Geology and Mineral Deposits of the Boleo Copper District Baja California, Mexico

By IVAN F. WILSON

In collaboration with VICTOR S. ROCHA

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ABSTRACT

The Boleo copper district, second largest producer of copper in Mexico, is near the town of Santa Rosalía, about midway along the Gulf of California coast of Baja California. The copper deposits are in a recently uplifted coastal belt of Pliocene sediments exhibiting a mesa-and-arroyo topography. The copper mines cover a zone 11 kilometers long and ½ to 3 kilometers wide, parallel to the coast.

The climate is hot and extremely arid. Rainfall is confined mainly to heavy cloudbursts at intervals of several years. Vegetation consists largely of a great variety of cactus and other thorny desert plants. The principal natural resources of the region are mineral deposits, such as copper, manganese, and various nonmetallic minerals, and rich fisheries in the Gulf of California.

The oldest rock, exposed only in small erosional windows, is a quartz monzonite, which has been considered to be either of Cretaceous or pre-Cretaceous age. This is overlain unconformably by the Comondú volcanics, of middle(?) and late Miocene age, which are probably at least 500 meters thick, consisting of andesitic and basaltic flows, sills, tuff, breccia, agglomerate, conglomerate, and tuffaceous sandstone, all the sediments being of nonmarine origin. Facies changes indicate that the sediments were derived from the present site of the Gulf of California.

When the area was invaded by the Pliocene seas, the Comondú volcanics had a youthful or early mature topographic surface with a local relief of as much as 450 meters. Overlying the Comondú with profound unconformity is the lower Pliocene Boleo formation, which is the host rock to the copper deposits. This formation consists mainly of interbedded tuff and tuffaceous conglomerate of latitic to andesitic composition, together with a local nonmarine basal conglomerate, a fairly persistent basal marine limestone, thick layers of gypsum, and a few lenses of fossiliferous sandstone. Its thickness ranges from 50 to 250 meters and averages 140 meters. The formation is considered to represent deltaic deposition along a shoreline.

Resting unconformably on the Boleo formation is the middle Pliocene Gloria formation, composed of sandstone and conglomerate averaging 60 meters in thickness and having a maximum thickness of 185 meters. It consists of a local basal conglomerate, a fossiliferous marine sandstone, and an overlying conglomerate that grades into a nonmarine facies inland. This and all the succeeding formations are postmineralization.

Overlying the Gloria formation with local unconformity is the upper Pliocene Infierno formation, which is 5 to 140 meters thick, averaging 55 meters. It consists of fossiliferous marine sandstone overlain by conglomerate.

This is overlain unconformably by the Pleistocene Santa Rosalía formation, consisting of a thin layer of fossiliferous marine sandstone and conglomerate 5 to 15 meters thick, which is limited to some of the mesa tops.

The mesas northwest of the Boleo district are covered by the Tres Vírgenes volcanics, of Pleistocene and Recent age, composed of latite flows, pumice, and welded tuff, which are overlain in places by olivine basalt flows, breccia, and cinder cones.

The mesas and terraces along the arroyos are blanketed by Quaternary gravels 1 to 20 meters thick, mainly of nonmarine origin. Alluvium is found in the arroyos, beaches, and dry lake beds.

Structurally, there is a complete discordance between the Comondú volcanics and the younger formations. The Comondú volcanics were faulted and tilted before deposition began in the Pliocene. They are cut in places by west-dipping normal faults with displacements of 50 to 100 meters, resulting in a series of eastward-tilted blocks. Dips in the volcanic rocks are as great as 55° NE., but more commonly they are 5° to 25°. The pre-Pliocene faults provided pathways for mineralizing solutions.

Much of the structure of the Pliocene and Pleistocene strata represents initial dips, developed over the irregular topographic surface on the Comondú volcanics. Such dips reach 30° in the basal marine limestone of the Boleo formation and range from 3° to 20° in the clastic beds, decreasing upward in the section. Superimposed on the initial dips are the effects of later tilting, faulting, and gentle warping. The beds were tilted gulfward from 3° to 10° and are offset by many normal faults, which strike generally N. 10°–45° W. and dip 65° to 70° SW or NE. The faults of greatest displacement dip southwest. The maximum known vertical displacement is 250 meters, along the Santa Agueda fault; the other faults have displacements of less than 80 meters. Many of the faults form in echelon systems. The major faulting, aside from the pre-Pliocene faulting, was probably near the close of the Pliocene, but some faulting continued into Pleistocene or Recent time.

The Boleo copper deposits occur in relatively impervious, moist, soft, dark-colored clayey tuff beds of the Boleo formation. Five principal clayey ore horizons have been identified, each underlain by conglomerate or its gulfward equivalent of tuffaceous sandstone.

The thickness of minable ore has averaged about 80 centimeters in recent years, although it ranged from 1 to 2 meters and exceptionally 5 meters in the older mines. The average grade of ore mined from 1886 to 1947 was 4.81 percent of copper, but it has ranged from more than 8 percent, in the earliest years, to about 3.5 percent in recent years. Some of the ore is in elongate, subparallel, riblike shoots, separated by ribs of lower-grade ore, but most of it is related to major irregularities in the basement rocks of the Comondú volcanics. Veins and stockwork bodies are found in the Comondú volcanics, and irregular replacement bodies occur in other types of rocks.

The main ore mineral in the sulfide zone is very fine-grained chalcocite, accompanied by chalcopyrite, bornite, covellite, and native copper. Pyrite and galena are less common. In the

oxidized zone are a great variety of copper oxides, carbonates, silicates, and oxychlorides, including the rare minerals boléite, pseudoboléite, and cumengite. Manganese oxides, mainly cryptomelane and pyrolusite, are commonly associated with the copper minerals and are also concentrated in separate beds. The gangue is composed mainly of montmorillonite, together with various rock-forming and secondary minerals, and veinlets of gypsum, calcite, chalcedony, and jasper.

Elements present in notably high amounts in Boleo ore include copper, manganese, zinc, cobalt, lead, silver, sulfur, and chlorine. A special study was made of the distribution of zinc and of cobalt. In many localities the zinc to copper ratio increases markedly toward the hanging wall of the ore beds.

The origin of the Boleo copper deposits is controversial, but the writers support the theory of replacement of favorable beds by hydrothermal solutions ascending along premineral faults and fractures in the Comondú volcanics. It is thought that the solutions rose along projecting hills and islands of the volcanic basement rocks and spread out through the beds of the Boleo formation, where they were trapped by the relatively impervious clayey tuff beds that overlie porous conglomerate and sandstone. The mineralization took place in post-Boleo and pre-Gloria (early Pliocene) time and is believed to have been related to the period of igneous activity that produced the tuffaceous beds.

The Boleo copper deposits were discovered in 1868 and have been worked by the French-owned Compagnie du Boléo since 1885. The total production from 1886 to June 30, 1947, was 13,622,327 metric tons of ore, from which 540,342 metric tons of copper was obtained. The average annual production has been 221,504 tons of ore and 8,786 tons of copper.

More than 588 kilometers of underground workings have been developed in the Boleo district. The mining methods are similar to those used in thin coal seams.

The Boleo ore is smelted directly in reverberatory furnaces fired by fuel oil, producing a high-grade copper matte which is treated in converters. The final product is blister copper containing an average of 99.3 percent of copper, and the average recovery is 87.4 percent. Ore-dressing tests have been conducted on the Boleo ores, which are very difficult to beneficiate because of the extremely fine size of the ore minerals and the swelling of the bentonitic clay matrix. The tests are not entirely favorable, but they indicate the possible application of a combined leach and flotation process.

The known reserves of currently minable copper ore are low, but the present small-scale operations of the *poquiteros*, who rework filled stopes and dumps, extract pillars from old mines, and open smaller, new deposits in outlying areas, can probably be continued for several years, assuming favorable economic conditions. Additional drilling might reveal some new, comparatively small ore bodies, but the discovery of unknown large deposits is unlikely. Several million tons of marginal reserves averaging about 2 percent of copper remain in thin beds at great depth.

Besides copper, the district contains low-grade manganiferous beds, whose exploitation depends upon developing some commercial process for recovering the manganese. Zinc, lead, cobalt, nickel, and silver occur in minor quantities in the copper ore or smelter products. Of these, only very minor quantities of silver have been recovered commercially from the blister copper. Other mineral deposits in the region include gypsum, limestone, calcareous sandstone, sulfur, pumice, and perlite.

INTRODUCTION

LOCATION OF THE AREA

The Boleo copper district is centered near the town of Santa Rosalía, a coastal port lying about midway along the western shore of the Gulf of California and nearly opposite the port of Guaymas, Sonora. Santa Rosalía is in the "Municipio" of Mulegé, in the Southern Territory of Baja California, Mexico.

The copper mines are in a northwest-trending belt which parallels the coast and lies generally from 3 to 4 kilometers inland. The area of continuous mine workings is 11 kilometers long and ½ to 3 kilometers wide. The topographic and geologic map of the district that accompanies the present report (pl. 1) covers an area that extends for 12.7 kilometers in a northwest direction and has a maximum width of 7.7 kilometers southwestward from the coast.

The Boleo copper district merges to the northwest into the Lucifer manganese district, an area of manganese deposits around the Lucifer mine, which is 12 kilometers northwest of Santa Rosalía. The Lucifer district was studied previously by Wilson and Veytia (1949), and the geologic map of that district, covering an area of 80 square kilometers, adjoins the map of the Boleo district accompanying the present report. Figure 1 and plate 2 indicate the relative position of the areas covered by the geologic maps of these two districts.

PURPOSE AND SCOPE OF THE INVESTIGATION

The Boleo copper mines have been operated since 1885 by the French Compagnie du Boléo, and for most of their history they have been the second or third largest producer of copper in the Republic of Mexico. At the end of World War II, because of depleted ore reserves, rising cost of mining, and the termination of wartime subsidies, it appeared that the Boleo company would soon be forced to cease operating. Because the Boleo operations have been one of the chief industries in Baja California, and as the residents of Santa Rosalía and its environs have been virtually dependent upon the copper production for their support, it became urgent for the Mexican Government to search for means of prolonging the life of the industry. Moreover, owing to the high demand for copper in the United States, the continued production from the Boleo mines was also of interest to the United States Government. As part of its program of cooperative geologic investigations in the American Republics, therefore, the Geological Survey, United States Department of the Interior, undertook a geologic study of the Boleo copper district, in cooperation with the Instituto Nacional para la Investigación de Recursos Minerales of Mexico.

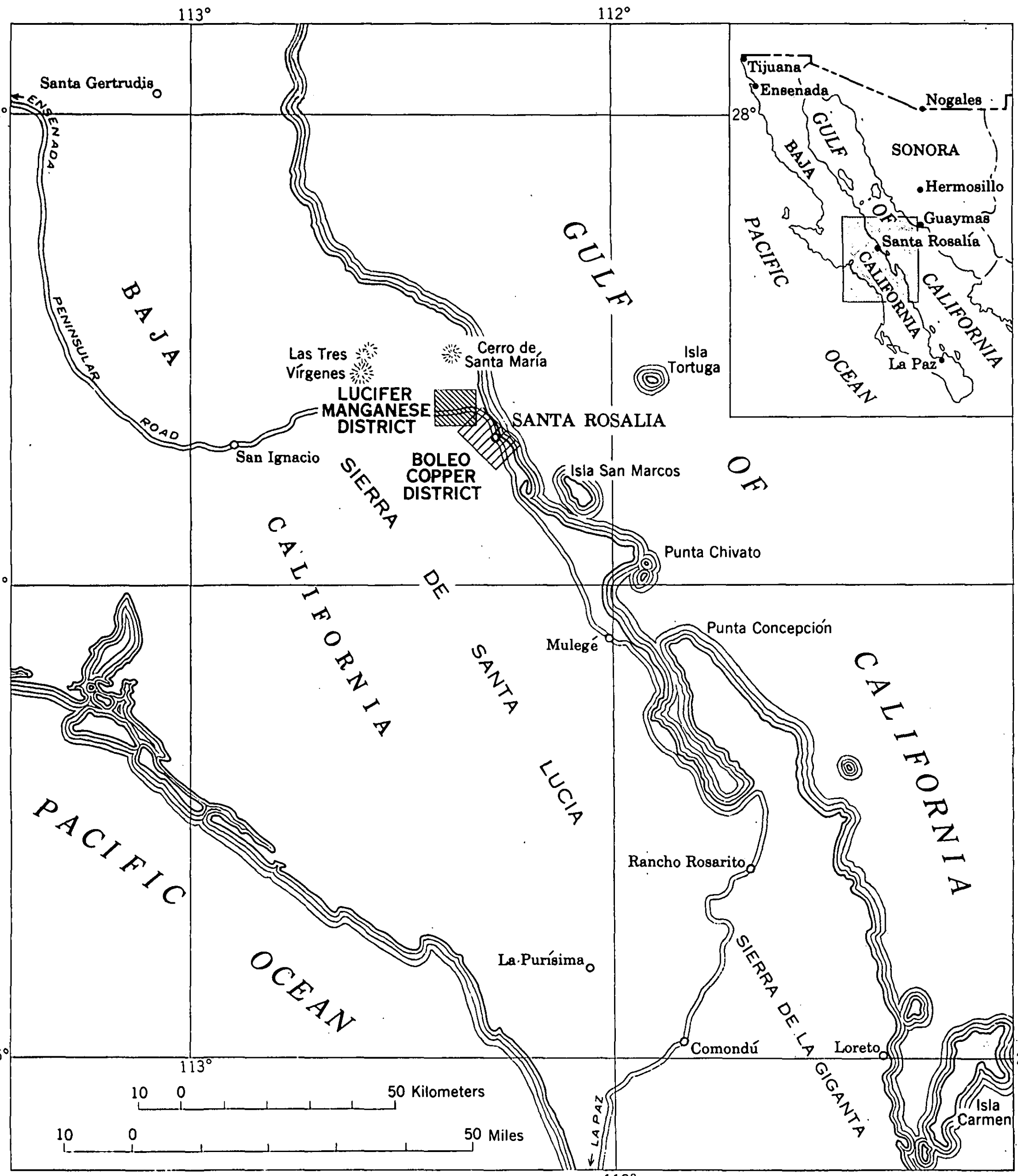

FIGURE 1.—Index map of part of Baja California, Mexico, showing location of the Boleo copper district and its relation to the Lucifer manganese district.

The purpose of the study was twofold: first, to appraise the resources of the district, with particular reference to the possibility of discovering new reserves by drilling or by other types of exploration; and second, to make a general geologic study of this unusual and highly interesting deposit, involving not only field studies but also an interpretation of the wealth of data on mine workings and drill holes contained in the company records. It was felt that most of these data would become unavailable when the company ceased operating, and most of them are irreplaceable, for the greater part of the underground workings are now inaccessible. An enormous amount of underground information had been accumulated, but a geologic interpretation of much of this material had never been made. By a study of these records, combined with detailed geologic mapping of the surface, an exceptional three-dimensional picture of the geology was obtained.

Since the localization of the Boleo copper deposits was known to have been controlled primarily by stratigraphy, and secondarily, perhaps, by structure, the stratigraphic and structural geology of the district were emphasized during the present study. The stratigraphy had not previously been worked out in detail, except for the copper beds themselves, and previous geologic maps had not differentiated any units of the sedimentary section, except for gypsum beds. The writers found it possible to map about 25 stratigraphic units, comprising 8 formations separated by unconformities, and it was discovered as a result that unconformities have an important influence on the localization of the ore deposits.

Systematic underground mapping was not possible, because only a small proportion of the many hundreds of kilometers of mine workings in the district is now accessible. Fortunately, however, the Boleo company had accurate maps of all the mines, and these were used as a basis for preparing structure sections and structure contour maps of the principal ore beds. Most of the currently accessible working faces of the mines were examined in order to study the geologic relations of the ore beds. Because of the present work of the *poquiteros* (small-scale independent miners) in reopening the old mines of the district, it was found possible to enter nearly all the important mines at one place or another.

The mineralogy of the ore beds was studied earlier by several investigators, at a time when a much wider variety of specimens was available than at present. A complete mineralogic investigation was therefore not attempted, although certain phases were chosen for further study and an attempt was made to compile and summarize the data previously published. The clay minerals and some of the ore minerals were studied in the Geological Survey laboratories in Washington by petrographic, X-ray, and differential thermal methods. The complete chemical composition of the ore was investigated, with particular reference to the minor elements, and a special study was made of the distribution of zinc and cobalt in the ore beds by means of more than 100 samples analyzed by the U. S. Bureau of Mines. Several large ore samples were also collected for ore-dressing studies by the Bureau of Mines to determine whether the lower-grade ores might be amenable to some method of concentration before smelting.

The geologic map (pl. 1) covers a land area of about 85 square kilometers. The geologic mapping was done on topographic base maps, some of which had a scale of 1:5000 and a contour interval of 5 meters, and others a scale of 1:10,000 and a contour interval of 10 meters. The final map was compiled on the latter scale, which was also used for the structure sections (pl. 3) and the structure contour map (pl. 4). Somewhat more than half the topographic base was redrawn from maps of the Boleo company; the rest was prepared by plane-table methods by Kenneth Segerstrom of the Geological Survey during the present investigation. Cultural features, such as roads and buildings, were also added by Segerstrom to the preexisting company maps.

Most of the geologic mapping was done from March to May 1946, and most of the underground studies and sampling were done in May and June 1948 and in November and December 1949. The office work, which consisted largely in compiling maps and sections and analyzing the various data collected by the company, was carried on mainly from the latter part of 1947 until the middle of 1949. Most of the data on current mining operations included in this report are given as of 1948 or 1949.

ACKNOWLEDGMENTS

The writers are greatly indebted to officials of the Compagnie du Boléo and especially to Messrs. A. Nopper, P. Mahieux, and F. L. García Quintanilla, for their kind hospitality and for providing free access to their maps and mine records. All the residents of Santa Rosalía were very hospitable during the course of the field work. Sr. Felipe Gutiérrez was highly cooperative in supplying information on the old mines of the district.

William G. Kane, formerly chief of the Mining Section of the Foreign Economic Administration in Mexico, was one of the principal advocates of the present investigation and gave helpful advice while on a visit in Santa Rosalía with the writers. Advice and assistance were likewise given by John Van N. Dorr, 2d, of the Geological Survey, who visited the field with the writers, and by W. D. Johnston, Jr., chief of the Foreign Geology Branch of the Geological Survey. Carl Fries, Jr., in charge of the Survey's program in Mexico, gave helpful advice throughout the period of office work and preparation of the report. Kenneth Segerstrom prepared the topographic map and cooperated in many ways during the period of field work.

Several other members of the Geological Survey have contributed to the present study. H. E. Vokes identified many fossils collected from the district, and C. W. Cooke identified some echinoids. Petrographic studies of rock and ore specimens were made by C. S. Ross, R. L. Smith, and E. S. Larsen, 3d, and mineralogical studies were made by Jewell J. Glass and Charles Milton. X-ray studies of ore specimens were made by J. M. Axelrod, and differential thermal analyses were contributed by G. T. Faust. A chemical analysis was made by Israel Warshaw and Charlotte Warshaw, and a spectrographic analysis was made by K. J. Murata. Michael Fleischer and Maryse H. Delevaux provided data on the copper content of rocks.

Alan Probert, G. M. Potter, and H. G. Poole, metallurgists of the U. S. Bureau of Mines, cooperated in many ways during their investigation of the problem of beneficiating the Boleo ores. Many chemical analyses

and certain preliminary results of the ore-dressing tests were furnished through the courtesy of S. R. Zimmerley, chief of the Salt Lake City Branch, Metallurgical Division of the Bureau of Mines.

Eduardo Schmitter, petrographer and mineralogist of the Instituto de Geología of Mexico, made some petrographic studies of rock specimens from the Boleo district, and Rodolfo del Corral, chemist of the Instituto, made two chemical analyses of rocks. The enthusiastic cooperation of the director of the Instituto de Geología during the period of the investigation, Ing. Ricardo Monges López, is gratefully acknowledged.

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PREVIOUS LITERATURE

Apparently the first published mention of the Boleo copper deposits is in a report by Blanco and Tinoco (1873), which appeared only 5 years after the discovery of the deposits. This report describes a survey of the 27th parallel of latitude in Baja California, but it includes a description (p. 968–970) of the mining operations that were being carried on in the Boleo district, then called the Santa Agueda mining district. A further brief report on the mining operations appeared the following year (Tinoco, 1874), and one of the first comprehensive reports on the district was published later by Tinoco (1885). This report is valuable for its description of the early mines, and it also describes the geology of the district and gives a stratigraphic section of the ore beds.

In 1884 a detailed study of the Boleo district was made for French mining interests by Bouglise and Cumenge, whose highly favorable report led to the organization of the Compagnie du Boléo in Paris on May 16, 1885. This report is said to have been published in Paris (Bouglise and Cumenge, 1885), but the writers have been unable to find a published copy; they have, however, seen a manuscript copy, dated December 15, 1884, in the files of the Compagnie du Boléo at Santa Rosalía. Conclusions of this report as to extent of ore, potential production, and industrial requirements have proved to be remarkably accurate.

Fuchs (1886a, 1886b), who studied the Boleo district in 1885, wrote an extensive report on the geology and mineral deposits of the district. Saladin (1892), who was one of the early directors of exploitation for the Compagnie du Boléo, also wrote a fairly complete report on the district. A report by Martínez Baca and Servín Lacebron (1898) contains valuable statistical data on the first 10 years of operation by the Compagnie du Boléo.

Krusch (1899) made a microscopic and chemical study of ores from the Boleo district and discussed the paragenesis and origin of the minerals. A brief description of the Boleo operations in the Boletín Minero (1917) is valuable particularly for a colored map showing the extent of the mine workings at that time. Some additional early reports on the Boleo district, containing data largely of historic interest, are those by Ramos (1887), Wendt (1887), Laforgue (1897), and Bossuat (1898).

One of the most important studies published on the Boleo district is by Touwaide (1930). His valuable studies of the mineralogy and paragenesis of the copper ores are particularly commendable in view of the difficulties involved in microscopic studies of ores of this type.

A report on the Boleo district by Peña (1931) gives a brief summary of the geology and considerable information on mining methods, equipment, and costs. Bellanger (1931), general director of the Compagnie du Boléo, published a good description of the mining and smelting methods, including data on costs, together with a brief description of the geology. Other reports on the mining and smelting operations of the Boleo company have been published by Lowry (1901), Mining and Scientific Press (1912), Duncan (1917), López and Espinosa (1918), Boletín Minero (1927), Huttl (1931), and Cárdenas (1939).

One of the best summary descriptions of the Boleo deposits is by Locke (1935), which, though brief, contains a comprehensive account of the geology and ore deposits. This report is based on field work done by Locke and his associates in the Boleo district in 1923 and 1924, the results of which are largely unpublished.

Recent studies of the ore reserves and future possibilities of the Boleo district have been reported on by Villafaña, Pérez Siliceo, and Aguayo Ibarra (1947), and Pérez Siliceo (1947).

Wilson (1948) described the initial structures and conditions of sedimentation resulting from a buried topography in the Santa Rosalía area. Wilson and Veytia (1949) described the geology and maganese deposits of the Lucifer district, which adjoins the Boleo district to the northwest.

The more comprehensive reports on the regional geology of Baja California, which have an important bearing on the geology of the Boleo district, are those by Gabb (1868, 1869, 1882), who made a reconnaissance of the entire peninsula; Lindgren (1889, 1890, 1891), who studied the area east of Todos Santos Bay and made pertinent observations on the general structure of the peninsula; Heim (1915, 1916, 1921, 1922), who did important stratigraphic work particularly near La Purísima and Comondú; Darton (1921), who published 21 geologic cross sections of the peninsula, including one in the latitude of Santa Rosalía; Gálvez and others (1922) and Hisazumi (1930), who reported on explorations for oil possibilities; Flores (1931), who compiled a geologic map of Baja California; and Beal (1948), whose report on the geology and oil possibilities of Baja California, accompanied by a geologic map, is the most comprehensive yet published. This report is based on a reconnaissance of the peninsula by a party of geologists in 1920 and 1921, the results of which were previously published in an abridged form (Marland Oil Co., 1924). A comprehensive memoir on the geology, paleontology, and oceanography of the Gulf of California, resulting from a cruise of the *E. W. Scripps* in 1940, has been written by Anderson (1950), Durham (1950), Shepard (1950), Natland (1950), and Revelle (1950).

Geographic descriptions of the Boleo district and surrounding region are included in the studies of Diguet (1899, 1912), a French naturalist and ethnologist who was employed for some years by the Boleo company, and Nelson (1921), who wrote an extensive monograph on the geography and natural resources of Baja California.

GEOGRAPHY

GENERAL GEOGRAPHIC FEATURES

Baja California is a long, narrow peninsula extending south-southeast for 1,200 kilometers from the California State Line. It is bordered to the southwest by the Pacific Ocean and to the northeast by the Gulf of California—that remarkable long, narrow, and deep trough which has been called by Beal (1948, p. 99), "the outstanding structural feature of its kind in North America," and by Osorio Tafall (1946, p. 104), "one of the most surprising and singular geologic structures that exist on our planet."

Along the length of the peninsula to as far south as La Paz Bay extends a line of asymmetric mountain ranges of high relief characterized by gentle westerly slopes and steep easterly slopes, the latter suggestive of fault scarps. The Peninsular Range is thus similar to the Sierra Nevada of California, as was early suggested by Lindgren (1889, p. 194–196). In part the peninsular divide lies very close to the Gulf of California, as in the Sierra de la Giganta, where the eastern scarp of the range drops abruptly into the gulf. Elsewhere, as in the Boleo district, a recently uplifted mesa-and-arroyo belt lies between the Peninsular Range and the gulf.

The dominant physiographic features bordering the uplifted coastal belt of mesas and arroyos of the Boleo district are the high Sierra de Santa Lucía to the west, the Tres Vírgenes volcanoes to the northwest, and Cerro de Santa María to the north. The Sierra de Santa Lucía, which forms the peninsular divide at altitudes of 1500 to 1600 meters, lies about 20 to 30 kilometers inland from the Gulf. The Tres Vírgenes, three prominent, well-shaped volcanic cones which have been active within historic times, are 35 kilometers northwest of Santa Rosalía and attain a maximum altitude of 1995 meters. Cerro de Santa María, situated near the coast 25 kilometers north of Santa Rosalía, is a complex volcanic mountain which reaches an altitude of 1348 meters. The Tres Vírgenes and Cerro de Santa María are surrounded by a lava plateau which extends southward into part of the Boleo district.

Much of Baja California is characterized by an extreme desert type of climate and vegetation, and the gulf side is perhaps as dry as any part of North America. Owing mainly to insufficient water resources, the peninsula is very thinly populated. The most important towns south of Ensenada are La Paz, on the gulf coast near the southern tip, and Santa Rosalía, the mining town described in this report.

ACCESSIBILITY AND TRANSPORTATION

The Boleo district is largely isolated from the rest of the Republic of Mexico and is much like an island to which all flow of commerce and nearly all travel have been by sea, and more recently by air. For travelers from the United States or from the mainland of Mexico, Santa Rosalía is most conveniently reached by plane. In 1948, regular flights were reaching Santa Rosalía about twice a week from Guaymas, Sonora, and from Tijuana and La Paz, Baja California.

Santa Rosalía has an artificial harbor, completed by the Boleo company in 1905, enclosed by two breakwaters of volcanic rocks capped by furnace slag (fig. 2). The harbor has an area of 15 hectares and a depth of 7 to 8 meters, although the channel was being deepened by dredging operations in 1948. Vessels of the size of the Liberty ships built during World War II may be accommodated within the harbor.

In their choice of the harbor site, directly across the mouth of Arroyo de la Providencia, as well as of the town site of Santa Rosalía, in the bottom of the same arroyo, the early French engineers were evidently misled by the deceptively arid appearance of the surrounding countryside. A cloudburst in 1945 resulted in the deposition of a sizable delta inside the harbor at the arroyo mouth.

FIGURE 2.—Harbor and town of Santa Rosalía. The town is in Arroyo de la Providencia; the smelter is visible at the right. At the left, below the mesa level, are two prominent marine terrace levels, the lower occupied by houses and the upper by the airport (light-colored strip). Photograph by Kenneth Segerstrom.

Small boats cross the Gulf of California from Guaymas to Santa Rosalía, a distance of 150 kilometers, generally two or three times a week. The crossing, always made at night, takes 10 to 14 hours, depending upon the size of the boat and weather conditions. A more comfortable means of reaching Santa Rosalía by sea is on one of the freighters of the Boleo company, which make frequent trips to the United States or to Mexican ports. The Boleo company has owned several ships, which have been used mainly for transporting blister copper to Tacoma, Wash., returning with mine timbers and lumber, and also for importing fuel oil and other supplies from San Pedro, Calif.

An automobile road 1,881 kilometers long traverses the entire length of Baja California, from Tijuana at the northern border to Cape San Lucas at the southernmost tip. Santa Rosalía lies slightly beyond the halfway point on the road, at a distance of 1,028 kilometers from Tijuana. Except for a paved section extending from Tijuana to a short distance south of Ensenada, most of the road is unimproved and parts of it are in very poor condition. A stage carrying passengers and mail makes the trip from Ensenada to Santa Rosalía, as well as from Santa Rosalía to La Paz, once or twice a week. A most interesting account of a journey over the peninsular highway has recently been written by Erle Stanley Gardner (1948).

Three methods have been used for transporting ore from the Boleo mines to the smelter at Santa Rosalía—railroad, aerial tramway, and truck. A network of narrow-gauge railroad lines extends from the smelter up the arroyo bottoms to the principal mines of the district. The Boleo company originally laid out more than 30 kilometers of lines, in Arroyos Providencia, Purgatorio, Soledad, and Boleo, but some of these have been washed out from time to time, necessitating their relocation or abandonment. At present, approximately 22 kilometers of railroad is in use (see pls. 1 and 2). This is the only railroad in the entire Southern Territory of Baja California. Its 50-year-old miniature Baldwin steam locomotives and its antique, highly decorated carriage car, now abandoned on a siding, are collectors' items for railroad enthusiasts.

An aerial tramway 5 kilometers long was installed in 1932 to transport ore from the San Luciano mine, in Arroyo de Santa Agueda, to Santa Rosalía. This tramway follows a spectacular course across several deep branches of Arroyo del Montado. The tramway, built in Germany, has a capacity of 250 tons of ore in an 8-hour shift.

A network of roads, mostly unimproved but passable for trucks, extends up the principal arroyos, along the coast, and on the tops of some of the mesas. Much of the ore mined by the small-scale independent miners in recent years has been hauled by truck, either to the nearest railroad or else directly to the smelter.

TOPOGRAPHY AND DRAINAGE

The topography of the Boleo copper district is of a mesa-and-arroyo type, which is typical of the youthful stage of erosion in gently dipping to flat-lying beds in an arid region. It consists of flattish-topped mesas separated by more or less parallel arroyos with wide, flat bottoms and steep sides. The arroyo bottoms have served as natural routes of access from the coast to the interior region, and they have accordingly been used as sites for railroads, roads, and centers of ore extraction, as well as for towns and mining camps. Travel may also be readily accomplished on the tops of the mesas, once these are reached, but the steep arroyo walls have served as natural barriers to transport. To the geologist, on the other hand, the arroyo walls are of chief interest as areas of outcrops, for the arroyo bottoms are generally covered with alluvium and the mesa tops are largely blanketed with gravels and in part by lava flows.

This mesa-and-arroyo topography is in a recently uplifted belt 7 to 15 kilometers wide lying between the foothills of the Sierra de Santa Lucía and the coast (figs. 3 and 4). The altitude of the mesas in most of the Boleo district ranges from 200 to 250 meters. They attain altitudes of 400 meters farther northwest near the Lucifer mine, but they descend gradually southeastward and merge into the coastal plain of San Bruno southeast of the copper district. The local relief between the tops of the mesas and the adjacent bottoms of the arroyos ranges in general from 90 to 170 meters, averaging 140 meters along the larger arroyos.

The arroyos run northeastward approximately at right angles to the coast (see pl. 2). The longest arroyos are Santa Agueda and Purgatorio, which head well within the Sierra de Santa Lucía, while the others, known as Montado, Providencia, Soledad, and Boleo, have their source in the mesa belt east of the sierra.

Rising above the level of the mesas are three distinct areas of rounded, rocky hills, which are important paleogeographic as well as topographic features. These are known as Cerro del Sombrero Montado, Cerro de Juanita, and Cerro del Infierno (see pl. 2).

The mesas are terminated rather abruptly near the coast by steep slopes, which are commonly broken by two intermediate terrace levels. The coastal beaches are pebbly and bouldery and are generally quite narrow, except at the mouths of the arroyos, where small deltas have been built outward into the gulf (fig. 5). In places the shoreline is marked by sea cliffs that descend abruptly into the gulf (fig. 6). In plan view, the fairly regular shoreline consists of a series of broad, sweeping curves or scallops, concave seaward, which are 3 to 4 kilometers from point to point. On a broader scale,

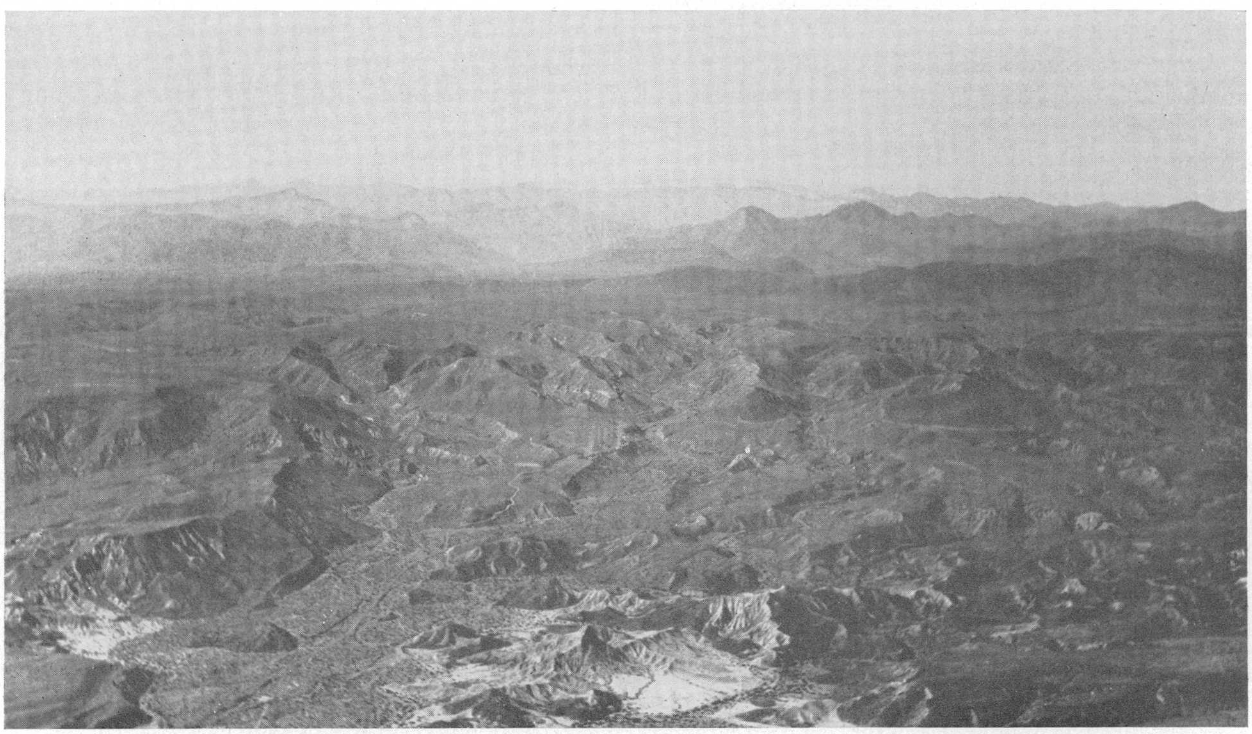

FIGURE 3.—Northern part of the Boleo copper district, looking up Arroyo de la Soledad. Arroyo-and-mesa and badlands topography in the foreground; Sierra de Santa Lucía appears in the background.

FIGURE 4.—Southern part of the Boleo copper district, looking up Arroyo del Montado. Arroyo de Santa Agueda appears in the middle distance and Sierra de Santa Lucía in the background. Foreground shows the rugged shoreline of the Gulf of California, bordered by two marine terraces. Photograph by Kenneth Segerstrom.

the Santa Rosalía area occupies a major scallop some 70 kilometers long, which extends from the salient opposite Cerro de Santa María, 30 kilometers to the north, to Point Chivato, 40 kilometers to the southeast. San Marcos Island lies partly within this scallop, 20 kilometers southeast of Santa Rosalía.

CLIMATE

The climate of the Santa Rosalía area is hot and extremely arid. The most remarkable feature is the highly erratic and intermittent nature of the rainfall, which comes generally in sudden, heavy cloudbursts, during which many inches of rain may fall within a few hours. As much as 200 millimeters (8 inches) of rain has been recorded in a single day, whereas the total annual rainfall for some years has been only 20 millimeters (0.8 inch).

In order to obtain exact data on the extremely intermittent character of the rainfall, the original daily rainfall records for Santa Rosalía were studied for the period 1927 to 1945, with the exception of 1939 for which no record is available. The records for earlier years could unfortunately not be found. The results of this study are presented in figure 7, which gives the total rainfall for each year, and shows the proportion of this total that was confined to a single day.

Exactly half the total rainfall of this 18-year period fell on the day of maximum rainfall of each of the 18 years. The rainfall during 6 days accounted for 33 percent of the 18-year total, and the rainfall during 26 days accounted for 66 percent of this total. The annual rainfall averaged 125.7 millimeters (4.95 inches), but it ranged from as little as 20.9 millimeters (0.82 inch) to as much as 304.1 millimeters (11.97 inches).

During the 60-odd years in which the Compagnie du Boléo has operated in the district, about six tremendously concentrated rainstorms, locally called chubascos, have taken place. Following such cloudbursts, the arroyos, which ordinarily are perfectly dry, are flooded with raging torrents which wash out roads, railroads, and buildings, inundate mines, and at times cause the loss of many lives. Such storms have been recorded in 1898, 1911 (two storms), 1931, 1936, and 1945.

Baja California is subject both to the tropical summer rains characteristic of the mainland of Mexico to the southeast, and to the winter rains characteristic

FIGURE 5.—Delta at the mouth of Arroyo del Purgatorio, Boleo copper district, looking north. The gravelly beach is typical.

FIGURE 6.—Rugged shoreline and narrow beaches southeast of Santa Rosalía, Boleo copper district, looking northwest. Cliffs are formed in Comondú volcanics; lower marine terrace appears at left.

