here most fully understood, and partly to the fact that ore-bearing solutions are known to have passed through the area, so that any places favorable for ore deposition have probably been mineralized. It may seem paradoxical to believe that the area most explored is also the one in which favorable places remain unexplored, but this belief seems at least partly justified by the fact that large potentially ore-bearing structures were neglected because two beliefs were

prevalent during the development of the mine that are now believed to be unsound.

The first of these unsound beliefs was that the ore almost everywhere lay along the upper side of a body of silica-carbonate rock and beneath the alta, the very name of which implies its supposed position above the ore. This belief had some foundation in that the majority of the ore bodies found were so situated—although one reason for this was that search for new bodies was concentrated beneath the alta. But since many other ore bodies that lay above the alta and on the lower sides of silica-carbonate rock masses were found unexpectedly, as described on page 115, this notion should not have been so closely followed in the development of the mine.

The second belief was that the serpentine, along the borders of which ore bodies were found, formed a stocklike intrusive mass, which though highly irregular widened downward. This idea is well illustrated in figure 100A, and for comparison our concept of two north-dipping convergent sills is indicated in figure 100B, which is a generalized cross section drawn along the same line as figure 100A.

In order to appraise the possibilities for finding new ore bodies in the mine that become apparent when these two beliefs are rejected, let us consider the contacts numbered 1 to 4 in figure 100B, along all of which there may remain unexplored places where ore bodies may be discovered. Along contact 1, large ore bodies were found in former years, including the great Santa Rita, the North and South Randol, Velasco, Harry, and Cora Blanca ore bodies. This contact, which according to the belief held during the development of the mine is the northern and eastern border of the stocklike mass, was far more thoroughly explored than any of the other three, but a few parts of it still seem worthy of further exploration. Contact 2 is explored in places between the 900 and 500 levels, and just above it in this interval the El Collegio, Santa Rosa, Buenos Ayres, Far West, Sacramento, and New Ardilla ore bodies were found (pl. 4). This contact was also penetrated near the 1800 level by the lower part of the Randol shaft and the 1800-level crosscut driven northward from it. (See section B-B' pl. 11.) Contact 3 is partly explored between the 800 and 500 levels, and in this interval some ore was found adjacent to it. It was also reached by a crosscut driven south from the Randol shaft on the 1800 level. Contact 4 is unexplored except where it was crossed on the 900 level, and followed on the 1000 level, in the southwestern part of the San Francisco area. The existence of the contact beneath the Day tunnel is largely inferred from the arch of silica-

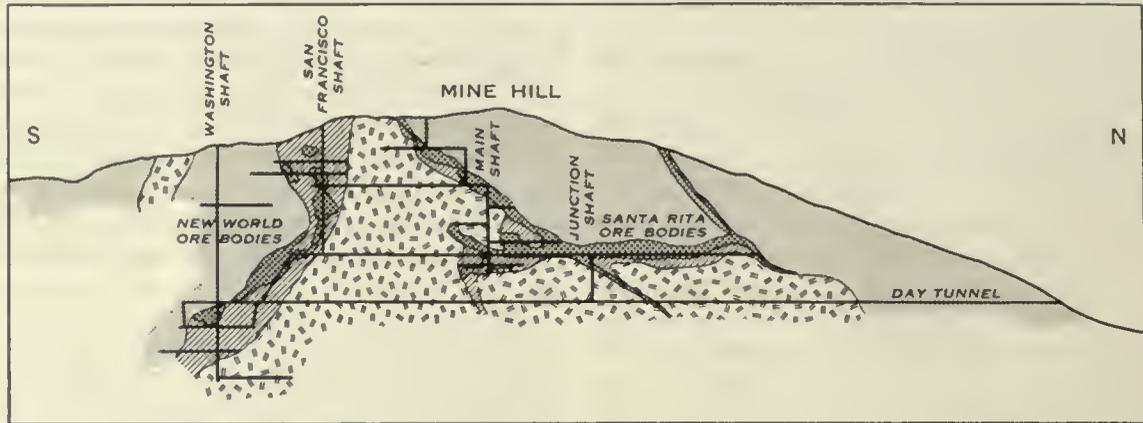
carbonate rock penetrated by the tunnel and by the fact that exploration in the lower levels of the San Francisco area extended back under the serpentine body without encountering it. The evidence afforded by the silica-carbonate rock body becomes increasingly strong when considered in connection with the fact that in the New Almaden mine area silica-carbonate rock is almost invariably found only along the margins of large serpentine bodies and not within them.

Contact 1

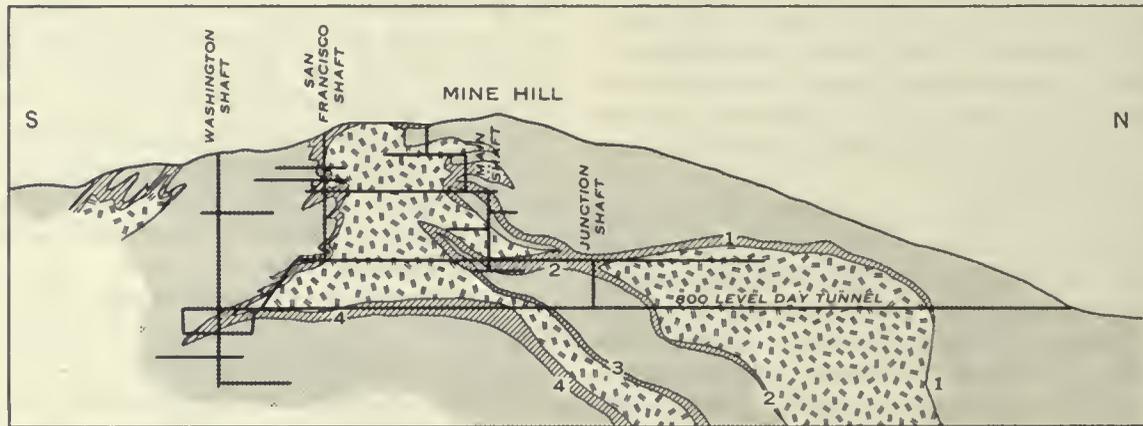
The shape of contact 1 and the positions of the stopes lying just beneath it are shown in figure 81. Unexplored parts of the contact are indicated by dotted contours where their approximate position is known, but between the Cora Blanca area and the isolated San Francisco area in the southern part of the area mapped, where the contact is believed to extend across an arch, even dotted contours have been omitted owing to the complete absence of data indicating its position. Places believed to deserve further attention are the gently plunging arch east of the Santa Maria shaft; the relatively flat part of the contact between the Santa Rita, Velasco, and Harry stopes; and the possible arch between the Cora Blanca and San Francisco areas.

The first of these places is thought to be particularly promising for several reasons. The contact forms a gently plunging arch, a favorable structure for the localization of ore bodies. Small quantities of cinnabar are reported to have been found in silica-carbonate rock at the north end of the 800 level (represented by the 1000-foot contour line) in the Harry area, and hilos are abundant in the northern parts of both the 700 and 800 levels in the same area. Ore solutions are known to have passed through this area, as thin films of cinnabar were found in the chert of the Franciscan group near the summit of Church Hill. This favorable structure could be tested most easily by exploratory drilling from the surface to depths of only a few hundred feet along a zone extending from the main camp to the top of Church Hill. It could also be explored underground by drifting on the 800 level: the contact could be followed eastward from the Day tunnel and raises put up in places where hilos were found to be abundant.

The second favorable area on contact 1 lies between the Santa Rita, Velasco, and Harry stopes, at an elevation of 1,200 to 1,300 feet. This area has been penetrated only by 2 raises from the Tonkin crosscut on the 700 level. The southern raise penetrated silica-carbonate rock containing some cinnabar; the north-



A



B

800 0 800 FEET
HORIZONTAL AND VERTICAL SCALE

EXPLANATION

Pliocene(?)	[Patterned Box]	Quicksilver ore	}	TERTIARY
Upper Jurassic to Upper Cretaceous	[Patterned Box]	Serpentine intrusive into Franciscan group	}	JURASSIC, CRETACEOUS, AND YOUNGER

3
Numbered contact discussed in text

Geology and workings by U. S. Geological Survey

FIGURE 100.—Generalized section through New Almaden mine along the Day tunnel. A, After C. N. Schuette, 1930, fig. 2, p. 14 (slightly modified). B, Shows geology as interpreted by the writers. See also section G-G', plate 11 for additional detail.

ern one passed directly from serpentine to alta, but may have failed to reach the true contact. This area also lies close enough to the surface to be readily explored by drilling from the surface, or it could be reached by relatively short underground drifts, provided the nearest old workings are accessible.

The third place on contact 1 that is worthy of at least some exploration lies between the southernmost Harry and Cora Blanca workings and the workings in the San Francisco area. Geologic information about this area is not sufficient to locate accurately any small structure that might contain an ore body, but the geologic relations both on the surface and in underground exposures indicate that a structural "nose" of the upper contact of the intrusive mass extends between the two groups of workings. On the surface in this area there is no silica-carbonate rock along the margin of the serpentine mass, but underground a shell of silica-carbonate rock has been formed along both flanks of the supposed "nose." This structural feature also lies close enough to the surface to be explored by surface drilling, or it might be better explored by drifting along the contact from the south end of the Harry 600 level.

Contact 2

Contact 2 is the lower contact of the upper serpentine sill, and its relation to contact 1 is indicated in sections *B-B'* and *C-C'*, of plate 11. It is believed that the best places to look for ore along this contact lie below the 900 level, but there has been so little exploration at this depth that it is hard to predict what parts of the contact would prove most favorable. If it be assumed that the serpentine body is more or less sill-like in shape, a favorable arch on this contact should lie below the arch on the upper contact of the sill, along which the Victoria ore bodies were localized. And if the hilos are developed along the lower side of the sill nearly underneath those on the upper side, this area would also contain hilos. The part of contact 2 below the Victoria stopes, together with a part of contact 3 at greater depth, could best be tested by drill holes put down from the 800 level near the Santa Rita shaft. Although much uncertainty exists as to what part of contact 2 will be most likely to border on ore bodies, the chance of finding extensive ore bodies above this contact is thought to be good enough to warrant the expense involved in extensive exploration. If a careful study is made of the geologic structure indicated by the rocks penetrated by the first few drill holes, the number of holes necessary to explore the contact should not be very large.

Contact 3

Contact 3 might be considered to offer at least as good possibilities for ore as contact 2; it even has a possible advantage in being overlain by alta, and on the 1800 level south of the Randol shaft it is underlain by a shell of silica-carbonate rock cut by hilos containing cinnabar. The explored parts of this contact on and above the 800 level, however, have not been as productive as the explored parts of contact 2. On contact 3 as on contact 2, it is not possible to deduce from the available geologic data what places below the 800 level offer the best structural setting for the localization of ore, but the Victoria-Velasco arch may affect contact 3 as well as contact 2. (See section *A-A'*, pl. 11.) This contact, because it offers such a large unexplored area along which ore bodies may have formed, is believed to provide good enough possibilities to justify the cost of exploring it.

Contact 4

What has been said about the uncertainty of the exact position of contacts 2 and 3 is even truer of the almost completely unexplored contact 4. One part of this contact, however, is so exceptionally promising, and could so easily be tested, that it probably offers one of the best chances in the district for the finding of new ore bodies. This is the part beneath the southern part of the Day tunnel; for the arch in the silica-carbonate rock here penetrated by the tunnel indicates that this underlying contact is also arched. As the thickness of the silica-carbonate rock is not known, we cannot state exactly how far below the tunnel the contact with the underlying alta may be, but judging from the usual thickness of the shells of silica-carbonate rock in the mine area, the distance is likely to be only a few tens of feet. From the distribution of the rocks east and west of the tunnel, the arch is inferred to be a section along the west flank of a domal structure whose apex is east of the Day tunnel, but the position of this favorable apex cannot be exactly located from the available data. One reason for believing that this domal structure is likely to contain ore is found in certain records of the mine superintendent, written when the tunnel was driven; these contain the statement that in the area of the "mule barn" (1630 N.-5120 W.) a flow of water containing fragments of cinnabar was encountered. Subsequently the source of this cinnabar was sought by putting up a raise, which passed into the overlying serpentine without finding cinnabar; but the geologic structure indicates that the possible ore body was more likely

to have been found by putting down a winze. At any rate this favorable domal structure has remained unexplored, and it can easily be tested, either by drilling downward and eastward from the "mule barn" for a short distance or by sinking a winze to the contact and exploring laterally from the winze. Deeper parts of contact 4 also should be regarded as favorable places in which to explore for new ore bodies, but they would not be so easily reached.

OTHER SUGGESTIONS

The places described are those that seem most clearly deserving of further exploration, but they do not by any means include all the places in the district that may contain ore bodies. Some other places have been mentioned in the detailed descriptions of the various mines, and still others that do not lie near any mines may be found to contain ore bodies. A notably large proportion of the known ore bodies in the Los Capitancillos Ridge have been found along the carbonatized borders of serpentine masses in places where these masses strike more nearly east-west than the regional trend. If this distribution means anything, the mass of silica-carbonate rocks cut by many hilos just north of the northwest corner of the New Almaden mine area deserves further attention. The occurrence, also, of cinnabar in the relatively little-prospectured east-trending bodies of silica-carbonate rock north of the Calero Reservoir indicates that these cannot be disregarded in the search for new ore bodies, even though none have been found in them hitherto.

SUMMARY

In summary, the New Almaden district, in spite of its record of declining production and the present abandoned appearance of its mines, is believed to offer good possibilities for future production. Its ore bodies have been exceptionally large and rich, and in spite of extensive unwarranted exploration the two largest mines—the New Almaden and the Guadalupe—have yielded about 5.5 flasks of quicksilver per linear foot of underground workings. As the ore bodies in the district have been fairly closely controlled by geologic structures, further exploration may be planned in advance to take advantage of the knowledge of these controls and thereby reduce the footage and cost involved in finding additional ore bodies. On the other hand, because all ore bodies cropping out at the surface are believed to have been found, enterprising management and considerable capital will be required if the district is to be brought back to yield the production that this geologic study indicates it is capable of yielding.

HISTORY OF THE NEW ALMADEN MINES

The recorded history of the great quicksilver mines on the New Almaden property extends through a period of more than 100 years and encompasses the transition of California from a sparsely populated Mexican territory to a rich and populous State—a transition that profoundly affected the mines, the miners, and the methods of mining and reducing ores. Many of the resultant changes that influenced the development of quicksilver mining in the United States are emphasized, whereas others only mentioned briefly will be of interest to persons specializing in different fields of historical research. The geologists, for example, will perhaps be most interested in the changing concept of the ore gangue, from an early belief that it was an extremely wide fissure filling to the present realization that it is the silicified and carbonatized border of intrusive serpentine. The mining engineer will be more interested in the development of methods of mining. In the early days of the district, ore was carried in leather bags by Mexicans who climbed up notched poles from stopes hundreds of feet underground, whereas in later times the mines had powerful hoists and pumps; and such new techniques as the methods of timbering large horizontal stopes were first developed at the New Almaden mine. The metallurgist's interest will center around the development of quicksilver-reduction equipment from crude retorts made of gun barrels to modern Herreshoff and rotary furnaces. A lawyer will find much of interest in the fact that many laws concerning ownership of land formerly held under grant from a foreign country were first tested in the legal battles over the New Almaden property, and he might diligently follow the cases through State and district courts to the U.S. Supreme Court, and to a final settlement by international arbitration. A sociologist will perhaps be surprised to learn of a mining community, half Mexican and half American, wherein as early as 1870 medicine, dentistry, entertainment, and educational lectures were provided for all through compulsory monthly payroll deductions. The history of the mine contains much of interest to a historian, especially the part relating to the critical Civil War period, when the quicksilver so necessary for the operation of the precious-metal mines of the Mother Lode and the Comstock Lode was nearly lost to the Northern States, through state-wide feeling against the governmental seizure of the New Almaden mine ordered by President Lincoln.

The original discovery of the bright-red eye-catching cinnabar on Mine Hill probably was made long before white men discovered California. According to an oft-repeated legend, Indians who lived on Los

Capitanillos Ridge knew of a "red cave" to which their forefathers had retreated to paint their bodies with vermilion. The red paint made from the rock of the cave caused skin eruptions, and the Indians, believing it possessed of an evil spirit, thereafter shunned it. This legend is somewhat strengthened by an interesting report by W. V. Wells (1863, p. 28) who visited the New Almaden mine in its early days. He claims to have been shown an irregular tunnel between 50 and 100 feet long, which was first thought to have been a natural opening, but which, when cleaned out and lengthened, was found to contain several Indian skeletons, together with rounded boulders that might have been used in making the crude excavation.

In contrast to the legendary tale of the Indians' discovery of ore on Mine Hill, the detailed story of its rediscovery in 1824 by a Mexican named Luis Chaboya is well authenticated. Possibly because he saw some native mercury in the cinnabar, Chaboya believed it to be a rich silver ore, and with Antonio Suñol and a man named Robles he began mining the red ore at what they termed the "Chaboya mine" and erected a mill in the nearby Almaden Canyon. They then sent to San Luis Obispo for a flask of quicksilver to use in amalgamating the silver they expected to extract from the ore, but on failing to recover any silver they abandoned the mine. Eleven years later, in 1835, a second unsuccessful attempt to recover silver was made. For 10 years thereafter the heavy red ore remained a well-known curiosity, but no one realized that it contained the valuable mercury-bearing cinnabar.