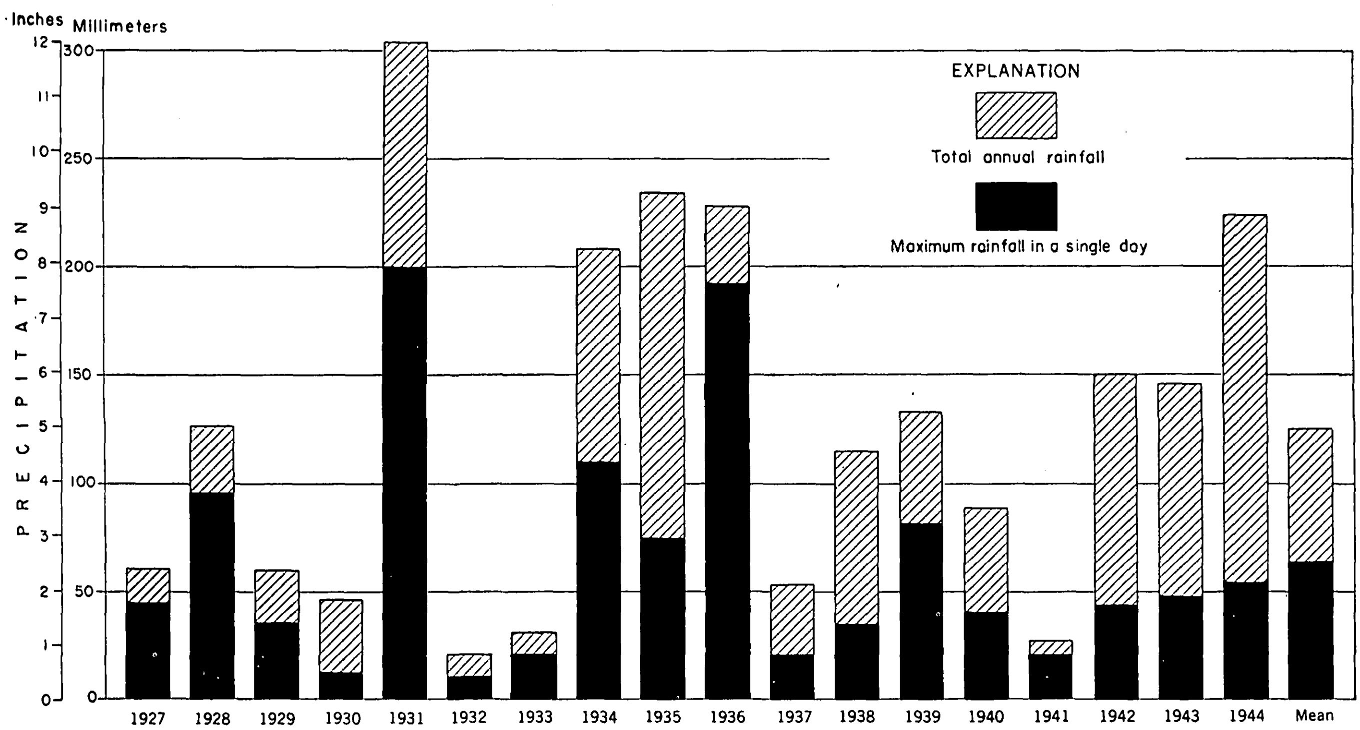

FIGURE 7.—Erratic character of rainfall at Santa Rosalía, Baja California, 1927–45.

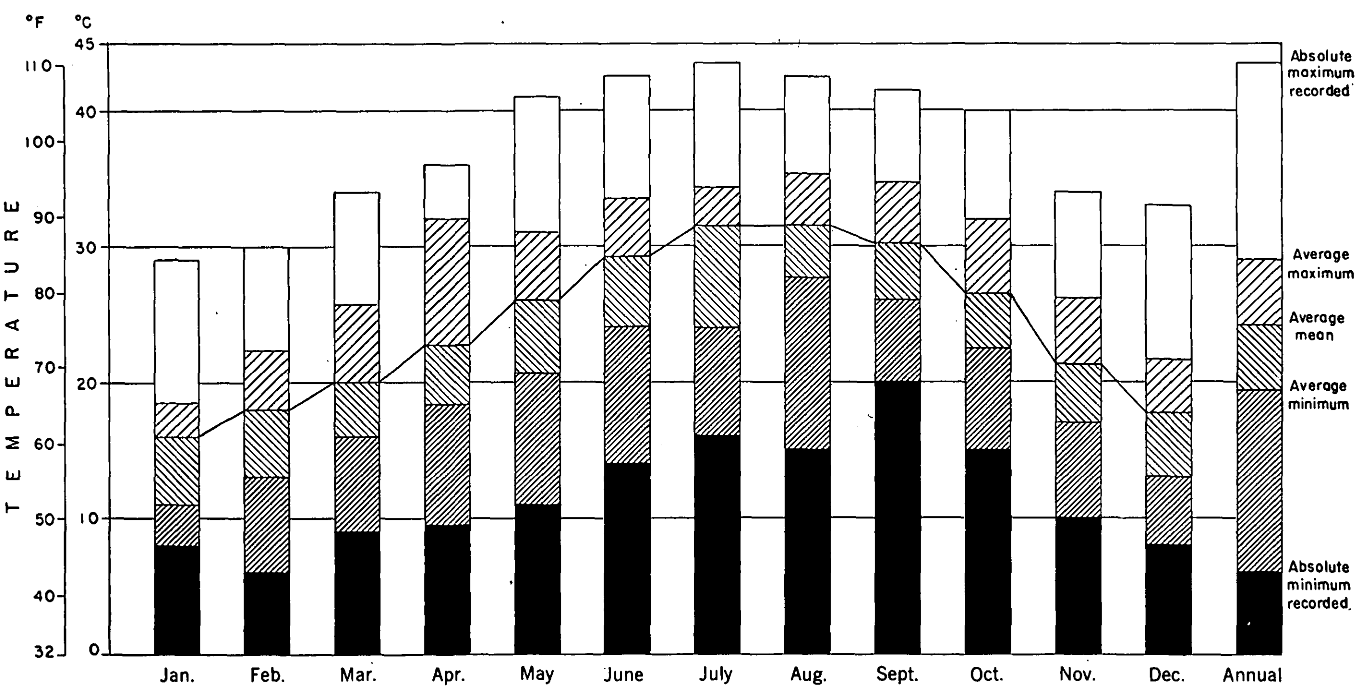

FIGURE 8.—Monthly and yearly temperature data at Santa Rosalía, Baja California. (Data taken from tables by Contreras Arias, 1942, p. 1–2.)

of the Pacific Coast of California. The Santa Rosalía area is on the fringe of these two rainy belts, and in some years it may receive rain during both seasons and in other years during neither. Records show that the month with the highest average rainfall is September, representing the tropical summer rains, and that the next highest month is December, representing the Pacific Coast winter rains.

Temperatures at Santa Rosalía commonly reach 35° C (95° F) or more during the summer months and have been known to reach 43.5° C (110.3° F); the year-round mean temperature is recorded as 24.2° C (75.6° F). Freezing temperatures are unknown, and the lowest temperature recorded was 6° C (42.8° F). Temperature data for the different months of the year are presented in figure 8.

The humidity is generally very low, but it is often noticeably higher directly along the gulf than it is a few kilometers inland. Very rarely, the gulf is covered by a low blanket of fog, a phenomenon which is much more common near the southern tip of Baja California and along the Pacific Coast.

The prevailing winds are from the southeast during the summer months, from May until September, and from the northwest during the rest of the year. In the winter the region is occasionally subject to severe windstorms from the northwest which have been known to reach hurricane proportions, causing damage to buildings and the loss of ships on the gulf.

According to the climatic classification of Contreras Arias (1942), who follows in a modified form the system of Thornthwaite (1931), the climate at Santa Rosalía is classified according to humidity as very dry, with moisture deficient at all seasons, and according to temperature as hot, with a mild winter. The humidity classification is based upon the index of effectiveness of precipitation, which may range from less than 16 (classified as very dry, characterized by a desert vegetation) to more than 128 (classified as very humid). On this scale the Santa Rosalía area has an index of 5, and only five stations in Mexico, all in Baja California and Sonora, have a lower index. The temperature classification is based on the index of effectiveness of temperature, which may range from 0 (polar) to more than 128 (hot). On this scale the Santa Rosalía area has an index of 131, which, though high, is exceeded by several localities along the tropical southern coastal belts of Mexico.

VEGETATION

Although the Boleo region is truly a desert, it is far from barren and supports a widespread and, in places, dense growth of thorny vegetation. Nelson (1921) states that the peninsula of Baja California "has developed the richest and most varied desert flora known in America and probably in the world." In parts of the Vizcaíno Desert, on the western side of the peninsula, a jungle of thorny plants makes the area practically impenetrable. In the Boleo district the growth is moderately dense on the tops of the mesas, but relatively sparse on the sides and bottoms of the arroyos. On the mesas the growth is more dense in areas covered by gravel or conglomerate than in areas covered by lava.

The vegetation consists largely of many varieties of cactus and other types of low thorny or spiny desert plants. Notable among the species of cactus are the giant organo, different types of pitahaya, noted for its edible red fruit, several varieties of the highly treacherous cholla, and the peculiar "creeping devil" cactus. Common among the other shrubs are ocotillo, mesquite, the palo verdes, palo blanco, yuccas, copal, creosote bush, brittle bush, and the curious elephant tree. The tropical mangrove grows in San Lucas Cove. Scattered fan palms grow near the few permanent pools of water in the region, as in Arroyo de las Palmas and Arroyo del Infierno. Shortly after one of the cloudbursts that sometimes visit the region, the vegetation becomes green and as if by magic the desert becomes covered with a blanket of wild flowers—a phenomenon which generally takes place only once in several years.

The Santa Rosalía area lies near the boundary between two life zones, according to Nelson (1921, p. 121–124), the Arid Tropical zone, which extends northward from the cape region, and the Lower Sonoran zone, which extends southward from the northern border of Baja California.

Some of the most comprehensive papers dealing with the plant life of Baja California are those by Goldman (1916), Nelson (1921), and Johnston (1924). A list and brief description of 91 species of plants collected from Santa Rosalía and Santa Agueda is given by Vasey and Rose (1890, p. 80–87).

WATER SUPPLY

Water is extremely scarce and is one of the major problems of life in the region. Practically the only surface water supply of any consequence in the vicinity of the copper district is at the Santa Agueda ranch, 12 kilometers southwest of Santa Rosalía, where springs provide a small but steady flow all year around, sufficient to support small fruit orchards and vegetable gardens. From this ranch the Boleo company has constructed a pipeline 17 kilometers long, which runs down Arroyo de Santa Agueda to a point near its mouth, and then parallels the coastline to Santa Rosalía (see pl. 2). This source of water is augmented by supplies from the deep mines that have penetrated far below the water table. The water is chlorinated to make it safe for drinking, although the content of dissolved salts is noticeably high.

The water table as originally found in the Santa Rita, Purgatorio, and William shafts, situated along a line about 3½ kilometers inland from the coast, ranged from 25 meters above sea level in Arroyos Soledad and Purgatorio, to 7 meters above sea level in Arroyo de Santa Agueda. In a drill hole (no. 52) southeast of Arroyo de Santa Agueda the water table was 19 meters above sea level. In the bottom of the San Agustín shaft in Arroyo de la Soledad, at an elevation of 27 meters above sea level, the original influx of water was at the rate of 70 cubic meters in 24 hours (2.92 cubic meters per hour). This water had a temperature of 41° C (106° F). In the deepest shaft in the district, the William shaft of the San Luciano mine, which reaches 199 meters below sea level, the original influx of water was at the rate of 8 to 9 cubic meters per hour. Later, however, the entire mine drained into this shaft, necessitating pumping at the rate of about 100 cubic meters per hour. Because of the high saline content this water is not used for drinking, although it serves locally for irrigation.

The arroyos in the district generally carry water for only a few hours after infrequent cloudbursts, except for a few natural rock basins called *tinajas* where small pools may stand for long periods. Such pools are found in volcanic rocks near the head of Arroyo del Infierno and in Arroyo de las Palmas, and small ones of short duration are found in some of the small canyons that cross the gypsum area in the vicinity of Arroyo del Boleo. The supply of water in these pools is, however, very scanty.

Because of the scarcity of fresh water, sea water is used for many purposes in the town of Santa Rosalía. It is pumped from the gulf and stored in large tanks and reservoirs built on the terraces north of the town. Sea water is used extensively for cooling purposes in the smelter, for condensors in the power house, for sprinkling the streets, for sewage disposal, and for emergency use in case of fire.

NATURAL RESOURCES

The natural resources of the region about Santa Rosalía consist mainly of mineral deposits and of fisheries in the Gulf of California. The mineral deposits that have been exploited include not only copper deposits but also manganese deposits, worked since 1941 in the Lucifer mine, and gypsum, limestone, and calcareous sandstone, which have been used in the Boleo smelter. Other potential mineral resources include pumice and perlite, sulfur near the Tres Vírgenes, and perhaps some of the metals, such as cobalt, zinc, and lead, that are found in the Boleo ore in minor quantities.

The waters of the Gulf of California abound in edible fishes and other types of sea food, such as shrimp and lobster. Only recently has an attempt been made to organize the fishing industry at Santa Rosalía on a large scale by installing canning, packing, and freezing plants. This will probably become the principal industry of the region, as mining activities decline.

The great problem of Baja California as an agricultural region is the erratic and undependable nature of the rainfall. Where water is obtainable, however, many varieties of fruits and vegetables are grown successfully. This is illustrated by San Ignacio, an oasis of date palms in the middle of the desert, and by the watered coastal area of Mulegé, where many temperate and tropical fruits and other crops are raised.

TOWNS AND MINING CAMPS

Before the discovery of the copper deposits in 1868, the area occupied by the Boleo district was an uninhabited desert. The only permanent habitation in the region was the ranch of Santa Agueda, 12 kilometers southwest of the present site of Santa Rosalía. The nearest towns were Mulegé, a village of 800 inhabitants situated 68 kilometers by road to the south, and San Ignacio, a village of 600 inhabitants situated 77 kilometers by road west of Santa Rosalía. These towns are the sites of early 18th-century missions built by the Jesuits.

The entire town of Santa Rosalía, including houses, stores, schools, smelter, railroad, harbor, and other buildings and industrial installations, has been built by the Compagnie du Boléo, beginning in 1885. Practically all the houses and buildings are of wood construction, a type of building material not commonly used elsewhere in Mexico. Most of the lumber has been imported by way of Tacoma, Wash. The main part of town occupies the floor of Arroyo de la Providencia, extending inland from the harbor for 1 kilometer.

In addition to the main town of Santa Rosalía, the Boleo company has constructed houses and other buildings in several surrounding mining camps. The principal camps in earlier years were known as Providencia, Purgatorio, and Soledad, situated in the arroyos of the same names. Purgatorio is now a ghost town in which only a few scattered houses and a forlorn church remain, and the other two camps have disappeared. Later camps include Santa Marta, also now a ghost town, in Arroyo de la Soledad; Ranchería, which adjoins Santa Rosalía to the southwest in Arroyo de la Providencia; and San Luciano, in Arroyo de Santa Agueda.

The total population of the district, including Santa Rosalía and the surrounding mining camps, ranged from 5,839 in 1896 to a maximum of 11,660 in 1918, declining to 7,945 in 1940. The town of Santa Rosalía itself had a population of 5,451 in 1940. The number of workers employed by the Boleo company averaged about 2,500 persons in the 1890's, reached a high point of 4,100 in 1910, and declined to 1,451 in 1940 and to approximately 1,000 in 1946. The French population at one time numbered about 200 persons, but the number has declined recently to scarcely more than a dozen persons.

GEOLOGY

STRATIGRAPHY

STRATIGRAPHIC SECTION

The stratigraphic section in the Boleo district is presented in figure 9. A quartz monzonite basement of unknown age, exposed only in small areas, is overlain by a considerable thickness of Miocene andesitic and

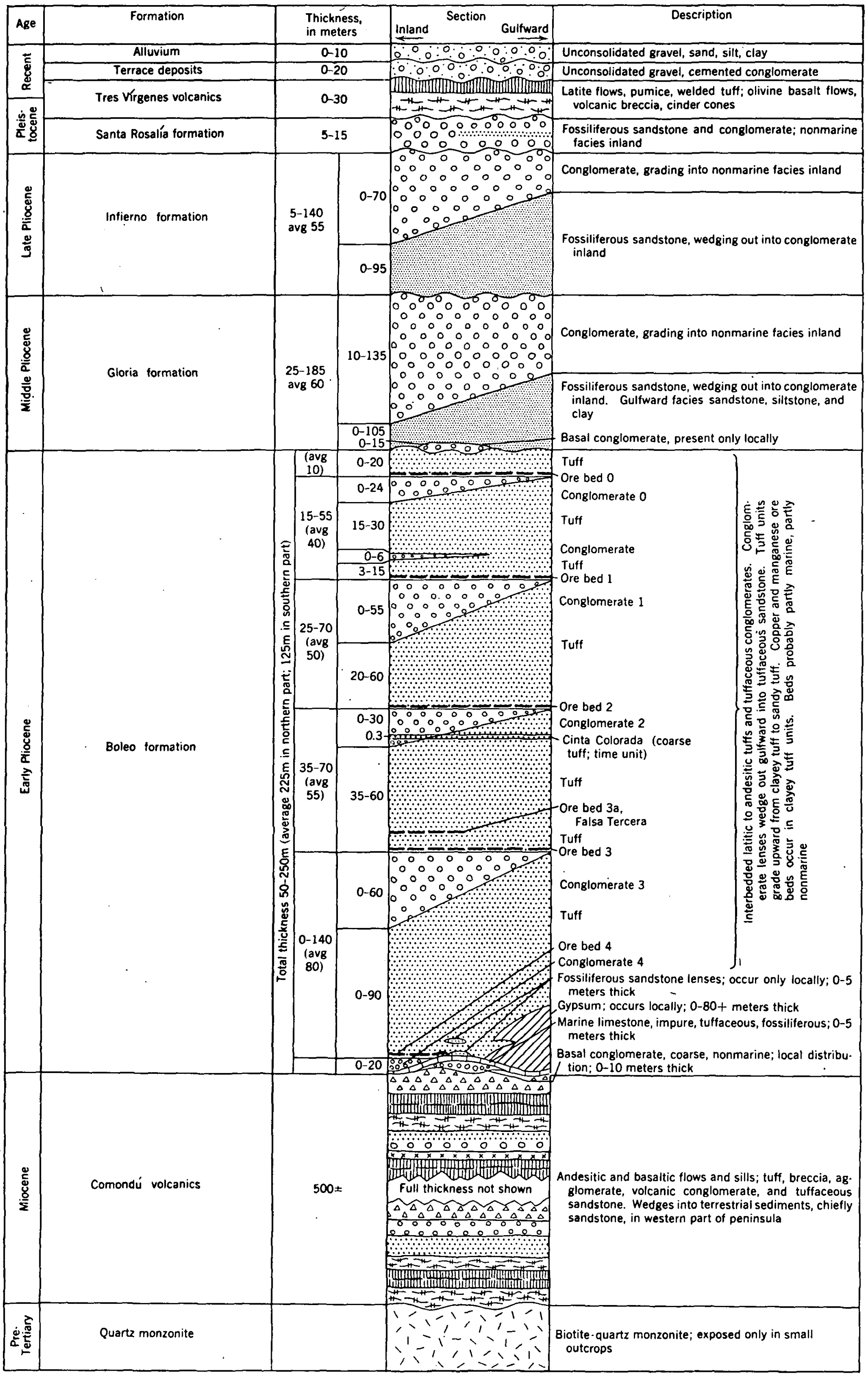

FIGURE 9.—Stratigraphic section in the Boleo copper district, Baja California.

basaltic volcanic and pyroclastic rocks, and terrestrial sediments, known as the Comondú volcanics. These are overlain with marked unconformity by three marine formations of Pliocene age, all with interfingering nonmarine facies inland, known as the Boleo, Gloria, and Infierno formations, all separated by unconformities. A thin marine formation of Pleistocene age, named the Santa Rosalía formation, is overlain by latite and basalt flows and pyroclastic rocks of Pleistocene and Recent age, called the Tres Vírgenes volcanics, and by terrace deposits and alluvium.

Although deposits of late Tertiary and Quaternary age are well represented in the Boleo district, pre-Miocene rocks are entirely absent, except for the plutonic basement. Along the Pacific Coast of Baja California is found in addition a fairly thick section of marine sediments of Jurassic, Cretaceous, Paleocene, and Eocene age. Data on the stratigraphic record elsewhere in the peninsula are summarized in the reports by Beal (1948), Durham (1944, 1950), and Anderson (1950).

The Miocene of Baja California is represented by three formations separated by unconformities, known as the San Gregorio, Isidro, and Comondú formations, of which only the latter is present in the Boleo district. The Isidro formation reaches the gulf coast in places, however, and is significant in providing a lower age limit for the Comondú formation.

The Comondú formation is the principal formation that extends entirely across the peninsula of Baja California from west to east. Toward the west it overlies the Isidro formation, but in the Boleo district it rests directly on the plutonic basement. The Comondú consists largely of volcanic rocks of andesitic and basaltic composition near the gulf coast, grading westward into terrestrial sediments, chiefly sandstone and conglomerate—the "Mesa sandstones" of Gabb (1868, p. 632–633).

The marine sediments of Pliocene age in Baja California have hitherto been classified as the Salada formation, a name given by Heim (1922, p. 544–546) to beds exposed in Arroyo de la Salada, along the Pacific Coast near Magdalena Bay. Pliocene marine beds have been noted at several places along both the Pacific and gulf coasts, and on islands in the gulf (Hanna and Hertlein, 1927), but they are nowhere known to extend continuously across the peninsula. Although geologists had recognized previously that various parts of the Pliocene were represented in different localities, the beds had not been definitely subdivided into different formations before the work of Anderson (1950) and Durham (1950) on the islands of the gulf and of Wilson (1948) and his associates in the Santa Rosalía area.

In the Boleo district the Pliocene deposits may be divided into three distinct formations, separated by unconformities and characterized by faunas believed to be of early, middle, and late Pliocene age. The names proposed for these formations by Wilson (1948, p. 1768) were the Boleo formation, named after the Boleo district, for a lower Pliocene succession of tuffs and conglomerates containing copper and manganese deposits; the Gloria formation, named after Cañada de la Gloria, for a middle Pliocene sequence of fossiliferous marine sandstone, siltstone, and conglomerate; and the Infierno formation, named after Arroyo del Infierno, for an upper Pliocene succession of fossiliferous marine sandstone and conglomerate.

Anderson (1950) and Durham (1950) noted a similar three-fold division of the Pliocene beds on the islands studied by them in the Gulf of California. The probable equivalence of their San Marcos, Carmen, and Marquer formations to the Boleo, Gloria, and Infierno formations, respectively, of the Santa Rosalía area was pointed out in a footnote by Anderson (1950, p. 12).

In the older reports on the Boleo district the sediments were divided in general into the "Ore Series" and the overlying "Calcareous Series," but the dividing line between these two series was not precisely defined and had never been portrayed on a geologic map, as far as the writers are aware. Touwaide (1930, p. 120) and Locke (1935, p. 409) used the name Lower Salada for the "Ore Series" and Upper Salada for the "Calcareous Series." The Lower Salada as used by those authors is more or less equivalent to the Boleo formation as used in this report, and the Upper Salada includes the Gloria, Infierno, and probably in part the Santa Rosalía formation as used in this report. The name Salada formation has not been used by the present writers because no direct relationship could be established between any of these formations and the type locality of the Salada, which is on the opposite side of the peninsula; and the age of the Salada at the type locality was not precisely determined, the only fossils reported by Heim having been casts, undetermined except for generic identification. The term Salada could be retained for undifferentiated Pliocene deposits in Baja California, however, in the sense in which it was used by the Marland Oil Co. (1924, p. 43); then it should be called the Salada group, which would include the three Pliocene formations of the Boleo district.

Marine beds of Pleistocene age have been noted in several parts of Baja California, but outside the Boleo district they have never been given any definite name. A thin fossiliferous marine sandstone and conglomerate in the Boleo district, containing abundant fossils assigned to the Pleistocene, was named the Santa Rosalía formation, after the town of Santa Rosalía (Wilson, 1948, p. 1769). Still younger are thin but widespread gravel deposits that blanket the tops of the mesas and cover marine terraces along the coast and nonmarine terraces along the sides of the arroyos.

Extensive volcanic and pyroclastic rocks of latitic and basaltic composition mantle the mesas northwest of Santa Rosalía. These rocks have been named the Tres Vírgenes volcanics (Wilson, 1948, p. 1769), after the three prominent volcanic cones called the Tres Vírgenes, which have been active within the past two centuries. The age of the Tres Vírgenes volcanics is Pleistocene and Recent; the volcanism may in part be contemporaneous with the Santa Rosalía formation and the terrace and gravel deposits described above.

QUARTZ MONZONITE (PRE-TERTIARY)

The basement rock is a quartz monzonite, which has been found only in three small outcrops in Arroyo de las Palmas, in the area covered by the map of the Lucifer manganese district and described in the report on that district (Wilson and Veytia, 1949, p. 187–188).

Although no outcrops of quartz monzonite were found in the area covered by the geologic map of the Boleo district (pl. 1), the rock presumably underlies the Comondú volcanics throughout the district. The depth below the surface to the top of the plutonic basement probably ranges from 500 meters or more in the northwest part of the district, near Arroyo del Boleo, to more than 800 meters in the southeast part, near Arroyo de Santa Agueda, based upon what is known of the structure and thickness of the overlying Comondú volcanics.

The outcrops of quartz monzonite in Arroyo de las Palmas are thought to represent areas of high relief which existed during the time of formation of the Comondú volcanics. The quartz monzonite is overlain by different members of the Comondú volcanics, and in part is overlapped directly by a basal marine limestone of the Boleo formation.

Plutonic rocks are exposed over wide areas in the northern part of Baja California, northwest of Santa Gertrudis (see fig. 1), and also in the southern part, southeast of La Paz Bay, but in the intervening area they are almost everywhere buried by younger rocks and are exposed only in small erosional windows. Petrographic descriptions of the plutonic rocks in the Sierra San Pedro Mártir have been given by Woodford and Harriss (1938), and petrographic descriptions, chemical analyses, norms, and differentiation diagrams of plutonic rocks from different parts of Baja California have been given by Hirschi (1926) and Hirschi and de Quervain (1927–33).

The Boleo district provides little direct evidence of the age of the plutonic basement, except that it is pre-Comondú, therefore pre-Miocene. The age of some granite and diorite intrusive bodies in the northern part of Baja California, near Ensenada, has been determined as the early part of Late Cretaceous (Turonian) by Böse and Wittich (1913, p. 349; see also Wittich, 1915, p. 394). Woodford (1940, p. 256) concluded that the main plutonic mass of Baja California is probably of Cretaceous age, although Darton (1921, p. 725) regarded most of it as pre-Cretaceous. Hirschi and de Quervain (1933) accepted a Late Cretaceous age for the plutonic rocks in the northern part of the peninsula, which they classified as "Pacific type," but they considered that the "Mediterranean type" plutonic rocks in the southern part of the peninsula were older, probably Paleozoic, although they presented no stratigraphic evidence for this conclusion.

COMONDÚ VOLCANICS (MIDDLE? AND LATE MIOCENE)

The Comondú volcanics, of middle (?) and late Miocene age, consist of andesitic and basaltic flows. sills, tuff, breccia, agglomerate, volcanic conglomerate, and tuffaceous sandstone, all of nonmarine origin. The Comondú formation was named by Heim (1922, p. 542) for exposures near the town of Comondú, 150 kilometers south of Santa Rosalía. (See fig. 1). At the type locality the formation consists mainly of terrestrial sediments, but toward the gulf in the Sierra de la Giganta, the formation is described by Heim as consisting largely of a basaltic breccia. The volcanic rocks extend continuously from the Sierra de la Giganta to the vicinity of Santa Rosalía, and according to the geologic map by Beal (1948, pl. 1), they continue much farther both to the northwest and southeast. Because the formation is composed dominantly of volcanic rocks in the Boleo district, it is referred to in this report as the Comondú volcanics.

DISTRIBUTION AND STRATIGRAPHIC RELATIONS

The Comondú volcanics underlie the entire area covered by the geologic map of the Boleo district, and for all practical purposes they form the basement rock of the mining district, although they in turn rest unconformably upon the plutonic basement just described. At the close of Comondú deposition, an irregular surface of strong relief was carved in the volcanic rocks and then largely buried by Pliocene sediments, although the highest hills formed islands that remained above the level of sedimentation throughout Pliocene time. The present outcrops of the Comondú volcanics are chiefly these islands and exhumed buried hills on the pre-Pliocene erosional surface (fig. 10).

The principal outcrop areas of the Comondú volcanics in the Boleo district are in the former islands of Cerro de Juanita and Cerro del Sombrero Montado (fig. 11), as well as a large irregular-shaped area of about

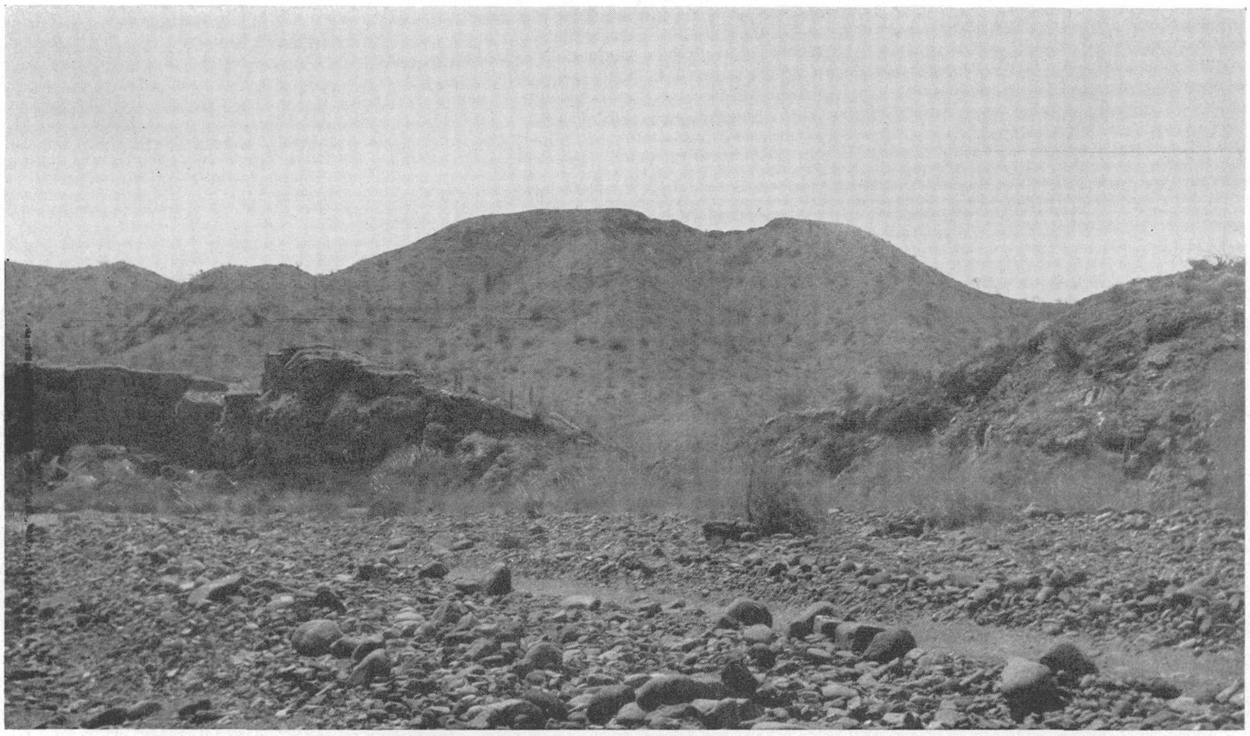

FIGURE 10.—Rugged hill of Comondú volcanics on the northwest side of Cañada de la Gloria. The hill was once an island that stood above the level of Pliocene sedimentation. In the foreground are cliffs of gypsum of the Boleo formation, which wedges out against the hill of Comondú volcanics.

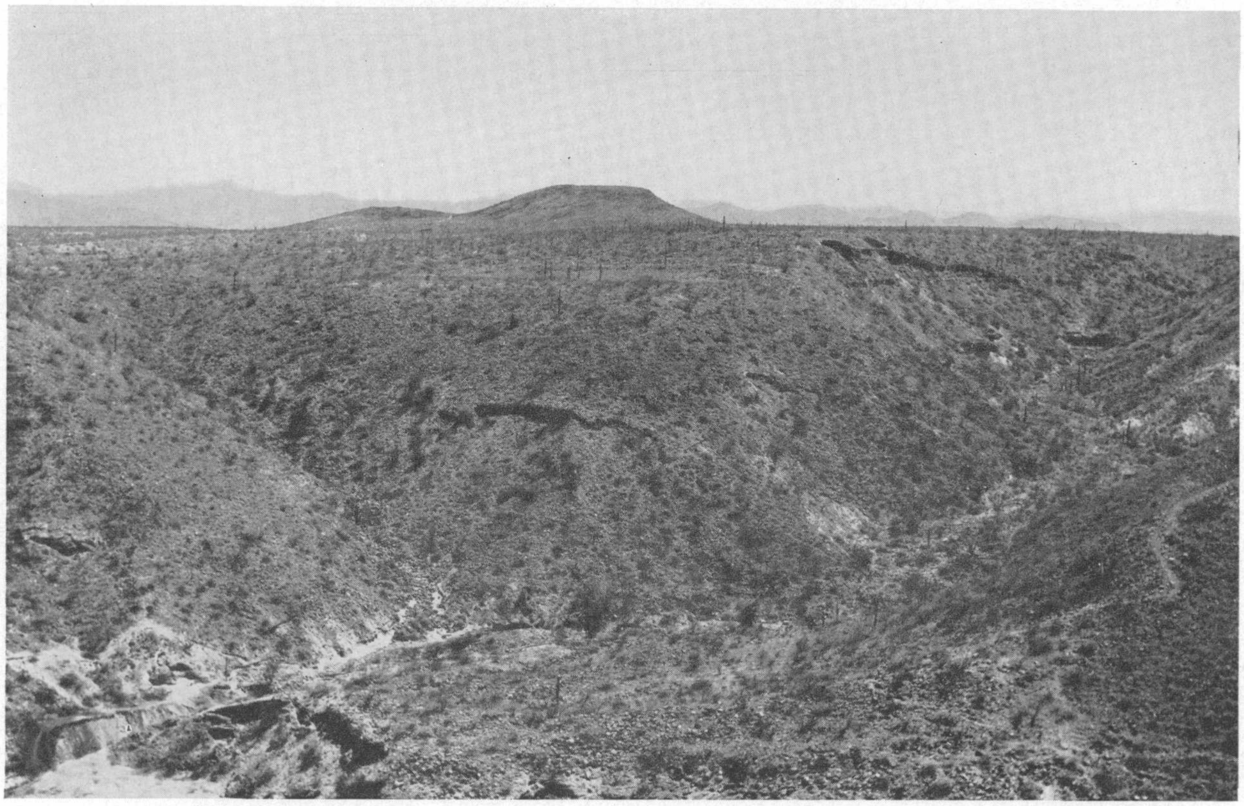

FIGURE 11.—Cerro del Sombrero Montado, rising above the general mesa level in the middle, was an island during the Pliocene. Thick Pliocene sediments in the foreground wedge out against the hill. The view is southwest across a branch of Arroyo del Montado.

TABLE 1.—*Drill holes, shafts, and mine workings cutting the Comondú volcanics in the Boleo district*

Locality	Coordinates, in meters from San Francisco shaft		Depth of Comondú volcanics below surface (meters)	Distance of top of Comondú volcanics above or below sea level (meters)	Unit of Boleo formation that directly overlies the Comondú volcanics
	North-south	East-west			
DRILL HOLES					
No. 2	3552 S.	4318 E.	279	−236	Gypsum (below ore bed no. 2).
No. 3	4308 S.	3586 E.	175	−112	Tuff 22 m below ore bed no. 2.
No. 19	1637 S.	4275 E.	183	−147	Tuff 5 m below ore bed no. 2.
No. 25	730 S.	4975 E.	17	−10	Conglomerate of uncertain correlation.
No. 27	1281 S.	4322 E.	99	−73	Gypsum.
No. 28	5425 S.	4416 E.	279	−139	Tuff 21 m below ore bed no. 1.
No. 36	5680 S.	4717 E.	204	−82	Gloria formation (Boleo formation absent because of lack of deposition over a buried hill).
No. 38	5540 S.	4850 E.	335	−221	Ore bed no. 1.
No. 42	5038 S.	4297 E.	201	−144	Ore bed no. 1 (?).
No. 44	5135 S.	4162 E.	169	−109	Ore bed no. 2.
No. 49	910 N.	920 E.	165	−114	Tuff 88 m below ore bed no. 3.
SHAFTS					
Amelia	863 N.	2894 W.	156	49	Ore bed no. 4 (141 m below ore bed no. 3).
La Ley	195 S.	1760 W.	98 (?)	78 (?)	Ore bed no. 4 (84 m below ore bed no. 3).
San Alejandro	395 N.	197 W.	135	−55	Ore bed no. 4 (97 m below ore bed no. 3).
San Eduardo	276 N.	994 W.	85	2	Ore bed no. 4 (103 m below ore bed no. 3).
San Julio	1324 S.	2343 E.	160	6	Tuff of uncertain correlation.
San Luciano	3821 S.	3275 E.	105 (?)	38 (?)	Conglomerate or breccia below ore bed no. 1.
WORKINGS					
Providencia-Purgatorio Second Bed mine, west end	780 S.	390 E.	93	146	
Providencia mine, south end	2320 S.	830 E.	136	41	
Do	2220 S.	905 E.	166	37	
Providencia mine, northeast end	10 S.	1850 E.	49	3	
Do	50 S.	1900 E.	48	4	
Providencia mine, Travers-Bancs Montado	1705 S.	1640 E.	198	29	
Montado mine, Travers-Bancs Montado	2195 S.	2525 E.	166	34	
Montado mine, Travers-Bancs Santa Agueda	2970 S.	3075 E.	153	39	
Do	3030 S.	3150 E.	150	39	

4 square kilometers in the headwaters of Arroyo del Boleo. The latter area, in which much of the pre-Pliocene topography is well preserved, is an appendage of Cerro del Infierno to the west. Some smaller isolated outcrops, many of them representing exhumed hills, are found in Arroyos Soledad, Purgatorio, Providencia, and Santa Agueda (see pl. 1).

SUBSURFACE CONFIGURATION

The mining operations of the Boleo company have reached the upper contact of the Comondú volcanics in enough places to provide valuable information about the relief of its surface. This is of considerable economic importance because all the important commercial ore bodies in the Boleo district occur above the Comondú. The upper contact of the Comondú volcanics ranges in depth below the surface from a few meters to more than 330 meters (more than 305 meters below sea level) in part of Arroyo de Santa Agueda. Table 1 gives the depth of the Comondú volcanics below the land surface and its relation to mean sea level where the formation was cut by 26 drill holes, shafts, and mine workings. The localities are plotted on the structure contour map (pl. 4) and on the general mine map (pl. 94).

The Comondú volcanics lie at depths even greater than those indicated in this table at the localities of five additional drill holes made in Arroyo de Santa Agueda. These holes were terminated upon reaching gypsum overlying the Comondú. Drill holes 4, 5, 6, 22, and 33 reached depths of 242, 262, 281, 266, and 305 meters below sea level, respectively, and the top of the Comondú volcanics lies at unknown depths (probably at least 20 meters or so) below these depths.

THICKNESS

All available evidence indicates the thickness of the Comondú volcanics in the Boleo district is at least 500 meters. The maximum thickness is unknown, however, because the original lowest and highest parts of the formation are nowhere seen. The base of the formation is exposed only in Arroyo de las Palmas around the outcrops of quartz monzonite where the latter apparently was once topographically high. Consequently, the lower units of the Comondú volcanics are probably missing around the outcrops. Some of the upper units of the formation are missing because they were eroded away before the Boleo formation was deposited. In the Sierra de Santa Lucía the Comondú volcanics may be more than 1,000 meters thick; and, according to Heim (1922, p. 543), in the Sierra de la Giganta, between Comondú and Loreto, the Comondú is more than 1,300 meters thick, but westward it thins rapidly to as little as 65 meters near La Purísima.

LITHOLOGY AND PETROGRAPHY

The Comondú volcanics consist chiefly of lava flows, which in many places have a vesicular structure. Also present are intrusive sills, which in places show slight crosscutting relations to the bedding planes of the enclosing rocks, but dikes are comparatively rare. Many thick layers of volcanic breccia and agglomerate and a few layers of well-indurated tuff are present. Intercalated with the volcanic rocks are thin beds of terrestrial sediments, consisting chiefly of conglomerate and less commonly of sandstone, including a reddish quartzitic sandstone in Arroyo de las Palmas. One conspicuous conglomerate layer, 10 to 15 meters thick, was mapped in Arroyo del Purgatorio. Elsewhere, however, the entire formation was mapped as a unit, and no attempt was made to differentiate the individual lithologic types. The best exposed section of the formation is in Arroyo del Infierno, where individual beds, though repeatedly faulted, may be traced for considerable distances.