Late in 1845 a Mexican army officer, Don Andreas Castellero, who had been sent from Mexico to attempt to purchase Sutter's Fort for that country, paused in his journey from Monterey to the fort at the Santa Clara Mission, about 15 miles from the mine. His curiosity was aroused by a piece of the ore shown to him, and after visiting the mine from which it came he returned to the mission, where, on November 22, 1845, he "denounced"¹⁶ the mine, naming it the Santa Clara and claiming that it contained "a vein of silver and a little gold." Castellero may have taken a piece of the ore along with him on the rest of his trip to the fort to ask those he met what it was. At any rate, on December 3, 1845, he returned to the mission, where he proved that the heavy red rock contained quicksilver by the following experiment, described by Jacob P. Leese (*in* Becker, 1888, p. 9):

He [Castillero] got up from the table and ordered the servant to pulverize a portion of this ore. After it was pulverized he ordered the servant to bring in a hollow tile full of lighted coals. He took some of the powdered ore and threw it on the coals. After it got perfectly hot he took a tumbler of water and sprinkled it on the coals with his fingers. He then emptied the tumbler and put it over the coals upside down; then took the tumbler off and went to the light to look at it; then made the remark that it was what he supposed it was—quicksilver. He showed all who were there the tumbler, and we found that it was frosted with minute globules of metal, which Castellero collected with his finger and said it was quicksilver.

After this demonstration Castellero of course claimed that quicksilver occurred in the ore of the Santa Clara mine, and on December 30, 1845, he was awarded possession of the mine property by Antonio Maria Pico.

Castillero immediately formed a mining company, and issued 24 shares of stock according to Mexican custom. He retained half of these for himself, and gave four shares each to the mission priest and a general at Monterey, and two apiece to two brothers named Robles. The new company employed William Chard, of New York, to develop the mine, and as actual production was required to hold title, Chard almost immediately attempted to recover quicksilver, using the crudest of methods. His first retort consisted of a battery of gun barrels, which were charged with small pieces of cinnabar, and, with remarkable persistence in the face of the small recovery, he used this crude apparatus for some 4 to 6 weeks. Soon, however, to increase the size of the charge, he made use of whalers' trying pots, placing them upside down over a pile of ore and building a fire on top. Although a large part of the quicksilver must have been lost as fumes, Chard is credited with having recovered some 2,000 pounds of metal by this ingenious method. By this time the priest of the Santa Clara mission had apparently received some word of how quicksilver was recovered in Spain, for he supervised the construction of an 8- by 10-foot furnace with an ore chamber above and a firebox below. This structure was made of adobes (sun-dried bricks), and must have been similar to furnaces built by prospectors in Mexico until recent years, but it apparently was poorly constructed, for it exploded at its first firing and salivated several workmen.

Castillero, as soon as the mining was started, returned to Mexico City, where he requested and was granted a governmental loan of \$5,000 to cover the cost of developing the mine. War between Mexico and the United States broke out at this time, however, and being unable to collect any money on the loan, Castellero sought capital from Barron, Forbes, & Co., an English banking firm doing business in

¹⁶ At that time a denouncement was not quite equivalent to the filing of a claim. No real claim could be made, as ore-bearing land, like other land, was the property of the governing country until bestowed upon one as a gift by its king or governing official.

Tepic, Mexico. This company took a 16-year lease on the mine, and gave it, without even seeing it, the optimistic name of "New Almaden," after the world's greatest quicksilver mine in Spain. They dispatched miners, money, and materials to California to start production on a large scale, but the ship carrying them was intercepted by the United States, and the equipment was confiscated. In 1848 they sent a similar outfit from Mexico under Alexander Forbes. When Forbes arrived at the New Almaden mine the only underground working besides the Indian "cave" was a shallow 25-foot adit. To prove the direction of the vein, as was required to hold title, he began a lower adit, and in November 1847 he reported that he had intersected a vein so irregular that he still was unable to tell its direction. To reduce the ore he obtained 4 iron pots, possibly the same whalers' trying pots that had been used by Chard, and had each one of them charged with 400 pounds of ore, covered and sealed, and heated for a full day. The following day, when the pots had cooled, the metal was dipped out, and by this crude method 200 to 300 pounds of quick-

silver per day was recovered. Forbes added lime to the charge, and in 1848 he extracted by this procedure 10,000 pounds of quicksilver in one 3-week period and 20,000 pounds in a 2-month period (Lyman, 1848, p. 270-271). Only 6 miners worked on the property, and by this time quicksilver was reported to have been found in 15 or 20 other places within a few miles of Mine Hill.

Little is known about activity at the mine during the next few years. The establishment apparently grew rapidly (figs. 101, 102), and new and better furnaces were added, yet the mining methods employed by the Mexican miners remained the same as those which had been used for hundreds of years in the mines of Mexico and Peru. The early workings near the top of Mine Hill are described as resembling rabbit burrows, for the miners had followed leads up and down in tortuous passageways, digging out "rooms" wherever they found pods of ore. Somewhat more systematic development resulted from the driving of the Main tunnel (fig. 103 and pl. 4), which was begun in 1850, was extended to 900 feet in 1853, and 1,800 feet



FIGURE 101.—New Almaden reduction works in 1851. Small structures with stacks in the right foreground are the six multichambered retorts used to treat the very rich ore being mined at this time. View looking north; Deep Gulch in center of drawing. From an original drawing by William Rich Hutton; reproduced by permission of the Huntington Library, San Marino, Calif.



FIGURE 102.—New Almaden Hacienda viewed from the north in 1852. Flats behind the building on the right were used in sorting the ore and making adobes (fist-sized mudballs) of the fine-grained material. From an original drawing by William Rich Hutton; reproduced by permission of the Huntington Library, San Marino, Calif.

by 1857. This early development must have been yielding ore, even though no production was recorded in 1848 and 1849, for in 1850 a production of 7,723 flasks was recorded and in the following year the production increased to 27,779 flasks.

Conditions at the mine in 1854 were described in some detail by W. V. Wells (1863, p. 25-41). He tells of the very pretty village of New Almaden, nestled in the canyon below the mine, where the mining officers and foremen lived in well-painted houses with flower gardens and trim picket fences. In sharp contrast was the Mexican settlement of straw-thatched houses, located on a windy spur of Mine Hill. In this camp lived the Mexicans and Yaqui Indians from Lower California, who did all the actual mining and were paid on the basis of the amount of ore delivered to the sorting sheds. These large sheds, or planillas, were located at the mouth of the Main tunnel, which furnished access to the huge cavernous stopes lying about 500 feet below the summit of Mine Hill. The extensive workings were illuminated by large central bonfires supplemented by candles set into crev-

ices in the walls, and as gunpowder was used for blasting, one can easily imagine what a pall of smoke hung over the working face when the miners returned to it, as was the custom, immediately after a blast. (See fig. 104.)

The ore was hoisted to the level of the tunnel on the backs of Yaqui Indians, each of whom carried a standard load of 200 pounds in a leather sack strapped onto his back and supported by a headband (fig. 105). With this incredible load the Indians hitched their way sidewise in the near darkness up ladders made of single poles into which notches had been cut for steps; and the expected day's work consisted of 25 to 30 such trips up more than 200 feet of ladders. The ore was partly sorted underground, and then resorted on the surface to bring the grade up to about 20 percent quicksilver. The sorted ore was trammed to the canyon below the mine and charged into 16 furnaces like the one shown in figure 106.

While Barron, Forbes, & Co. were bringing the mine up to a production of more than \$1,000,000



FIGURE 103.—View of Mine Hill in 1854 showing the portal of the Main tunnel. This adit on the 300 level served as the main haulageway until the mining progressed below the 600 level. Shortly after this drawing was made the building in the foreground was replaced by a two-story sorting shed, or planilla, in which the ores were hand sorted to obtain a grade of about 20 percent mercury. The waste dump, known as the China dump, therefore, contained much rejected material which at later dates was regarded as rich ore, and consequently this dump was reworked many times until largely removed during World War II. From Harpers Monthly Magazine.

worth of quicksilver a year, other events were taking place that profoundly affected the subsequent history of the mine. Gold was discovered in California, and the New Almaden mine became the principal source of the mercury vitally needed for amalgamation; California was admitted to the Union on September 9, 1850; and arguments between "squatters" and the holders of real or fictitious land grants from Mexico were of everyday occurrence.

In an endeavor to settle the land disputes, Congress passed in March 1851 an Act establishing a Board of Land Commissioners in California, and declaring that everyone claiming ownership of land by virtue of title derived from the Spanish or Mexican Government should present his claim to the Board within 2 years, under penalty of losing the land to the public domain. One of the most valuable pieces of land held under such a grant was the New Almaden property, and as the legal battles over its ownership

attained national prominence, the proceedings in the various State and Federal courts are recorded in a large number of official, semiofficial, and popular accounts.

The basis for the various claims lay in two Mexican land grants and a special mining grant to Castellero which overlapped the other two, but the ownership of the mine was still further complicated by the vagueness with which the boundaries of the original grants had been defined. The Castellero claim, which comprised 3,000 varas¹⁷ of ground "in every direction from the mine" and also a 2-league grant, had been purchased by Barron, Forbes, & Co. One of the land grants had been made to José Reyes Berryessa and likewise was controlled by the operating company. A second land grant, to Justo Larios, which actually contained the mine, had been acquired by Charles

¹⁷ Spanish and Portuguese measure of length; it varies from 32 to 43 inches in different localities.



FIGURE 104.—Drawing made in 1854 shows the Mexican miners petitioning at an underground shrine to the Virgin of Guadalupe for success and safety. The Virgin is reported to have been made in Sienna, Italy, from a 700-pound block of cinnabar from Idria, in Yugoslavia. Such shrines are a common feature of old Latin American mines, and in most of these there is a shrine near the main entrance to the mine at which the miners offer devotion and a petition for care before each day's work. The Virgin of Guadalupe was in a working extending from the Main Tunnel and is reported to still be there in an area now inaccessible. From Harpers Monthly Magazine.

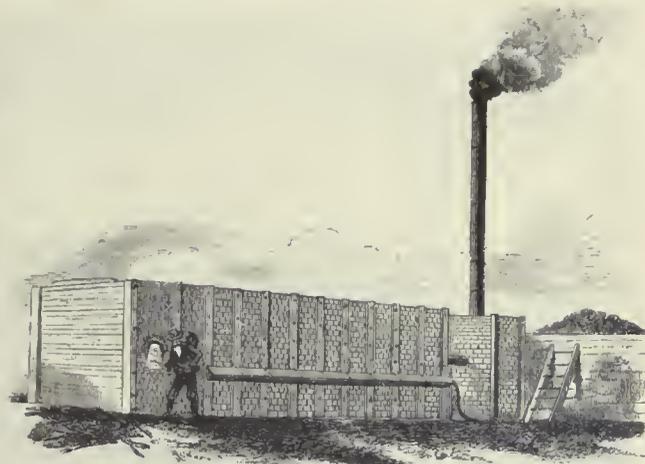


FIGURE 106.—Reduction furnace in use at the Hacienda in 1854. The furnace is built of brick and consists of 11 chambers. The first of these is the firebox, the second holds the charge of rich ore, and the rest are condensing chambers. The liquid metal flows into the flume along the side. From Harpers Monthly Magazine.

tween 1852 and 1854, leaving the title to the mining property as muddled as before. In 1854 Fossat sold a three-fourths interest in his title to Henry Laurencel and James Eldridge, who later sold their interest to the Quicksilver Mining Co. This company, which eventually acquired the mine, consisted of a group of eastern capitalists, who incorporated in March 1859 with a capital of \$10,000,000 but no quicksilver mine.

To straighten out the title muddle in California, early in 1858 the Attorney General under President Buchanan sent Edwin M. Stanton to San Francisco. With characteristic vigor Stanton began immediately on his arrival to try to invalidate Castillero's title. The ramifications of the resulting trial are described by Browne (1865, p. 548) as follows:

The arguments occupied weeks, and comprehended every reference, illustration, and authority that bore the remotest relation to the subject. Perhaps since the beginning of the Government no cause had been presented for adjudication in the courts involving greater interests, or graver or more complicated questions, embracing as they did the learning of the French juriconsults, the principles of law of nations, the history of all mining countries, ancient and modern, the doctrines of the Common Law of England as to the rights of miners and the tenure of the soil, and the language, literature, and law of Spain and Mexico.

As a result of this trial Castillero's title, and consequently that of Barron, Forbes, & Co., was declared void, and an injunction was levied on the mine by the Federal Court, stopping all work on October 31, 1858. To the time of its closing the New Almaden mine had yielded about a quarter of a million flasks of quicksilver, which had been sold for more than \$10,000,000. Nearly all the ore that had yielded this great produc-



FIGURE 105.—Labor, or stope, in the upper levels of the New Almaden mine in 1854. Drawing shows the large leather backpacks in which the Yaqui Indians carried 200 pounds of ore up the notched log ladders to the Main Tunnel a hundred feet above. These large chambers in the central stope area of the mine were excavated in silica-carbonate rock and required virtually no timbering. Most of them were still open in 1946 when the mine was remapped for this report. From Harpers Monthly Magazine.

Fossat. In spite of the fact that these grants included overlapping land, all of them apparently were approved by the Board of Land Commissioners be-

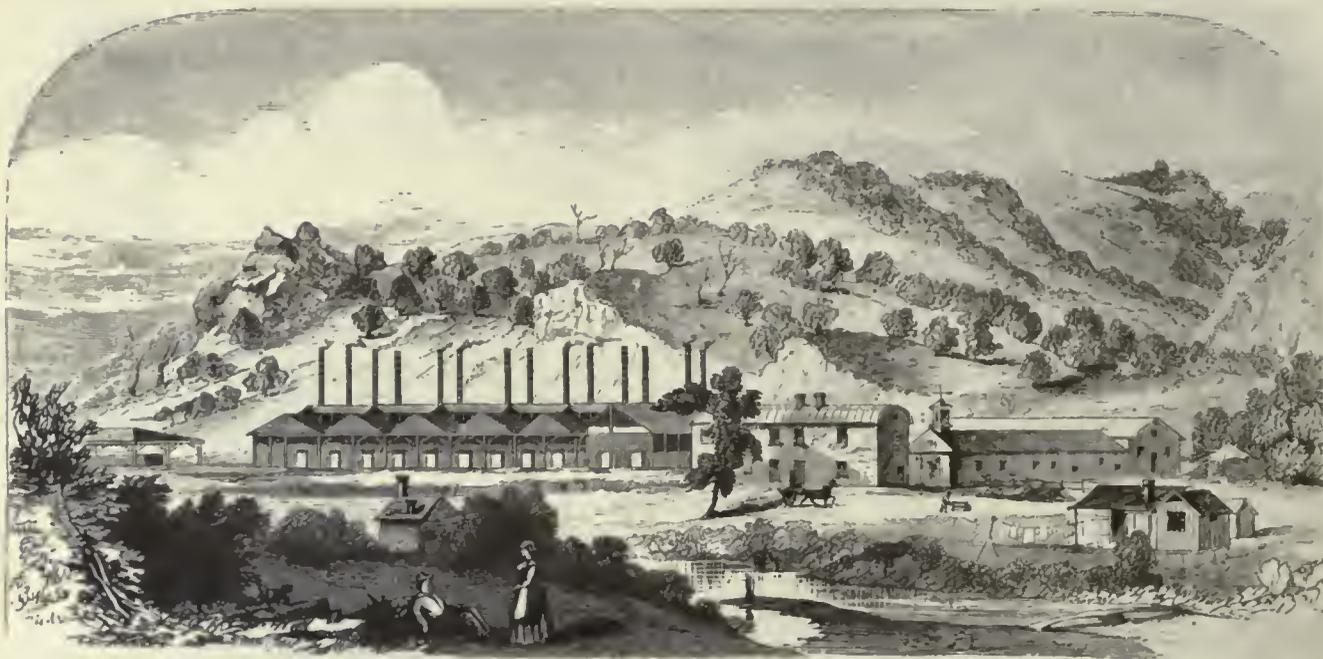


FIGURE 107.—The Hacienda, or furnace area, in 1854. The buildings with the smokestacks house 12 furnaces like that illustrated in figure 106. The long building with the weather vane, shown on the right, was the Hacienda office and part of it remained standing in 1949. Deep Gulch leading up to the mine is shown on the extreme right of the drawing. From Harpers Monthly Magazine.

tion had been mined from a compact group of stopes lying under the original outcrops near the summit of Mine Hill and extending down to a depth of only 600 feet.

In January 1861, when the court's decision had been reappealed to the U.S. Supreme Court, Barron, Forbes, & Co. again began operating the mine even though the injunction had not been lifted. And they continued to operate it without any title after the Supreme Court, late in 1862, decided by a vote of 4 to 3 against the Castellero claim. On May 8, 1863, President Lincoln, with the authority of the Supreme Court, dispatched Leonard Swett to California with a writ ordering C. W. Rand, the U.S. Marshal for northern California, to enter onto the New Almaden property, to put off the operators by force if necessary, and to turn everything over to Swett. Oddly, Swett arrived in San Francisco accompanied by S. F. Butterworth, the president of the Quicksilver Mining Co. When these two, accompanied by Rand, reached the mine they were refused entry, and the refusal was backed by 170 tough miners armed with rifles and shotguns. The official party withdrew, and Federal cavalry were ordered to be in readiness to seize the mine by force. Before this could be done, however, public opinion was inflamed by scorching editorials in the newspapers, which suggested that the Government was planning to seize all mines, and because of

the importance of gold mining in California many of its citizens were clamoring to withdraw from the Union and join the Southern States in the Civil War. The Governors of California and Nevada, with many other influential friends, sent frantic telegrams to Lincoln demanding that he rescind his order, and he did so in a telegram which explained that no wholesale seizure of the mines by the Government was contemplated.