The volcanic rocks show a great variety of colors—purple, green, red, orange, and brown, the dominant one perhaps being a reddish-brown. The formation produces rocky slopes, having little or no soil cover, although they are sometimes mantled by a residual rubble. The tops of some of the hills are rounded, but very steep irregular slopes and cliffs are formed on the sides of the arroyos. The general appearance of typical exposures of Comondú volcanics is shown in figure 12.

Andesite and basalt are the dominant petrographic types, although in some places rhyolitic tuffs and rocks of intermediate composition have been identified. In some of the older reports on the Boleo district, and in the mine records of the Boleo company, the rocks of the Comondú volcanics are referred to generally as "trachyte," regardless of their composition or appearance, a tradition that apparently stems from an early classification by Bouglise and Cumenge (1885). The variety trachyte, however, is extremely rare if present at all.

Several thin sections of Comondú volcanics from different parts of the Boleo district were studied by Robert L. Smith of the Geological Survey. He states that many of these rocks are on the borderline between basalt and andesite, and that without chemical analyses, precise identification is difficult. Most of these rocks formerly contained olivine, and they are basaltic in texture and general appearance. An andesitic trend is indicated, however, by the composition of the major feldspar (about An_{50} or below), as well as by the residue of alkalic feldspar and biotite in some of the rocks.

An olivine-bearing pyroxene basalt from Cerro del Sombrero Montado contains phenocrysts of sodic labradorite and a few scattered grains of iddingsite after olivine. The groundmass minerals are principally clinopyroxene, plagioclase (about An_{50}), and magnetite. The plagioclase occurs in lathlike crystals which exhibit a well-oriented flow structure. The groundmass

FIGURE 12.—Comondú volcanics in a branch of Arroyo del Boleo, showing alternating layers of flows and breccias. This exposure is typical of the Comondú.

contains some iddingsite and scattered aggregate pyroxene replacing a mineral which was probably olivine or iddingsite. A few grains of faintly pleochroic hypersthene, accessory apatite, and abundant cristobalite are found in streaks throughout the rock.

An olivine (iddingsite)-augite basalt from Arroyo del Purgatorio contains phenocrysts of augite and olivine, which is now completely altered to a mixture of iddingsite, iron oxides, and a claylike mineral. The groundmass consists chiefly of plagioclase (about An_{50}), iddingsite, augite, magnetite, and apatite. A clay mineral, probably montmorillonite, is interstitial to the plagioclase laths in the groundmass; it has been derived either from a residual glass or from alkalic feldspar. Biotite and alkalic feldspar are found in notable amounts in the interstices, where they were formed in the end stages of recrystallization. A similar rock from Arroyo del Boleo, showing a good flow structure, contains the same minerals just noted, except that the plagioclase in the groundmass is strongly zoned (An_{55-35}), and has been altered to a clay material along cleavages and cracks.

A vesicular pigeonite basalt from Arroyo del Purgatorio is described as an even-grained vesicular rock consisting of plagioclase (An_{50-55}) and pigeonite as primary minerals. Interstitial to the feldspar and pyroxene are abundant secondary iron oxides, derived from primary magnetite, pyroxene, and possibly from olivine. An interstitial clay material, probably saponite, is associated with the iron oxides. The vesicles contain saponite, unidentified zeolites, calcite, and opal.

An andesitic basalt from Cerro de Juanita is a fine-grained, even-textured rock containing plagioclase, clinopyroxene, and magnetite as the principal constituents. The plagioclase is about An_{50} in composition, although a few scattered crystals of slightly larger size are a little more calcic. The rock contains a few phenocrysts of iddingsite after olivine, a few grains of interstitial biotite, and traces of cristobalite.

An olivine (iddingsite)-bearing basaltic andesite from Cañada de la Gloria contains phenocrysts of olivine, completely altered to a mixture of iron oxides, iddingsite, and a claylike mineral. The principal minerals in the groundmass are laths of plagioclase (An_{45-50}), augite, and magnetite. Alkalic feldspar and biotite are present in notable quantity interstitial to the plagioclase laths. Many tiny brown needles, which may be basaltic hornblende, are found generally in close proximity to the altered olivine. Apatite is an accessory mineral.

An olivine-bearing augite andesite showing an excellent flow structure, from a branch of Arroyo del Boleo, contains crystalline areas which have more the appearance of included basic clots than true phenocrysts. They consist of altered olivine, clinopyroxene, and calcic plagioclase, sometimes occurring as separate crystals and sometimes as clotlike aggregations. The olivine has been completely altered to iddingsite or an iron oxide. The groundmass is composed chiefly of feldspar (An_{30-45}), augite, and an abundant material that appears to be leached or altered biotite; some of it may be hydromica. The groundmass also contains a few grains of fresh biotite, fairly abundant magnetite, and a small amount of apatite. An abundant interstitial clay material has probably formed from alkalic feldspar.

A welded rhyolitic tuff from a northern branch of Arroyo de Santa Agueda is described as a very compactly welded and completely devitrified tuff. Large areas of the original shard structure have been obliterated by coarse devitrification. The identifiable minerals are tridymite in the more porous areas and a few crystals and fragments of sodic plagioclase and brown hornblende. A few fragments of an andesitic rock are also present.

Another welded rhyolitic tuff from Arroyo del Purgatorio is only slightly welded and shows minimum compaction. It consists largely of fragments of pumice and shards of glass, as well as fragments and crystals of sodic plagioclase, brown hornblende, biotite, magnetite, and andesitic and basaltic rock fragments. Patchy areas of a secondary mineral, probably alunite, which is regarded as of hydrothermal origin, occur interstitial to and replace glass. Most of the glass shards are slightly altered along their edges to a clay mineral.

Thin sections of some additional volcanic rocks have been studied by Eduardo Schmitter. An olivine basalt from the buried hill near the mouth of Arroyo del Purgatorio is described as having a partly ophitic, intergranular texture and as consisting essentially of labradorite, andesine, augite, and olivine. The accessory minerals are magnetite and apatite, and the secondary minerals are iddingsite and limonite or hematite. A basaltic tuff from the same exposure has a breccialike structure, and consists of andesine and labradorite, with secondary calcite, clay minerals, zeolites, quartz, and hematite. A more acidic tuff from the same area has a cellular, breccialike structure and is composed of glass, quartz (?), and sanidine, with secondary hematite. A vesicular basalt from the buried hill farther inland in Arroyo del Purgatorio consists of labradorite, andesine, and augite, together with secondary hematite, opal, and zeolites (?).

Hirschi and de Quervain (1933, p. 244–257) gave detailed petrographic descriptions of about 25 specimens of volcanic rocks, probably all from the Comondú volcanics, collected in the vicinity of Mulegé, Point Concepción, the Sierra de Zacatecas near La Purísima, and the Sierra de la Giganta near Comondú. The rock types they described include augite andesite, hornblende andesite, hornblende-pyroxene andesite, hypersthene andesite, basalt, olivine basalt, andesite tuff-breccia, and dacite tuff.

COPPER CONTENT OF THE VOLCANIC ROCKS

The copper content of the fresh volcanic rocks is a matter of interest, since it was reported by Touwaide (1930, p. 124, 140) that the andesite averages 0.2 percent of copper, although such a content was doubted by Locke (1935, p. 412). In order to clarify this point seven samples of the fresh volcanic rocks were collected by the author and sent to the University of Minnesota for analysis by E. K. Oslund and S. S. Goldich, using the "trace methods" described by Sandell and Goldich (1943). These rocks were collected from widely separated parts of the district: from Cerro de Juanita and Cerro del Sombrero Montado, and from Arroyos Santa Agueda, Purgatorio, Boleo, and Gloria. The results obtained by Oslund and Goldich, given in table 2, show an average of only 0.004 percent of copper, ranging from 0.002 to 0.007 percent.

TABLE 2.—*Copper content of Comondú volcanics from the Boleo district*

[Analyzed by E. K. Oslund and S. S. Goldich, University of Minnesota, 1950]

No.	*Percent of copper*	*Type of rock*	*Locality*
B-49-2	0.005	Andesitic basalt	Cerro de Juanita
B-49-3	.004	Olivine-bearing pyroxene basalt	Cerro del Sombrero Montado
B-49-4	.002	Welded-rhyolitic tuff	Northern branch of Arroyo de Santa Agueda, near limestone quarry
B-49-7	.007	Olivine- (iddingsite) augite basalt	Arroyo del Purgatorio, west of Humboldt mine
B-49-10	.002	Olivine- (iddingsite) bearing basaltic andesite	Cañada de la Gloria
B-49-11	.006	Olivine-augite basalt	Arroyo del Boleo, near Neptuno mine
B-49-12	.005	Olivine-bearing augite andesite	Branch of Arroyo del Boleo, near Santa Teresa mine

LATERAL VARIATION AND ORIGIN

The Comondú formation shows distinct changes in lithology going westward from the Gulf of California, as noted by several investigators beginning with Gabb (1868, p. 634). Along the gulf the formation is dominantly volcanic, while toward the Pacific it is mainly sedimentary in origin and is also much thinner. The few intercalated sediments near the gulf are chiefly conglomeratic, as in the Boleo district, but westward they become finer grained and give way mainly to sandstone. These facies changes indicate that the formation was derived from the east, somewhere in the present site of the gulf, or perhaps near the western margin of the gulf as thought by Anderson (1950, p. 47–48). During the time of formation of the Comondú volcanics, therefore, the Gulf of California either did not exist or at least had nothing like its present extent.

The Comondú formation is of terrestrial origin throughout, so far as known. Periods of nonmarine sedimentation, perhaps on flood plains, alternated with periods of volcanic activity which produced flows, sills, and thick deposits of agglomerate, breccia, and tuff.

AGE

No fossils have ever been found in the Comondú formation, so far as the writers are aware, but the age of the formation may be fixed within fairly narrow limits by its relation to the underlying Isidro formation and to the overlying Boleo formation. Evidence of the age of the Isidro formation will first be reviewed because of its bearing upon the age of the Comondú.

The Isidro formation underlies the Comondú formation in places with marked angular unconformity (Beal, 1948, p. 69–73). Many fossil collections have been reported from the Isidro formation by Hertlein and Jordan (1927) and Beal (1948, p. 64–67). Hertlein and Jordan (1927, p. 618) state, concerning the age of the faunas: "Possibly they are in part equivalent to the upper Vaqueros, but the assemblage as a whole indicates a lower Temblor, lower Miocene age." The Temblor is now generally considered to be middle Miocene, rather than lower Miocene. Loel and Corey (1932, p. 160), who made a general study of early Miocene faunas, state: "Viewed as a whole, the assemblage as listed indicates later Vaqueros, lower Miocene age." Beal (1948, p. 67) concluded that the Isidro formation is late lower Miocene or middle Miocene, or both, and Durham (1944, p. 575) states: "[The] best-known fauna correlates with the Vaqueros-Temblor transition fauna of California, but the formation may also contain correlatives of both the Vaqueros and the Temblor."

The author obtained a small collection of fossils, principally of Turritellas, from the Isidro formation in Arroyo de San Ignacio, about 5 kilometers southwest of the town of San Ignacio. This locality was pointed out by Federico Mina, geologist of Petróleos Mexicanos. H. E. Vokes determined the following species from this locality (U. S. National Museum locality 15616):

Thais wittichi Hertlein and Jordan
Macron hartmanni Hertlein and Jordan
Turritella ocoyana Conrad
Turritella ocoyana var. *bösei* Hertlein and Jordan
Balanus sp. aff. *californicus* Pilsbry
Barnacles, 2 sp. indet.

Concerning this fauna, Vokes states: "*Turritella ocoyana* is considered the principal guide fossil for the recognition of the Temblor formation, middle Miocene, of California. A correlation with this formation is indicated by the fauna."

The Comondú formation is thus limited at its base by strata that appear at least in part to be of middle Miocene age. The Comondú is overlain with profound unconformity by the Boleo formation. As will be discussed later, the fossils from the Boleo formation are assigned by Vokes and by Durham to the lower Pliocene. The Comondú is therefore limited to the interval between middle Miocene and lower Pliocene; it probably represents mainly the upper Miocene, but may also include part of the middle Miocene.

The geologic map accompanying the Marland Oil Co. report (1924) listed the Comondú formation as of Pliocene age, but Beal (1948, p. 53–54), principal author of the Marland report, later corrected this and assigned it to the upper Miocene (?), in part on the basis of evidence found by Anderson (1941) in the Gulf of California and by Wilson in the Santa Rosalía area.

ECONOMIC IMPORTANCE

Rocks from the Comondú volcanics have been used to some extent for building stone in the Boleo district. Specifically, the foundation for the breakwater enclosing the artificial harbor at Santa Rosalía is made of large blocks of volcanic rocks quarried from the exposures on Cerro del Sombrero Montado.

With regard to the ore deposits, the Comondú volcanics form the basement rocks underlying the ore-bearing beds of the Boleo district. The limits of possible ore reserves are thus outlined by outcrops of the Comondú, as well as by its subsurface areas of high relief that rise above the level of the ore beds.

A few veinlets and veins containing copper and manganese minerals are scattered through the Comondú volcanics. Although these are regarded to have considerable genetic significance, they are of slight commercial value. Comondú volcanics are the host rock for the manganese oxide veinlets of the Gavilán deposit on Point Concepción, 70 kilometers southeast of Santa Rosalía, and for a few other manganese deposits scattered along the east coast of Baja California (Wilson and Veytia, 1948, p. 233–238).

BOLEO FORMATION (EARLY PLIOCENE)

GENERAL FEATURES

The Boleo formation of early Pliocene age consists largely of interbedded tuff and tuffaceous conglomerate of latitic to andesitic composition, together with a local nonmarine basal conglomerate, a fairly persistent basal marine limestone, scattered gypsum lenses, and a few fossiliferous sandstone layers. The formation rests unconformably on the irregular surface of the Comondú volcanics and is overlain with slight unconformity by the middle Pliocene Gloria formation. The Boleo formation was named by Wilson (1948, p. 1768) for exposures in the Boleo copper district. The type locality, which was not specified in the paper cited, is hereby designated as the section in Arroyo del Purgatorio near the old San Eduardo shaft, where conglomerates no. 1, 2, and 3 of the formation are all exposed, and where the base of the formation may be seen resting on the Comondú volcanics.

DISTRIBUTION AND STRATIGRAPHIC RELATIONS

The Boleo formation is distributed widely over the Boleo district, extending inland from the coast for a distance of 6 to 10 kilometers, where it terminates against the rising mass of Comondú volcanics that constitutes the Sierra de Santa Lucía. It once covered the entire area shown on the geologic map of the Boleo district, except for the tops of the former islands of Cerro del Sombrero Montado and Cerro de Juanita and the foothills of Cerro del Infierno. The formation extends along the coast for an unknown distance beyond the limits of the Boleo district, continuing northwestward probably at least as far as Cerro de Santa María and southeastward as far as the San Bruno plain.

The present exposures of the Boleo formation are confined mainly to the sides of the arroyos. In the mesa areas between the arroyos the formation is generally concealed by the younger Pliocene and Pleistocene beds. This post-Boleo cover is thickest to the southeast, in Arroyos Montado and Santa Agueda, where the Boleo formation is entirely concealed except in the uplifted belt northeast of the Santa Agueda fault zone.

The Boleo formation rests unconformably on the Comondú volcanics throughout the Boleo district. This is the most conspicuous unconformity in the stratigraphic section, aside from that on top of the plutonic basement rocks, and is marked by a complete structural discordance between the two formations. Either formation may dip more steeply than the other, in the same or in opposite directions. In places, for example, the Comondú volcanics dip as steeply as 45° and are overlain by nearly horizontal beds of the Boleo formation, while in other places the Comondú volcanics are nearly horizontal and are overlain by beds of the Boleo formation dipping as steeply as 30°, as a result of initial dip (see fig. 25).

THICKNESS

The thickness of the Boleo formation ranges in general from 50 to 250 meters within the area mapped. Variations in thickness result mainly from nondeposition of basal units, occasioned by irregularities in the underlying topographic surface, and from early Pliocene erosion of the top, marked by the unconformity at the base of the Gloria formation. Around the former islands and the edges of the mainland that existed during the Pliocene, the formation thins and wedges out. It also thins southeastward, toward Arroyos Montado and Santa Agueda, where the average thickness is only 125 meters and is locally much less because of nondeposition of the lower members. In the northwest part of the district the average thickness is nearer 225 meters, and the average thickness of several sections representing the district as a whole is 140 meters.

BASAL NONMARINE CONGLOMERATE

Lenses of nonmarine conglomerate appear at the base of the Boleo formation in a few widely scattered localities, mainly on steep slopes around former islands or buried hills of the underlying Comondú volcanics. The nature of the material, as well as the place of deposition, suggests that these deposits represent small alluvial fans or talus slopes, composed of debris derived locally from the surface on the Comondú. The conglomerates of this type are very poorly sorted and contain coarse subangular or angular fragments of volcanic rocks a meter or more in diameter, indicating little transportation. The individual lenses are rarely more than 5 or 10 meters in thickness and are seldom exposed for lengths of more than 100 meters.

The principal localities in which lenses of nonmarine conglomerate were noted are in the drainage basin of Arroyo del Boleo, near some of the buried hills and other irregular exposures of Comondú volcanics. Lenses were also found in Arroyo del Purgatorio, south of the California mine, and on both sides of Arroyo de Santa Agueda, northeast of the Santa Agueda fault zone.

In a few places where conglomerate or breccia forms the uppermost unit of the Comondú volcanics, the older rock may be difficult to distinguish from the basal conglomerate of the Boleo formation. This leads to uncertainty in interpreting the exact position of the Comondú-Boleo contact in some shafts and drill holes, as, for example, in the San Luciano and La Ley shafts.

BASAL MARINE LIMESTONE

A genetically significant layer in the Boleo formation is a thin impure marine limestone found at or near the base of the formation. In the few localities where the basal nonmarine conglomerate is present, the limestone overlies the conglomerate, but elsewhere it rests directly on the eroded surface of the Comondú volcanics, commonly with steep initial dips (figs. 13 and 25).

The limestone is resistant to erosion and tends to be preserved on dip slopes. This accounts for some of the extensive exposures shown on the geologic map, cover-

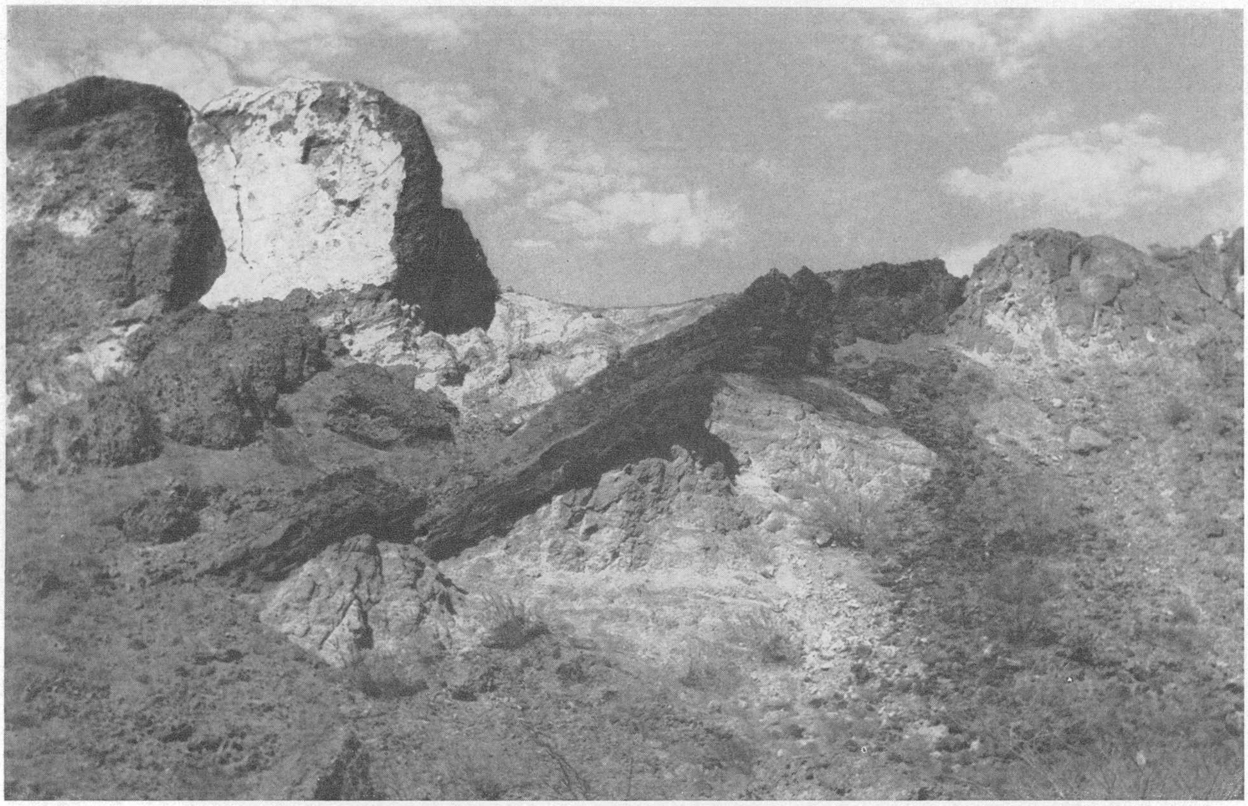

FIGURE 13.—Basal marine limestone of the Boleo formation in a branch of Arroyo del Boleo. The limestone is the dark layer dipping to the left off the Comondú volcanics and overlain by tuff and conglomerate of the Boleo formation.

ing areas as much as 200 meters in diameter, even though the layer is generally only 1 to 5 meters thick. Because the limestone has a greater structural relief than the overlying beds, it transgresses stratigraphic horizons and is overlain by different units of the Boleo formation. In places it is overlain by gypsum and in others by fossiliferous sandstone, but in general it is overlain by the various tuff and conglomerate units of the Boleo formation—by the lowest units in structural valleys, and by successively higher units over structural highs. A few patches of limestone were found to overlie the main gypsum mass exposed in Arroyo del Boleo, but in general the limestone underlies the gypsum.

The present exposures of the basal limestone are chiefly around buried hills of Comondú volcanics that have been exposed to erosion. Nearly all of these hills are capped by this limestone, although in places the exposures consist of tiny patches and remnants too small to show on the geologic map. The largest exposures of limestone are in Arroyo del Boleo and its various branches. The inland limits of the limestone are regarded as indicating roughly the maximum extent of the early Pliocene seas, for no fossiliferous marine beds have been found in the Boleo formation farther inland.

The exact subsurface limits of distribution of the limestone are unknown. In most of the drill holes and shafts that reached the Comondú volcanics, the limestone was not reported as such in the driller's records, but as the layer is very thin and the lithologic appearance is not that of a typical limestone, it could easily have been overlooked.

The limestone is very impure, is generally manganiferous and ferruginous, and is commonly tuffaceous, grading in places into what might be called calcareous tuff. In places it may be magnesian or dolomitic, and it has sometimes been referred to as a dolomite, but analyses by the Boleo company indicate that magnesia is generally present only in minor quantities. A sample analyzed for the writers by the Instituto de Geología contained only 1.65 percent of magnesia. Thin chert layers are in places intercalated in the limestone. The rock contains considerable detrital material, particularly where it was deposited on steep slopes, and in some localities it becomes conglomeratic. The general color is dark brown, which gives a distinctive appearance to the outcrops.

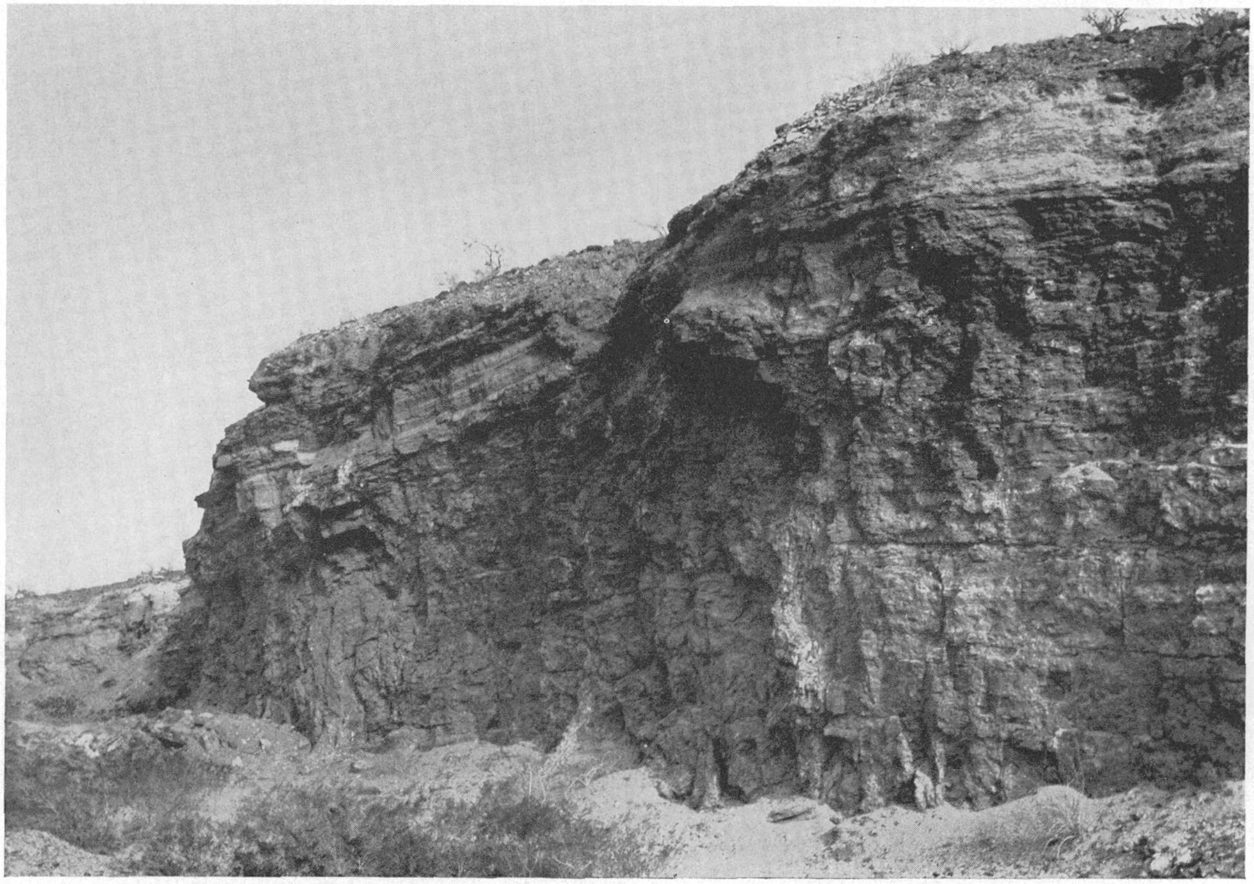

FIGURE 14.—Banded gypsum of the Boleo formation on the south side of Arroyo del Boleo. The gypsum has been quarried here for use in the Boleo smelter.

An analysis of a composite sample of the limestone, collected from a branch of Arroyo de Santa Agueda where it has been quarried for use in the Boleo smelter (pl. 1, coordinates 1700 S., 5250 E.), is given in table 3.

The limestone is in many places highly fossiliferous, although the fossils are for the most part very poorly preserved, consisting of unidentifiable casts and molds of pelecypods and gastropods. The fossils indicate clearly that the limestone is of marine origin. It is regarded as the basal deposit of the encroaching early Pliocene seas, and it is the oldest bed known in this area that was deposited by the waters of the Gulf of California.

TABLE 3.—*Analysis of a composite sample of limestone, in percent, from the Boleo formation, Arroyo de Santa Agueda, Boleo copper district*

[Analyzed by Rodolfo del Corral; Instituto de Geología, Mexico, analysis no. 8933]

SiO_2	7.95	K_2O	.10
Al_2O_3	2.56	CO_2	34.40
Fe_2O_3	1.95	SO_3	none
MnO	1.94	H_2O at 110° C	1.28
MgO	1.65	Loss on ignition	1.08
CaO	47.01		
Na_2O	.11	Total	100.03

GYPSUM

Thick gypsum layers are found in certain areas near the base of the Boleo formation (figs. 14–16). In

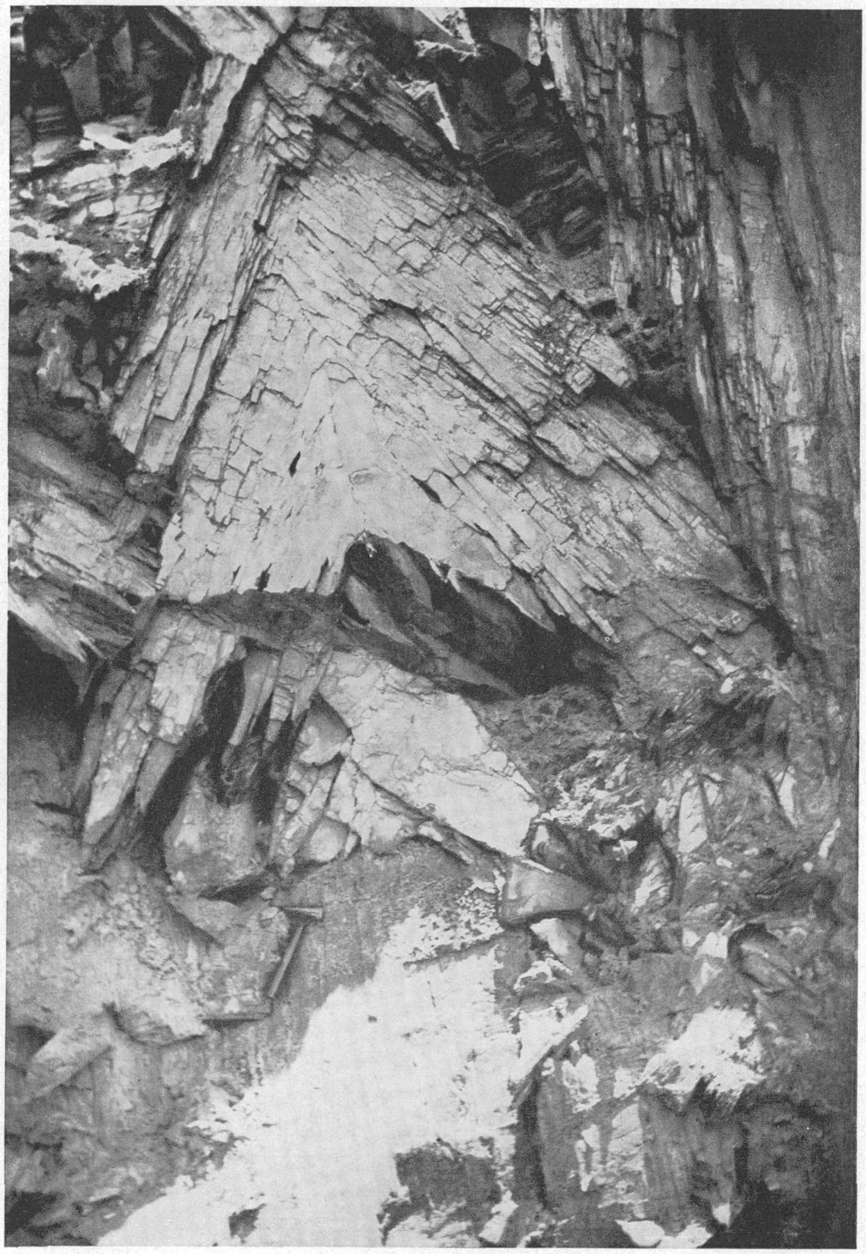

FIGURE 15.—Large twinned crystal of gypsum developed in a secondary vein of gypsum, Boleo formation, north side of Arroyo del Boleo. Geologic pick at lower left indicates size of crystal.

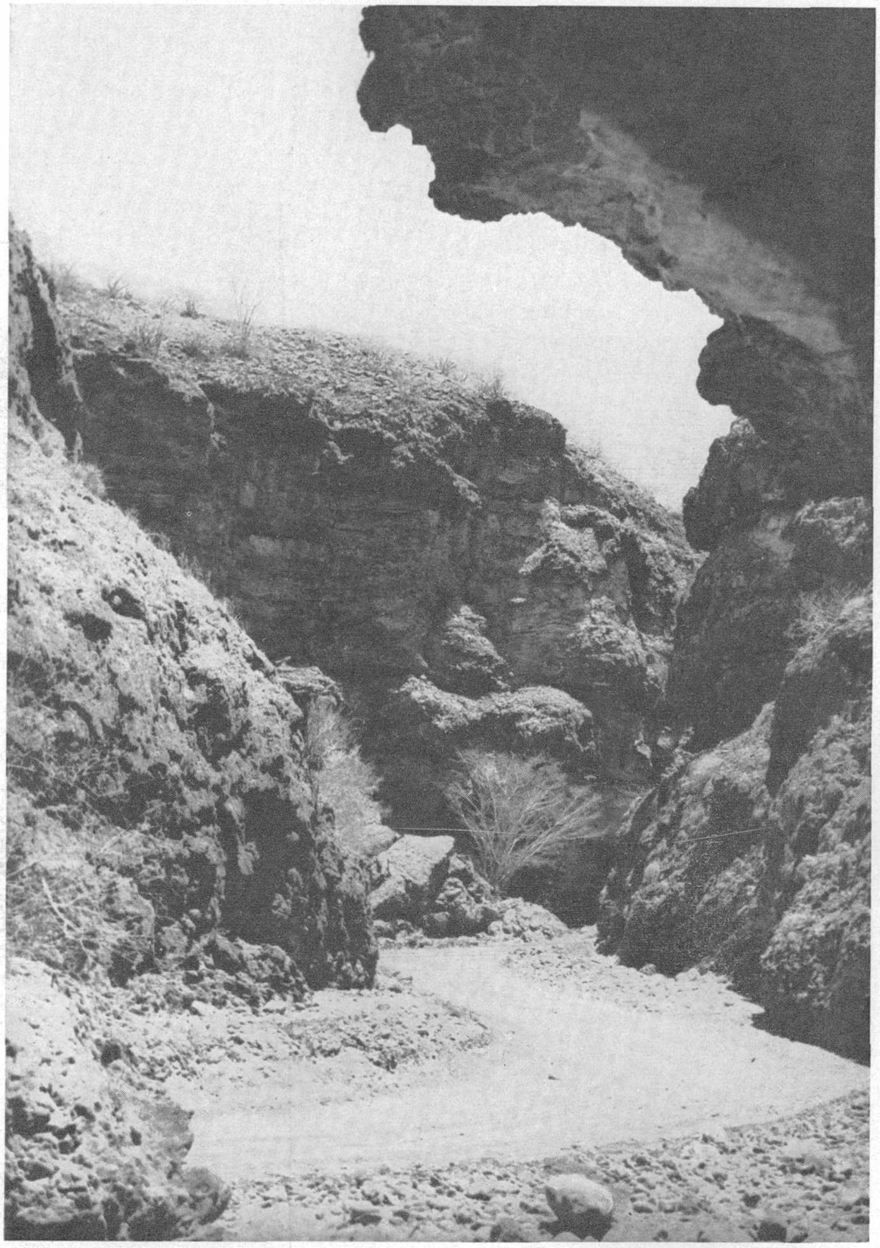

FIGURE 16.—Steep narrow canyon and overhanging cliffs developed in gypsum of the Boleo formation in Cañada de la Gloria near its junction with Arroyo del Boleo.

general the gypsum overlies the basal marine limestone, although in places it rests directly on the Comondú volcanics. Elsewhere it is intercalated in tuff near the base of the formation, and in a few localities it overlies conglomerate.

The gypsum was deposited mainly in two widely separated areas: in the environs of Arroyo del Boleo, extending northwestward through part of the Lucifer district to Arroyo del Infierno and Arroyo de las Palmas, and in the vicinity of Arroyos Montado and Santa Agueda to the southeast. The two areas are separated by a gap of 5½ kilometers in a northwesterly direction, in which gypsum was apparently not deposited. Both gypsum areas lie near the coast and are mainly northeast of the areas containing minable copper deposits. The thickness of the gypsum in the northwest area ranges from 20 to 80 meters or more, and in the southeast area it reaches 40 meters in the outcrops and ranges from 14 to 70 meters in the subsurface.

A map showing the distribution of outcrops of gypsum and of areas believed to be underlain by gypsum is given in plate 11, which covers both the Boleo and Lucifer districts. All the drill holes, shafts, and mine workings that are known to have reached the base of the Boleo formation are also shown on this map, and

TABLE 4.—*Drill holes in the Boleo copper district in which gypsum of the Boleo formation was penetrated*

No. of drill hole	Coordinates, in meters from San Francisco shaft: South	Coordinates, in meters from San Francisco shaft: East	Depth of top of gypsum below surface (meters)	Depth of top of gypsum below sea level (meters)	Remarks
2	3552	4318	257	−214	Gypsum rests on Comondú volcanics at −236 meters.
4	4209	4171	279	−241	Hole terminated in gypsum.
5	4197	4691	295	−260	Do.
6	4596	4537	314	−280	Do.
22	5153	4727	390	−264	Do.
27	1281	4322	29	−2	Gypsum rests on Comondú volcanics at −73 meters.
33	3254	5026	331	−304	Hole terminated in gypsum.

the presence or absence of gypsum in each hole or working is indicated. The areas believed to be underlain by gypsum are based partly on this subsurface information and partly on surface outcrops. A list of the drill holes in which gypsum was penetrated is given in table 4.

The gypsum was 22 meters thick in hole 2 and 70 meters thick in hole 27, but the full thickness was not revealed in the other holes. Besides the drill holes, one of the mine workings in the Ranchería mine east of the San Marcelo shaft (pl. 11, coordinates 500 S., 2800 E.) reached gypsum below ore bed 2 at a depth of 67 meters below sea level. The gypsum there has a thickness of 14 meters and overlies conglomerate.

The gypsum beds wedge out rapidly in many places around the margins, as indicated not only by subsurface information but also by outcrops. Some of the gypsum beds finger out into tuff, and in places thin bands of tuff are also intercalated in the gypsum. The gypsum is wrinkled into several local domelike folds with irregular axes and steep dips. Although this is probably due in part to initial deposition over an irregular topography, the initial dips may have been accentuated by folding resulting from expansion of the rock, perhaps in turn, due to hydration of original anhydrite, as suggested by Anderson (1950, p. 32) for the gypsum on San Marcos Island.

The gypsum is in part massive and in part distinctly banded (see fig. 14). The bedded rock is cut by veins 1 to 3 meters wide of coarsely crystalline gypsum of secondary origin. One vein in Arroyo del Boleo contains enormous twinned crystals as much as 2 meters across (see fig. 15). These crystals would doubtless serve as fine museum specimens if they could be dislodged from the surrounding rock. The gypsum is highly varicolored, presenting different shades of red, brown, orange, purple, and green, as well as white and gray.

The rock reported as gypsum in the drill holes near Arroyo de Santa Agueda was actually a pure, white crystalline anhydrite, according to Sr. P. Mahieux of the Boleo company, although in the outcrops anhydrite is uncommon. Since the beds cut in the drill holes are mostly 200 meters or more below the surface, well below the reach of surface weathering, the possibility arises that anhydrite may have been the original substance deposited and that the gypsum in the outcrops may be a result of surface hydration. This possibility has not, however, been proved. In a thin section of a sample of gypsum from Arroyo del Boleo, Eduardo Schmitter noted the following order of deposition of the constituents: 1. gypsum, making up the main mass of the rock; 2. very little anhydrite, distributed sporadically along some of the cleavage planes; 3. iron oxides (hematite and limonite), distributed along cleavage planes and cracks; and 4. secondary gypsum occupying fractures.