As the title dispute involved parties of two nations, it was submitted for international arbitration, and King William I of Prussia was agreed upon as arbitrator. A compromise was reached whereby the Quicksilver Mining Co. was granted a clear title to the Castellero claim on payment of \$1,750,000 to Barron, Forbes, & Co., and on September 1, 1863, the new company began a 50-year period of operation of the mine.

When the Quicksilver Mining Co. took over the property they found that the former operators had stopped development work 8 months before and had concentrated their energies on mining out all the really good ore from the stopes. As a result the new operators were obliged to furnace a large amount of low-grade ore previously rejected, and meanwhile they began exploring for new ore bodies. In this exploration they were particularly fortunate, for in August 1864 they struck the exceedingly rich Velasco ore body. Then early in 1865 the North Ardilla ore was

found, and this led into the great flat Santa Rita ore body, which was discovered in August 1865 and furnished the bulk of the ore mined for the next 5 years. (See figs. 81, 108.) Exploration south of the previously known ore bodies disclosed some small, but comparatively rich, ore bodies in the vicinity of the San Francisco shaft, and exploration to the east found some ore in the Cora Blanca mine. (See fig. 109.)

At this time the ore was being treated in 6 furnaces, which had a combined capacity of nearly 300 tons and were intermittently charged from 4 to 6 times a month. The ore treated was of three kinds, termed "gruesso" (purest cinnabar), "granza" (low-grade chunks), and "tierras" (small pieces and loose fines). As the tierras would clog the furnaces if fed directly, they were first mixed with water and formed into mudballs or "adobes," which were dried in the sun before they were roasted. The furnaces were charged with a complex stack of all three kinds of ore, arranged with the richest ore near the center and base of the pile, and when they were in full operation the quicksilver is said to have flowed from the condensers in a steady stream a little smaller in diameter than a pencil.

About 2,000 men, most of whom were Mexicans who lived with their families on Mine Hill, were employed by the Quicksilver Mining Co. in 1865. The mining was done largely by contract, and the daily wage averaged about \$2.50, which was then regarded as generous. The high wages encouraged liberal spending, and the camp was notorious for its payday celebrations and lawlessness.

In spite of the lack of order in the camp and a considerable loss of quicksilver by theft under the

several general managers who directed the mining between 1864 and 1870, the mine was yielding so much quicksilver that it not only supplied all demands in the United States but also shipped thousands of flasks to China, Mexico, and South America. Yet the mine was apparently being rapidly exhausted, for by 1870 production had dropped to one-third of what it had been in 1865; the great Santa Rita ore bodies were nearly mined out, and the grade of the ore furnaced had reached the unprecedentedly low level of about 5 percent quicksilver. (See fig. 110.)

In the summer of 1870 J. B. Randol, the secretary of the Quicksilver Mining Co., was sent from New York to the mine as its new general manager. During his first year he was content to let his mining captains direct the underground operations while he merely observed. These mining captains were men thoroughly familiar with the mine, and carried on the old practice of obtaining ore from the nearly exhausted Velasco workings and from the Victoria and Oregon stopes found to the northwest of the Santa Rita ore body. From the first, however, Randol set about to change the surface camp from a notoriously lawless and dirty one to a clean, orderly community. He adopted the autocratic method of posting edicts in both English and Spanish on a great many bulletin boards throughout the camp, and then saw to it that the edicts were carried out. The first one must have been a real shock to the camp, for it decreed that every able-bodied man living on the property must be working in some capacity for the mining company. How Randol's edicts were enforced is well illustrated by the story told of a gambler who refused to leave because he owned his house—though he did not own the ground on which it stood. The gambler was notified of the time when he must move out, and when he still remained after the time limit, the camp constable and a crew of carpenters seized his house, sawed it into pieces, loaded it into wagons, and transported it several miles to a place outside the company property, where it was unloaded and reassembled.

An English camp, largely populated by Cornish miners trained in the Almaden mine in Spain, had grown up around the company store on Mine Hill. (See fig. 111.) Apparently there was little, if any, friction between the Mexicans and English. Each group recognized the other's special abilities; the Cornish miners were experts on sinking shafts and running long straight drifts, whereas the Mexican miners excelled in following and mining the ore. Randol treated all alike, requiring all to obey the same rules and inviting everyone to an annual open house at his palatial home, "Casa Grande," in the mouth of



FIGURE 108.—Tramming large pieces of rich ore through the Main Tunnel in the 1860's. Engineer Sherman Day on right, son of Jeremiah Day, president of Yale University, was surveyor under Barron, Forbes, & Co. and later superintendent for the Quicksilver Mining Co.



FIGURE 109.—View of China dump at mouth of Main tunnel and Spanish camp beyond, about 1870. The long two-decked building on top of the dump was a planilla, or sorting shed. From there the ore was originally trammed to the head of the chute, but at a later date it was let down on the incline shown at the left of the photograph. The small dump in the canyon in the foreground probably marks the portal of the Cora Blanca adit. From L. E. Bullmore collection.

Alamitos Canyon. Everyone was required to donate a dollar a month to the "Miners' Fund," which provided the miners and their families with free treatment by a first-class physician and surgeon, free dentistry, and literary programs and educational lectures. By way of promoting greater cleanliness, which was previously discouraged by the fact that all water was hauled in by donkeys, an elaborate water system was laid that piped water to every house. However, not everything Randol did was approved by the miners, for he also issued edicts requiring everyone to purchase all supplies at the company store and tried to constrain everyone to remain on the property all the time by putting locked gates across all the access roads.

It soon became obvious, however, that full production could not be maintained, in the face of dwindling reserves and rising mining costs, unless new mining

practices were employed. The ore that had been followed a little below the Day tunnel on the 800-foot level required considerable handling for removal, and it was still being mined and handled by primitive Mexican methods. In order to explore deeper ground down the plunge of the known ore bodies, Randol decided to put down the first of the more than a dozen shafts which have been sunk on the property. This shaft, which apparently was known from the first as the Randol shaft, was begun on June 10, 1871, and Randol's lack of mining experience resulted in its being far too small: it was only 4 by 9 feet and close cribbed, and contained only a single hoisting compartment. (See figs. 112, 113.) As the shaft was to serve as the principal outlet for most of the ore mined in the next 20 years, its small size profoundly affected the rate of production, and consequently the profits of the mine.



FIGURE 110.—View of China dump area in 1874. Photograph shows that even at this early date the China dump was being worked over for ore previously discarded, and from time to time since then it has been reworked. The building at the foot of the dump houses a boiler and steam engine, originally intended to power a crusher but later connected by a cable to provide hoisting and pumping for the Cora Blanca shaft. From L. E. Bullmore collection.

The Randol shaft was not completed to its final depth of 1,340 feet for 9 years; the work was hampered by repeated floodings, inadequate pumps and hoists, partial cave-ins which required retimbering, and the laborious method used in sinking it. Below the first 200 feet it was sunk by Cornish miners working with hand drills under a penthouse of very strong and heavy timbers, which contained a windlass and bucket used to hoist the broken rock. After gaining each 100 feet of depth the penthouse was knocked down and lowered to the bottom of the shaft, where it was again assembled. In the first half year the shaft was sunk 383 feet by this method. By the end of 1872 it was down 515 feet, with connections run to the Day tunnel; a crosscut had nearly reached the Victoria stope, which was being mined at that depth, although the ore had to be backpacked up to the 800 level and trammed 2,400 feet to the portal of the Day tunnel. By the end of 1874 the shaft had gotten below the 1,100 level, where a crosscut driven westward to the vein had struck so much water that the lower 80 feet of the shaft was flooded. The water was soon pumped out, however, and only a little drifting on the vein revealed an ore body 250 feet wide. This wide ore body was the cause of great rejoicing, for

drifting on higher levels had found only small bodies of ore which were quickly exhausted, and production during 1874 had been the smallest since the first year of recorded production, 1850.

There followed a period of years during which the other Randol ore bodies were found and mined out, resulting in a nearly steady increase in production for 10 years and a gradual decline for the next 10 years. The ore body struck on the 1100 level was followed northward down the dip for about 700 feet to the 1600 level, and a second ore body which overlapped it began near the 1400 level and pitched in the same direction to the 2000 level. "Vein rock?" (silica-carbonate rock) was also struck in the Randol shaft in 1877 on the 1200 level, and the virtually continuous North Randol ore body, lying to the north and east of the shaft, was followed upward nearly to the 800 level and downward to the 1800 level.

Even with an unprecedented supply of developed ore, however, the mine was hard pressed to return a profit, largely because of the inadequacy of the Randol shaft. The Scott furnace, which was continuously fed and could handle fine ore, was invented at the New Almaden mine in 1875. It was so efficient in extracting quicksilver that in spite of a lawsuit with the



FIGURE 111.—Open-cut on east side of Mine 11111 between English and Spanish camps in the 1880's. Portal of abandoned Main tunnel is in right foreground. No trace of any of the buildings shown remained in 1946 when the writers mapped this area (compare with figure 124). From L. E. Bullmore collection.

inventor of the similar Knox furnace, 4 such furnaces with a daily capacity of 100 tons each were soon in operation at the Hacienda. (See figs. 114, 115.) These furnaces were large structures of brick requiring considerable wood, as well as a lengthy period of time, to reheat them if they were allowed to cool, and it was therefore customary to keep a furnace fired continuously for more than a year. This feature of continuous firing was almost the undoing of the New Almaden mine, for the Randol shaft equipment was incapable of hoisting more than 300 tons per day, and, with the directors clamoring for increased production, the hoisting of ore could not be stopped long enough to enlarge the shaft.

To lighten the burden on the Randol shaft, the Santa Isabel shaft was started in 1877 from a point 1,300 feet farther west. (See figs. 81, 116.) This was a modern three-compartment shaft with large pumps, and it served its purpose in draining the water out of the Randol workings. But it was located

so far to the west that it did not greatly alleviate the hoisting burden, and late in 1881 the Randol stopes contained 800,000 tons of broken ore waiting to be hoisted to the hungry furnaces. On July 5, 1882, in a last effort to relieve the burden on the Randol shaft, another shaft, known as the Buena Vista, was started 1,000 feet to the north. It was planned on a grand scale, to contain three large compartments, 18-inch pumps, and all the most modern hoisting and pumping equipment. (See figs. 117, 118.) By March 1886 it had been sunk to the 2300 level and was connected to the Randol and Santa Isabel shafts by a long crosscut on the 2100 level. Although the Buena Vista shaft was doubtless one of the best in the State, and although its pumps proved useful in dewatering, it was so unfortunately placed that not 1 ton of ore was ever hoisted by its ponderous steam engines.

While the Randol shaft (fig. 119) was supplying its daily stint of 300 tons of ore an additional 100 tons had to be mined elsewhere to keep the furnaces



FIGURE 112.—Shaft houses for the famous Randol shaft. Note the tremendous piles of mine timbers to the left of the buildings. The headframe shows the unique construction wherein the hoist cable extends toward the hoist house at an oblique angle to the head frame. From C. N. Schuette.

fully charged. The New World ore bodies, which lay to the south of Mine Hill in the vicinity of the San Francisco shaft, had been discovered in June 1874, and these were found to pitch southward to about the level of the Day tunnel, which was therefore extended to facilitate handling this ore. In December 1884, to explore the ground above the Santa Rita stopes, the Santa Rita shaft was started. To prospect the ground lying farther south at lower levels the Washington shaft (fig. 120), originally known as the Garfield shaft, was started in November 1881 and sunk to the 1100 level by 1885. Although extensive drifts were run on the 900, 1000, and 1100 levels only a little ore was obtained between the 800 and 900 levels. The Cora Blanca mine, on the east slope of Mine Hill, had yielded a little ore in 1865; so in 1873 another shaft, named after the mine, had been put down to explore that area at depth. Unexpectedly it penetrated ore at a depth of only 50 feet, and this opened out into fair-sized ore bodies which extended down below the 800 level. To prospect the ore-bearing structures at greater depth another shaft, named the Grey shaft in honor of one of the mining captains, was begun in 1876 from a point some 700 feet farther east. This shaft reached the 1100 level and was connected to the Cora Blanca shaft on the 800 level, but although apparently favorable structures persisted to the deepest workings, no ore was found.

A more ambitious undertaking was the Hacienda tunnel, which was begun in Almaden Canyon at the level of the furnaces in January 1867, with the intention of draining the whole mine to the 1200 level and furnishing a more direct haulage route to the furnace. This tunnel would have had to be more than a mile long to reach under the central part of the mine, but it was worked on only intermittently until it had almost reached the structures already explored on the 1100 level from the Grey shaft. When it was abandoned in October 1879, it had been enlarged to a diameter of 8 by 8 feet and was more than half a mile long. At the time of its conception the Hacienda tunnel was a worthwhile undertaking, for transporting the ore from stopes to the furnaces was costly. The ore that was backpacked up to the Main tunnel (300 level) was trammed to the head of an incline above the Cora Blanca mine, let down the incline (fig. 109), trammed around the hill to the head of a second incline, again let down, and again reloaded for a short haul to the furnaces. Later, when the Day and Randol tunnels provided outlets on the 800 level, the situation was somewhat improved, but it was still necessary either to utilize the lower incline or to haul the ore down the hill in wagons.

In October 1885 a very costly attempt to expand the mine westward commenced with the sinking of the America shaft and the simultaneous driving of a 2,000-



FIGURE 113.—Miners in two-decked cage in Randol shaft. The descent in this shaft is reported to have been an experience likely to be remembered to one's dying day. Owing to the constriction of the shaft, it was necessary to loosen the holst mechanism and let the cage fall free to gather enough momentum to pass the tight places, and this ride was generally accompanied by the Cornish miners singing an appropriate old hymn, such as "Jesus, Savior, pilot me." From L. E. Bullmore collection.

foot crosscut toward its projected bottom from the Santa Isabel shaft on the 1400 level. The America shaft was located in the vicinity of old caved workings which had yielded about 1,000 flasks of quicksilver during 1863-66, and almost from the first its sinking was hampered by excessive amounts of water. However, by intermittent sinking and pumping it was put down more than 800 feet to about the 1000 level, and exploratory drifts were run from it on the 500, 600, and 700 levels. The workings on the 700 level cut some ore, but in June 1888, after repeated floodings, the shaft caved from near this level and the project was abandoned. Yet the difficulties encountered in sinking the shaft were mild compared with those encountered in driving the 1400-level crosscut. Almost from its beginning the miners had to contend with large volumes of water and caving ground, but when

they reached a point about 900 feet from the projected bottom of the America shaft they released such a heavy flow of carbon dioxide that they had to stop all work for a month. To conduct air to the working face, 11-inch pipes coupled to blowers were installed, and ventilation was further aided by installing an 8-foot fan at the mouth of the drift and a 12-foot fan at the head of the Washington shaft. Work was continued through treacherous ground to a point 500 feet from the shaft, where gas made further progress impossible, despite the large blowers and pumps. After a bulkhead had been put in, the miners backed up 200 feet and had managed to drive a bypass for 80 feet when the America shaft caved. Drifting was then stopped, and a brick bulkhead 4 feet thick was built in the crosscut 700 feet from its mouth to prevent the gas from flowing into other workings of the mine. A way of utilizing this gas was found in 1895, when it was compressed in tanks to a pressure of 1,650 pounds per square inch and sold. According to one report (Anonymous, 1895, p. 235) this was the only commercial source of carbon dioxide in the United States other than Saratoga Springs, N. Y.

In 1889 J. B. Randol left the New Almaden mine in order to develop a promising quicksilver mine in northern California in which he had acquired a sizable interest. It is appropriate to summarize here the progress of the mine through his administration. When he arrived in 1870 the production had declined to less than 15,000 flasks per year, and the grade of the ore being treated had fallen to 5 percent. The known ore bodies were nearly exhausted, and mining was becoming increasingly costly. By farsighted, though expensive, development work he had increased the production to nearly double what it was when he arrived, and although the grade of the ore treated steadily declined, this was partly offset by increased efficiency resulting from the introduction of more modern mining methods and the development of the Scott furnace. The company, when he arrived, labored under a sizable debt, but by 1881 this had all been paid off and \$525,391 returned in dividends to the stockholders.

At the time of his departure, however, the outlook for the mine was much like what it had been on his arrival. Considerable money had been spent on non-productive exploration and useless shafts, the known ore bodies were nearing exhaustion, and production had fallen to 13,000 flasks per year, recovered from ore containing 1.73 percent quicksilver. Even though no dividends had been paid for 8 years very little capital was available for the search for new ore bodies. Mine Hill was considered to have been thoroughly explored, and during the last few years workmen who



FIGURE 114.—The Hacienda in 1875. On extreme right is the new Scott furnace, which was the first of its type ever built. The other large buildings enclose the older batch furnaces consisting of a series of chambers, similar to those shown in figure 106. Note in the central part of the photograph the huge piles of wood used in firing the furnaces. From L. E. Bullmore collection.

had spent their entire lives on the hill had been dismissed.

When Randol departed in 1889 he retained for a time his position as general manager, though until near the end of 1891 the actual mining was directed by the mine superintendent, Col. F. Von Leicht. Capt. James Harry succeeded Von Leicht as mine superintendent, and shortly after Randol resigned, in March 1892, Robert R. Bulmore, who had been cashier for many years, was appointed as the general agent of the company. The position of general manager was abolished, and the mine superintendent directed the mining while the general agent directed the furnacing and all other company business. In January 1896 C. C. Derby was appointed mine superintendent; and at the end of 1899, when the position of general

agent was abolished, he assumed all the duties formerly handled by the general manager. He was succeeded in 1901 by his father, Thomas Derby, who remained in charge to the end of 1909. As all these men had worked for years under Randol, they were thoroughly familiar with the mine; and they put forth every effort to maintain the greatest possible production with the limited capital at their disposal.