A composite sample of gypsum was collected by the writers from exposures along the south side of Arroyo del Boleo, extending a length of about 100 meters. Analysis of this sample, which is believed to be more or less representative of the bulk of the gypsum, is presented in table 5.

TABLE 5.—*Analysis of a composite sample of gypsum, in weight percent, from the Boleo formation, Arroyo del Boleo, Boleo district*

[Analyzed by Rodolfo del Corral; Instituto de Geología, Mexico, analysis no. 8932]

SiO_2	1.14	K_2O	.25
Al_2O_3	.56	CO_2	.27
Fe_2O_3	.78	SO_3	44.46
MnO	.11	H_2O at 110° C	17.05
MgO	tr.	Loss on ignition	2.23
CaO	32.70		
Na_2O	.65	Total	100.20

Solution weathering is well shown in the gypsum (fig. 16). Arroyos crossing the gypsum areas are generally deep, constricted, and steep-sided, and some of the smaller canyons have narrow, tortuous paths and vertical or overhanging walls barely far enough apart to permit the passage of a man, although they may be 10 to 15 meters high. Large blocks which have tumbled from the cliffs on either side have become wedged into these gorges to form small caves below. Pot holes have been formed in the bottom of the gypsum canyons, and in some protected, permanently shady localities are pools of water which remain for long periods after the infrequent storms.

The gypsum generally has no soil cover and is nearly barren of vegetation. One of the few varieties of plants that seem to thrive in gypsum is the ocotillo, and the concentration of the long thorny stems of that plant, together with the typical gray barren appearance of the ground, aid in recognizing gypsum outcrops from a distance.

Two possibilities have been suggested for the origin of the gypsum: It may have been formed by precipitation from hydrothermal submarine springs, as suggested by Touwaide (1930, p. 119), or it may have been formed by evaporation in bodies of water partly enclosed and cut off from the sea.

FOSSILIFEROUS SANDSTONE

A few thin lenses of fossiliferous sandstone are found locally near the base of the Boleo formation. Half a dozen separate lenses were noted along the north side of Arroyo del Boleo, between the Boleo shaft and the Neptuno mine, and in the area between Arroyo del Boleo and Cañada de la Gloria. The sandstone lenses, as seen in exposures, are 2 to 5 meters thick and 50 to 200 meters long. In part the sandstone rests directly on the basal limestone, and in part it is intercalated in tuff a short distance above the limestone.

The fossiliferous sandstone is calcareous, fine- to medium-grained, well cemented, and dark brown. It contains abundant fossils, chiefly Pectens and oysters, which are, however, rather poorly preserved. The fossiliferous sandstone serves as corroborative evidence, along with the basal marine limestone, that at least part of the Boleo formation is of marine origin.

TUFF AND TUFFACEOUS CONGLOMERATE

The bulk of the Boleo formation is composed of alternating layers of tuff and tuffaceous conglomerate (fig. 17). The beds of greatest economic importance are certain distinctive layers of clayey tuff, which contain all the minable ore bodies in the district. At an early stage in the history of mining operations, four distinct ore beds were recognized and were numbered 1 to 4 from top to bottom. At a later time an ore bed higher than no. 1 was found and called no. 0. Each of these five beds is underlain by a conglomerate, or by a tuffaceous sandstone representing the gulfward continuation of the conglomerate.

Although a better numbering system might be devised, these numbers have become so firmly established in the records and literature on the Boleo district that any attempt to change them now would only cause confusion. They have been adopted by the writers, who have applied the same number to the conglomerate underlying each ore bed, that is, conglomerate no. 1

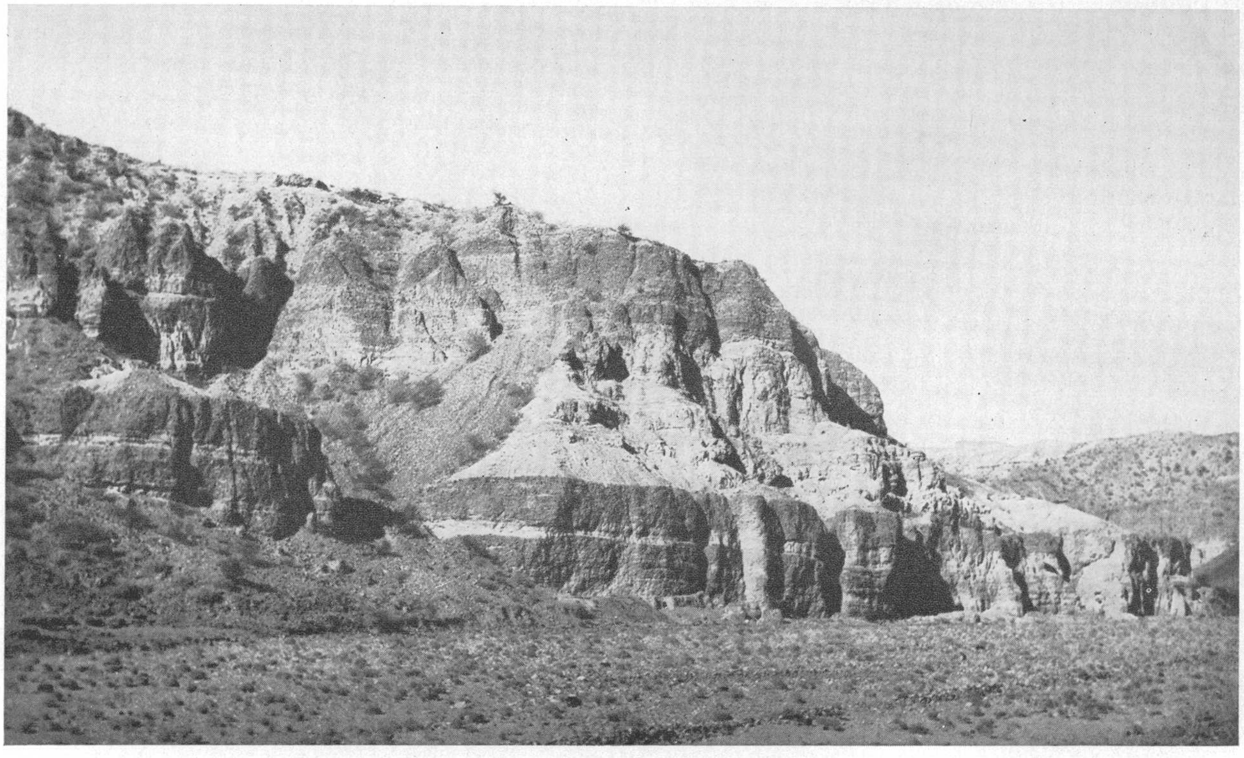

FIGURE 17.—Interbedded tuff and conglomerate of the Boleo formation on the northwest side of Arroyo del Purgatorio near Purgatorio shaft. Cliff-forming layer at bottom is conglomerate no. 2, overlain by light-colored tuff; higher cliff-forming layer is conglomerate no. 1. Conglomerate contacts are sharp at top, but gradational at base.

is the conglomerate immediately underlying ore bed no. 1, and so forth. In certain areas other unnumbered ore beds and other conglomerates are intercalated in the section. The principal conglomerate and tuff layers have been differentiated on the geologic map (pl. 1) and structure sections (pl. 3).

The tuff beds grade upward in general from clayey tuff into sandy tuff and tuffaceous sandstone, followed by conglomerate. Pebbly sandstone layers are commonly interfingered with the base of the conglomerate. The upper contact of each conglomerate is generally abrupt, however, and is overlain by a very persistent and widespread layer of clayey tuff. In this clayey tuff a relict brecciaiike structure is often preserved, formed by original angular volcanic fragments, but the fragments, as well as matrix, have been completely altered to a mass of montmorillonite. These clayey tuff layers probably resulted from explosive volcanic eruptions that blew out large quantities of volcanic glass—the principal material from which montmorillonite is derived (Ross and Hendricks, 1945, p. 64). The sandy tuffs and tuffaceous sandstones, however, seem to have been formed more largely of reworked material.

The tuffs are well stratified and are latitic to andesitic in composition. They contain varying proportions of detrital grains and angular lithic, vitric, and crystal fragments in a matrix of montmorillonite. The commonest crystals and crystal fragments are feldspars, chiefly andesine and andesine-labradorite, together with biotite, green hornblende, basaltic hornblende, clinopyroxene, and magnetite. Fragments of glass and glassy volcanic rocks are abundant, as are andesitic rock fragments. Secondary calcite and gypsum are common, and celadonite, halloysite, allophane (?), dolomite, epidote, chlorite, and zeolites have been identified in certain specimens. Quartz, however, is extremely rare.

The tuff particles of sand size commonly have a glaucous coating, similar to that of some of the Tertiary andesitic sandstones of California. According to Robert L. Smith, this bluish coating seems to be the cementing agent, and appears to consist of two minerals, one nearly isotropic and the other weakly birefringent. The nearly isotropic mineral may be chalcedonic silica and the other may be a clay mineral.

The tuffs commonly have a pinkish or purplish appearance, although in places they are almost white. A pink color of similar tuffaceous sediments partly altered to montmorillonite in the Santa Rita area of New Mexico was attributed by Graf and Kerr (1950, p. 1033) to the presence of manganese, as determined by spectrographic analyses, and this may also be true at Boleo. One exceptionally bright pink clayey specimen from the San Pedro claim at the northwest end of the Boleo district was at first taken for a pink manganese mineral, since it is surrounded by manganese oxides. X-ray study by J. M. Axelrod, however, showed that it is essentially montmorillonite. A chemical analysis of the pink montmorillonite by Charles Milton showed 0.39 percent of manganese oxide. Milton concludes that the manganese may be present as an impurity in this particular sample or that the montmorillonite itself may contain a minor amount of manganese.

The conglomerates are generally poorly sorted and consist of subangular to subrounded fragments ranging in size from pebbles to boulders. The grain size decreases rapidly northeastward toward the gulf, where the pebbles become smaller and more scattered and eventually give way altogether to sand-sized grains. The pebbles consist almost entirely of rock types found in the Comondú volcanics—chiefly andesites and basalts. A few pebbles of quartz monzonite occur in the conglomerates near the outcrops of quartz monzonite in Arroyo de las Palmas, but elsewhere these are extremely rare.

The conglomerates have a tuffaceous matrix similar to the tuffs. Robert L. Smith has identified in thin section crystals of brown hornblende, hypersthene, augite, and plagioclase, along with andesitic and basaltic rock fragments, including some fragments of a porphyritic hypersthene andesite. Lapilli have a bluish coating of the same type as that described as coating grains of the tuff.

Crossbedding is commonly exhibited in the conglomerates, and channeling is also common both at the base and within the beds. Diastems, slight erosional intervals, may be observed in different parts of the Boleo formation.

Conglomerate dikes appear in some places, evidently as a result of filling of fissures in the tuff with material from the overlying conglomerate layers. Some of these conglomerate dikes are several meters across and are large enough to show on the geologic map (pl. 1), as in the southwest part of Arroyo del Purgatorio.

The conglomerates, which are fairly well cemented, are more resistant to erosion than the tuffs and commonly form cliffs, resulting in a steplike topography of alternating cliffs and benches on the sides of the arroyos.

THE "CINTA COLORADA"—A TIME MARKER

A distinctive key bed in the Boleo formation is a thin layer of coarse-grained tuff, known locally as the "cinta colorada" because of its reddish to purplish color. The thickness of the layer averages about half a meter, ranging from a few decimeters to about 2 meters. The "cinta colorada" is a true time marker because it must have been deposited everywhere simultaneously, perhaps as the result of a single violently explosive volcanic eruption.

The "cinta colorada" is a nearly pure lithic tuff, composed largely of volcanic cinders of coarse ash to lapilli size. According to a thin-section study by Robert L. Smith, the volcanic fragments are chiefly of andesitic composition, although a few are probably basaltic. The fragments represent a wide range of textures; some are coarsely crystallized, others are fine grained, and many are quite glassy. A few of the glassy fragments are vesicular. Many of the fragments are altered, although others are quite fresh. The glass has altered to palagonite, and the feldspars have altered to sericite and clay minerals. The fragments are cemented by iron oxide.

The "cinta colorada" lies between ore beds nos. 2 and 3 wherever it is found. In detail, however, it transgresses lithologic boundaries, particularly that between conglomerate no. 2 and the underlying tuffaceous sandstone, thus demonstrating that such lithologic contacts are not true time boundaries. This is particularly well illustrated in Arroyo del Purgatorio, where the "cinta colorada" lies within conglomerate no. 2 near the California shaft. Farther northeast it gradually approaches the base of this conglomerate and forms the contact on top of tuffaceous sandstone for some distance; still farther northeast, near the San Alejandro shaft, the "cinta colorada" descends well below the conglomerate-sandstone contact. This means that part of the conglomerate in the inland area is equivalent in time to part of the sandstone farther gulfward.

The "cinta colorada" was early recognized as a useful stratigraphic guide in the search for buried ore beds, since it lies everywhere above ore bed no. 3, the most important bed, and is exposed in many places where that ore bed lies below the arroyo levels. The stratigraphic interval between the two beds ranges in general from 30 to 45 meters, although the extremes are from 20 to 70 meters. The offsets on many faults are also clearly shown by the "cinta colorada."

The "cinta colorada" appears roughly in the western quarter of the area mapped. It dies out northeastward along all the arroyos in which it is exposed, and it also disappears southeastward beyond Arroyo de la Providencia. The known distribution suggests that the cinders forming the bed were derived from a volcanic center somewhere to the west of the western corner of the Boleo map (pl. 1).

Although the "cinta colorada" must have been deposited as a nearly continuous bed over the area mentioned, it is now interrupted in various places because of removal by scouring and channeling below the overlying beds. Such channels occur throughout the Boleo formation, but they are particularly well exhibited where they cut through such a distinctive key bed.

VARIATIONS IN THICKNESS AND DISTRIBUTION OF STRATIGRAPHIC UNITS

Because the ore deposits are confined to particular beds in the Boleo formation, the details of the stratigraphic and areal distribution of these beds are of considerable importance. The variations in thickness and distribution of particular beds depend upon two main factors: 1. The irregular topography of the basement rocks prevented deposition of the basal units of the Boleo formation over areas of high relief. For this reason the lowest beds—conglomerate no. 4 and its overlying tuffs—are the most limited in extent. 2. Erosion, indicated by the unconformity at the base of the Gloria formation, removed beds from the top of the Boleo formation. This has removed conglomerates no. 0 and no. 1 and their overlying tuffs from large areas, and in places erosion has proceeded downward through conglomerate no. 2.

A diagram showing the presence or absence and thickness of the stratigraphic units of the Boleo formation in different parts of the Boleo district is given in figure 18. This figure includes also a summary of the range in thickness of the stratigraphic units and of the stratigraphic intervals between the ore beds, based on many sections besides those illustrated. The sections are grouped by arroyos, which are arranged geographically from northwest to southeast, and the sections within each arroyo are arranged in general from southwest to northeast, that is, from landward to gulfward.

Data on the stratigraphic intervals between successive ore beds are given in the last column of figure 18. Although the intervals show considerable variation, they are more constant than the thicknesses of lithologic units, for as a conglomerate thins gulfward, the underlying tuff tends to thicken in a somewhat compensating fashion.

More detailed columnar sections of the strata cut in particular shafts and drill holes, including not only the Boleo formation but also the overlying and underlying formations, are given in plates 5–8. These sections are arranged roughly in geographic order from northwest to southeast.

It may be seen from figure 18 and plates 5–8 that in no single locality are all the stratigraphic units of the Boleo formation represented. The lower part of the section is more nearly complete in the northwest part of the district, and the upper part is more nearly complete to the southeast. No one stratigraphic unit is present in all the sections. The middle unit, ore bed no. 2, is more widespread than any of the others, but even it is missing in some sections, either from the base or from the top.

FACIES CHANGES AND PATTERN OF SEDIMENTATION

The conglomerates of the Boleo formation become finer grained and wedge out gulfward into tuffaceous sandstone, as recognized by Touwaide (1930, p. 121) and Locke (1935, p. 410–411). The place of wedging out of each conglomerate is different. Each conglomerate is typically an elongate lens, having a distinct bulge in the middle and surrounded by a thin blanket. The facies changes have been illustrated by a stratigraphic section and isopach map (Wilson, 1948, p. 1777–1778, figs. 6 and 7).

The locus of sedimentation changed with geologic time, for the thickest part of each conglomerate lens migrated gulfward in progressively younger beds. This is demonstrated particularly well in Arroyo del Purgatorio, where conglomerate no. 3 attains its greatest thickness near the inland border of the geologic map (pl. 1), conglomerate no. 2 is thickest farther gulfward, at a point slightly northeast of the California shaft, and conglomerate no. 1 is thickest still farther gulfward, near the Santiago shaft.

Besides these facies changes from landward to seaward, the locus of sedimentation also migrated along the shore, from northwest to southeast. Thus the oldest sediments, conglomerates no. 4 and no. 3, are confined to the northwest part of the district; conglomerates no. 2 and no. 1 are more widespread, having their centers in the middle of the district, near Arroyo del Purgatorio; and conglomerate no. 0 is confined to the southeast part of the district, reaching its greatest thickness near the San Luciano mine.

ORIGIN OF THE FORMATION

The Boleo formation is believed to be partly marine and partly nonmarine in origin. It is thought to represent deltaic deposition near a shoreline, interrupted from time to time by the deposition of tuffaceous material derived from explosive volcanic eruptions. Part of the formation is definitely marine, as attested by the presence of marine fossils in the basal limestone and in some sandstone lenses intercalated in tuff near the base of the formation. The bulk of the tuff and conglomerate layers, however, appear to be nearly barren of fossils, except for fragments of petrified wood. At least the inland facies of the conglomerates, which are very coarse-grained and poorly sorted, are believed to be nonmarine. These are believed to grade into marine beds northeastward toward the gulf, in which direction the sediments become progressively finer grained and better sorted. It is difficult to draw any line, however, between the marine and nonmarine beds, as is probably true of many deltaic deposits.

Stratigraphic unit of Boleo formation	Sections of Boleo formation present in different parts of Boleo district, indicating thickness of each stratigraphic unit, in meters																											Summary of range of thickness: Thickness of stratigraphic unit, in meters			Stratigraphic interval between ore beds, in meters		
	Arroyo del Boleo			Arroyo de la Soledad			Arroyo del Purgatorio				Arroyo de la Providencia			Arroyo del Montado			Arroyo de Santa Agueda: Northwest side			Middle of arroyo				Southeast side									
	Near San Andrés mine	Near Texcoco mine	Near Boleo shaft	Near Amelia shaft	Near San Agustín shaft	Santa María shaft	Near La Ley shaft	Near San Eduardo shaft	Near San Alejandro shaft	Near drill hole 49	Near San Roberto shaft	Near Carré shaft	Near San Eugenio shaft	Near Ranchería mine entry	San Julio shaft	Near San Marcelo shaft	Drill hole 19	San Luciano shaft	Drill hole 2	Drill hole 3	Drill hole 4	Drill hole 5	Drill hole 33	Drill hole 44	Drill hole 28	Drill hole 22	Drill hole 38	Minimum	Maximum	Average	Minimum	Maximum	Average
Tuff above ore bed 0												15			10	9	3	5	6	20	3	1½	6	14	3	3	6	1½	20	8	2	27	10
Ore bed 0	Absence of higher beds in this area is due to											½			1	1½	2	1½	6	7	1	1	1	1½	1	2	1½	½	7	2			
Conglomerate 0	erosion of top of Boleo formation											3			1					12	7	6		5	7	6	8	1	24	6			
Tuff above ore bed 1							15	15			5	12	10	30	25	37	33	32	39	26	38	37	45	26	37	48	49	5	49	32	15	58	40
Ore bed 1							½	½			½	½	1	1	2½	2½	1	2½	2	2	1	2	½	2	1½	2	1½	½	3½	2			
Conglomerate 1							3	3	30	55	15	3								3	4	4½		1	1½			1	55	18			
Tuff above ore bed 2	15		10	20	2	20	30	25	45	?	70	65	60	50	34	62	50		41	32	52	52	13	12	19	57		2	70	39	14	86	50
Ore bed 2	½		½	½	½	1½	1	1	1		1	½	1?	1?	2	1½	1		5	2	2	<½	Gypsum	½		6		½	6	1½			
Conglomerate 2			3	3		13	15	30	20			10									12	3				Gypsum		3	30	10			
Tuff above ore bed 3	45	45	60 ss	37	53	40	55	45	53	?	27	55	50	?	15	27	5		8	22	3	Gypsum						27	60	48	27	77	55
Ore bed 3	2	2	2	1	2	2	1½	2	4	½	½	2	2			17			22		Gypsum							½	4	2			
Conglomerate 3	25	10	10	51	34	?	30	38	37		?	?	?			? Gypsum on conglomerate			Gypsum on Comondú volcanics									5	60	25			
Tuff above ore bed 4	25	30	75?	81	67		53	56	58	88																		10	88	51	42	141	80
Ore bed 4	2	2 ls	? ?	9	11		1 ls	9 ls	2½		Absence of lower beds in this area is due to																	1	11	5			
Conglomerate 4	20 ls						16				nondeposition over irregular surface of Comondu volcanics																	16	20	18			
Total thickness of Boleo formation, in meters	135	89	160?	202	170+	77+	221+	224	250	223	119+	167+	124+	82+	90	158+	95	41	129	126	123+	107+	66+	62	70	124+	66	Average total, 140 meters					

EXPLANATION: Stratigraphic unit absent (hatched); Gypsum (black); ls Limestone; ss Fossiliferous sandstone lens; Wavy line indicates unconformable contact at top or bottom of Boleo formation with Gloria formation above and with Comondú volcanics below. Where wavy line is omitted, top or base of formation is not exposed

FIGURE 18.—Sections of the Boleo formation indicating distribution of its units and their range of thickness in the Boleo copper district.

The deltaic origin of the conglomerate beds is indicated not only by the rapid gulfward gradation in grain size, but particularly by the shape of the conglomerate lenses, which are elongated parallel with the shoreline, bulge rapidly toward the center, and are surrounded by a thin blanket of material which was probably deposited on a piedmont plain. The migration of each successively higher lens farther gulfward indicates that material was being extended farther out from the original shoreline as the basins were filled in. The crossbedding, in which the laminae are rather steeply inclined toward the gulf, is of a type that might be expected in foreset beds.

FOSSILS AND AGE

Fossils are scarce and poorly preserved in the Boleo formation, as compared with the highly fossiliferous beds of the overlying Gloria, Infierno, and Santa Rosalía formations. The most diagnostic collection from the Boleo formation was found in a fossiliferous sandstone above the basal limestone in Cañada de la Gloria, at locality F3.[1] H. E. Vokes determined the following species in the collection obtained at this locality:

SPECIES	KNOWN RANGE
Ostrea vespertina Conrad	Lower to upper Pliocene
Pecten (*Pecten*) *beali* Hertlein	With lower Pliocene species at type locality
Pecten (*Euvola*) *keepi* Arnold	Lower Pliocene
Aequipecten abietis (Jordan and Hertlein).	Lower to upper Pliocene

Vokes makes the following statement concerning this fauna:

> The ranges indicated are those given by Durham (1950, p. 18–19) as representing the known ranges of these species in the fossil faunas of the Gulf of California region. They are based upon a study of the large faunas obtained by the 1940 cruise of the *E. W. Scripps*. Durham had no specimens of *Pecten* (*Pecten*) *beali* Hertlein, which was described from the Arroyo de las Palmas, Santa Rosalía area, being collected in association with *Aequipecten mendenhalli* (Arnold), a lower Pliocene species. The fauna seems to be of early Pliocene age, and to be correlated with the Imperial fauna of southern California.

Fossils are found also in the basal limestone of the Boleo formation at many localities, but they are largely very poorly preserved casts and molds and are of little diagnostic value. They include unidentified pelecypods, minute gastropods, a cerithiid of indeterminate genus and species, and a form identified by Vokes as a new species of *Laevicardium*. The latter, obtained from localities F1, F2, and F5, was briefly described in the report on the Lucifer district (Wilson and Veytia, 1949, p. 193).

From locality F23, in a fossiliferous sandstone lens on the north side of Arroyo del Boleo, opposite the Texcoco mine, were obtained an indeterminate echinoid fragment and some specimens of *Aequipecten abietis* (Jordan and Hertlein), which ranges throughout the Pliocene and is therefore not too diagnostic.

From locality F22, in a brownish sandstone overlying the basal limestone of the Boleo formation in a northern branch of Arroyo del Boleo, the following collection was made:

- *Ostrea* cf. *erici* Hertlein
- *Ostrea megodon* Hanley
- *Pecten* (*Nodipecten*) cf. *subnodosus* Sowerby
- *Aequipecten*? n. sp.
- *Chlamys*? n. sp. A (same as in locality F19, table 7)
- *Patinopecten* n. sp.? (same as in locality F19, table 7)

In the field this locality was thought to pertain to the Boleo formation. On the basis of *Chlamys*? n. sp. A, *Patinopecten* n. sp.?, and *Ostrea* cf. *erici* Hertlein, however, Vokes considers this fauna to be more closely related to the faunas of the Gloria formation, as represented by localities F11 and F19 listed in table 7, although he does not exclude the possibility that it could be the same age as the Boleo fauna from locality F3. The question is left undecided: Locality F22 may be in the Gloria formation if the field relations were incorrectly interpreted; or, the specimens listed above may range from the Boleo formation into the Gloria formation.

Several fossil collections have previously been reported from the Santa Rosalía area, some of which seemingly came from the Boleo formation. An assemblage collected by G. P. Merrill and listed by Arnold (1906, p. 84–85) and Aguilera (1907, p. 244), included *Aequipecten mendenhalli* (Arnold), *Pecten* (*Pecten*) *carrizoensis* Arnold, and *Pecten* (*Euvola*) *keepi* Arnold. The beds containing these fossils were correlated by Arnold with the Imperial formation of southeastern California (then called the Carrizo Creek beds).

Hertlein (1925, 1931) identified several fossils collected by geologists of the Marland Oil Company expedition. Although these geologists did not subdivide the Pliocene beds, probably at least two localities—nos. 45 and 64—belong to the Boleo formation. Touwaide (1930, p. 121) collected fossils from a tuff overlying the basal limestone of the Boleo formation (his Lower Salada formation). This collection was reexamined by Durham (1950, p. 27), who remarks: "The presence of *Pecten* (*Pecten*) *carrizoensis* Arnold and *Pecten* (*Euvola*) *keepi* Arnold indicates an age corresponding to that of the Imperial formation."

The close relation of the Boleo formation to the Imperial formation was also pointed out by Vokes, on the basis of the fauna from locality F3. A fauna that is even more clearly related to that of the Imperial formation, in that it contains *Turritella imperialis*

[1] A list of fossil-collecting localities is given on page 127.

Hanna, was collected by the author near Point Concepción, 70 kilometers southeast of Santa Rosalía, and listed in the paper by Wilson (1948, p. 1780).

The age of the Imperial formation of southeastern California, near the head of the Gulf of California, has long been controversial, opinions having been divided between a Pliocene and a Miocene age. The subject was recently reviewed at some length by Durham (1950, p. 30–34), who concludes that the Imperial formation is best assigned to the lower Pliocene.

ECONOMIC IMPORTANCE

The Boleo formation is of major economic importance in the Boleo district because it contains all the known ore deposits of commercial value, both of copper and manganese. Other deposits of economic value in the Boleo formation include gypsum and limestone, both of which have been used in the Boleo smelter.

GLORIA FORMATION (MIDDLE PLIOCENE)

GENERAL FEATURES

The Gloria formation is a middle Pliocene sequence of sandstone and conglomerate which rests unconformably upon the Boleo formation. It consists of a basal conglomerate which is present only locally, a fossiliferous marine sandstone which thins and wedges out inland but thickens gulfward and grades into siltstones and clays, and an overlying conglomerate which thickens and grades into a nonmarine facies inland. The formation was named by Wilson (1948, p. 1768) for exposures in Cañada de la Gloria, where the unconformable relation to the Boleo formation is well shown, and where fossils were collected which establish the age as middle Pliocene. The type locality is at fossil-collecting locality F7, on the north side of Cañada de la Gloria.

The Gloria formation, along with all the succeeding formations, is younger than the mineralization that affected the region, and from an economic standpoint it merely covers and obscures the ore-bearing beds.

DISTRIBUTION AND STRATIGRAPHIC RELATIONS

The Gloria formation was deposited over most of the area shown on the map of the Boleo district, except for the highest parts of the former islands and mainland. The formation crops out to some extent in all the major arroyos of the district.

The most extensive exposures are along the coast, where the formation lies fairly close to sea level. As a result of tilting, the exposures are at higher levels farther inland along the arroyos extending from Arroyo del Boleo southeastward to as far as Arroyo de la Providencia. There the Gloria formation is exposed in belts along the sides of the arroyos, occupying a position intermediate between the Boleo formation, which forms the bottoms of the arroyos, and the Infierno formation, which caps the mesas between the arroyos. Southeast of Arroyo de la Providencia the Gloria formation extends to greater depths, so that in the branches of Arroyo del Montado it is exposed chiefly along the bottoms of the arroyos, and in Arroyo de Santa Agueda it lies mainly below the arroyo level, only the top being exposed here and there, although the formation in that area has become revealed in drill holes.

An unconformity between the Gloria formation and the underlying Boleo formation may be observed in many places. Although it is by no means as pronounced as the one between the Boleo and Comondú formations, it is nevertheless of economic significance, since the higher ore-bearing beds have been cut out in places by this unconformity. The degree of angular discordance between the two formations is generally slight. Locally the difference in dip amounts to 5° to 10°, particularly in those places where the Boleo has steep dips formed over topographic irregularities on the underlying surface of the Comondú. In such places the higher parts of the structures in the Boleo formation were planed off before deposition of the more gently dipping Gloria formation. More commonly, however, the angular discordance is not so perceptible and the unconformity is revealed by mapping certain beds of the Boleo formation which terminate gradually against the overlying Gloria formation.

The unconformity is shown particularly well at the type locality of the Gloria formation on the north side of Cañada de la Gloria, where the formation cuts gently across the different layers of the Boleo formation, which there have fairly high dips. In Arroyo del Boleo the unconformity is well shown near the Texcoco mine, where conglomerates no. 1 and no. 2 of the Boleo formation have been cut out, over an anticlinal structure, by the more gently dipping Gloria formation. In Arroyo del Purgatorio the unconformity may be observed near the San Guillermo fault, where the base of the Gloria formation descends into conglomerate no. 1 of the Boleo formation, cutting out a considerable thickness of tuff.

The Gloria formation directly overlaps the Comondú volcanics on some of the former islands and other areas of once high relief, as, for example, around Cerro de Juanita. This seems to take place also over a buried hill revealed by drill hole no. 36. In some places the Gloria formation rests directly on the basal marine limestone of the Boleo formation. Only in the gulfward area, particularly near the mouth of Arroyos Boleo and Soledad, does the unconformity at the base of the Gloria formation appear to die out, and in part of this area the Boleo-Gloria contact, based on lithologic changes, was located with some doubt.

LITHOLOGY, FACIES CHANGES, AND THICKNESS

The first unit of the Gloria formation to be deposited was a conglomerate, which has a lenticular form and appears only in local areas. Lenses 1 to 7 meters thick were found in certain parts of Arroyos Boleo, Soledad, Purgatorio, and Providencia. A conglomerate lens 3 to 15 meters thick, believed to represent the same unit, was penetrated in many of the drill holes in Arroyo de Santa Agueda. The conglomerate contains poorly sorted and slightly rounded pebbles and boulders, composed chiefly of rocks from the Comondú volcanics, in a sandy matrix. A few fragments of the underlying pink tuff from the Boleo formation were noted in one place. The base of the conglomerate is irregular in detail, and in places it has filled in channels cut into the underlying Boleo formation. The basal conglomerate was differentiated as a mappable unit only in the area where it is overlain by sandstone; farther inland where the Gloria formation is represented solely by conglomerate, the basal beds could not be distinguished from the rest of the conglomerate.

The most characteristic member of the Gloria formation is a fossiliferous marine sandstone, which ranges in thickness from a few meters to as much as 105 meters. This overlies the basal conglomerate wherever that unit is present, but elsewhere it rests directly on the Boleo formation. Sandstone is in places the sole component of the Gloria formation. It is calcareous, well cemented, fine to coarse grained, and generally buff to tan, or gray to white. The sandstone is resistant to erosion and has a tendency to form cliffs. The outcrops are in many places characterized by irregular cavities, presumably due to solution weathering of the calcareous cement. The sandstone becomes thicker but finer grained gulfward, in which direction it grades into massive siltstones, fine-grained sandstones, and clays (fig. 19). Gypsiferous veinlets are common in the siltstones and clays.

The sandstone thins inland, where it becomes more highly fossiliferous just before wedging out, indicating a shoreline environment. In part of the inland area the sandstone becomes a thin reef bed only 2 to 5 meters thick, filled with echinoids (*Encope*), as for example on the north side of Arroyo del Purgatorio near the Santiago shaft.

The sandstone is commonly overlain by conglomerate, which thins gulfward and thickens inland, in which direction it replaces the sandstone altogether. The contact between sandstone and overlying conglomerate is fairly sharp but appears to be conformable. The conglomerate consists of moderately well rounded pebbles and boulders of volcanic rocks in a sandy matrix, having a calcareous cement (fig. 20). It is in general less resistant to erosion and does not form such

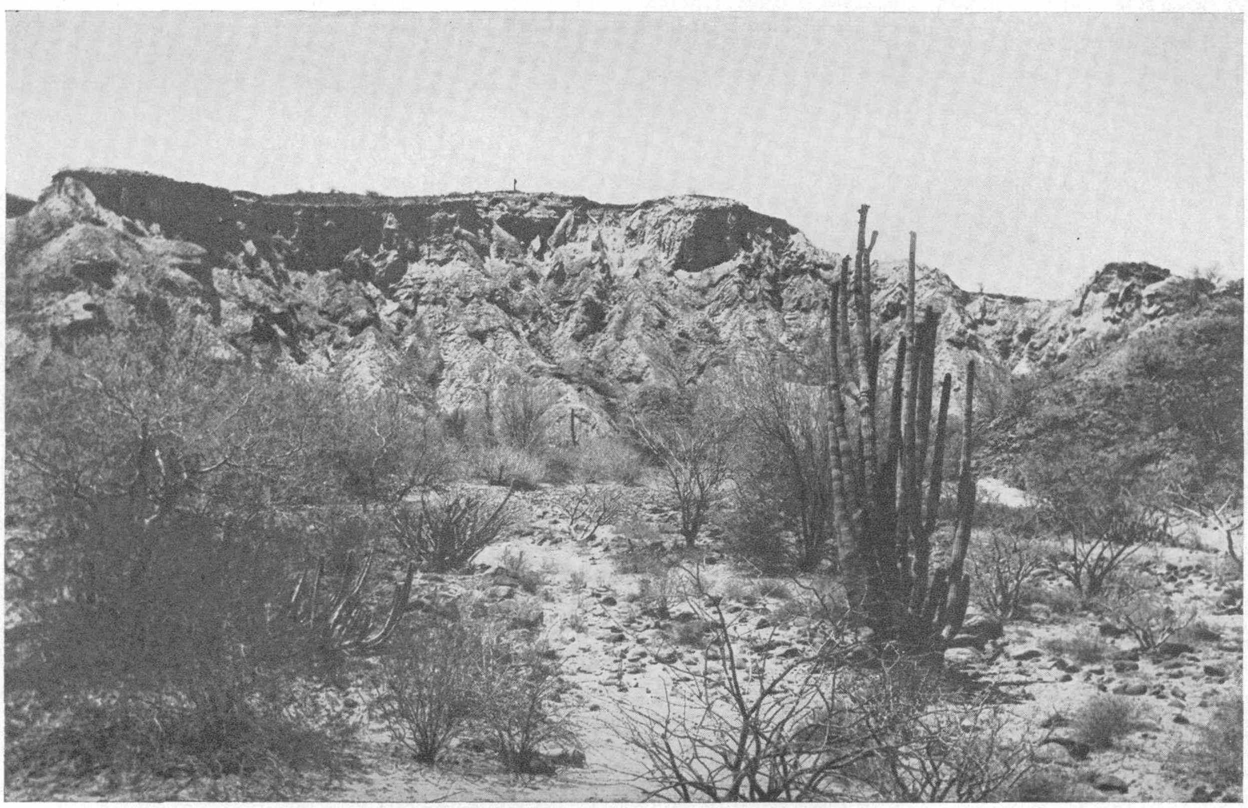

FIGURE 19.—Gulfward facies of the Gloria formation; fine-grained sandstone and siltstone. This view near the mouth of Arroyo de la Soledad shows typical badlands topography.

steep cliffs as do the conglomerates of the Boleo formation. The general color is purplish or yellowish. The pebbles become more angular, more poorly sorted, and coarser inland.

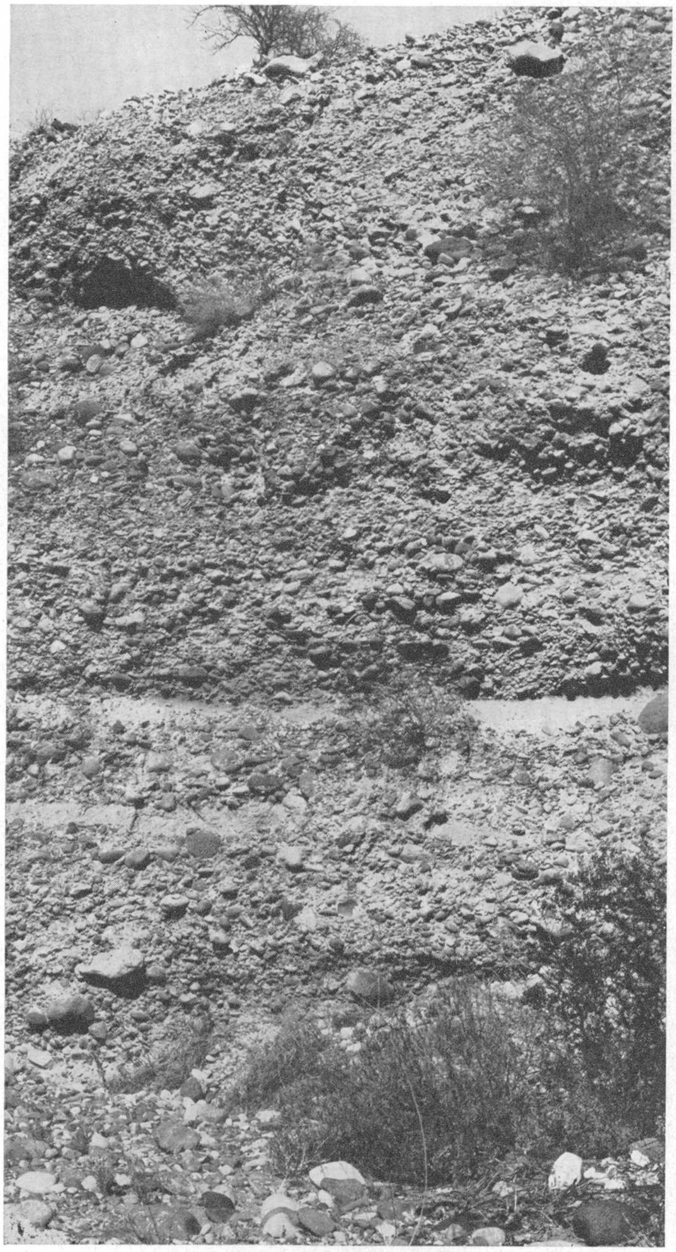

FIGURE 20.—Conglomerate of the Gloria formation in Arroyo del Montado. This view of the inland facies shows interbedded sandy layers.

The sandstone and conglomerate show reciprocal relations of thickness—gulfward the sandstone thickens and the conglomerate thins, while the reverse is true inland. The sandstone reaches a maximum thickness of 105 meters, and the conglomerate 135 meters. The maximum total thickness of the Gloria formation is 185 meters, although the average is closer to 60 meters. The formation thickens as a whole toward the southeast, in Arroyo de Santa Agueda. Table 6 shows the variations in thickness of the lithologic units of the Gloria formation, as well as of the Infierno formation, in different parts of the district.

ORIGIN

The sandstone is evidently of marine origin throughout, as indicated by the abundance of marine fossils. This applies as well to the thick gulfward siltstone with a clay facies, which contains scattered fossils. Some of the conglomerate may also be of marine origin, but the inland facies is probably nonmarine, judging from the angularity, coarseness, and poor sorting of the fragments, as well as the absence of fossils. The sandstone wedges out along a line extending from 3 to 4 kilometers inland from the present shoreline, and this line is believed to represent the approximate inland limit of the middle Pliocene shoreline, as shown in a Pliocene paleotopographic, paleogeographic, and facies map of the Santa Rosalía area that was published by Wilson (1948, p. 1772). The conglomerate extends farther gulfward toward the top of the formation, indicating probably a gradual filling up of the basin and seaward migration of the shoreline during the course of sedimentation.

Near the line of wedging out of the sandstone appear layers containing abundant echinoids of the genus *Encope*. In this connection Durham (1950, p. 13–14) has stated:

> Steinbeck and Ricketts (1941, p. 193, 400–401) note that *Encope grandis* and *E. californica* were found living in large numbers at depths of 1 to 3 feet below low tide in quiet-water sand flats [in the Gulf of California]. It is thus suggested that sediments * * * where the afore-mentioned species of *Encope* or their close relatives are abundant were deposited in protected areas in very shallow waters, probably less than 10 feet deep.

It is interesting that this ecological conclusion of Durham is confirmed by the physical evidence of shoreline deposition of these *Encope*-rich beds of the Gloria formation.

FOSSILS AND AGE

The sandstone unit of the Gloria formation contains abundant fossils, some of which are very well preserved. Pectens of several different genera and species, as well as oysters, form the great bulk of the fossils, although echinoids are locally abundant. Table 7 gives a list of fossils from the Gloria formation that were identified by H. E. Vokes, except for the echinoids which were identified by C. W. Cooke.

Vokes considers these collections to be probably of middle Pliocene age. Among the more diagnostic species are *Aequipecten antonitaensis* Durham, *Aequipecten* aff. *revellei* Durham, *Patinopecten bakeri diazi* Durham, *Pecten* (*Euvola*) cf. *refugioensis* Hertlein, and

TABLE 6.—*Range in thickness of lithologic units of the Gloria and Infierno formations*

Locality	Thickness, in meters						
	Gloria formation				Infierno formation		
	Basal conglomerate	Sandstone	Conglomerate	Total of formation	Sandstone	Conglomerate	Total of formation
Arroyo del Boleo, between Texcoco and Mangle mines	0-3	0-10	15-20	25-30	10-20	10	20-30
Arroyo del Boleo, near mouth of arroyo	0	60	0	60	(?)	(?)	Eroded
Arroyo de la Soledad, near San Agustín shaft	3	10	30-40	40-50	0-5	(?)	0-5
Arroyo de la Soledad, near Santa Rita shaft	0-3	15-40	35-40	55-70	15-30	5-10	20-30
Arroyo de la Soledad, near mouth of arroyo	0	70	0	70	(?)	(?)	Eroded
Arroyo del Purgatorio, near San Alejandro shaft	0	0	40	40	(?)	(?)	Eroded
Arroyo del Purgatorio, near Santiago shaft	0	5-15	50-60	55-65	20-30	30-50	50-80
Arroyo del Purgatorio, near San Roberto shaft	0	5-15	20-35	35-40	25-35	20	45-55
Arroyo del Purgatorio, near Cinco de Mayo mine	0-7	5-30	15-25	30-45	15-40	15-25	30-65
Arroyo de la Providencia, near San Víctor mine	0	0	35	35	0-15	15-25	25-40
Arroyo de la Providencia, near San Guillermo fault	0	0-5	40	40-45	20-25	30-35	50-60
Arroyo de la Providencia, near Ranchería mine	0	20-30	25-35	45-60	30-55	30-40	65-85
Arroyo del Montado, near Sombrero Montado shafts	1	9	40	50	10-20	25-35	45-50
Arroyo del Montado, near Montado fault	0	15-20	25-30	45-50	40-50	30	70-80
Arroyo del Montado, near Santa Agueda fault	0	20-30	20-30	40-50	65-95	30	95-125
Arroyo de Santa Agueda, near drill hole no. 3	0	14	45+	60+	(?)	(?)	Eroded
Arroyo de Santa Agueda, near William shaft	0-15	35-75	60-135	110-185	(?)	(?)	Eroded
Arroyo de Santa Agueda, near drill hole no. 2	0	75	50	125	30+	(?)	30+
Arroyo de Santa Agueda, near Santa Agueda fault	0	105	15	120	80	25	105
Southeast of Arroyo de Santa Agueda, near drill hole no. 28	0	50	55	105	35	65	100
Southeast of Arroyo de Santa Agueda, near drill hole no. 38	0	80	40	120	70	70	140
Minimum thickness where present	1	5	10	25	5	5	5
Maximum thickness	15	105	135	185	95	70	140
General average for district	6	30	30	60	30	25	55

TABLE 7.—*Fossils from localities in the Gloria formation* (*middle Pliocene*)

	F7	F8	F11	F13	F15	F18	F19	F20	F27
Encope michelini Agassiz [1]	--	--	--	×	--	×?	--	--	--
Clypeaster speciosus Verrill [2]	--	--	--	--	--	---	--	--	[2] ×
Ostrea cf. *O. angelica* Rochebrune	--	×	--	--	--	---	--	--	--
cf. *O. erici* Hertlein	--	--	--	--	×	---	--	--	--
megodon Hanley	×	×	×	--	--	---	×	×	--
vespertina Conrad	×	--	×	--	--	---	--	×	--
Pecten (*Euvola*) cf. *P.* (*E.*) *refugioensis* Hertlein	--	--	×	×	--	×?	×	--	--
n. sp	--	--	--	--	--	---	--	×	--
(*Nodipecten*) *subnodosus* Sowerby	--	--	×	--	--	---	--	--	--
Aequipecten abietis (Jordan and Hertlein)	--	×	--	--	--	×?	--	--	--
antonitaensis Durham	×	--	--	--	--	---	--	--	--
callidus (Hertlein)	--	--	×	--	--	---	--	--	--
circularis (Sowerby)	--	--	--	--	--	---	--	×	--
aff. *A. revellei* Durham	×	--	--	--	--	---	--	--	--
cf. *A. subdolus* (Hertlein)	--	--	×	--	--	---	--	--	--
n. sp	×	--	--	--	--	---	--	--	--
sp. indet	--	--	--	--	×	---	--	--	--
Chlamys? n. sp. A	--	--	×	--	--	---	×	×	--
Patinopecten bakeri diazi Durham	×	--	--	--	--	---	--	--	--
aff. *diazi* Durham	--	--	--	--	--	---	×	--	--
var.[3]	--	×	--	--	--	---	--	--	--
sp. aff. *P. bakeri* (Hanna and Hertlein)	--	--	×	--	--	---	--	--	--
cf. *P. stearnsii* (Dall)	--	×	--	--	--	---	--	--	--
n. sp	×	--	--	--	--	---	--	--	--
n. sp.? [4]	--	--	×	--	--	---	×	--	--
n. sp. B?	--	--	×	--	--	---	--	--	--
sp	--	--	--	×	--	---	--	--	--
Anomia sp. indet	×	--	--	--	--	---	--	--	--
Placunanomia hannibali Jordan and Hertlein [5]	--	--	--	--	--	---	--	×	--
Dosinia? sp. (not *D. ponderosa*)	--	--	×	--	--	---	--	--	--
Turritella aff. *T. gonostoma* Valenciennes	×	--	--	--	--	---	--	--	--
Balanus sp	×	--	--	--	--	---	--	--	--

[1] A species of the Atlantic. Poriferous zones wider than in the very similar species *Encope micropora* Agassiz of the Pacific.

[2] It is not absolutely certain that locality F27, containing *Clypeaster speciosus* Verrill is in the Gloria formation.

[3] Similar to *Patinopecten bakeri diazi* Durham but has 18 to 20, instead of 23 to 25, ribs on the right valve.

[4] The *Patinopecten* n. sp.? from localities F11 and F19 is close to *Patinopecten* n. sp. from locality F7, but has fewer (21 instead of 25) ribs.

[5] *Placunanomia hannibali* Jordan and Hertlein has been reported only from upper Pliocene deposits. For this reason Vokes is uncertain of the age of the beds at locality F20, although the *Chlamys*? n. sp. A at that locality seems to be the same as in localities F11 and F19. Field relations indicate that locality F20 belongs to the Gloria formation.

Ostrea cf. *erici* Hertlein, which, according to Durham (1950, p. 18–19), are confined to the middle Pliocene. Vokes states also that several of the species listed are identical or similar to those in the San Diego formation of southern California of middle Pliocene age, including *Aequipecten callidus* (Hertlein), *Aequipecten* cf. *subdolus* (Hertlein), *Patinopecten* cf. *stearnsii* (Dall), and *Ostrea* cf. *erici* Hertlein.

INFIERNO FORMATION (LATE PLIOCENE)

GENERAL FEATURES

The Infierno formation is a sequence of fossiliferous marine sandstone and overlying conglomerate which rests with slight unconformity upon the Gloria formation. Inland, the sandstone thins and wedges out into conglomerate, which grades into a nonmarine facies. The Infierno formation was named by Wilson (1948, p. 1768) for exposures in Arroyo del Infierno, where the unconformable relation to the underlying Gloria formation is well shown, and where fossils establish the age of the formation as late Pliocene. The type locality is at fossil locality F10, on the south side of Arroyo del Infierno, shown in fig. 21.

DISTRIBUTION AND STRATIGRAPHIC RELATIONS

The Infierno formation was probably deposited over much of the Boleo district, but being one of the youngest formations it has been widely eroded. In the northwest part of the district it caps some of the mesas between the arroyos, although in places it is in turn capped by thin deposits of the Santa Rosalía formation, by lava flows, and by terrace and gravel deposits. The most extensive exposures of the Infierno formation are in the southeast part of the district, in Arroyos Montado and Santa Agueda, where the formation is much thicker than it is to the northwest, and where, owing to southeastward tilting, it lies close to the level of the arroyos.

An unconformity at the base of the Infierno formation was recognized in at least two widely separated places. At the type locality of the formation on the south side of Arroyo del Infierno, 4 kilometers east of the Lucifer manganese mine, a difference in dip of 10° appears between the Gloria and Infierno formations (fig. 21). Fossils that established a difference in age were found both above and below the unconformity at that place. On the south side of Arroyo de Santa Agueda, near its mouth, the unconformity is also well exposed, again with a difference in dip of as much as 10° between the two formations.

Over much of the Boleo district, however, no definite unconformity could be recognized between the two formations, and the contact was distinguished mostly on the basis of lithologic boundaries and here and there

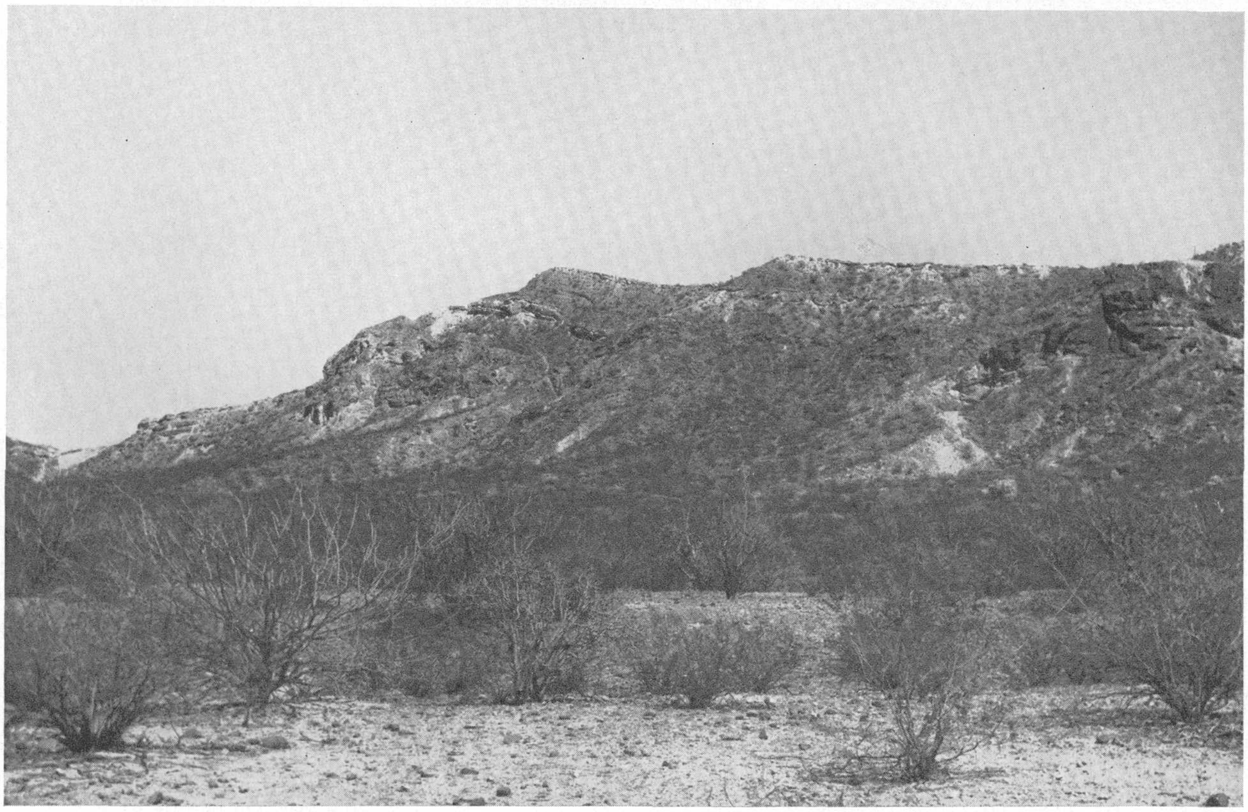

FIGURE 21.—Unconformity between Gloria and Infierno formations at type locality of Infierno formation on south side of Arroyo del Infierno. The underlying Gloria formation dips toward the left; the overlying Infierno dips toward the right.

by fossil collections. The lithologic boundaries that were mapped may transgress time horizons.

Mapping was particularly difficult in the inland area where the fossiliferous sandstone at the base of the Infierno formation wedges out and the conglomerate of that formation thereafter rests directly on the similar conglomerate of the Gloria formation. Farther inland it becomes practically impossible to differentiate these conglomerates, and in mapping they were therefore lumped in that area as "undifferentiated post-Boleo deposts" (QTu on the geologic map, pl. 1). This map unit may also include some younger conglomerate of Pleistocene age.

LITHOLOGY, FACIES CHANGES, AND THICKNESS

The Infierno formation consists essentially of a fossiliferous marine sandstone overlain by a conglomerate, although the sandstone wedges out inland and the conglomerate wedges out gulfward. Where the sandstone disappears, it fingers out into several layers intercalated with conglomerate.

The sandstone is rather fine grained, calcareous, well cemented, generally yellowish to buff or white, and commonly crossbedded. It has a tendency to form steep cliffs, although parts of it are weaker. It is quite similar in appearance to the sandstone of the Gloria formation, although in part it is somewhat less resistant to erosion and slightly lighter in color. The two are distinguished, however, mainly by their different fossil content, along with their different position in the stratigraphic sequence.

Much of the sandstone of the Infierno formation is highly fossiliferous (fig. 22). A calcareous sandstone in Cerro de la Calera, on the north side of Arroyo de la Providencia, is so closely packed with shells that it was mined for many years for use as a lime flux in the Boleo smelter.

The conglomerate is similar to the older conglomerates in that it consists largely of pebbles and boulders of the Comondú volcanics in a sandy matrix. It is more poorly cemented, however, than the older conglomerates and has a greater tendency to form topographic benches. A few sandy layers are enclosed in the conglomerate, which becomes coarser and more poorly sorted inland.

The formation thickens in general from northwest to southeast. In the area northwest of Arroyo del Purgatorio, it has a thickness in general of 20 to 30 meters, ranging from 5 to 50 meters. In the central part of the area, between Arroyos Purgatorio and Providencia, the thickness ranges from 20 to 90 meters, while in the southeast part of the area it ranges from 70 to 140 meters. The average thickness for the district as a whole is about 55 meters (see table 6).

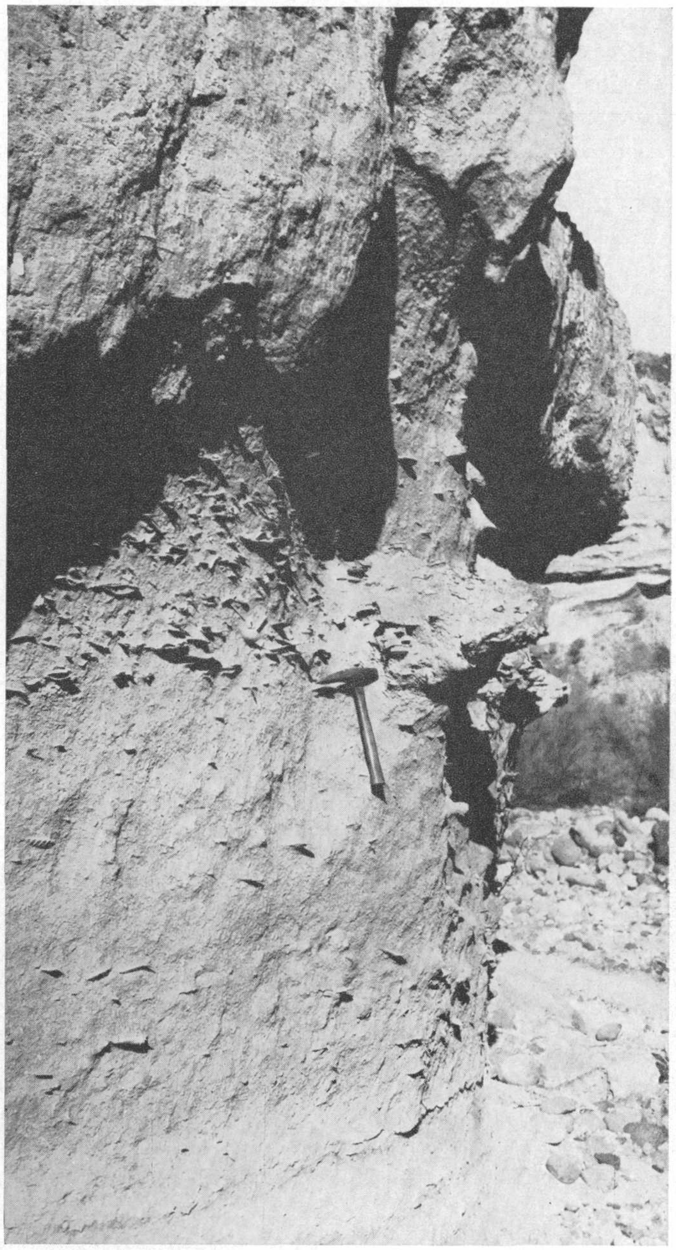

FIGURE 22.—Fossiliferous sandstone of the Infierno formation in Arroyo del Montado. Pectens are the most abundant fossils.

ORIGIN

The Infierno formation seems to represent much the same conditions of deposition as does the Gloria formation. Evidently the conglomerate forming the top unit of the Gloria formation was slightly eroded, and then followed a period of subsidence and a renewed invasion of the sea, resulting in the deposition of a marine sandstone. Then, just as in deposition of the Gloria formation, conglomerate deposition encroached farther and farther seaward into the area of sandstone deposition, indicating, presumably, a receding shoreline.

The marine origin of the sandstone is indicated by the presence of many marine fossils, while nonmarine origin of at least the inland facies of the conglomerate is suggested by the poor sorting, coarseness, and angularity of the fragments in that direction. The inland limit of the fossiliferous sandstone, considered to be the probable inland limit of the shoreline in late Pliocene time, lies fairly close to the line representing the shoreline in middle Pliocene time, but it is for the most part situated about half a kilometer nearer the gulf (see paleogeographic map, Wilson, 1948, p. 1772).

FOSSILS AND AGE

The Infierno formation is even more fossiliferous than is the Gloria formation. Again, Pectens and oysters predominate, but many of the species are different and the large Patinopectens seem to make up a greater proportion of the specimens. The fossils proved useful in the field work, even before their age was known, for it was easy to distinguish the *Encope*-rich beds of the Gloria formation from the *Patinopecten*-rich beds of the Infierno formation. Table 8 lists the fossils from the Infierno formation identified by H. E. Vokes, including some echinoids identified by C. W. Cooke.

Probably the most diagnostic form is *Patinopecten marquerensis* Durham, which, according to Durham (1950, p. 19), is representative of the upper Pliocene. Another form previously reported only from the upper Pliocene, according to Vokes, is *Placunanomia hannibali* Jordan and Hertlein.[2] Also, *Ostrea cumingiana* Dunker and *Aequipecten circularis* (Sowerby),[2] both Recent species, do not appear until the upper Pliocene according to Durham. Vokes thinks that probably all the localities listed in table 8 belong to the upper Pliocene, except for localities F24 and F26, which may be middle or upper Pliocene. Because of the field relations, these two localities are tentatively placed with the Infierno formation.

SANTA ROSALÍA FORMATION (PLEISTOCENE)

The youngest sedimentary formation in the Boleo district is the Santa Rosalía formation, of Pleistocene age. This consists of a thin layer of fossiliferous sandstone and conglomerate which unconformably overlies the Infierno formation. It was named by Wilson

[2] Both *Placunanomia hannibali* Jordan and Hertlein and *Aequipecten circularis* (Sowerby) were also reported from locality F20 which was tentatively placed in the Gloria formation, but which is of uncertain age, as indicated in footnote 5 of table 7.

TABLE 8.—*Fossils from localities in the Infierno formation (late Pliocene)*

	F10	F12	F14	F16	F21	F24	F25	F26	F28
Dendraster excentricus (Eschscholtz) var	--	--	--	--	--	--	--	--	X
Lytechinus? sp. (fragment)	--	--	--	--	--	--	--	--	X
Meoma ventricosa Lamarck? [1]	--	--	--	--	--	--	--	--	X
Glycymeris sp. indet. (cast)	--	--	--	--	--	--	--	X	--
Anadara sp. indet. (cast)	--	--	--	--	--	--	--	X	--
Ostrea cf. *O. angelica* Rochebrune	--	--	--	--	--	--	--	X	--
aff. *O. cumingiana* Dunker [2]	--	X	--	--	--	X	--	X	--
fischeri Dall	X	--	--	--	--	--	--	--	--
cf. *O. fischeri* Dall	--	--	--	--	--	--	--	--	X
megodon Hanley	--	X	X	--	X	X	--	X	X
vespertina Conrad	--	X	X	--	--	--	--	--	--
Pecten bellus Conrad, n. subsp.[3]	--	--	--	--	--	--	--	--	X
(*Nodipecten*) *subnodosus* Sowerby	--	X	X	--	--	--	--	--	--
"*Pecten*" sp	X	--	--	--	--	--	--	--	--
Aequipecten abietis (Jordan and Hertlein)	X	X	X	--	X	--	--	X	X
callidus (Hertlein)	--	X	--	--	--	--	--	--	--
circularis (Sowerby)	--	X	--	--	--	--	X	--	--
purpuratus (Lamarck)	--	--	--	--	X	--	X	X	--
subdolus (Hertlein)	--	--	--	--	--	X	--	--	--
Patinopecten bakeri aff. *diazi* Durham	--	X	--	--	--	--	--	--	--
marquerensis Durham	X	--	X	--	--	--	--	--	X
cf. *marquerensis* Durham	--	--	--	--	X	--	--	--	--
sp.[4]	--	--	--	--	--	--	--	X	--
sp	--	--	--	X	--	--	--	--	--
Placunanomia hannibali Jordan and Hertlein	--	X	X	--	--	--	X	--	--
Cardita sp. indet. (cast)	--	--	--	--	--	--	--	X	--
Chione (*Lirophora*) sp. indet. (cast)	--	--	--	--	--	--	--	X	--
Corbula sp. indet. (cast)	--	--	--	--	--	--	--	X	--
Panope cf. *P. generosa* Gould (cast)	--	--	--	--	--	--	--	X	--
Turritella gonostoma Valenciennes	--	--	--	--	X	--	--	X	--
aff. *gonostoma* Valenciennes	--	X	--	--	--	--	--	--	--
Crucibulum sp. cf. *spinosum* (Sowerby)	X	--	--	--	--	--	--	--	--
Conus sp. (cast)	--	--	--	--	--	--	--	X	--
Balanus sp	--	X	--	--	--	--	--	--	X

[1] A species of the Atlantic, very similar to *Meoma grandis* Gray, a species of the Pacific.
[2] Much larger and more evenly sculptured than any *Ostrea* in the collections of Recent shells in the U. S. National Museum.
[3] Has 22 instead of 15 to 17 radiating ribs that are proportionately wider and more round-topped. Interspaces of left valves bear a riblet, as in *Pecten bellus*—absent in *P. heimi* Hertlein, *P. hemphilli* Dall, and others.
[4] Very similar to *Patinopecten marquerensis* Durham, but has only 19 to 20 ribs instead of 23 to 25.

(1948, p. 1769) for the town of Santa Rosalía, and the type locality was designated as fossil-collecting locality F9 on the south side of Arroyo de las Palmas.

The Santa Rosalía formation is not widely exposed in the Boleo district. It has been removed over large areas by recent erosion, and where it has been preserved on the mesas it is commonly obscured by a thin capping of terrace gravels; consequently, exposures are confined to a few narrow outcrops here and there just below the tops of the mesas. The principal exposures noted in the district are in the different branches of Arroyo de la Soledad southwest of the Santa Rita fault, on the northwest side of Arroyo del Purgatorio near the Santiago fault, and in a few places in Arroyos Montado and Santa Agueda.

The formation may be more widespread than indicated on the geologic map, but it was mapped only where it seemed to be well identified by fossil evidence or by the unconformable relation to the underlying Infierno formation. The thick unfossiliferous nonmarine conglomerates in the inland area that were mapped as "undifferentiated post-Boleo deposits" (QTu on pl. 1) may include some sediments of Pleistocene age assignable to the Santa Rosalía formation. The formation may also lie not far below the surface over considerable areas that were mapped as terrace and gravel deposits (Qt).

The basal contact of the formation is generally not well exposed, but its unconformable nature may be observed in some places. The Santa Rosalía formation generally overlies the Infierno formation, although on the south side of Arroyo del Infierno and in part of Arroyo de las Palmas it cuts out the Infierno and overlaps the Gloria formation.

The Santa Rosalía formation consists chiefly of calcareous fossiliferous conglomerate, which contains moderately well rounded pebbles in a sandy matrix. The pebbles are composed mainly of rocks from the Comondú volcanics, but some pumice fragments are also present and probably represent the beginning of the volcanic activity that formed the Tres Vírgenes volcanics. Sandy layers are found in the conglomerates and in some localities the formation consists largely of fossiliferous sandstone. The formation has a known thickness of only 5 to 15 meters. The fossiliferous beds were not found farther inland than about 3.5 kilometers from the present shoreline, and they probably give way inland to nonmarine beds.

The Santa Rosalía formation is abundantly fossiliferous. Although Pectens and oysters are abundant as in the older formations, the variety of other types of pelecypods and gastropods is much greater. Table 9 lists the species identified by H. E. Vokes, from three collections made by the writers in the Santa Rosalía formation.

TABLE 9.—*Fossils from localities in the Santa Rosalía formation (Pleistocene)*

	F6	F9[1]	F17
Anadara (Larkinia) multicostata (Sowerby)	--	×	--
Ostrea cumingiana Dunker	×	--	--
cumingiana Dunker or *jacobaea* Rochebrune	--	--	×
fischeri Dall	×	--	--
Aequipecten circularis (Sowerby)[2]	×	--	--
cf. *purpuratus* (Lamarck)	--	--	×
sp	--	×	--
Spondylus cf. *princeps* Broderip	--	--	×
Divaricella eburnea (Reeve)	--	×	--
Americardia biangulatum (Sowerby)	--	×	--
Dosinia (Dosinidia) ponderosa (Gray)	--	--	×
n. sp	--	×	--
Chione fluctifraga (Sowerby)	--	--	×
succincta (Valenciennes)	--	×	--
sp. aff. *kellettii* (Hinds)	--	×	--
Megapitaria squalida (Sowerby) (immature specimen)	--	×	--
aurantiacus (Sowerby), n. subsp	--	×	--
Pitar n. sp	--	×	--
Cerithium uncinatum Gmelin	--	×	--
Crepidula sp. (fragments)	--	×	--
Nassarius sp. (immature specimen)	--	×	--
Parametaria coniformis (Sowerby)	--	×	--
Oliva cf. *venulata* Lamarck	--	×	--
Olivella n. sp?	--	×	--
Terebra variegata Gray	--	×	--
Bullaria sp. (fragments)	--	×	--
Balanus sp	--	×	--
Echinoid fragments	×	--	--

[1] Several microscopic gastropods that have not been studied also were found at this locality.
[2] Specimens show dim remnants of color patterns.

Vokes considers the beds at locality F17 to be definitely of Pleistocene age, on the basis particularly of *Dosinia (Dosinidia) ponderosa* (Gray) and *Chione fluctifraga* (Sowerby), which range from Pleistocene to Recent. A Pleistocene age is also suggested for the beds of locality F9 from the traces of color patterns preserved in some of the specimens, together with the known range of the few forms previously reported, which have been listed by Durham (1950). Vokes considers that the sediments at locality F6 may be of latest Pliocene age or of Pleistocene age, the latter being favored because of dim remnants of color patterns on some of the specimens of *Aequipecten circularis* (Sowerby).

Touwaide (1930, p. 123) mentions the presence of mammoth remains in the youngest conglomerate of the Boleo district. A collection of fossils obtained by Touwaide from his "upper conglomerate," apparently the Santa Rosalía formation of this report, was reexamined at Stanford University by Durham (1950, p. 28), who reports the following:

Chama pellucida Broderip
Ostrea fischeri Dall?
sp. indet.
Gyrineum strongi Jordan
Oliva spicata (Bolten)
Turritella cf. *gonostoma* Valenciennes

Durham notes that *Gyrineum strongi* Jordan has been found thus far only within Pleistocene deposits.

TRES VÍRGENES VOLCANICS (PLEISTOCENE AND RECENT)

The Tres Vírgenes volcanics consist of lava flows and pyroclastic rocks of Pleistocene to Recent age, which cover large areas on the mesas northwest of Santa Rosalía. They were named by Wilson (1948, p. 1769) for the Tres Vírgenes volcanoes, which, together with Cerro de Santa María, were the chief centers of eruption.

The Tres Vírgenes volcanics occupy large areas northwest of Arroyo del Infierno, in the area covered by the geologic map of the Lucifer manganese district, and they have been described in the report on that district (Wilson and Veytia, 1949, p. 199–201.) Southeast of Arroyo del Infierno, only small patches of these volcanic rocks are present. Within the area covered by the geologic map of the Boleo district, only one patch of the Tres Vírgenes volcanics was observed, capping a mesa between two branches of Arroyo del Boleo (pl. 1, coordinates 1000–2400 N., 4500–5500 W.). This patch is exposed on a flattish mesa for a length of 1,400 meters and a width of 300 to 400 meters, and it lies at an altitude of 230 to 250 meters. The thickness of the volcanic rock in this area ranges from 5 to 10 meters, although the thickness in the Lucifer district is as much as 30 to 50 meters in certain buried valleys.

The rock exposed in the locality mentioned in Arroyo del Boleo appears to be a welded tuff. In field appearance it is a firmly compact pumiceous rock containing many inclusions of glassy volcanic material. The rock is gray on fresh exposure but weathers reddish. A thin section was examined by Eduardo Schmitter, who identified the rock as a tuff of questionably andesitic composition. The chief constituents are glass, andesine, and augite, with secondary hematite and zeolites.

A greater variety of volcanic rocks was found in the Lucifer district, where the main constituents are latite flows, pumice, and welded tuff, overlain in places by olivine basalt flows, volcanic breccia, and cinder cones.

The Tres Vírgenes volcanoes, which represent the main centers of eruption, are three well-formed volcanic cones (fig. 23), which are said to have erupted during historic times. An eruption in the year 1746 was recorded by Grewingk (1848, p. 143–144), and another one in 1857 was listed by Russell (1897, p. 190), who states that "since then steam has been emitted, sometimes in large volumes." A leucite-bearing rock from the vicinity of the Tres Vírgenes was described by Chrustschoff (1885), although no rocks of this type have been found by the writers. Some specimens of the volcanic rocks studied by Ritter (1895) were described as porphyritic andesite.

In the area shown on the map of the Boleo district, the Tres Vírgenes volcanics rest on undifferentiated sediments of post-Boleo age, but in the Lucifer district to the northwest, they lie, in part, unconformably on the Pleistocene Santa Rosalía formation, thus indicating that the age is confined to the Pleistocene and Recent. The volcanism may have commenced during the time of deposition of the Santa Rosalía formation, however, as indicated by the presence of pumice fragments in that formation.

Lava flows and cinder cones, probably of the same age as the Tres Vírgenes volcanics, are scattered over the central part of Baja California and are particularly conspicuous in the vicinity of La Purísima, where they were described by Heim (1921). Tortuga Island, a perfectly shaped volcanic cone rising 300 meters above

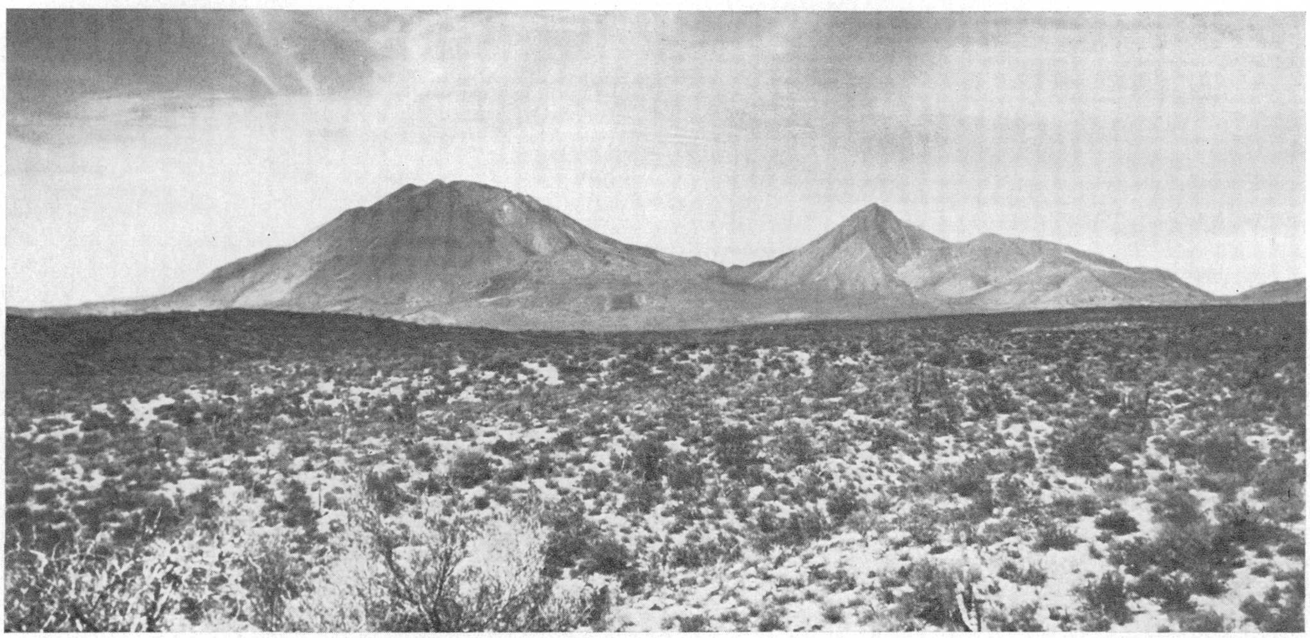

FIGURE 23.—The three volcanic cones of the Tres Vírgenes.

the water level and at least 1,500 meters above the floor of the Gulf of California, 40 kilometers east of Santa Rosalía, may represent the same period of volcanism, as may also some thin basaltic lava flows on the east side of San Marcos Island.

TERRACE AND GRAVEL DEPOSITS (RECENT)

The tops of the mesas and terraces along the sides of the arroyos are blanketed by terrace and gravel deposits of Quaternary age. The thickness of the deposits ranges from only 1 or 2 meters to as much as 20 meters. The gravel is for the most part an unconsolidated deposit of poorly sorted pebbles and boulders, but some of the terraces consist of well-cemented conglomerate. The surface layer of gravel has in places been cemented by caliche, while a meter or so below the surface the material is uncemented. In places this has led to the formation of small overhanging cliffs along the sides of the mesas.

Although the gravel deposits generally form only a thin veneer, they effectively mask the underlying formations and cause the principal gaps in the otherwise good exposures of the region. Several terrace levels may be observed in different parts of the district, but in general two principal levels are found below the mesas, as discussed further in the part on geomorphology.

Most of the terrace and gravel deposits are of nonmarine origin, but along the coast are marine terraces that contain a thin layer of marine shells in a poorly cemented sandy matrix at the base of a gravel layer. Such a shell layer was observed, for example, along the south side of Arroyo del Purgatorio, near its mouth, at altitudes of 10 to 20 meters.

The Tres Vírgenes volcanics are only thinly covered by terrace and gravel deposits, and over broad areas they are not covered at all. This suggests that much of the period of gravel deposition preceded the formation of the Tres Vírgenes volcanics. It probably continued throughout the period of Tres Vírgenes volcanism, however, and was in part later, for in some places a thin gravel layer is intercalated between two flows in the volcanic rocks, and elsewhere the highest flow is overlain by a very thin mantle of gravel.

On the geologic map (pl. 1), all these terrace and gravel deposits have been mapped as a single unit labeled "Qt," although it is realized that they may not all be of precisely the same age, and some of the deposits on the mesas may actually be the nonmarine inland facies of the Santa Rosalía formation.

ALLUVIUM (RECENT)

Alluvium is found in three types of environment in the Boleo district: in the bottom of the arroyos, on beaches along the coast, and in dry lake beds on top of the mesas. The bottoms of the arroyos are covered with sand and gravel, except in certain places where they cross volcanic rocks or gypsum, where they may be barren of alluvium. The alluvium in the arroyos consists of silt, sand, and poorly sorted pebbles and boulders which are subangular to subrounded. Where observed in shafts, the thickness has been found to range from 2 to 10 meters.

The beaches along the coast are entirely gravelly in the vicinity of Santa Rosalía. The material ranges in size from pebbles a few centimeters in diameter to coarse boulders several decimeters across, most of which are subrounded. Sandy beaches occur in the vicinity of San Lucas Cove, 14 kilometers southeast of Santa Rosalía. The beaches are usually fairly narrow, averaging only 30 to 50 meters in width, except at the mouths of the arroyos where deltas have been built out as much as 150 meters (see fig. 5).

A peculiarity of the beach deposits, as well as of the alluvium in the arroyos, is the relative scarcity of quartz, which is due to the extreme paucity of that mineral in the source rocks of the region. The dominant source rocks for the sand and pebbles are the Comondú volcanics, both as outcrops and reworked fragmental material forming the principal constituents of the younger formations. As these source rocks are dominantly andesitic and basaltic, and as the younger tuffaceous rocks are mainly andesitic and latitic in composition, free quartz is nearly absent in them. This scarcity of quartz in the alluvial deposits is characteristic all along this part of the east coast of Baja California, and the lack has been felt when quartzose sands were wanted for making concrete for construction purposes. The sandy beaches, where present, are composed largely of comminuted rock fragments or of shelly material.