The Almaden shaft, lying between the America shaft and the San Francisco shaft, had been started by Randol to explore the continuation of the ore shoot mined in the near-surface San Ramon stope, and James Harry continued sinking it to below the 600 level. Exploratory drifts on the 500 and 600 levels Cut "favorable vein" containing some cinnabar, but as no real ore was found the project was abandoned.



FIGURE 115.—The Hacienda in late 1880's. Main office and storeroom in foreground. Compare with figure 114. Building behind to left is woodshed; large buildings are over the four Scott furnaces. Tall chimney on the right skyline is at end of one of the long exhaust lines. The chimney and a part of the office building in right foreground were the only structures remaining in 1949. From L. E. Bullmore collection.

Another shaft—the Victoria (fig. 121)—was put down close to the Victoria stope to facilitate the handling of old stope fill, abandoned in the early days but now thought of as good ore. The deeper ore bodies of the Randol stope were rapidly being depleted, and in 1892 the Randol shaft was hoisting ore only during one shift a day.

To find new ore bodies, Randol, apparently impressed with Dr. Becker's study of the mine (see Becker, 1888), had employed two other geologists, S. B. Christy, of the University of California, and John A. Church, of New York, to examine the property and submit recommendations for further exploration. Christy, who had been on the property 7 times during the previous 14 years, recommended against further exploration at depth, whereas Church advised exploration to the 2500 level north of the Randol ore bodies. Church's advice was followed in 1892, when an internal shaft was sunk to the 2450 level from the Buena Vista workings, and a crosscut was run toward the vein. As large amounts of water

and gas caused the project to become very expensive, work was stopped in 1893 without having reached the main "vein," but these workings have the questionable distinction of being the deepest exploration in any quicksilver mine in the world. Shortly after this project was abandoned the Buena Vista shaft and the Randol workings were allowed to fill with water, and on January 25, 1896, all mining through the famous Randol shaft was stopped.

Early in 1892 James Harry managed to wheedle enough money to put down the Santa Maria shaft, behind the camp schoolhouse, to explore the ground in the vicinity of the old very rich Velasco stopes. One year later ore was discovered on the 600 level run from this shaft, and subsequent mining revealed that it extended southward for about 1,200 feet. This large new ore body, found in a supposedly exhausted mine, was extracted economically through the Harry shaft (fig. 122) and Harry tunnel, which were driven as soon as the continuity of the ore had been established, and it was the principal source of ore up to

1901. For many years after 1901 the ore mined came chiefly from the Mine Hill opencut, various dumps, and stope fill in old workings. (See fig. 123.)

While Randol was in charge of the property he had always turned down all suggestions for work at any of the so-called outside mines that lay along the ridge extending west of Mine Hill and that were first developed under Barron, Forbes, & Co. In the 20-year period after his departure attempts were made to reopen and develop the Providencia, Enriquita, San Mateo, San Antonio, and Senator mines, but all these

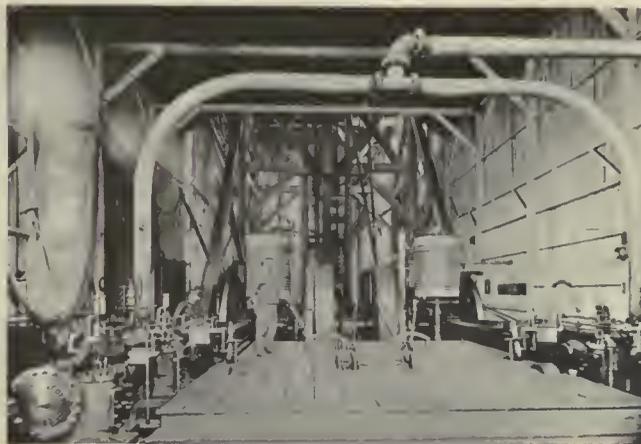


FIGURE 118.—Hoisting equipment used at the Buena Vista shaft about 1885. The two upright cylindrical drums are the level indicators which enable the operator to stop the hoist at the proper places many hundreds of feet underground. The braided belt-type wire cable and small cages are visible in the background between the two indicators.



FIGURE 116.—Santa Isabel shaft buildings in late 1880's. Shed in foreground was apparently used in hand sorting the ore, whereas shed behind and to the left protects a pile of coal used to fire the steam boilers. Not a trace of any of the buildings shown in photograph remained in 1947.



FIGURE 119.—View of the Randol shaft hoisting works about 1885, with the Buena Vista shaft building in the lower right. The ends of the large timbers to be used in the lower levels of the mine are conveniently labeled as to size. The largest of these are 16 by 16 inches and 20 feet long.



FIGURE 117.—Building housing the boilers, steam engines, and pumps for the Buena Vista shaft. This large and costly shaft, which was the deepest of more than a dozen put down in the New Almaden mine area, was poorly located and served only for exploration and dewatering for a few years. Had the money invested in this deep exploration been used otherwise, it might have materially prolonged the life of the mine.

attempts were handicapped by lack of capital, and all were abandoned before any more than a small amount of ore had been recovered. In addition, several new prospect shafts were put down but none of these revealed any minable ore. As the yield from known ore bodies and dumps on Mine Hill was likewise diminishing, the populace of the camp was slowly drifting away; and at the close of Thomas Derby's administration in 1909 the once-thriving community was little more than a ghost town of empty weather-beaten houses.

A change in the board of directors was largely responsible for Thomas Derby's departure, and the new board appointed E. J. Furst to take his place. As the Guadalupe mine, near the western boundary of the



FIGURE 120.—Washington shaft buildings in the middle 1880's. The shaft was originally named the Garfield shaft, but after the assassination of President Garfield its name was changed in hopes of overcoming the ill luck which seemed to plague it. Landslides that have crossed the area had by 1947 removed all signs of this shaft except for a single timber. From L. E. Bullmore collection.

New Almaden property, was reopened at about this time, Furst's attention was drawn to the Senator pros-

pect, just east of the Guadalupe, which in previous years had yielded a small amount of ore. John Drew was placed in charge of developing the prospect, and when preliminary trenching gave favorable results a new shaft was begun in November 1909. While the shaft was going down in the summer of 1910 Furst left and was succeeded by R. Nones, who employed J. F.



FIGURE 121.—Shaft house of the Victoria shaft with sorting shed and brick powder house to right. From C. N. Schuette.



FIGURE 122.—Harry shaft buildings; Capt. James Harry in foreground. This shaft, sunk in 1893, was the last major shaft put down on Mine Hill. Even at this late date, however, it was necessary to install large steam boilers and steam engines for hoisting. From L. E. Bullmore collection.



FIGURE 123.—Square-set timbering used at New Almaden to support walls of a stope raised to the surface. This type of timbering was used to support the ground only in the deep parts of the mine and near the surface where the silica-carbonate rock is leached and ochreous. From L. E. Bullimore collection.

Tatham as mining superintendent. Under the direction of Tatham and Drew good ore was found in the Senator mine and hauled 7 miles to the Hacienda for reduction. But any profits that may have resulted were quickly used by Nones on various other projects, such as an electric railroad, a chain of stores in San Jose, and an elaborate mill to make fireproof paint from burnt ore. In 1912, even though the Senator mine was producing and part of the property was sold for farmlands, the Quicksilver Mining Co. was declared bankrupt.

In 1915 George H. Sexton, who ultimately gained complete control of the property, obtained a 25-year lease and appointed W. H. Landers, a specialist in quicksilver mining, as general manager. Landers reopened the Senator mine with John Drew again in charge, and installed near the mine a 40-ton Herre-

shoff furnace and an electrolytic dust precipitator. This was the first time that either a Herreshoff furnace or an electrolytic precipitator was used at a quicksilver mine, and they both proved very successful. Encouraged by the stimulus of the high wartime price of quicksilver, Landers also undertook the reopening of the Day and Deep Gulch tunnels to gain access to the Mine Hill stopes. As mechanical concentration of quicksilver was then in vogue, he also installed elaborate shaking tables, ball mills, and flotation cells at the mouth of the Day tunnel, below the Randol dumps, and at the Senator mine. On the declaration of war, in 1917, however, Landers left to join the armed services.