Certain poorly drained areas on the tops of the mesas are the sites of dry lake beds in which thin deposits of sandy, silty, and clayey alluvium have accumulated. Drill holes in such a lake bed northwest of the Lucifer manganese mine indicated a thickness for the alluvium of as much as 9.5 meters in one hole and 6.1 meters in another. Water remains in these lake beds for only brief periods after storms.

STRUCTURE

STRUCTURE OF THE COMONDÚ VOLCANICS

The structure of the Comondú volcanics is almost everywhere discordant with that of the younger formations. The Comondú volcanics owe much of their structure to a period of deformation—tilting and faulting—that took place before the Pliocene formations were deposited.

The results of this pre-Pliocene deformation are best exposed near the head of Arroyo del Infierno, where the Comondú volcanics are cut by a series of mainly westward-dipping normal faults with displacements of 50 to 100 meters, producing a series of eastward tilted blocks (see structure section, Wilson, 1948, p. 1771, fig. 4). Some of the faults in Arroyo del Infierno do not affect the overlying Boleo formation, which rests with strong unconformity on the Comondú, thus indicating that the deformation involved was post-Comondú and pre-Boleo—that is, probably late Miocene in age.

Farther southeast in the Boleo district it is more difficult to distinguish the older faults from younger faults that cut the Pliocene beds. There is evidence that some of the major faults which cut both the Comondú volcanics and the Pliocene formations, such as the Juanita and Santa Agueda fault zones, originated in pre-Pliocene time and underwent renewed activity at a later epoch.

In most of the larger exposures of the Comondú in the Boleo district, the volcanic rocks have a moderate northeasterly dip ranging from 5° to 25°, and the dip is nearly horizontal in some places (see structure sections, pl. 3). Near the mouth of Arroyo de Santa Agueda, however, the Comondú volcanics dip as much as 50° to 55° NE. A component of at least 40° to 45° of this dip seems to be due to pre-Pliocene tilting, for the immediately overlying Pliocene beds dip only 10° NE. in this area.

Throughout most of the peninsula of Baja California where the Comondú formation is exposed, the dip is gently westward, as shown for example in sections by Darton (1921, p. 723).[3] Near the Gulf of California, however, the Comondú formation shows moderate to steep dips toward the east, not only in the Boleo and Lucifer districts but also farther south. The eastward-tilted blocks of Comondú volcanics near Santa Rosalía may represent fragmentation along a zone of faulting that bordered the downfaulted gulf to the east and the uplifted westward-tilted block of the main peninsula of Baja California to the west. Further work over a broader area would be necessary to prove this, but it seems the most likely picture based on what is now known of the structural and historical geology of the region.

The economic significance of the pre-Pliocene deformation of the Comondú volcanics is that the faults provided channels along which mineralizing solutions could ascend. That this actually happened is indicated by the presence of veinlets containing manganese and copper minerals along many of these faults.

[3] The Comondú is shown in the west part of Darton's sections as "mesa sandstone," grading eastward into "agglomerate, conglomerate, and igneous."

STRUCTURAL FEATURES OF THE PLIOCENE AND PLEISTOCENE FORMATIONS

STRUCTURES PRODUCED BY DEPOSITION ON SUBMERGED TOPOGRAPHY

The most remarkable structural features of the Pliocene and Pleistocene formations in the Santa Rosalía region resulted from deposition on an irregular surface. When the Boleo formation was deposited, erosion of the surface of the Comondú volcanics had reached only late youth or early maturity, leaving a surface of high relief that was partly buried by the sea. The resulting irregular surface of deposition consisted of submarine hills and ridges bordered by submerged valleys, interrupted here and there by islands that remained above sea level. The lowest sediments tended to conform to the submerged topography, so that initial anticlinal structures were formed over buried hills and initial synclinal structures were formed over submerged valleys. The sediments rose up steeply against the islands and mainland before wedging out against the bedrock surface. The exceptional character of these structural features has been described in another report by Wilson (1948) in which he showed that the dips in the Boleo formation lie within the limits of the subaqueous angle of repose for the type of beds concerned.

The basal marine limestone of the Boleo formation apparently adhered like plaster to the steep surfaces, and in places to small cliffs, of the Comondú volcanics, which in the immediate vicinity of the shoreline at the time of submergence had a relief of as much as 450 meters. The limestone shows the highest dip of any of the beds of the Boleo formation, commonly 30°. Its maximum structural relief is 200 meters. The clastic sediments had a tendency to fill in the basins and wedge out over the hills. Their dip locally reaches 30° but commonly ranges from 3° to 20°, decreasing in successively higher beds. The maximum structural relief of conglomerate no. 3 is 150 meters, and of conglomerate no. 1 it is 70 meters.

The steep dip of the beds of the Boleo formation is due to the high relief of the surface on which they were deposited rather than to later deformation. This is indicated in many places where the basal contact of the sediments with the Comondú volcanics is well exposed, and the volcanic rocks themselves have not been deformed in a way compatible with the structure of the overlying beds. The dip of the sediments shows no relation to the dip of the volcanic rocks, which may dip more steeply, less steeply, or in the opposite direction. For example, figure 24 shows the top of a buried hill where flat-lying limestone rests upon more steeply dipping volcanic rocks. In contrast, figure 25 shows the side of a buried hill where steeply dipping limestone overlies gently dipping volcanic rocks. Other examples

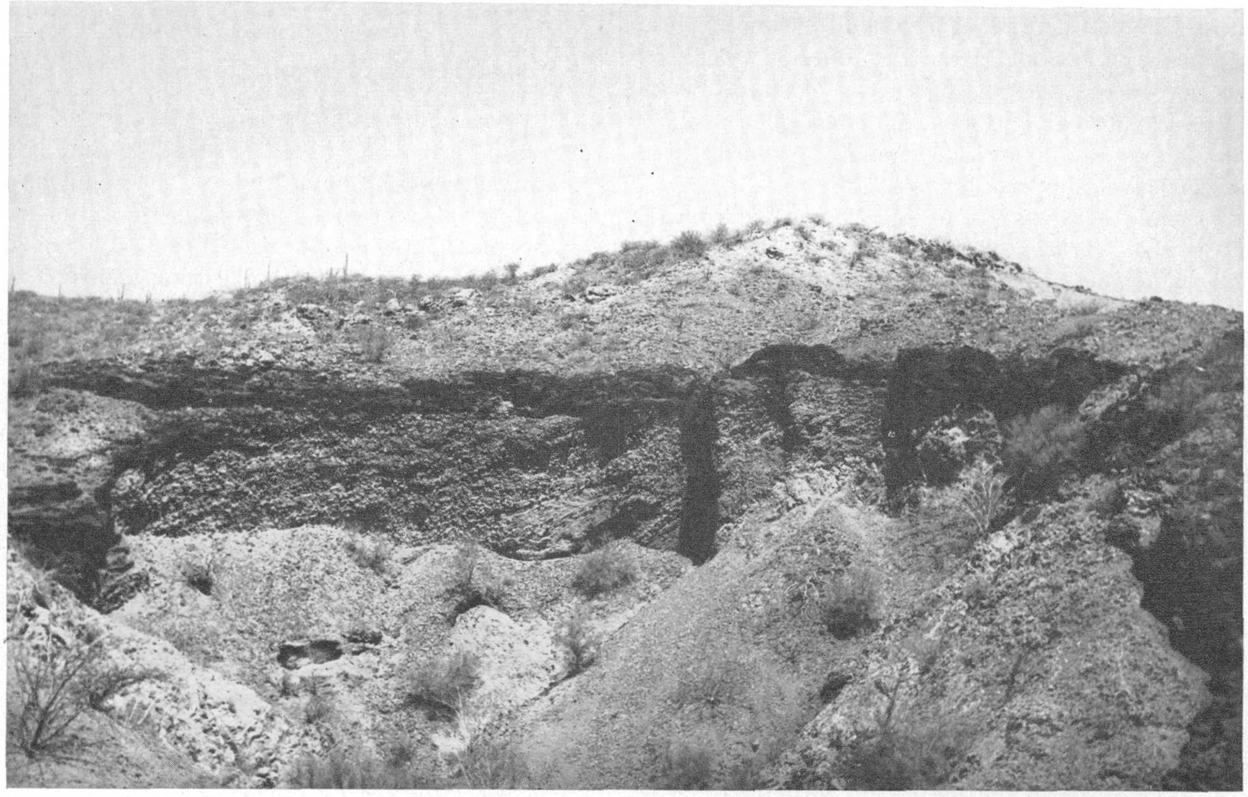

FIGURE 24.—Flat-lying limestone of the Boleo formation overlying gently dipping Comondú volcanics on top a buried hill, Cañada de la Gloria, near El 160 mine. The limestone is the dark layer.

FIGURE 25.—Steeply dipping limestone of the Boleo formation overlying gently dipping Comondú volcanics on the side of a buried hill near Texcoco mine, looking west. The two formations dip in opposite directions here.

of steep initial dips of the Boleo formation are shown in figure 13.

It is thought that differential compaction accentuated the initial dips and helped to transmit the surface configuration of the Comondú volcanics to even the highest beds of the post-Boleo formations.

STRUCTURES PRODUCED BY DEFORMATION

The effects of regional deformation, consisting of tilting, faulting, and gentle warping, have been superimposed upon the initial structures of the Pliocene and Pleistocene formations, as well as upon the older structures of the Comondú volcanics. Where the later tilting has been in the same direction as the initial dip, it is difficult to separate the exact degree of each; but where the tilting has been at right angles to the initial dip, the degree of each may generally be distinguished. On the sheet of structure sections (pl. 3), those sections that run parallel to the coastline (*A–A′* and *B–B′*) illustrate structures due mainly to buried topography, while the other sections, which run at right angles to the coast, illustrate the effects of tilting and faulting superimposed on initial structures.

In general, the beds are tilted northeastward or eastward toward the coast. In areas away from the steep initial structures, the average dip of the beds ranges from 3° to 10°. The dips are locally steepened by drag along faults. The gulfward dip is partly compensated for by faults which repeatedly step up the downdip side of the beds. Thus, for example, in section *E–E′* of plate 3, if a line were drawn from ore bed no. 3 of the Boleo formation at its elevation in the Curuglú mine to its elevation near the Santiago shaft 4 kilometers to the northeast, the average dip of the line would be only 3°, while its actual dip in the various segments between the faults is commonly 5° to 10°. If the faults could be eliminated, and the segments of the bed fitted together, the drop in elevation of the bed toward the gulf would be 450 meters; actually it is only 200 meters.

Unconformities indicate that tilting and uplift have taken place as many as four times since the beginning of deposition of the Boleo formation, or at the close of deposition of the lower Pliocene, the middle Pliocene, the upper Pliocene, and the Pleistocene beds. The uplift brought about by the most recent tilting has raised the Pleistocene deposits to a level of 250 meters above sea level at a distance of 4 kilometers inland from the shore in the Boleo district. Farther northwest, in the vicinity of Arroyo de las Palmas, the Pleistocene deposits have been uplifted to 340 meters above sea level. The uplift dies out to the southeast in the San Bruno plain, where almost no uplift of the Pleistocene beds has taken place. Eastward tilting or downwarping in Arroyo de Santa Agueda has carried ore bed no. 1 of the Boleo formation down to 205 meters below sea level near the San Luciano mine, while it lies as much as 170 meters above sea level in Arroyo de la Providencia.

The Pliocene beds are offset by many faults, which, with very few exceptions, are normal faults (figs. 26 and 27). Most of them parallel the shoreline and the regional strike of the beds, having an average strike of N. 10°–45° W., although a very few small faults strike northeast, or in the direction of the dip of the beds. The faults have an average dip of 65° to 70°, ranging from as little as 48° to nearly vertical. Those of greatest displacement, with only one or two exceptions, dip southwest, which is also the direction of downthrow, but a large number of faults of small displacement dip and are downthrown to the northeast.

The maximum vertical displacement known is about 250 meters along the Santa Agueda fault, near the mouth of Arroyo de Santa Agueda. This fault has brought the Comondú volcanics, on the northeast side, in contact with the Infierno formation on the southwest side, below which is the whole thickness of the Gloria and Boleo formations. The San Antonio fault has a vertical displacement of as much as 80 meters, as shown by the offset of ore bed no. 3 of the Boleo formation in the mine workings of the San Antonio mine on the northeast side of the fault, and the Santa Rita mine on the southwest side. Four other faults, the Curuglú, Juanita, Santiago, and Calera faults, have maximum displacements of 60 meters, but the rest have offsets that are less than this and many of them have moved 10 meters or less.

The faults have known lengths of as much as 3 kilometers, as the Curuglú fault, but most of them have lengths of only a few hundred meters. Some of them are remarkably short in comparison with their maximum displacement, and the displacement commonly dies out rapidly at either end. The mine workings provide particularly good evidence of the places where individual faults end—a feature that may be difficult to determine from surface exposures alone.

Table 10 lists the essential data, such as strike, dip, displacement, and length, for 12 of the principal faults of the Boleo district, which have been indicated by name on the geologic map (pl. 1). Many other less important faults are shown on the geologic map, structure sections (pl. 3), and structure contour map (pl. 4).

One of the most interesting features of the fault systems is their echelon pattern. The individual faults commonly die out within short distances along their length, and the displacement is taken up by other faults arranged in echelon. In most of these systems,

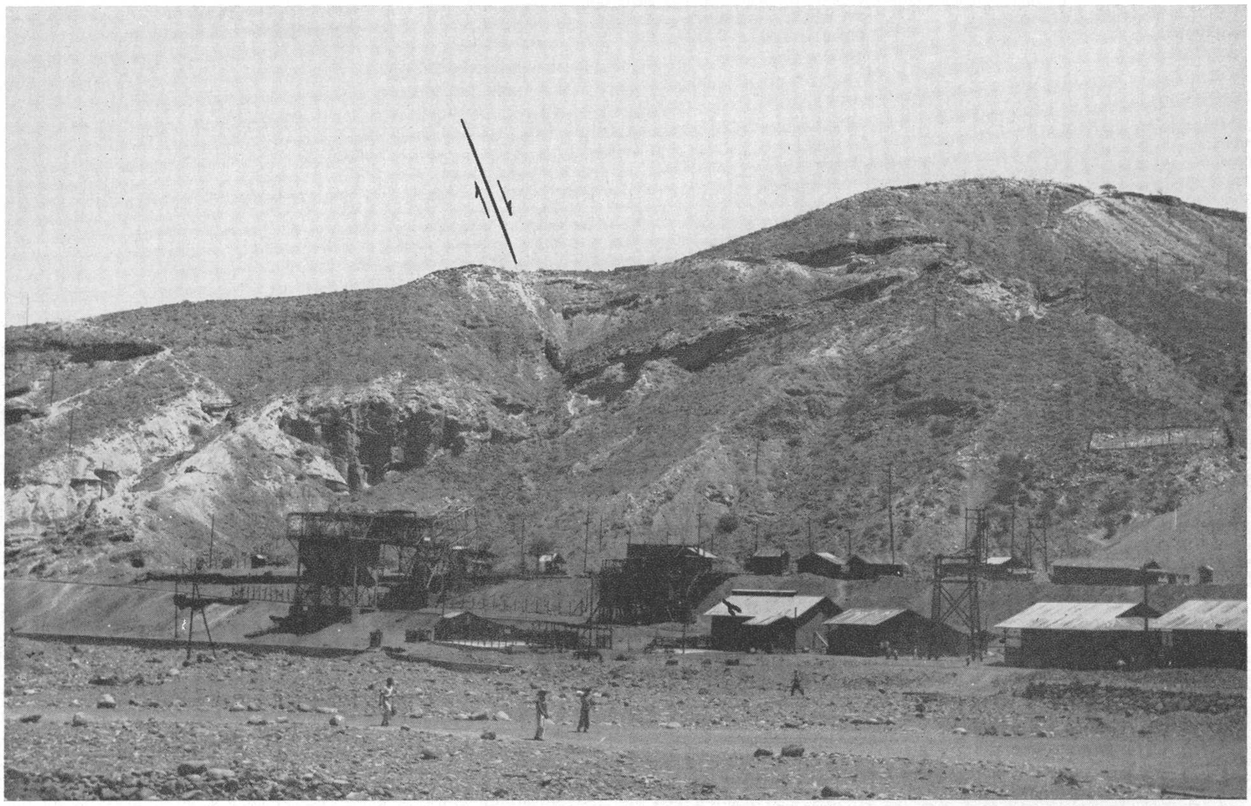

FIGURE 26.—Ranchería fault on southeast side of Arroyo de la Providencia, looking toward Ranchería mine. Beds on southwest (right) side of fault displaced relatively downward 35 meters.

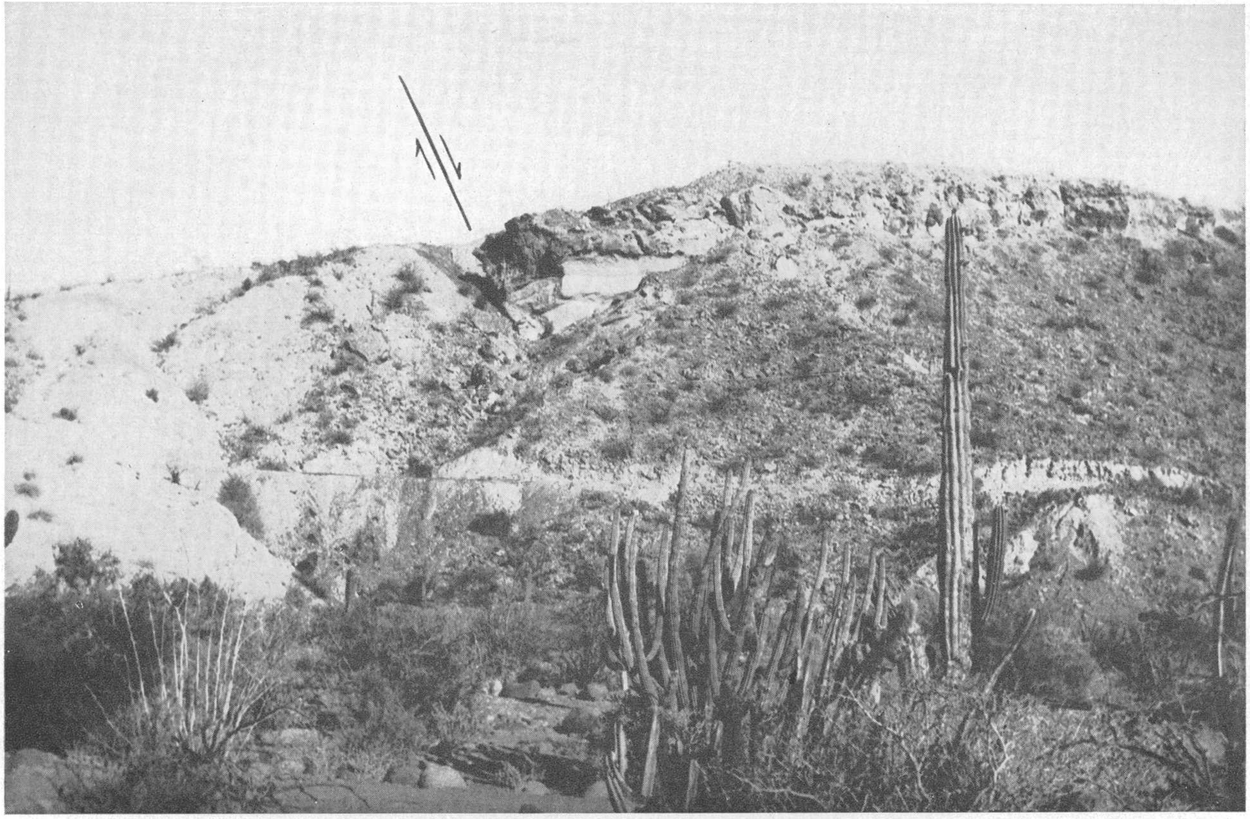

FIGURE 27.—Small fault on southeast side of Arroyo del Purgatorio. Southwest (right) side of fault has dropped relatively downward, bringing cliff-forming sandstone of Gloria formation against tuff :Boleo formation.

individual faults that terminate to the northwest are replaced by others whose position is shifted slightly to the southwest. The in echelon systems might thus be described as left handed, for the shift in position of the members is toward the left as one looks along a particular fault.

One of the best examples of such an echelon system is that formed by the San Antonio, Santiago, and San Guillermo faults. The San Antonio fault, traceable for 2,500 meters, has a displacement of 80 meters in the San Antonio mine in Arroyo de la Soledad. The mine workings indicate that this displacement decreases rapidly southeastward and dies out altogether within a distance of 1 kilometer from the point of maximum displacement. The offset is then taken up farther southeast by the Santiago fault, situated parallel to the San Antonio fault but 200 meters to the northeast. The Santiago fault has a maximum displacement of 60 meters near the Santiago shaft, but the displacement disappears within a distance of 400 meters to the southeast. It is replaced by the San Guillermo fault, situated 150 meters northeast of the Santiago fault, and the San Guillermo is replaced in turn by another fault situated slightly farther northeast in Arroyo de la Providencia. The Santa Agueda fault zone is the same type of echelon system. The Ranchería and Calera faults, farther northwest, probably represent the continuation of the Santa Agueda fault zone.

The major period of faulting, aside from the pre-Pliocene faulting of the Comondú volcanics that was previously described, probably took place toward the close of the Pliocene, for the Pleistocene deposits seem not to be affected by the larger faults. Some faulting continued or was renewed in Pleistocene or even Recent time, however, for on the mesas northwest of Arroyo del Infierno the Tres Vírgenes volcanics were observed to be offset by several very small faults.

TABLE 10.—*Principal faults in the Boleo copper district*

Name of fault	Location	Coordinates of extremities, in meters, from San Francisco shaft		Known length, in meters	Strike	Dip	Downthrown side	Maximum displacement, in meters	Remarks
		N.-S.	E.-W.						
Curuglú	Cañada de Curuglú, and branches of Arroyo del Boleo.	250 N. 3000 N.	3050 W. 4400 W.	3,050	N. 25° W.	53°–73° SW.	SW.	60	Separates Curuglú and Amelia mines. Fault plane well exposed.
Amelia	Head of Arroyo de la Soledad at Amelia shaft.	100 N. 2100 N.	2600 W. 3400 W.	2,150	N. 20° W.	75°–82° SW.	SW.	40	Displaces ore bed no. 3 (Boleo formation) as much as 40 meters in Amelia mine.
Texcoco	Arroyo de la Soledad, and branch of Arroyo del Boleo near Texcoco mine.	1000 N. 2500 N.	2500 W. 2850 W.	1,550	N. 15° W.	70°±SW.	SW.	15	Repeats outcrop of ore bed no. 3 (Boleo formation) at north end of fault.
La Ley	Arroyo del Purgatorio, near La Ley shaft.	1100 S. 200 N.	1700 W. 2050 W.	1,350	N. 10° W. (N. 15° E.–N. 25° W.)	65° NE.	NE.	30	Is principal fault having northeast side downthrown.
Juanita	Southwest side of Cerro de Juanita.	2850 S. 550 S.	750 E. 850 W.	2,800	N. 35° W. (N. 20°–50° W.)	61°–65° SW.	SW.	60±	Echelon system of faults. Forms southwest border of large mass of Comondú volcanics.
San Antonio	Arroyo de la Soledad, between San Antonio and Santa Rita mines.	1950 N. 3750 N.	300 W. 2050 W.	2,500	N. 45° W. (N. 40°–55° W.)	70° SW.	SW.	80	Separates San Antonio and Santa Rita mines. Displacement decreases rapidly at southeast end.
Santiago	Cañada de Santiago, on northwest side of Arroyo del Purgatorio.	1250 N. 1750 N.	650 E. 200 E.	700	N. 40° W.	70°±SW.	SW.	60	Arranged in echelon with San Antonio and San Guillermo faults. Displacement decreases rapidly toward both ends.
San Guillermo	Arroyo del Purgatorio and Cañada de San Guillermo, near San Guillermo shaft.	350 N. 1250 N.	1450 E. 750 E.	1,150	N. 40° W.	78° SW.	SW.	15	Part of echelon system. Displacement at northwest end taken up by many small faults.
Montado	Arroyo del Montado, at northeast end of Montado mine.	2050 S. 1050 S.	3450 E. 2550 E.	1,400	N. 45° W. (N. 25°–55° W.)	70° SW.	SW.	30	Displacement of Gloria and Infierno formations well exposed in arroyo walls; of ore bed no. 1 (Boleo formation) in mine workings.
Calera	Southeast side Arroyo del Purgatorio, near Cerro de la Calera.	1350 N. 1850 N.	2000 E. 1500 E.	750	N. 45° W.	70°±SW.	SW.	60	Possible northwest continuation of Santa Agueda and Ranchería echelon system.
Ranchería	Southeast side Arroyo de la Providencia, at northeast edge of Ranchería mine.	400 N. 650 N.	3150 E. 2850 E.	400+	N. 35° W.	60° SW.	SW.	35	Forms northeast border of Ranchería mine. Northwest continuation of Santa Agueda echelon zone.
Santa Agueda	Near mouths of Arroyo de Santa Agueda and Arroyo del Montado.	2750 S. 700 S.	5600 E. 4000 E.	2,600	N. 42° W.	48°–75° SW.	SW.	250±	Fault of greatest displacement in district. Echelon system. Displacement taken up to northwest by several branching faults.

STRUCTURE CONTOUR MAP

A structure contour map (pl. 4) of the Boleo district, which covers the same area as the geologic map (pl. 1), shows structure contours on two beds in the Boleo formation, faults, and exposures of Comondú volcanics, as well as data on the depth to the surface of the Comondú volcanics in shafts, drill holes, and mine workings. In the mined areas where certain beds are honeycombed with underground workings, it was possible to show the structure contours in considerable detail.

The map is based largely on the detailed mine maps of the Boleo company, supplemented by information obtained from surface outcrops. The contours were drawn first on sheets having a scale of 1:2,000, and then reduced to a compilation scale of 1:10,000. The ore beds of the Boleo formation that have been most extensively explored were chosen for the horizons to be contoured. Thus the contours are drawn at the base of ore bed no. 3 in the northwest part of the district, and at the base of ore bed no. 1, which is 115 meters stratigraphically higher, in the southeast part of the district. The contours are not projected very far beyond the limits of the mine workings except where drill holes or other reliable data provide adequate control.

Aside from bringing out the fault pattern and regional tilting more clearly than does the geologic map, the structure contour map shows in considerable detail some of the initial structures in the Pliocene beds. In the northwest area particularly, between the Boleo and San Agustín shafts, the eastward plunging anticlinal structures, formed over submerged hills, and the intervening synclinal structures, formed in submerged valleys, are strikingly revealed. The curving and steepening of the structure against the northeast side of Cerro de Juanita is also noteworthy.

GEOMORPHOLOGY

GENERAL FEATURES

The rounded volcanic hills preserved from pre-Boleo time project above a general mesa level that forms one of the dominant topographic features of the region. The mesas are in turn dissected by a number of deep, steep-walled arroyos which run northeastward at right angles to the coast. Between the bottoms of the arroyos and the tops of the mesas are commonly two distinct terrace levels.

The present erosional surface is still in the stage of youth in the arid cycle of erosion. This is indicated by the broad, flattish, undrained or poorly drained areas that remain on the mesas between the arroyos. When erosion of the interarroyo areas has proceeded to the stage when the mesas have largely disappeared, the stage of maturity will have been reached, and maximum relief will have been attained.

MESAS

A great contrast exists between the topographic surface and type of erosion on the mesa tops and in the arroyos. The mesa tops are flattish or gently rolling surfaces, surmounted by the rounded hills of Comondú volcanics. The mesas contain many broad undrained depressions, which become the site of short-lived shallow lakes after storms. Some of the drainage lines on the mesas are meandering and irregular, but others are long and straight, seeming to follow the lines of recent faults. The contact between the mesas and the heads of the arroyos is generally sharp and is commonly bordered by a steep cliff, which forms the locus of a waterfall during the infrequent times when water is present. The arroyos are gradually eating back into the mesas by headward erosion, but on the mesa tops, beyond the limits of the arroyos, erosion appears at present to be practically at a standstill.

The width of the uneroded mesas still preserved between the arroyos ranges in general from 500 to 1,000 meters in the inland part of the mapped area of the Boleo district. Farther northwest, the uneroded mesa between Arroyo del Infierno and Arroyo de las Palmas attains a width of 6 kilometers. Near the coast the mesas have been completely dissected, leaving steep, narrow ridges between the arroyos, and in part of that area a typical "badlands" topography has been developed.

The elevation of the mesas increases in general from southeast to northwest. Southeast of Arroyo de Santa Agueda, for example, the mesa level is 90 to 170 meters above sea level; between Arroyos Santa Agueda and Infierno it is 190 to 290 meters above sea level; and northwest of Arroyo del Infierno the mesa attains elevations of 320 to 430 meters above sea level.

The mesas also increase in elevation inland, but in an irregular fashion, and in some parts of the area mapped (pl. 1) the highest parts of the mesa are intermediate between the coast and the inland border of the map. The differences in level probably represent in part an irregular initial surface of erosion and deposition, but in part they are due to later differential uplift and warping. The mesa level cuts obliquely across different formations, and consequently the surface was not determined by the structure of any one formation.

The mesa surface is regarded as mainly of nonmarine origin, and as representing an uplifted coastal plain along which debris was accumulated from the Sierra de Santa Lucía. To the northeast, however, it probably merged into a marine plain, just as does the San Bruno plain that lies near sea level southeast of the Boleo district.

ARROYOS

The sides of the arroyos present two contrasting types of surfaces, erosional and depositional. The erosional surfaces are generally steep and intricately dissected, consisting of narrow-crested ridges separated by steep ravines. A profile of the arroyo walls drawn along the ridges is generally slightly convex upward, and along the ravines slightly concave upward, but an average profile along the slopes is not markedly either concave or convex. It is very irregular in detail and commonly consists of a series of cliffs and benches determined by the differential resistance of the rock layers exposed in the slope. Conglomerate, sandstone, gypsum, and volcanic rocks are the principal cliff-forming layers in the region, and the tuffs and siltstones form more gentle slopes.

The depositional surfaces are more gentle, broad, smooth surfaces, distinctly concave upward in profile, which terminate downward in one or two gently sloping terrace levels. They are covered by a layer of gravel that buries the underlying rocks, and instead of the cliff-and-bench topography of the erosional surfaces, these depositional surfaces seem to extend indiscriminately across beds of differential resistance without much visible effect on the form of the surface. A depositional terrace may terminate in a terrace level part way down the slope, giving way below to an erosional surface, but in other places a depositional surface extends over the entire side of the arroyo.

An example of the contrast in the two types of surfaces is illustrated in figure 28, which shows topographic contours and profiles of part of the southeast side of Arroyo de la Providencia. Areas of rock exposures and areas covered by gravel are distinguished on this map. A depositional surface extends in part of this area from the mesa down to a terrace level at 140 meters above sea level, or 60 meters above the arroyo level. The figure shows the strong contrast between the shape of the contours and of the profile on this depositional surface and on the erosional surfaces that surround it on either side.

The bottoms of the arroyos are flat and wide and are generally covered by alluvium, except where they cross particularly resistant rocks which form solid outcrops. The flat arroyo bottoms range most commonly from 100 to 300 meters in width, exceptionally attaining a width of 500 meters. They are constricted where they cross

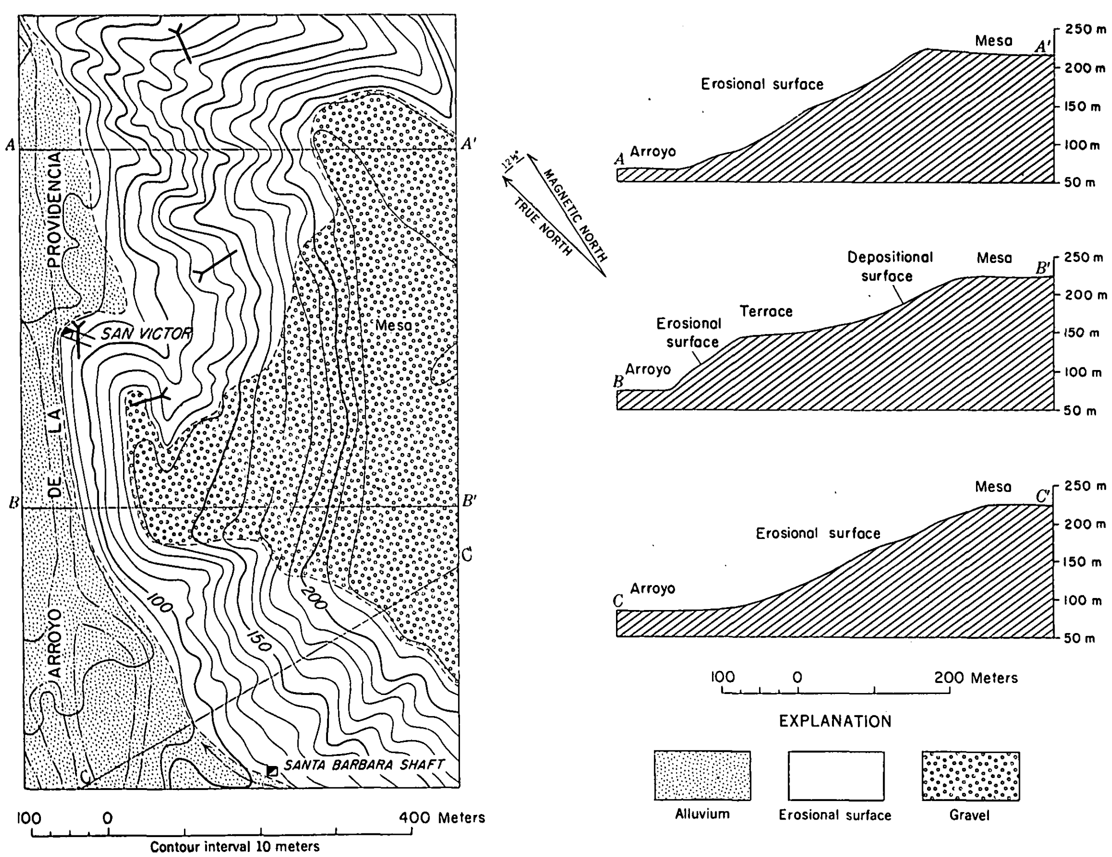

FIGURE 28.—Topographic map and profiles showing contrast between erosional surfaces and depositional surfaces on sides of arroyos. (Southeast side of Arroyo de la Providencia, near Santa Bárbara shaft).

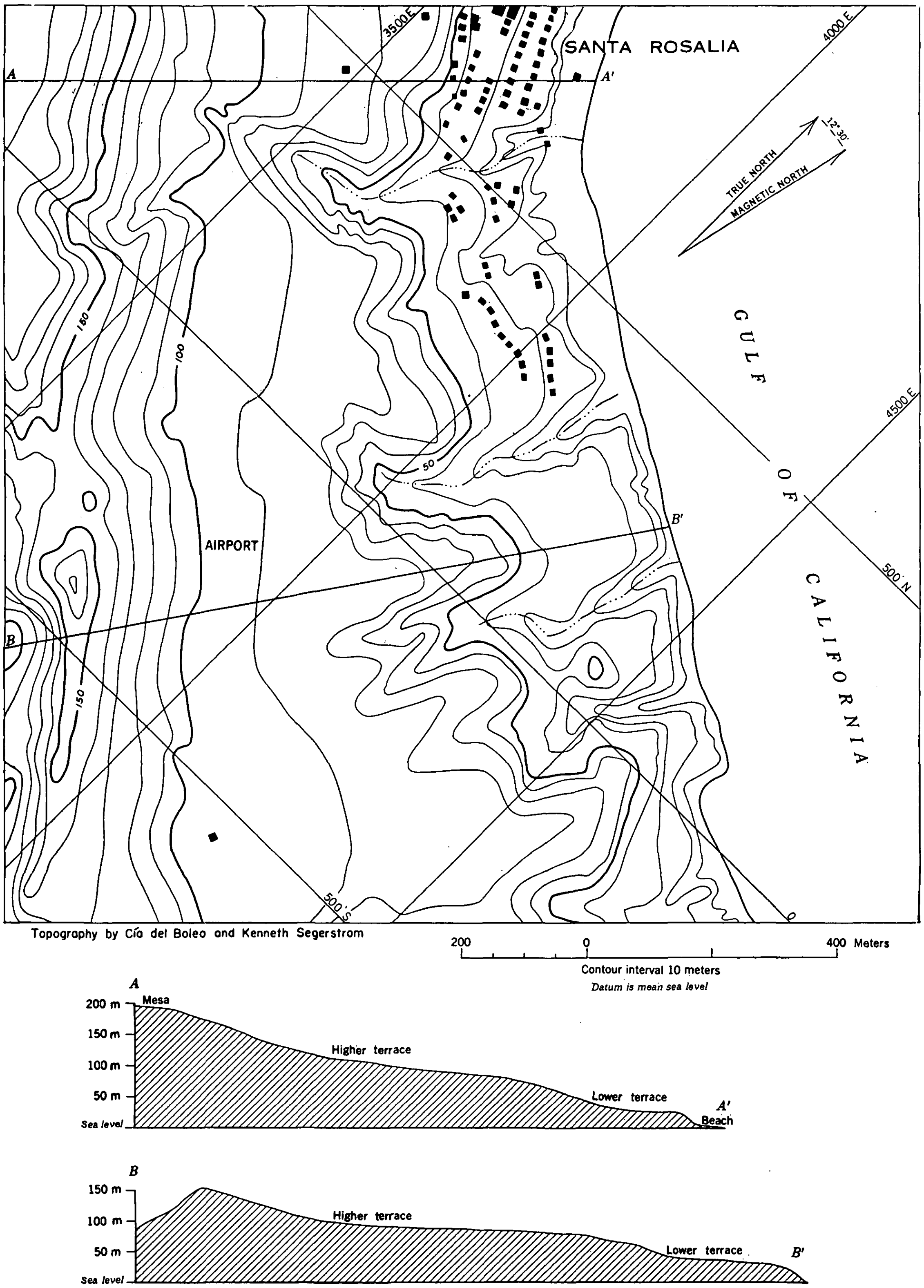

FIGURE 29.—Topographic map and profiles showing marine terraces along the coast southeast of Santa Rosalía.

areas of Comondú volcanics or of gypsum. A profile across the arroyos is neither V-shaped nor U-shaped, but rather is like a flat-bottomed wash basin. The smaller side canyons, however, are V-shaped and are still being actively entrenched. The arroyos have an average grade of about 2 percent within the area covered by the topographic map (pl. 1), ranging from 0.9 percent in Arroyo de Santa Agueda, the longest arroyo, to 3.3 percent in Arroyo de la Soledad, one of the shortest arroyos.

TERRACE LEVELS

Two principal intermediate terrace levels are sufficiently widespread and persistent to provide evidence for temporary base levels of erosion between successive uplifts. The mesa level itself might be considered as the oldest terrace level. These terrace levels are found both along the coast, where they are partly of marine origin as shown by marine fossils, and along the sides of the arroyos, where they are of terrestrial origin.

The term "terrace level" is used only in a relative sense, for the terraces do not lie at a uniform elevation above sea level, and indeed it is not to be supposed that the terraces along the arroyos ever were at the same elevation. It is reasonable to suppose, however, that the marine terraces were once topographic levels from which any present variations may be attributed to later tilting or warping, which also modified the nonmarine terraces. In some places, particularly in Arroyo del Infierno, a number of minor terrace levels appear between the two principal levels mentioned above, but such levels may form during a normal cycle of erosion and do not necessarily indicate significant epochs of stability between successive uplifts.

The marine terraces are well exposed adjacent to the town of Santa Rosalía, as shown in figure 29. The lower terrace, used as a site for scattered buildings and houses, lies between 20 and 40 meters above sea level. The higher terrace, on which the airport is situated, lies between 80 and 100 meters above sea level. The mesa level begins at 180 to 190 meters above sea level at that place.

The nonmarine terraces are found along almost all the arroyos of the region, but they are perhaps most extensively developed in Arroyo de Santa Agueda, as shown in figure 30. The lower terrace, the site for the town of San Luciano, lies at 50 to 70 meters above sea level (10 to 30 meters above the arroyo level), while the higher terrace lies at 130 to 150 meters above sea level (90 to 110 meters above the arroyo level). The mesa level begins at 190 meters above sea level, or 150 meters above the arroyo level. Many more examples of terraces are shown on the topographic map (pl. 1).

DRAINAGE PATTERNS

The principal arroyos have a subparallel drainage pattern trending approximately at right angles to the coast. Their courses show very little relation in detail to the structure of the beds. It is believed that these courses were developed on a coastal plain represented by the present mesa tops, and that uplift caused them to be entrenched into the underlying beds. At first, they were simple consequent streams, but now they may be considered as superimposed. Many of the smaller side canyons, however, have their courses determined by local structural features, particularly faults, although in detail the bottom of a canyon commonly diverges slightly from the fault line.

The influence of faults in determining drainage patterns is also notable on the tops of the mesas, where some of the drainage has a linear pattern, believed to be determined by recent faults. These fault lines show up more clearly on aerial photographs than they do from the ground, but some of the lines have been traced to the sides of the arroyos where they prove to be faults of small displacement. In some places drainage in opposite directions on a mesa top follows the same geometric line, a pattern which is considered good evidence that the drainage was localized by some structural feature, presumably a fault or major joint.

In large areas where the Comondú volcanics are exposed to erosion, as in the headwaters of Arroyo del Boleo, a dendritic drainage pattern has developed.

PALEOGEOLOGY

Paleogeology, following Levorsen (1933), is the science of the geology of ancient time. A paleogeologic map shows the distribution of geologic formations on an ancient surface; it is a map showing the formations that would be exposed if certain overlying layers were stripped off. The study of paleogeology and of paleogeologic maps has become increasingly emphasized in recent years, both because of its scientific interest in the interpretation of the earth's history and because of its economic importance. The economic applications have been utilized particularly in the search for petroleum, but important applications can also be made to the distribution of certain types of ore deposits, as exemplified in the Boleo district.

In post-Comondú and pre-Boleo time the surface was completely composed of Comondú volcanics, with the single exception of a small exposure of quartz monzonite in Arroyo de la Palmas, which projected up through the volcanic rocks. This exposure was buried by the Boleo formation and was not again exposed until the cutting of the arroyo in Recent time. A paleogeologic map of pre-Boleo time would be prac-

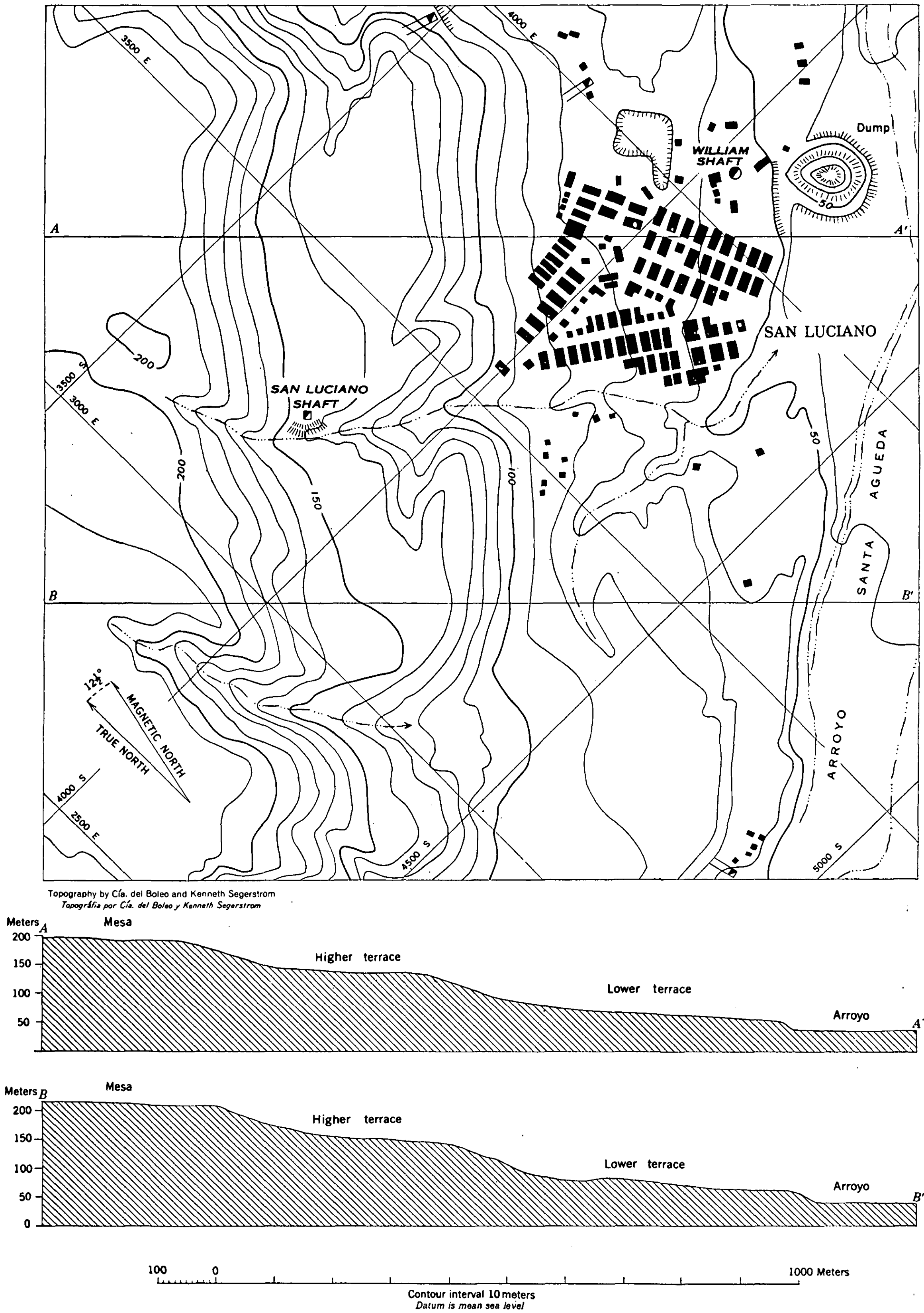

FIGURE 30.—Topographic map and profiles showing nonmarine terraces along the northwest side of Arroyo de Santa Agueda, near San Luciano.

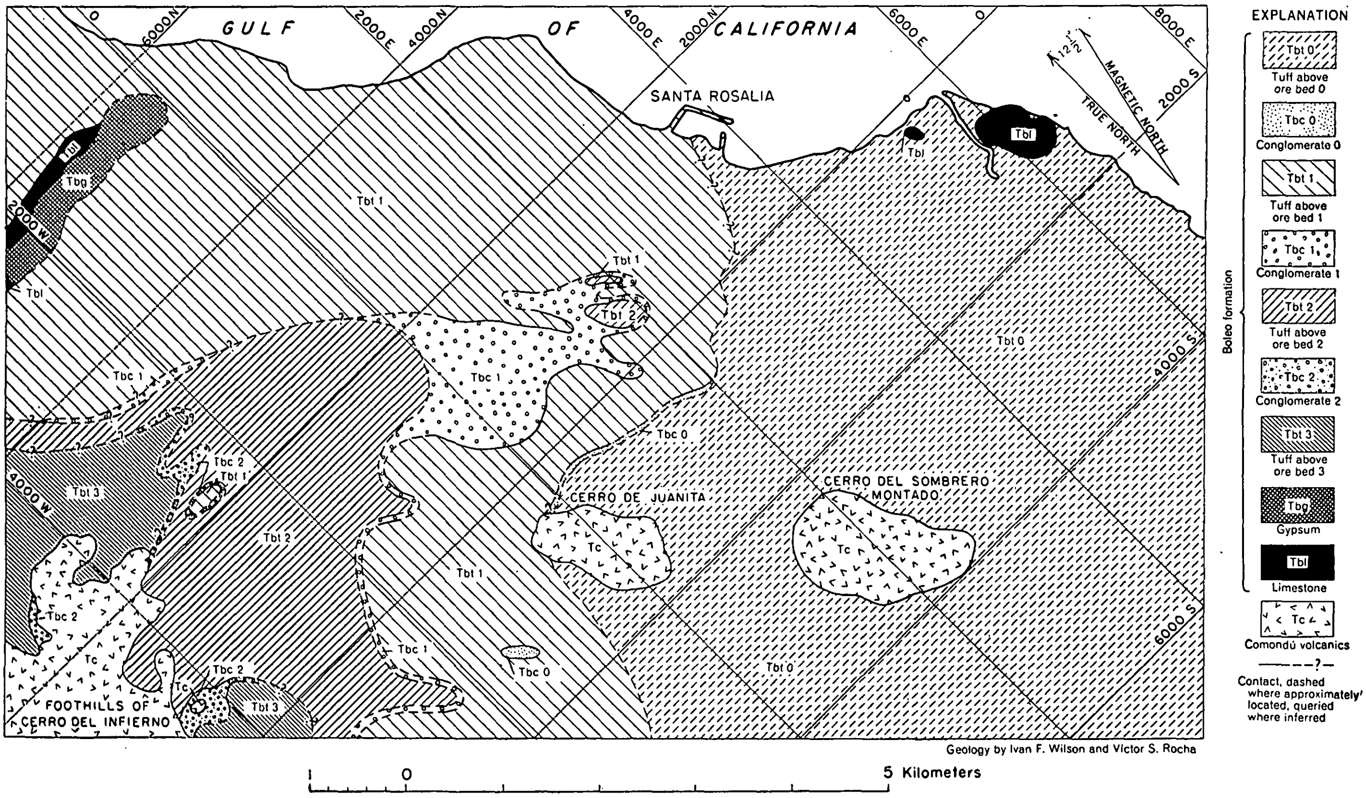

FIGURE 31.—Paleogeologic map of the Boleo copper district at the end of early Pliocene (post-Boleo and pre-Gloria) time.

tically uniform, therefore, unless it should be possible to differentiate the lithologic units of the Comondú volcanics, but not enough data are available to do this.

A geologic map of the area during post-Boleo and pre-Gloria time would show a more varied aspect, and this period has been chosen for making the paleogeologic map given in figure 31. This is a geologic map of the surface that was preserved at the close of the erosional interval following deposition of the Boleo formation; it attempts to portray the distribution of the different beds that would be exposed if the Gloria formation were stripped away, and all effects of more recent erosion eliminated.

This paleogeologic map is naturally much less accurate than the surface geologic map (pl. 1), owing to the relatively meager data on which it is based. The outline of the areas of Comondú volcanics that projected above the surface of the Boleo formation is fairly well known. The other contacts were determined from studies of shafts and drill holes, as well as outcrops along the sides of the arroyos where in many places the different members of the Boleo formation terminate against the Gloria formation. Thus, a series of scattered points serve as control, but the contacts between these control points are largely conjectural.

Figure 31 shows the Comondú volcanics and nine lithologic units of the Boleo formation. The tuff above ore bed no. 0 was the unit exposed over most of the southeast part of the district, but to the northwest erosion had exposed conglomerates no. 1 and no. 2 and even the tuff above ore bed no. 3 in part of the area. Basal limestone and gypsum overlying buried hills were also exposed in pre-Gloria time. The greatest amount of pre-Gloria erosion was in the northwest part of the district, where the topography had been more irregular and uplift greater.

Paleogeologic maps of later periods would show little of interest. Erosion in post-Gloria and pre-Infierno time never proceeded sufficiently to remove completely the Gloria formation, so far as known. A paleogeologic map of that time would show only broad exposures of the Gloria formation, interrupted by the same projecting masses of Comondú volcanics, slightly reduced in area, that were exposed in pre-Gloria time. A paleogeologic map of the post-Infierno and pre-Santa Rosalía surface would show vast exposures of the Infierno formation, and, in local areas, the Gloria formation, interrupted by the same islands of Comondú volcanics, whose exposures would be still further restricted, though very slightly, over those of pre-Infierno time.

GEOLOGIC HISTORY

PRE-MIOCENE HISTORY

Very little is known about the pre-Miocene geologic history and paleogeography of the Boleo district. The region was invaded by a plutonic batholith, possibly during Cretaceous time or perhaps earlier. The batholith was exposed at the surface after a long period of erosion.

The west side of the peninsula of Baja California was covered by shallow seas during parts of Jurassic, Cretaceous, Paleocene, Eocene, Oligocene (?), and early and middle Miocene time, but no deposits of those ages are known on the east side of the peninsula in the vicinity of Santa Rosalía. It is not known whether such deposits once covered the area and were later eroded, or whether the area stood as a highland during the periods mentioned. Evidence on this point could perhaps be found in a study of the facies changes in the sediments on the west side of the peninsula, but the published data seem too meager to permit drawing any conclusions.

MIOCENE HISTORY

Extensive volcanism began in the Santa Rosalía area in middle or late Miocene time. Andesitic and basaltic flows, breccias, and tuffs (the Comondú volcanics) accumulated over broad areas. The source of the volcanic eruptions was somewhere in the present Gulf of California, perhaps near the western margin, so that the gulf either did not exist at that time or at least had nothing like its present extent. At intervals between the volcanic eruptions, clastic material, consisting of gravel near the gulf and sand farther westward, was deposited under terrestrial conditions, probably on flood plains. The geographic conditions at that time were the reverse of those today, for highlands must have occupied the present gulf, and the high sierra of the peninsula must have been a low plain.

The deposition of the volcanic rocks and intercalated sediments was ended near the close of the Miocene epoch by deformation—the strongest of any known to have affected the district during the Cenozoic era. Locally, near the present site of the gulf, the volcanic rocks were tilted eastward and sliced into blocks by normal faults. This was accompanied to the east by profound sinking of the former highlands in the gulf, and to the west by uplift and westward tilting. Both the sinking and the uplift were most likely brought about by faulting, the tilted blocks of the Boleo district representing a fragmented area on the margin between the two major blocks.

The deformed Comondú volcanics were subjected to erosion and carved into a dendritic pattern of canyons with intervening hills and ridges. This erosion had proceeded only to a stage of late youth or early maturity, leaving a surface of strong relief, when the region was invaded by the sea, which encroached westward against the uplifted mass of Comondú volcanics.

PLIOCENE HISTORY

The first invasion by the sea was during early Pliocene time. Aside from local accumulations of detrital material around the steeper hills, the basal deposit was an impure limestone. Evidently the submergence of the region was rapid enough for a thin chemical deposit to be precipitated before much clastic material was supplied by erosion. Over local areas thick gypsum beds were deposited not long after the beginning of sedimentation.

This chemical deposition was followed by a long period of clastic sedimentation and by a new period of volcanism in which tuffaceous material of latitic to andesitic composition was supplied by volcanic eruptions. The source of the sediments changed from the east to the west. The clastic sedimentation was of deltaic type and nonmarine gravels inland gave way to sandy deposits gulfward. The shoreline gradually receded as the deposits accumulated. This process of normal clastic deposition was interrupted at least five times by violent volcanic eruptions which spread volcanic ash, dust, and lapilli over broad areas, producing at first layers of pure tuff, and later, because of erosion of the ash-covered land, layers of reworked tuff.

Toward the end of deposition of the Boleo formation, copper and manganese minerals were deposited from solutions in certain of the tuffaceous layers. As will be explained later, the solutions are believed to have arisen from the same underlying igneous sources that produced the volcanism represented by the tuffs of the Boleo formation.

As a result of the irregular topography on the surface of the underlying Comondú volcanics, the sediments of the Boleo formation were deposited with strong initial dips. Initial anticlinal structures were formed over submerged hills and initial synclinal structures in submerged valleys. The shoreline at the time of deposition probably resembled the modern shoreline at Concepción Bay, which is also carved in the Comondú volcanics. It was characterized by irregular bays and headlands, and offshore by islands and submarine hills. Toward the close of deposition the basins had been partly filled and the sediments wedged out against the buried hills, but a moderate relief of the uppermost sedimentary layer still existed at the end of deposition. The structural relief of the higher beds was probably increased somewhat by differential compaction over the buried topography.

Early Pliocene deposition was ended by slight uplift, tilting, and erosion over most of the district, although part of the gulfward area may have remained below sea level. The higher parts of the initial structures of the Boleo formation were planed off, and erosion proceeded through conglomerate no. 2 in certain areas.

This erosional interval was followed in the middle Pliocene by another marine invasion, resulting in the deposition of the sediments of the Gloria formation. A thin gravel was deposited locally, followed by a deposit of sand that wedged out along the shore and thickened and graded into silt and clay gulfward. Mollusks and echinoids abounded on some of the sandy beaches, but were less prevalent in the deeper water where silt and clay were being deposited. The sand gave way inland to gravel, which was probably deposited mainly under nonmarine conditions. The gravel encroached farther gulfward as time went on, indicating a recession of the shoreline. Volcanism had apparently ceased for the time being.

Deposition of the Gloria formation was ended at least locally by slight tilting, uplift, and erosion, which were not so strong as those that affected the Boleo formation.

Deposition of the Infierno formation in the late Pliocene followed the same general pattern as that of the Gloria formation. A deposit of sand was laid down which thickened gulfward and wedged out inland. Shellfish lived in abundance on the sandy shores. The shoreline in general did not extend quite as far inland as did that of the middle Pliocene seas. The sand gave way inland to gravel which encroached farther gulfward above the sand as deposition continued.

Deposition of the Infierno formation was ended by further uplift and tilting, and considerable faulting probably took place at the same time. This was followed by erosion, which removed the Infierno formation over certain areas before deposition of the succeeding Pleistocene beds.

PLEISTOCENE AND RECENT HISTORY

Another brief period of marine deposition, that of the Santa Rosalía formation, took place during the Pleistocene. Thin deposits of sand and gravel accumulated near the shore, and nonmarine gravels were probably deposited farther inland. The sea probably extended no farther inland than did that of the late Pliocene.

Deposition of the Santa Rosalía formation was ended by uplift, tilting, continued or renewed faulting, and erosion. The Pleistocene marine beds were raised to as much as 340 meters above sea level near Arroyo del Infierno, and 250 meters above sea level in the central part of the Boleo district, but essentially no uplift occurred farther southeast at the San Bruno plain. The uplift seems to have taken place in three principal stages. During and after the uplifts, erosion of the high sierra to the west resulted in the spreading of gravel deposits over the mesas and terraces.

The final phase of volcanism began in the Pleistocene but continued into historic times. Lava flows, pumice, and welded tuff deposits, first of latitic and later of basaltic composition, accumulated around the Tres Vírgenes volcanoes and Cerro de Santa María, and cinder cones were formed near Arroyo de las Palmas. The volcanic activity was partly contemporaneous with the formation of the gravel and terrace deposits mentioned above.

The most recent event has been erosion, which began with the uplift mentioned in a previous paragraph and has continued to the present. The erosion, noteworthy for its intermittent character, has been confined to the cutting of arroyos and has not proceeded beyond the stage of youth. Contemporaneously with the erosion, alluvium has been deposited locally in the arroyos, in dry lake beds on the mesas, and on the beaches. The most extensive Recent deposition has been of delta deposits, mainly gravels, built at the mouth of the arroyos.

COPPER DEPOSITS

GENERAL FEATURES

The Boleo copper deposits are thin, gently dipping, tabular bodies confined to certain relatively impervious clayey tuff beds of the Boleo formation. There are five principal ore beds, numbered 0 to 4 from top to bottom, each underlain by a conglomerate or its gulfward equivalent of tuffaceous sandstone. Most of the production has come from ore bed no. 3 in the northwest part of the district and ore bed no. 1 in the southeast part.

The mined areas, excluding some outlying deposits, are 11 kilometers long in a northwest direction and ½ to 3 kilometers wide in a northeast direction. The best deposits are clustered around the gulfward side of the projecting hills of the volcanic basement, and the ore beds decrease in grade and eventually become barren gulfward.

The primary ore is a soft dark-colored clayey tuff with a high moisture content. The main primary ore mineral is finely disseminated chalcocite, with subordinate chalcopyrite, bornite, covellite, and native copper. In the oxidized zone, extending down to about 25 meters above sea level, is a great variety of oxides, carbonates, silicates, and oxychlorides, including some rare mineral species. The main gangue mineral is montmorillonite, along with manganese and iron oxides and smaller quantities of gypsum, calcite, chalcedony, and jasper. Minor metals occurring in notable quantities are zinc, cobalt, and lead.

GEOLOGIC NATURE OF THE COPPER ORE BEDS

The host rock for the copper ore of the Boleo district is a highly altered clayey tuff, through which the copper minerals are finely disseminated. The original tuff contained fragments of crystals, glass, and volcanic rocks, but the constituents have been almost entirely altered to a mass of clay minerals, composed chiefly of montmorillonite. A characteristic of the ore beds is their high content of moisture, which commonly ranges from 25 to 30 percent.

Microscopic examination indicates that the primary copper minerals, mainly chalcocite, have replaced the tuff, and that veinlets of chalcocite cut across the layers of the rock. As pointed out by Locke (1935, p. 410; see also Touwaide, 1930, p. 142), the chalcocite crystallized after the softening of the rock; that is, after formation of the clay, for the crystals grew freely in a manner demanding a soft matrix.

The primary ore at Boleo is deceptive in appearance. Apart from occasional crystals or grains of chalcopyrite and the bluish-black color imparted by faintly visible chalcocite, there is little to suggest a metallic ore. The general appearance of a sample of sulfide ore freshly obtained from the mines is that of a dark-colored, compact, slightly moist clay. Upon exposure to the atmosphere the clay desiccates and becomes exceedingly friable, and within a few days it has generally disintegrated into small fragments. The ore shows the swelling properties of bentonitic clays when placed in water.

The general color of the sulfide ore is sooty black to dark gray. This gives way in the lower-grade hanging-wall material to medium or light gray, brownish gray, and reddish brown. A mottled appearance commonly results from the presence of fragments or bands of different colors. In zones that have been slightly oxidized, the normal gray may be mixed with green and blue, as well as yellowish and reddish tints imparted by iron oxides. Where chalcocite is sufficiently abundant it may impart a dusky-blue to the ore. The darkness of the color is used by the miners as a rough guide to the quality of the ore.

The grain size of the ore material ranges from clayey to silty and rarely reaches the size of fine sand. Some of the clayey ore has a distinctly soapy feel and is called *jaboncillo* by the miners. Banded and brecciated structures are common, although some of the best ore is a massive clay without any visible structure or texture. Chalcocite is sometimes distributed in the form of bands. Relict brecciated structures, revealing angular outlines 0.5 to 2 centimeters in diameter of original volcanic fragments in the clayey tuff, are common. Within the fragments an original porphyritic texture is sometimes preserved. The brecciated structure is more prevalent and coarser grained in the lower-grade hanging-wall part of the ore bed. Where laminated structures are present, the individual laminae are generally not continuous but are contorted and fragmented into separated wisps.

The ore beds are highly sheared and possess many slickensides having irregular curved surfaces and striae. The clayey ore forms the locus of many small faults and fractures that roughly parallel the bedding planes. The beds seem to be under a state of strong internal pressure, which causes pieces to slab off readily in newly exposed mine workings.

Carbonized plant remains have been noted in the ore beds, and in places specimens of petrified wood have been found which are partially replaced by chalcocite. In run-of-mine samples of ore analyzed by the U. S. Bureau of Mines, however, the proportion of organic carbon was found to be surprisingly low, averaging only 0.2 percent in five samples.

The boundaries of the minable ore layers are commonly sharp at the bottom but less so at the top. The footwall of the ore bed is generally a well-cemented conglomerate or tuffaceous sandstone, referred to by the miners as the *muro* (wall). In many places, however, the ore is separated from that type of rock by a thin layer of unmineralized, finely laminated sandy or silty tuff 10 to 50 centimeters thick, which is called the *falso piso* (false footwall). The upper contact of the ore is commonly gradational, and in many places a considerable thickness of tuff containing a small proportion of copper lies above the minable ore. During the process of mining, a part of the hanging wall is usually shoveled out and used as fill in the stopes. In many of the old mines this fill, or *retaque*, has later been found to be high enough in grade to be mined, and much of the present production of the *poquiteros* is coming from such material in the old stopes.

Some typical sections of the primary ore beds, representing each of the six mines that were being operated in the sulfide zone in 1949, are given in table 11.

TABLE 11.—*Sections of ore beds in the sulfide zone of six mines*

Thickness (centimeters)	Copper content (percent) [1]	Section (from top to bottom) [2]
San Luciano mine, ore bed no. 1; −135-m level; 4065 S., 4020 E. [3]		
35	0.06	Upper material of hanging wall. Brownish gray. Fine-grained relict brecciated structure. Texture silty; slightly coarser than next lower unit.
50	3.97	Lower material of hanging wall. Medium gray. Fine-grained, relict brecciated structure; fragments 1 to 3 mm in diameter. Partly banded; bands irregular and broken. Texture more silty and less clayey than main ore bed.
40	8.97	Main ore. Grayish-black to black matrix, with medium dark-gray fragments and some greenish patches. Relict brecciated structure; angular fragments 1 cm in diameter. Mostly clay; in part finely banded. Slickensided.
45	2.95	Footwall material. Brownish gray to grayish black. Shows faint irregular streaks or bands, otherwise massive. Faint relict brecciated structure in places. Mostly clay.

See footnotes at end of table.

TABLE 11.—*Sections of ore beds in the sulfide zone of six mines*—Continued

Thickness (centimeters)	Copper content (percent)[1]	Section (from top to bottom)[2]
		Rancheria mine, ore bed no. 1; −22-m level; 403 N., 2970 E.
40	0.16	Upper material of hanging wall. Medium gray, with brownish-gray fragments. Relict brecciated structure; fragments mostly less than 0.5 cm in diameter. Slightly banded.
60	.24	Lower material of hanging wall. Light gray to medium gray, with a tinge of brownish gray in brecciated part. Finely laminated clay with relict brecciated structure; fragments 0.5 cm in diameter or less.
40	5.57	Upper part of ore. Medium gray to dark gray. Relict brecciated structure; fragments generally 0.5 cm in diameter or less. Irregular banding in part. Texture clayey.
25	17.6	Lower part of ore. Black, with a slight dusky blue tinge. Chalcocite and chalcopyrite in minute crystals, visible to unaided eye. Massive clay; no relict structures visible. Heavy. This was the richest specimen of sulfide ore found in the mines.
		El Cuarenta mine, ore bed no. 1; 43-m level; 214 N., 2578 E.
40	0.13	Upper material of hanging wall. Medium gray. Relict brecciated structure, with some laminated wisps, and dark clay fragments. Texture mainly silty.
80	1.09	Lower material of hanging wall. Very light gray. Relict brecciated structure, with fragments of darker clay 2 to 3 mm in diameter; also brecciated laminated wisps. Texture mainly silty.
35	9.55	Main ore. Mottled black and green. Massive clay; no relict brecciated structure. Black part is clayey to silty, faintly laminated, black to dark gray, with a few patches of lighter gray. Green part is massive clay; appears to contain some oxidized copper minerals; also limonitic in part.
		San Guillermo mine, ore bed no. 3; 15-m level; 49 N., 1498 E.
60	3.24	Hanging wall material. Light gray, with dark-gray and reddish streaks. Laminated silty clay with relict brecciated structure; laminae are partly brecciated.
65	4.72	Upper part of ore. Dark gray or brownish gray, with reddish fragments. Relict brecciated structure; fragments as much as 1 cm in diameter. Partly laminated; laminae are brecciated. Texture mostly clayey. Many slickensides.
50	7.47	Lower part of ore. Black. Mostly a dense clay, with a few irregular elongated areas of light-gray material having a finely laminated and brecciated structure. A few reddish clayey areas. Many slickensides; soapy feel.
35	.13	Footwall material (*falso piso*). Mottled colors—limonitic yellow, hematitic red, greenish, brownish gray. Laminated clay with relict brecciated structure.
		La China mine, ore bed no. 3; 38-m level; 346 S., 1425 E.
65	1.37	Hanging wall material. Mottled color; mostly reddish brown to brownish gray, in part dark gray. Relict brecciated structure; fragments as much as 2 cm in diameter. Texture silty to clayey.
40	6.25	Main ore. Dark gray, with some reddish fragments. Some relict brecciated structure with fragments as much as 0.5 cm in diameter. Texture clayey to fine silty. Many slickensides with irregular curved surfaces and striae.
40	4.05	Footwall material. Highly mottled colors; dark gray matrix, with fragments of very light gray, limonitic yellow, and reddish brown. Relict brecciated structure; fragments 0.5 to 2 cm in diameter. Texture clayey to silty.
		San Victor mine, ore bed no. 3; 0-m level; 857 S., 1552 E.
75	3.02	Hanging-wall material. Light brownish gray, with reddish-brown and a few greenish fragments. Relict brecciated structure; fragments as much as 1 cm in diameter. Texture of matrix silty; some fragments are clayey.
70	12.7	Upper part of ore. Black. Massive clay, in part silty. No relict structure visible. Slickensided.
60	3.62	Lower part of ore. Dark gray to nearly black. Texture clayey and silty, with a few elongated, slightly laminated fragments 1 cm thick and 4 cm long, of light-gray silty material. These fragments contrast strongly with the rest of the rock.

[1] Copper analyses by U. S. Bureau of Mines. Dry basis.
[2] Sections measured and described by Ivan F. Wilson.
[3] Levels are in meters above or below sea level. Coordinates are in meters from San Francisco shaft.

The ore minerals have been rather thoroughly oxidized down to the level of the water table, which was originally about 25 meters above sea level in the northwest part of the district and 7 meters above sea level in the southeast part. No sharp dividing line separates the oxidized and sulfide zones, however, and much of the ore is a mixture of the two types of minerals. In some of the mines near the water table, notably in part of the Providencia group of mines, the ore bed consists of a thin layer of sulfide ore at the base, overlain by a thicker zone of oxidized ore. In the deepest mine in the district, the San Luciano, which extends to 185 meters below sea level, the ore is mainly of the sulfide type but contains a few oxidized minerals as thin films along fractures in the rock.

In the oxidized zone the copper minerals are commonly irregularly distributed in the form of bands, lenses, or nodules. Prominent nodules, or *boleos*, of carbonate and oxide minerals led to the discovery of and provided the name for the Boleo district.[4] The oxidized ore is generally bluish or greenish because of the copper carbonates and silicates, but reddish and black colors caused by ferruginous and manganiferous layers are also common. In order to give an idea of the oxidized ore beds in the older and richer mines which are now inaccessible, sketches of some typical ore faces in those mines as given by Saladin (1892, pl. 2, fig. 1) are reproduced in figure 32.

The specific gravity of the ore ranges from 2.1 to 2.5, according to six determinations made by the U. S. Bureau of Mines of samples collected by the senior author. The Boleo company has found that the specific gravity of the ore in place, for the purpose of making calculations of tonnages, ranges from 2.0 to 2.1 for different ore beds. The temperature of fusion of the ore has been determined as 1050° C.

STRATIGRAPHIC AND AREAL DISTRIBUTION OF THE ORE BEDS

The ore beds are found at several different horizons in the Boleo formation, each underlain by conglomerate or tuffaceous sandstone and overlain by a tuffaceous sequence that grades upward from clayey tuff into sandy tuff (figs. 33 and 34). The five principal ore beds have been numbered 0 to 4 from top to bottom. In addition to the numbered ore beds, an ore bed called the Sin Nombre, occurring a short distance below ore bed no. 1 and locally coalescing with it, is known only in part of the Montado mine; and another ore bed called the Falsa Tercera, which lies a short distance above and locally joins ore bed no. 3, is known only

[4] The most common definition of the Spanish term *boleo* is bowling green, but in mining terminology, at least in Mexico, the word is also used for nodule or concretion.

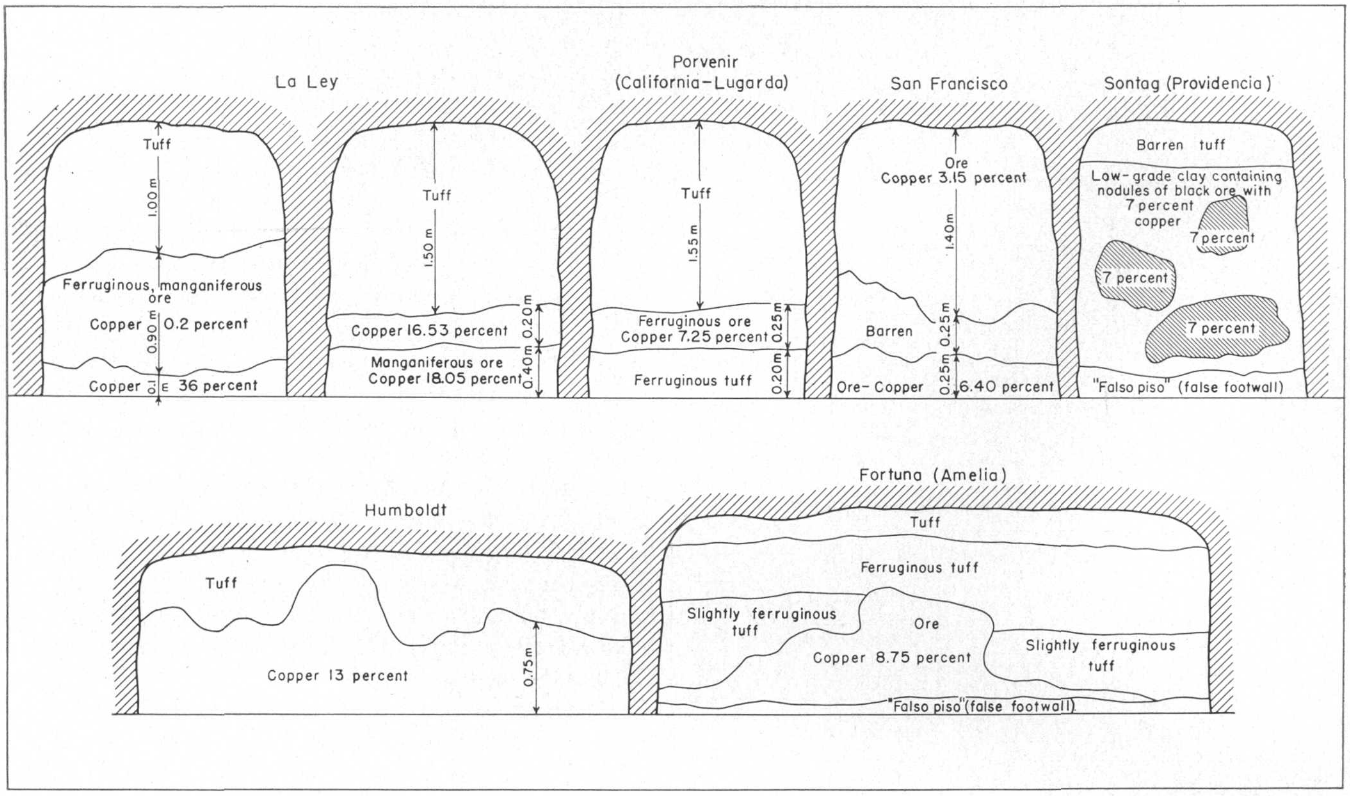

FIGURE 32.—Sketches showing distribution of ore in the working faces of some old mines in the oxidized zone of ore bed no. 3 (after Saladin, 1892, pl. 2, fig. 1).

FIGURE 33.—Ore bed no. 3 on the northwest side of Arroyo del Boleo near the old Boleo shaft, now caved. Outcrops of ore have been mined in open cuts. The ore bed rests on conglomerate, which forms cliffs to right.

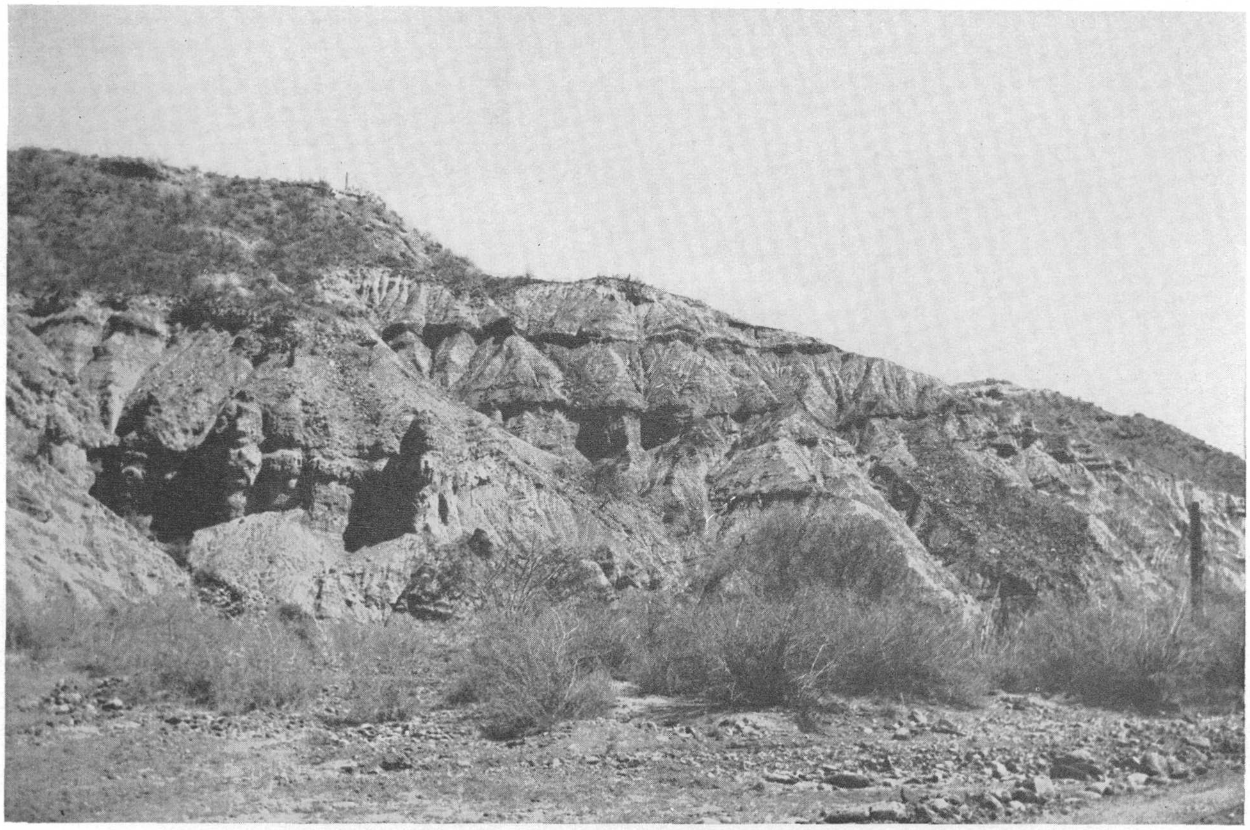

FIGURE 34.—Manganiferous and ferruginous beds on the southeast side of Arroyo del Boleo near the old Buena Suerte mine. Ore beds are the darker colored layers enclosed in lighter colored tuff. These beds are too low in grade to be minable.

in the vicinity of the Santa Rita mine. At some places other unnumbered ore beds, usually of poor quality, occur at intermediate horizons in the tuffaceous beds.

The outcrops of the principal ore beds, indicated by number wherever possible, are shown on the geologic map (pl. 1), and their subsurface position is given in the structure sections (pl. 3). The subsurface position in plan view of the principal ore beds mined—no. 3 in the northwest part of the district and no. 1 in the southeast part—is indicated on the structure contour map (pl. 4). The distribution of the productive areas of the different ore beds is shown on the general mine map (pl. 9). Data on the ore beds cut in the shafts and drill holes are given in the columnar sections (pls. 5–8). Data on the stratigraphic intervals between the ore beds have been given in the description of the Boleo formation and illustrated in figures 9 and 18.