Edmund Juessen, who succeeded Landers, found that the concentrating equipment functioned perfectly, but as the little ore available could be treated more cheaply by furnacing, the ball mills were junked. Juessen then devoted his energy to the building of a 60-ton Scott furnace at the Senator mine, which was barely able to keep the 40-ton Herreshoff supplied. This not only turned out to be an ill-advised expenditure but was nearly disastrous. Under the supervision of Robert Scott, inventor of the Scott furnace, the new furnace was completed in 1918, but because of several innovations it did not function properly. An 80-ton brick ore bin, superimposed on the furnace and supplied with ore by a conveyor belt, was torn down and replaced by a wooden bin, and, after other alterations, the furnace was first fired on May 7, 1919. It remained in operation only until the end of the month, when it caught fire and ignited the entire reduction works. By the time Juessen left, early in 1920, the Herreshoff had been rebuilt and production resumed, and under various operators it remained in production until March 11, 1926, when the Senator mine closed down after having yielded about 20,000 flasks of quicksilver.

Shortly after the Senator mine was closed down, George H. Sexton, the president and principal stockholder of the New Almaden Co., Ltd., died, and a prolonged period of litigation ensued. As a result of a court decision the title of the mining property passed to Mrs. Mary Lord Sexton, and a mortgage on it was held by William Lord Sexton. The property made no recorded production in 1927, which was its first unproductive year since 1850, except for the early period 1859-60 when the mine was closed by an injunction. From 1928 through 1935, however, lessees retorting ore from old dumps and recovering quicksilver from beneath the old furnaces at the Hacienda reported a small annual production. In the latter part of this period a C.C.C. camp, established at the

site of the old English camp on Mine Hill, benefited the property by erecting new buildings, repairing the waterlines, and keeping up the roads.

In 1935, C. N. Schuette was called upon as a quicksilver-mining expert to evaluate a part of the New Almaden property that was to be flooded as a result of the erection of water conservation dams in Guadalupe and Almaden Canyons. The sale price of these parcels of land was established without court action, and Mr. Schuette was retained by the owners to prepare a comprehensive report on the mining possibilities of the entire property. His report served to call attention to the property, and in 1939 members of W. H. Newbold's Sons & Co., of Philadelphia, undertook the promotion of a company to lease and operate it. A new company, known as the New Almaden Corp., was formed, and took over the property on May 1, 1940, with Schuette as general manager.

The new operation, which was to continue through World War II, was begun by stripping overburden from the top of Mine Hill and the contiguous east slope. (See fig. 124.) This work resulted in the un-

covering of some minable ore, and by the middle of November 1940 a modern reduction plant (fig. 125) containing a 100-ton rotary furnace had been installed near the opencuts. Furnacing of ore began immediately after the plant was completed, but it soon became apparent that the ore in the opencut was capriciously distributed and could not be followed to any great depth without removing an excessive amount of overburden. It was therefore decided to make a new attempt to find additional ore in the then inaccessible New Almaden mine, and to achieve this the Day tunnel and Santa Rita shaft were reopened. This underground venture, however, was seriously handicapped by a lack of experienced miners, and although most of the mine at and above the 800 level was made accessible and short new workings were driven in the central stope area, little ore was obtained. Meanwhile, the old dumps, particularly the China dump at the mouth of the Main tunnel, were worked to maintain production, and they were the principal sources of ore. When the dump ore was exhausted, the large San Francisco opencut on the south slope of Mine Hill was



FIGURE 124.—Opencuts developed on Mine Hill by the New Almaden Corp. between 1940 and 1945. Note landslide descending from face of large waste dump in center foreground. The curved portal of the old Main tunnel is just to the right of the dump and above the landslide pond. Headframe of the Santa Rita shaft, reopened in 1941, is visible on right skyline.



FIGURE 125.—Rotary furnace plant built on Mine Hill in 1942. Ore bin at top of photograph, furnace room in lower right, condensing pipes in center, and exhaust stack going uphill to left. The furnace was removed in 1946, and in 1947 an unsuccessful attempt was made to use a vertical retort hull in the central building.

begun. (See fig. 126.) This supplied the bulk of the ore treated in the last year before the New Almaden Corp. stopped work on December 1, 1945. In 1946 the furnace and other mine equipment were sold and hauled away, and the corporation was dissolved by vote of the stockholders. Their 6-year operation of the mine had yielded nearly 7,000 flasks of quicksilver from ore that came chiefly from dumps and opencuts.

Since 1945, a little ore has been taken from the lower part of the San Francisco opencuts and from the reopened Upper America tunnel. A more interesting operation was begun in the fall of 1945 and continued until the fall of 1947: along the north margin of the furnace dumps of the old Hacienda, at the junction of Deep Gulch and Almaden Canyon, H. F. Austin mined, by means of a drag line, stream gravels con-



FIGURE 126.—Mining equipment employed by New Almaden Corp. in San Francisco opencut on Mine Hill in 1945. Ore was distinguished from waste largely by panning, and about 15 truckloads of waste was removed for each truckload of ore. Photograph by C. N. Schuette.

taining large nuggets of very rich ore. In the summer of 1948, with the death of Mrs. Mary Lord Sexton, the ownership of the property passed to her two nephews. In the fall of 1948, the once renowned New Almaden mine was deserted, except that one man was mining in the vicinity of the San Francisco opencuts. Neither prospectors nor geologists any longer swarmed over the hill; it had once again become range land, whereon grazing cattle chewed their cud in peaceful solitude, disturbed only by an occasional prowling mountain lion.

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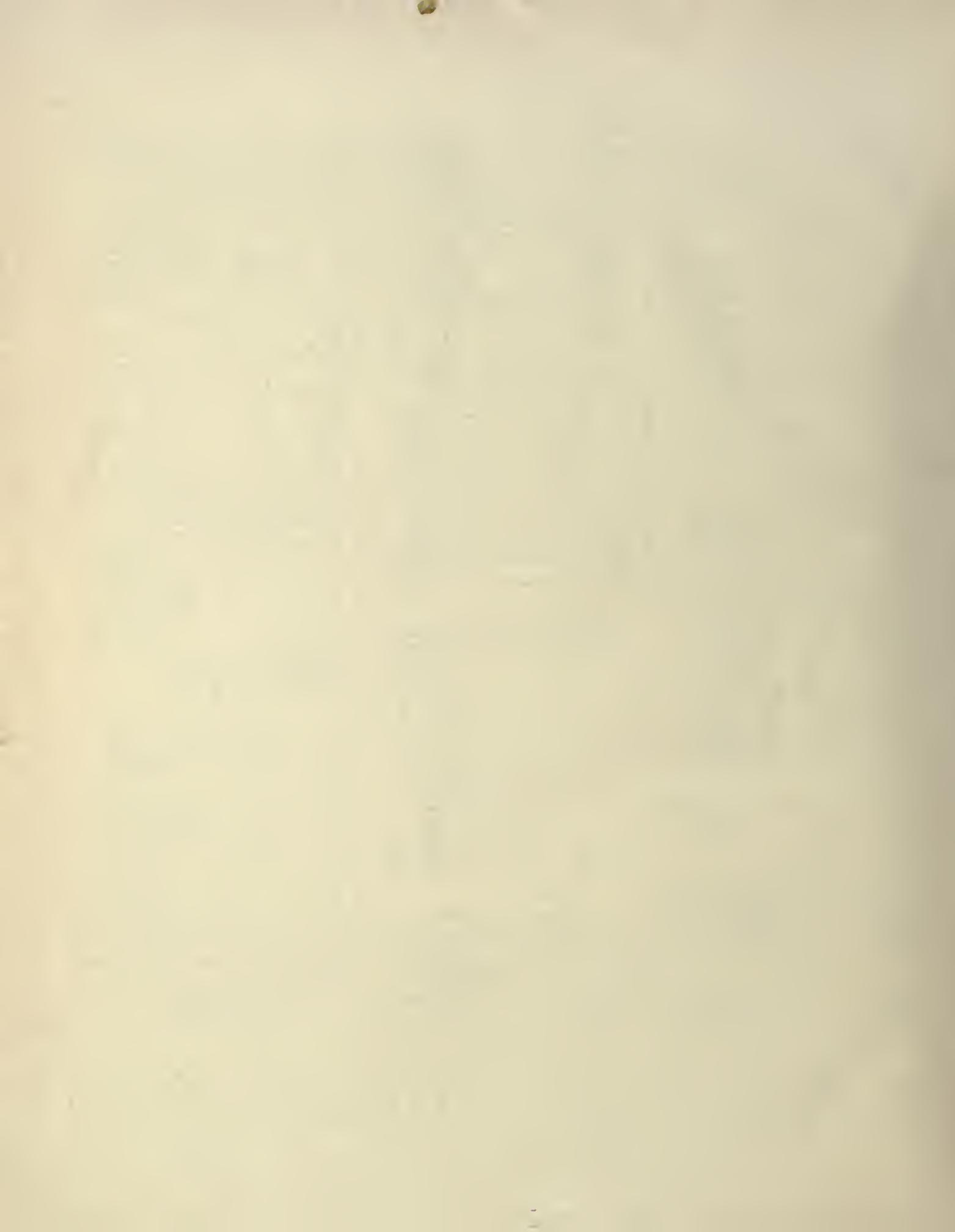
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