The ore beds are not of uniform extent, and as pointed out in the description of stratigraphy in this report, the distribution of any particular bed depends mainly on the unconformities both above and below the Boleo formation, as well as recent erosion. Ore bed no. 4 occurs only locally in the northwest part of the area, and ore bed no. 3 is confined to the area extending northwest from Arroyo de la Providencia. Ore bed no. 2 is the most widespread, although in part of the area it disappears over irregularities of the basement and in a few places it had been removed from the top of the Boleo formation before deposition of the Gloria formation. This erosion also has removed ore bed no. 1 over wider areas and has removed ore bed no. 0 from the entire area northwest of Arroyo del Purgatorio.

The average stratigraphic section of the Boleo formation in the northwest part of the district consists of ore beds nos. 1, 2, and 3, with ore bed no. 4 present only locally, while in the southeast part of the district the section consists of ore beds nos. 0, 1, and 2. The relationship of the section in the northwest part of the district to that in the southeast part is shown in structure sections *A–A′* and *B–B′* of plate 3.

Aside from differences in the areal distribution of the ore beds, variations in the mineralization have been such that the different ore beds are productive in different areas. With a few exceptions, only one bed is minable in a given area.

By far the most important ore bed is no. 3, which yielded 83.3 percent of the total production recorded for individual ore beds through 1947. Nearly all the important mines in the northwest part of the district, extending northwestward from Arroyo de la Providencia across Arroyos Purgatorio and Soledad to Arroyo del Boleo, are in this ore bed, and they form, in general, a

TABLE 12.—*Averages of determinations of thickness and grade of ore in the Boleo copper district, calculated for individual mines and ore beds*

Name of mine and no. of ore bed	Average thickness of ore (centimeters)			Average grade of ore indicated by assays (percent of copper)			Average grade of ore, deducting 25 percent from assays as a dilution factor[1] (percent of copper)			Number of determinations of thickness and grade		
	Stoped areas	Unstoped areas	All areas	Stoped areas	Unstoped areas	All areas	Stoped areas	Unstoped areas	All areas	Stoped areas	Unstoped areas	All areas
Averages for individual mines												
San Luciano (ore bed no. 1)	77	68	76	6. 1	5. 2	6. 0	4. 6	3. 9	4. 5	2, 060	241	2, 301
Santa Agueda shaft (ore bed no. 1)	----	58	58	-----	3. 3	3. 3	-----	2. 5	2. 5	-----	99	99
Montado (ore bed no. 1)	74	58	67	6. 3	4. 7	5. 6	4. 7	3. 5	4. 2	617	481	1, 098
Ranchería (ore bed no. 1)	73	66	71	6. 6	4. 6	5. 9	4. 9	3. 5	4. 4	2, 341	1, 137	3, 478
Ranchería (ore bed no. 2)	----	63	63	-----	1. 3	1. 3	-----	1. 0	1. 0	-----	14	14
Purgatorio (ore bed no. 3)	87	58	76	6. 3	4. 3	5. 5	4. 7	3. 2	4. 1	1, 099	659	1, 758
Santa Rita-San Antonio (ore bed no. 3)	87	70	82	6. 1	5. 0	5. 8	4. 6	3. 8	4. 3	1, 801	738	2, 539
Infierno (ore bed no. 3)	66	52	56	6. 8	5. 8	6. 1	5. 1	4. 3	4. 6	105	257	362
Providencia (ore bed no. 3)	----	64	64	-----	2. 8	2. 8	-----	2. 1	2. 1	-----	39	39
San Guillermo low-grade area (ore bed no. 3)	----	69	69	-----	3. 3	3. 3	-----	2. 5	2. 5	-----	32	32
San Alejandro shaft (ore bed no. 4)	----	61	61	-----	4. 1	4. 1	-----	3. 1	3. 1	-----	13	13
Averages for individual ore beds												
Ore bed no. 1	75	64	72	6. 3	4. 7	5. 9	4. 7	3. 5	4. 4	5, 018	1, 958	6, 976
Ore bed no. 2 [2]	----	63	63	-----	1. 3	1. 3	-----	1. 0	1. 0	-----	14	14
Ore bed no. 3	86	63	78	6. 2	4. 8	5. 7	4. 6	3. 6	4. 3	3, 005	1, 725	4, 730
Ore bed no. 4 [2]	----	61	61	-----	4. 1	4. 1	-----	3. 1	3. 1	-----	13	13
Averages for all mines and ore beds												
All mines and ore beds	79	64	74	6. 3	4. 7	5. 8	4. 7	3. 5	4. 3	8, 023	3, 710	11, 733

[1] It has been found from experience that the grade of ore as sampled in the mines is approximately 25 percent higher than the grade of ore as shipped to the smelter because of the admixture of waste during the mining operations.

[2] Averages for ore beds no. 2 and no. 4 are not representative for these beds as a whole, because of the small number of samples available.

single large intercommunicated area of mine workings.

Ore bed no. 1, situated 115 meters stratigraphically above no. 3, is the second most important producer, having yielded 16.6 percent of the production classified by individual ore beds through 1947. This bed is productive only in the southeast part of the area, where ore bed no. 3 is absent. It has been mined in continuous workings extending from Arroyo de la Providencia southward across Arroyo del Montado to Arroyo de Santa Agueda. Both ore beds no. 3 and no. 1 have been mined in Arroyo de la Providencia, but the mined area of ore bed no. 3 is farther inland than that of ore bed no. 1.

Ore bed no. 2 is widely distributed but generally thin and has been mined only in a few small areas. The principal area is in a narrow belt along the gulfward side of Cerro de Juanita, between Arroyos Providencia and Purgatorio. Most of this area covers a part of the mined area of ore bed no. 3 and constitutes the principal exception to the statement that, in general, only one ore bed is productive in a particular area. The recorded production from ore bed no. 2 is less than 0.1 percent of the total production of the district, but much of the production from this ore bed has not been separately recorded.

Ore bed no. 4 has yielded a very small but unrecorded production, mainly from small mines in part of Arroyo del Boleo and Cañada de la Gloria, northwest of the principal part of the copper district. Ore bed no. 0 has never been mined. A small production from the Sin Nombre ore bed in part of the Montado mine has been combined with the production figures for ore bed no. 1, and likewise a small production from the Falsa Tercera ore bed in part of the Santa Rita mine has been included in the figures for ore bed no. 3.

Although ore bed no. 1 lies 115 meters stratigraphically above ore bed no. 3, the mine workings in ore bed no. 1 are not, peculiarly enough, any higher in elevation than those in ore bed no. 3; on the contrary, they are generally lower. The highest workings that are in ore—209 meters above sea level—are in ore bed no. 3, in the Amelia mine in the northwest part of the district; the lowest workings in ore—182 meters below sea level—are in ore bed no. 1, in the San Luciano mine in the southeast part of the district. This is a result of differential tilting and warping of the Boleo formation, which lies at higher elevations in the northwest part of the district than in the southeast part.

THICKNESS OF ORE

The thickness of minable ore is different from bed to bed and place to place, but the average thickness for the district as a whole is probably close to 80 centimeters. According to 11,733 measurements, made chiefly in mines that have been worked during the past 30 years, the average thickness for all ore beds is 79 centimeters in the areas that have been stoped, compared with 64 centimeters in areas that have been left unstoped. In the stoped areas included in these measurements, ore bed no. 1 has an average thickness of 75 centimeters, and ore bed no. 3 has an average thickness of 86 centimeters. In the older mines that are not represented by these measurements, such as part of the Providencia, California-Lugarda, Amelia, and San Agustín mines, the thickness of ore bed no. 3 ranged between 1 and 2 meters in many places, and in a few local areas it is said to have reached as much as 5 meters.

The minimum thickness of ore that can be mined has been considered to be approximately 60 centimeters, although in a few places even thinner ore has been worked. In the area explored by drill holes in ore bed no. 1, down the dip from the San Luciano mine, the ore bed has an average thickness of 50 centimeters. Table 12 presents the averages of all the thickness determinations available, together with determinations of the grade of ore, summarized for individual mines, individual ore beds, and the district as a whole.

GRADE OF ORE

The grade of ore, like the thickness, varies greatly from bed to bed and place to place. The average grade of all the ore mined from 1886 to 1947, weighted for tonnages, was 4.81 percent of copper.[5]

The average grade has varied considerably in the course of mining operations, and the ore mined in the earliest years was much higher in grade than that mined in later years. Thus the average grade of ore mined during various epochs was 9.58 percent of copper in 1886, 7.81 percent from 1886–93, 5.43 percent from 1894 to 1916, 5.05 percent from 1917–25, 4.52 percent from 1926–32, and 3.83 percent from 1933–47. The lowest average grade for any particular year was 3.10 percent in 1939–40; since then the grade of ore mined has increased somewhat, to an average of 4.05 percent in 1946–47, because of reworking of the older and richer mines by the *poquiteros*. The average grade of ore mined during each year of operation by the Boleo company is included in table 27, and the trend of grade of ore through the years is shown graphically in figure 38.

The grade of ore mined before the advent of the Compagnie du Boléo in 1886 was much higher than that indicated above, judging from early reports such as those by Tinoco (1874, 1885) and by Bouglise and Cumenge (1885). At that time the ore was shipped directly to Europe without concentration or smelting, and it was not considered profitable to ship ore containing less than 20 percent of copper. Although a considerable amount of sorting was doubtless necessary to produce such high-grade ore, the copper content of the ore mined at that time must nevertheless have been high, for a considerable tonnage of material was discarded that averaged 8 percent of copper. Tinoco (1885) estimated that the average copper content of some 60,000 tons of ore shipped before 1884 was about 24 percent. Moreover, Fuchs (1886a, p. 85; 1886b, p. 419) gives an analysis of an average of 180 samples taken from all the mines being worked in 1884, which shows a content of 15 percent of copper.

Large areas of the ore beds have a grade much lower than the 4.8-percent average of the ore mined to date. Some of these are unstoped areas in the mines, and others are beyond the limits of the mines. Particularly down the dip toward the gulf from the areas mined are large bodies of ore that average about 2 percent of copper. These are the areas that seem to hold the greatest promise for the future, if some method could be found of concentrating the Boleo ores or otherwise working such lower-grade ores at a profit. The grade continues to decrease farther gulfward to 1 percent and less, until the beds become virtually barren of copper.

Most of the mines worked during the past 30 years or so have been sampled in considerable detail by the Boleo company, and the results, as averaged by the writers for different mines and ore beds, have been given in table 12.

It should be pointed out that the assays forming the basis for table 12 represent only the mines that have been worked in the past 20 to 30 years—principally the San Luciano, Montado, and Ranchería mines in ore bed no. 1, and the lower levels of the Purgatorio, Santa Rita, and San Antonio mines in ore bed no. 3. No assay maps are available for the older mines in ore bed no. 3, such as the California-Lugarda, Humboldt, Amelia, and San Agustín mines, the older parts of the Purgatorio and Santa Rita mines, and most of the Providencia mine. Both the average thickness and the average grade of ore in these older mines are believed to have been higher than the averages presented in table 12. Examples of the thickness and grade of ore shown by the working faces in some of these older mines in ore bed no. 3 have been presented in figure 32.

Some reports on the Boleo district have remarked on the uniformity of the grade of ore. In the writers' opinion this has been overemphasized; on the contrary, there seems to be a considerable lack of uniformity, if one compares different parts of the district, different ore beds, the history of the grade of ore mined as a whole, or even the variations along a given working in a particular ore bed.

A lack of uniformity is indicated most strikingly by the assay maps of particular mine workings, which

[5] All the analyses for copper discussed in this report, unless otherwise noted, are on a wet basis, which is the basis customarily used by the Boleo company in its records of ore shipments and on its assay maps. On a dry basis, the percent of copper would be increased by 1/5 to 1/4 in most of the analyses.

show great differences among individual analyses. To cite an example of a single mine working from among the several hundred recorded, a series of 76 determinations of thickness and grade along a particular working of the Montado mine is given in table 13. The samples were taken at intervals of approximately 4 meters along each side of an inclined working, which follows the dip of the ore bed downward to the east.

TABLE 13.—*Example of differences in thickness and grade of ore bed along a particular mine working (5th incline—10 Pedregoso, Montado mine, ore bed no. 1)*

North side of working		*South side of working*	
Thickness (centimeters)	*Copper (percent)*	*Thickness (centimeters)*	*Copper (percent)*
78	5.4	90	3.4
40	3.5	90	6.6
90	4.9	97	5.4
60	9.1	95	5.0
80	8.2	80	11.0
57	2.7	105	4.9
90	6.7	75	5.0
60	7.1	48	7.4
45	5.5	88	3.6
30	10.8	70	4.8
60	7.1	20	8.3
60	10.5	60	9.7
40	8.4	75	10.2
70	3.3	40	6.6
105	2.7	45	3.2
105	4.5	100	4.4
60	3.8	65	4.2
90	3.9	25	1.1
80	8.9	85	4.9
25	6.8	60	6.4
35	6.2	40	4.8
30	6.1	25	9.1
20	3.1	40	2.8
30	3.0	20	1.8
25	8.1	20	9.5
25	6.6	35	3.2
20	3.4	30	6.0
25	6.5	10	2.9
20	.3	20	4.7
20	6.7	30	.2
20	.7	20	9.4
36	.2	85	4.3
40	2.7	30	0.6
30	9.8	40	18.2
70	.6	15	7.8
30	32.7.	20	.5
56	1.8	52	3.9
30	7.6	70	3.9

Average of entire working: Thickness, 51 cm; copper, 5.7 percent

Although the average grade weighted for thickness along this working is 5.7 percent of copper,[6] the limits ranged from as little as 0.2 percent in one sample to as much as 32.7 percent in another. Although the range is not everywhere so great as in the example cited, most of the detailed assay maps show considerable difference in successive samples along a given working.

EXTENT, THICKNESS, AND GRADE OF INDIVIDUAL ORE BEDS

ORE BED NO. 0

Ore bed no. 0, the uppermost ore bed of the Boleo formation, is fairly extensive but is nowhere sufficiently rich to be mined commercially. It is the poorest of the numbered ore beds, is generally less than half a meter thick, and is commonly manganiferous or ferruginous. In places it contains a few streaks of copper minerals, but the grade is nowhere known to be as high as 1 percent of copper.

The ore bed crops out intermittently over a length of 600 meters on the southeast side of Arroyo del Purgatorio, southeast of the San Francisco shaft. Both to the northeast and northwest, the bed is cut out by the unconformity below the Gloria formation; it is missing in the entire area northwest of Arroyo del Purgatorio. Scattered outcrops appear along the southeast side of Arroyo de la Providencia, extending for a length of 2 kilometers northeast of the Juanita fault. No other outcrops could be definitely assigned to this ore bed.

Ore bed no. 0 was found in 42 of the exploratory holes drilled in Arroyos Santa Agueda and Montado, but without exception it was considered too thin and much too low in grade to be mined commercially. In hole no. 2 it had a thickness of 30 centimeters and contained 0.06 percent of copper; in hole no. 3 it was 1.20 meters thick and showed 0.21 percent of copper, and in hole no. 33 it was 30 centimeters thick and assayed 0.15 percent of copper. A manganiferous bed cut in the San Julio shaft may also be correlated with ore bed no. 0; this ore bed had a trace of copper, 2.11 percent of FeO, and 11.40 percent of MnO. Ore bed no. 0 was also penetrated in some of the inclined shafts in the Ranchería and Montado mines, but in those places the bed was likewise considered unprofitable to mine.

ORE BED NO. 1

Ore bed no. 1 is second in importance to no. 3 as a producer of ore in the Boleo district, having yielded a recorded total of 2,045,537 tons of ore from 1886 to 1947, or 16.6 percent of the total production of the ore that was classified by individual mines for that period.[7] This ore bed is one of the most extensive in the district but has been productive only in the southeast area, southeast of Arroyo del Purgatorio. In the Ranchería, Montado, and San Luciano mines, ore bed no. 1 has been mined in a nearly continuous area extending from the southeast side of Arroyo de la Providencia southward across Arroyo del Montado to Arroyo de Santa Agueda, a distance of 5.6 kilometers. The width of mining reaches a maximum of 1,300 meters in the Ranchería mine, averages 300 meters in the Montado mine, and averages 600 meters in the San Luciano mine. The mine workings range in elevation from 124 meters above sea level to 64 meters below sea level in the Ranchería mine, and from 59 meters above sea level to 28 meters below sea level in the Montado mine. In the San Luciano mine the area mined is farther down the dip of the ore bed, and the workings in ore range in elevation from 59 to 182 meters below sea level.

As compared with the mines in ore bed no. 3, the

[6] If one weights the seemingly erratic high assays of 18.2 and 32.7 percent by reducing them to twice the mean, the weighted average would become 5.4 percent of copper.

[7] Of the total production of 13,722,192 tons of ore from 1886 to 1947, some 1,412,613 tons was unclassified as to individual mines or ore beds.

area mined in ore bed no. 1 is much narrower, and the areas stoped are more sporadic and make up a smaller proportion of the area explored, a result of the generally lesser thickness and lower grade of the ore bed.

Assay maps of the three principal mines in ore bed no. 1 show an average thickness of 75 centimeters of ore in areas that have since been stoped, and 64 centimeters in areas that were left unstoped. The average grade is 6.3 percent of copper in stoped areas and 4.7 percent in unstoped areas. These figures are reduced to 4.7 and 3.5 percent, respectively, after deducting a dilution factor of 25 percent. The grade of ore shipped to the smelter from the mines in ore bed no. 1 averaged 5.9 percent of copper in 1909, 5.5 percent in 1919, and about 5 percent in 1926, but it dropped to about 4 percent from 1935 to 1948.

Northwest of Arroyo de la Providencia, ore bed no. 1 has been exploited only in one small mine, the Cinco de Mayo, on the southeast side of Arroyo del Purgatorio. In much of the northwest area, ore bed no. 1 has been removed by erosion below the unconformity at the base of the Gloria formation.

Ore bed no. 1 does not crop out in the mined area that extends southward from Arroyo de la Providencia to Arroyo de Santa Agueda, as the Boleo formation is buried in that area by younger sediments. The ore bed was explored in that area by mine workings and drill holes, and it was found to extend over a considerable area down the dip eastward from the Montado and San Luciano mines, but it is considered to be too deep, too thin, and too low in grade to be minable in that area.

SIN NOMBRE ORE BED

An ore bed called the Sin Nombre (no name) appears only in the western part of the Montado mine. It is from 3 to 10 meters stratigraphically below ore bed no. 1, with which it coalesces locally. It has been explored along the strike for 1,200 meters but mined for a length of only 350 meters and for widths of 50 to 100 meters.

Although not extensive, the Sin Nombre ore bed was rich locally. Exact data on thickness and grade are not available, but the ore was considered to be some of the best found in the Montado mine and it is said to have contained about 7 percent of copper. The rich ore seems to disappear rapidly, however, along both the strike and dip. In general the areas stoped in the Sin Nombre and no. 1 ore beds are different, but in part they overlap along the eastern edge of the Sin Nombre stoped area. The production from the Sin Nombre bed is unknown, as it was combined with the rest of the production from the Montado mine. The bed is not known to crop out anywhere in the Boleo district.

UNCORRELATED MANGANIFEROUS BEDS

A few manganiferous beds, which in places contain small quantities of copper, are found here and there at different horizons in the tuff between ore beds nos. 1 and 2, as well as between ore beds nos. 2 and 3. These beds are generally discontinuous, thin, low in grade, and have nowhere been exploited. They are shown on the geologic map (pl. 1) in several places, particularly in Arroyo del Boleo. A manganiferous bed between ore beds nos. 1 and 2 was noted in drill hole no. 56, and some manganiferous bands with traces of copper, lying between ore beds nos. 2 and 3, were noted in the Santa Rita shaft. Some thin manganiferous and ferruginous beds near the mouth of Arroyos Boleo and Soledad are of uncertain correlation. They appear to be without commercial value.

ORE BED NO. 2

Ore bed no. 2 is one of the most widespread in the district, but it is generally so thin that it has been exploited only in comparatively small areas. The records indicate a production from mines in this ore bed of only 6,218 tons of ore, which is less than 0.1 percent of the total for the district from 1886 to 1947, but these figures are incomplete as some production was combined with that from ore bed no. 3.

The principal area mined in ore bed no. 2 is a narrow belt along the northeast side of the volcanic mass of Cerro de Juanita, extending northward from the north side of Arroyo de la Providencia to the south side of Arroyo del Purgatorio. Much of this area overlies the mined area of ore bed no. 3 in the Providencia mine. The mine in ore bed no. 2 in this area is called Providencia at the south end and Purgatorio at the north end, but the mine workings are continuous from one arroyo to the other. A smaller area mined in ore bed no. 2 on the north side of Arroyo del Purgatorio is called the Margarita mine, and two small mines farther northwest in Arroyos Soledad and Boleo are called the Artemisa and Prosperidad mines, respectively.

Exact figures on grade of ore in the mines in ore bed no. 2 are not available, but most of the ore mined presumably contained not less than 4 to 5 percent of copper. Some of it must have been richer, for the ore bed along the northeast flank of Cerro de Juanita was one of the earliest mined, and Saladin (1892, p. 20–21) states that in Arroyo de la Providencia this bed provided some ore that contained 20 to 25 percent of copper. The thickness exposed in the outcrops and mine workings now open is generally half a meter or less, although it may have attained a meter or perhaps more in the oldest mines. The thickness and grade of ore decrease rapidly down the dip toward the gulf.

All the mines in ore bed no. 2 are in the zone of oxidized minerals. Many of the ores in this bed are manganiferous and also in part siliceous. This ore bed contained many of the concretionary bodies of copper carbonate and oxide minerals which were called *boleos* and which led to the discovery of the district.

Ore bed no. 2 crops out extensively along the walls of many of the arroyos, such as Boleo, Soledad, Purgatorio, and to a lesser extent Providencia. Southeast of the latter it is buried below the arroyo levels, but it has been cut in some of the drill holes in Arroyos Santa Agueda and Montado. The ore bed was found in 11 holes in that area, but in most it was reported to be too low in grade to warrant assaying. In hole no. 3 in Arroyo de Santa Agueda it has a thickness of 1.25 meters and an average copper content of 1.80 percent, ranging from 1.20 to 3.36 percent, and in hole no. 4 it has a thickness of 1.2 meters and a grade of 0.20 percent of copper. In hole no. 29 in Arroyo del Montado the ore bed is 60 centimeters thick and contains traces of copper. A bed cut in the San Julio shaft, probably correlative with no. 2, contains 0.5 to 1.0 percent of copper, besides considerable manganese and iron.

Ore bed no. 2 was also penetrated in the Santa María, San José, Indios, San Roberto, and San Marcelo shafts, but in none of those was it considered to be exploitable. In the San José inclined shaft of the San Antonio mine, it has a reported grade of 0.64 percent of copper, and in the San Roberto shaft in Arroyo del Purgatorio, it has a thickness of 95 centimeters and a grade of 0.45 percent of copper. Ore bed no. 2 was explored in a long working in the Ranchería mine, near the San Marcelo shaft, at a depth of 53 to 60 meters below the mined area of ore bed no. 1 in that mine. This working follows the ore bed down the dip, between elevations of 8 and 50 meters below sea level, for a distance of 450 meters. In that area the bed has an average thickness of 63 centimeters and an average grade of 1.3 percent of copper, based on a series of 14 determinations.

If it should become possible to work thinner and lower-grade ores in the Boleo district, certain unmined areas in ore bed no. 2 might become exploitable, particularly in the northwest part of the district, from Arroyo de la Providencia northwestward to Arroyo del Boleo. Although the bed is comparatively thin, it has the advantage of lying above the arroyo levels in most of the northwest area and is thus readily accessible from the arroyo walls.

FALSA TERCERA ORE BED

An ore bed called the Falsa Tercera (false third) is found in the northwest part of the district, in parts of Arroyos Soledad and Boleo. This bed, shown on pls. 1 and 3 as ore bed 3a, is in tuff a short distance above ore bed no. 3. The stratigraphic interval between the two ore beds averages about 4 meters but ranges from 1 to 9 meters, and locally the beds join. The Falsa Tercera bed has been exploited in the northeast part of the Santa Rita mine, in the Buena Suerte mining area. The production figures for this ore bed have been combined with the production from ore bed no. 3 in the Santa Rita mine.

In the Santa Rita mine the Falsa Tercera bed has been explored for 1 kilometer along the strike, from outcrops on the southeast side of Arroyo del Boleo southeastward to the vicinity of the Santa Natalia shafts. The area stoped has a length of 500 meters and extends down the dip for an average width of 100 meters, reaching a maximum of 250 meters. The workings lie at elevations of 38 to 123 meters above sea level. In general, the area stoped in the Falsa Tercera ore bed is distinct from that in ore bed no. 3, but in places the two beds have been stoped in the same area.

A series of 93 determinations of thickness and grade of the Falsa Tercera ore bed along and near the 55-meter level in the Santa Rita mine, in an area that is mainly unstoped, indicates an average thickness in that area of 43 centimeters of ore having an average grade of 5.4 percent of copper. Elsewhere the thickness decreases, in places to 20 centimeters; this is the main reason for the limited exploitability of this ore bed. The average grade of the ore produced from the Falsa Tercera is said to have been about 5 percent of copper.

Outcrops of the Falsa Tercera bed were noted in places along the south side of Arroyo del Boleo. The ore bed was found in several workings in the San Antonio mine, east of the Santa Rita mine in Arroyo de la Soledad, but it was not considered exploitable in that area. It was penetrated at a level of 148 meters above sea level in the San Agustín shaft in Arroyo de la Soledad, where it is said to have a thickness of 20 centimeters.

ORE BED NO. 3

Ore bed no. 3 is by far the most important in the Boleo district in terms of production, area mined, thickness, and grade of ore.

The production from this ore bed is recorded as 10,257,824 tons of ore, which is 83.3 percent of the total production classified by individual ore beds from 1886 to 1947. This percent is probably somewhat too high, however, for it includes some of the production from other ore beds, such as the Falsa Tercera and probably ore beds nos. 2 and 4. Ore no. 3 also seems to have the largest reserves of lower grade ore which might become exploitable at some future time.

Ore bed no. 3 has been mined over a large, almost continuous area extending northwestward from Arroyo de la Providencia across Arroyos Purgatorio and Soledad to the south side of Arroyo del Boleo. The mine workings over this area are nearly all intercommunicated, except for a few small isolated mines such as the Humboldt and Curuglú. These mines have been divided administratively into three main groups, called the Providencia, Purgatorio, and Soledad, after the arroyos that constituted the mining center of each group. The principal mines in the Providencia group have been called the Carmen, Sontag, and San Alberto; in the Purgatorio group the California-Lugarda, Humboldt, San Francisco, and Purgatorio; and in the Soledad group the Amelia, Curuglú, San Luis, San Agustín, Santa Rita, San Antonio, and Santa Marta.

The area mined in ore bed no. 3 has a maximum length along the strike of 6.4 kilometers and a width down the dip ranging from as little as 500 meters in the Providencia group to as much as 3.3 kilometers in the Soledad group. Elevations of the workings in ore bed no. 3 range from 209 meters above sea level in the Amelia mine to 73 meters below sea level in the deepest part of the Purgatorio mine.

The thickness and copper content of ore bed no. 3 have varied considerably from one area to another. The best ore was in the inland part of the areas mined, near Cerro de Juanita and the foothills of Cerro del Infierno. Later, mining extended eastward down the dip where the bed becomes thinner, lower in grade, and eventually unexploitable.

The average grade of the ore mined has probably been close to 5 percent of copper. The percent of copper ran as high as 20 in certain localized areas that were first mined, ranged from 7 to 8 percent in larger areas of the early mines, and dropped to 3 or 4 percent in parts of the Purgatorio and Santa Rita mines. The thickness of minable ore averaged 1 meter or more in some of the older mines, and was commonly 2 meters and exceptionally 5 meters in certain local areas of the Carmen and Amelia mines, according to De Launay (1913, p. 791), but it decreased to about 85 centimeters in the more recently mined area of the Purgatorio and Santa Rita mines.

Detailed assay maps are available for only a small part of the area mined in ore bed no. 3, mainly in the lower levels of the Purgatorio and the Santa Rita-San Antonio mines, in which both the thickness and grade are believed to have been considerably less than in the older mines at higher levels in this ore bed. The average thickness indicated by these maps is 86 centimeters in areas stoped and 63 centimeters in areas not stoped. The average grade of the areas stoped is 6.2 percent of copper, reduced to 4.6 percent after deducting a 25-percent dilution factor. The assay maps indicate an average grade of 4.8 percent of copper in the unstoped areas, which, after a deduction of 25 percent for dilution, would leave an average grade of 3.6 percent.

Ore bed no. 3 crops out most extensively in the extreme northwest part of the district, in the drainage basin of Arroyo del Boleo, where it lies above the arroyo level for the most part. It also crops out in two or three small areas in Arroyo de la Soledad, where it is mostly below the arroyo level. In Arroyo del Purgatorio ore bed no. 3 is below the arroyo level northeast of the San Francisco shaft, but southwest of the shaft it rises above the arroyo level. Some of the most extensive exposures are around the Humboldt mine, an isolated area on the southeast side of the arroyo. There the ore bed may be seen to rise southwestward against a ridge of Comondú volcanics, and eventually it rests directly on the volcanic rocks. The same relationship exists in part of the Providencia mine. The ore bed lies below the arroyo level in Arroyo de la Providencia.

Ore bed no. 3 does not appear in the area southeast of Arroyo de la Providencia, and all the evidence indicates that it was never deposited there. All the drill holes and shafts in Arroyos Santa Agueda and Montado that reached the Comondú volcanics revealed the absence of the ore beds and of most of the rest of the stratigraphic section below ore bed no. 2. In places even ore bed no. 2 is absent. Ore bed no. 3 wedges out against a buried ridge of Comondú volcanics along the southeast edge of the Providencia mine, as indicated by a few workings that follow the bed downward at the southeast extremity of the mine, and particularly by the long haulageway (Travers-Bancs Montado) 1.6 kilometers in length that runs from the Montado mine to the Providencia mine at a level of 29 to 34 meters above sea level, and is in Comondú volcanics for most of its length. Farther northeast in Arroyo de la Providencia, ore bed no. 3 also wedges out against the Comondú volcanics, as revealed in a mine working near the San Eugenio shaft.

One of the largest areas of marginal reserves of low-grade ore in the district is along the northeastern border of the Purgatorio and Providencia mines, down the dip of ore bed no. 3 from the areas mined. One long working in this area is known, from 32 determinations, to contain an average thickness of 69 centimeters of ore with an average grade of 3.3 percent of copper, equivalent to 2.5 percent after deducting a dilution factor of 25 percent. The most favorable area for the possible discovery of new high-grade reserves is also in ore bed no. 3, northwest of the main part of the district, in the drainage of Arroyo del Boleo, Cañada de la Gloria, and Arroyo del Infierno.

ORE BED NO. 4

Ore bed no. 4, the lowest ore bed in the Boleo stratigraphic sequence, is of small extent and has been of slight importance as a producer, although it is a possible source of reserves. It is confined to the northwest part of the district, being unknown southeast of Arroyo del Purgatorio, and it has been mined only in small areas northwest of the main part of the district. Two small mines in this ore bed have been worked recently by the *poquiteros*—El Bajío mine in Arroyo del Boleo and El 160 mine in Cañada de la Gloria. The production from these mines is not known exactly but is probably a few thousand tons of ore. Several other prospect pits and small exploratory workings have been made in ore bed no. 4, and some of these may have furnished a small production.

Ore bed no. 4 is less well defined than most of the others; it commonly consists of a considerable thickness of tuff through which the ore minerals are scattered in irregular masses, lenses, or pockets. Thus more selective mining is required than in such ore beds as no. 3. The ore minerals may be scattered through 10 meters of tuff, but the minable part, if any, is generally 1 meter or less. The ore mined from this bed has averaged about 4 percent of copper. The ore bed is highly manganiferous in some places. The manganiferous and cupriferous parts are in some localities separated by a layer of tuff, elsewhere they are mixed together, and in places manganese oxides may be present to the exclusion of copper minerals. A sample collected by the writers from a manganiferous bed on the El 160 claim contained 16.4 percent of manganese and 0.63 percent of copper.

Outcrops of ore bed no. 4 are few, for the bed lies below the arroyo levels in the area southeast of Arroyo del Boleo. The most extensive exposures are in some of the branches of Arroyo del Boleo and Cañada de la Gloria, in areas where the buried hills of Comondú volcanics are near the surface and where the ore beds lap onto the volcanic rocks. In only one small area was ore bed no. 4 observed to overlie conglomerate, as do most of the other ore beds in the district. More commonly the ore bed lies directly on the Comondú volcanics, or on the basal limestone of the Boleo formation, or in tuff a short distance above the base of the formation. In some places the ore penetrates the underlying limestone, which is itself partially replaced by manganese oxides and less commonly by copper minerals.

Ore bed no. 4 has been explored by several shafts in Arroyos Soledad and Purgatorio. In the San Agustín shaft a thickness of 10.2 meters of argillaceous and ferruginous rock was found to have traces of copper. In the Amelia shaft the bed consists of a layer of tuff 9.42 meters thick, which contains 0.14 to 1.74 percent of copper. In the La Ley interior shaft, the bed consists of 1.10 meters of tuff and manganiferous and ferruginous limestone containing 0.36 to 0.70 percent of copper. In the San Eduardo shaft the bed consists of several mineralized zones containing 0.42 to 14 percent of copper scattered through 9.41 meters of tuff. Some exploratory workings were made at the bottom of this shaft, at an elevation of 2 meters above sea level, but the bed was considered unexploitable.

Short workings in ore bed no. 4 were also driven at the bottom of the San Alejandro shaft, at a level of 55 meters below sea level, where the bed was found from 13 determinations to have an average thickness of 61 centimeters and an average grade of 4.1 percent of copper. At the bottom of the Santa Natalia inclined shaft, east of the Santa Rita mine and north of the San Antonio mine, ore bed no. 4 lies about at sea level and has a thickness of 1.8 meters and a grade of 0.35 percent of copper.

The greatest possibilities for production from ore bed no. 4 seem to lie in the drainage basin of Arroyo del Boleo and Cañada de la Gloria, in an area that is still imperfectly explored and where the bed, in at least a few places, has been found to be of minable grade and thickness. The bed is inclined to be irregular and pockety, however, so that the possibilities are slight for mining large continuous areas like those in ore bed no. 3. Ore bed no. 4 is one of the most highly manganiferous beds in the district and would be of considerable importance if some ore-dressing process should be developed for profitable recovery of manganese from low-grade ores of this type.

LIMITS OF ORE BODIES

The ore bodies of the Boleo district are limited in general by one of four conditions: termination of the ore beds against the basement of Comondú volcanics, truncation of the beds by erosion, either at the unconformity at the base of the Gloria formation or in recent time, faults, and assay walls.

In different places the ore beds wedge out against elevations of the basement of Comondú volcanics. Cerro de Juanita, for example, forms the westward limit of ore bed no. 3 in the Humboldt mine and in part of the Providencia group, and it also forms the westward limit of the principal mine in ore bed no. 2. A buried ridge southeast of Arroyo de la Providencia forms the southeast and northeast limits of ore bed no. 3 in that arroyo. The Sin Nombre and no. 1 ore beds in a part of the Montado mine are limited toward the west by the volcanic mass of Cerro del Sombrero Montado. In the northwest part of the district ore bed no. 4, as well as ore bed no. 3 in places, is limited by irregularities in the basement topography.

The truncation of the higher beds of the Boleo formation by the unconformity at the base of the Gloria formation has removed in places ore beds nos. 0, 1, and 2. Recent erosion of course limits the ore bodies wherever they are above the level of the arroyos.

Faults in some places form the borders for individual minable ore bodies. In very few places has an ore bed actually been "lost" on one side or the other of a fault, but where the faults are very closely spaced they may create conditions under which commercial mining of the ore is impossible.

Most of the limits of the areas mined, however, are determined by assay walls—that is, the ore bed is mined up to the line where the reduced grade or thickness renders further exploitation impossible. The gulfward borders of most of the mines are of this type, for the ore beds gradually decrease in grade and thickness in that direction. In some places the ore beds pinch out altogether or become quite barren of copper, either within some of the mines or along the edges of the mines. The ore bed in the Santa Rita mine gives way down the dip to a bed consisting largely of gypsum and iron oxides.

The depth of the ore bed below the surface, amount of water, problems of overburden, and accessibility are other factors that must be considered in determining the profitably minable limits of the ore bodies.

PATTERN OF ORE SHOOTS AND OF DISTRIBUTION OF ORE

The ore is commonly concentrated in elongate areas or ribs that are more or less parallel and separated from one another by other ribs of lower grade ore. The ribs of richer ore have the characteristics of ore shoots. The pattern of ore shoots is best revealed in some of the old mines, particularly those that have not been reworked, for in the earlier years only the rich ore was mined and the stope boundaries consequently reveal the approximate form of the higher grade areas. In recent years, however, there has been a greater tendency to work the lower grade areas as well, and hence the distinction between the higher grade and lower grade areas is less easy to see, except where detailed assay maps are available.

One of the best examples of the pattern of ore shoots is perhaps revealed by the map of the Amelia mine, which is in ore bed no. 3 at the southwest end of the Soledad group (fig. 35). From west to east in this mine are three rather distinct northwest-trending narrow, elongate stoped areas of higher grade ore, separated by explored but unstoped areas of lower grade ore.

The longest and narrowest of these ribs of higher grade ore is the most westerly one, revealed in the Curuglú mine at the northwest end and in a belt called Olvido Viejo at the southeast end. This rib is offset near the middle by the Curulgú fault, but the essential continuity of the ore shoot on either side of the fault is apparent. This ore shoot is 1.5 kilometers long but is only 50 to 150 meters wide. It is bordered to the northeast by a belt 250 meters wide of lower grade ore, which is in turn bordered by another ore shoot 1 kilometer long and 150 meters wide in the Olvido Nuevo region. This is bordered by another belt 100 meters wide of lower grade ore that runs northwestward from the Amelia shaft, and in turn by another belt of higher grade ore about a kilometer long and 50 to 200 meters wide that runs northwest into the San Andrés region. The ore shoots tend to coalesce at the southeast end.

In this area the ore shoots have an average strike of N. 50° W. and cut obliquely across the Curuglú and Amelia faults, which strike N. 20–25° W., as well as across the structure contours of the beds, which have an average strike in this area of about N. 20° W. These ore shoots are reported to have contained 7 to 8 percent of copper, and the intervening areas 2 to 4 percent.

Similar but less well-defined ribs or ore shoots occur over much of the area explored in ore bed no. 3 between Arroyos Purgatorio and Boleo. Early reports indicate that the Providencia mine contained several ribs or ore shoots that were developed by elongated stopes in the early years of mining. The intervening areas were found to be high enough in grade to be mined later, and the original pattern has been obliterated on the maps of that mine.

Aside from the ore shoots just described, the most evident trend in degree of the mineralization through the district as a whole is a decrease in grade of ore toward the gulf. The highest grade ore bodies—those that were first mined, when only ores containing more than 20 percent of copper could be shipped—are largely in the inland area, close to the large masses of Comondú volcanics such as Cerro de Juanita (fig. 36). Later, as mining progressed down the dip of the ore beds, the copper content was found in general to decrease with increasing distance from the volcanic masses. The areas mined are bordered on the gulfward side by areas in which the ore beds contain 2, 1, or only a fraction of a percent of copper.

Some of the richest ore bodies rest directly on the surface of the Comondú volcanics. This is true, for example, of ore bed no. 4 in various parts of Arroyo del Boleo, of ore bed no. 3 in the Humboldt mine and part of the Providencia mine, of ore bed no. 2 in the Providencia mine, and of ore bed no. 1 and the Sin Nombre bed in part of the Montado mine. An example of a small but high-grade ore body related to an isolated buried hill of Comondú volcanics is at the place called El Crestón or Lazareto, near the coast on the northwest

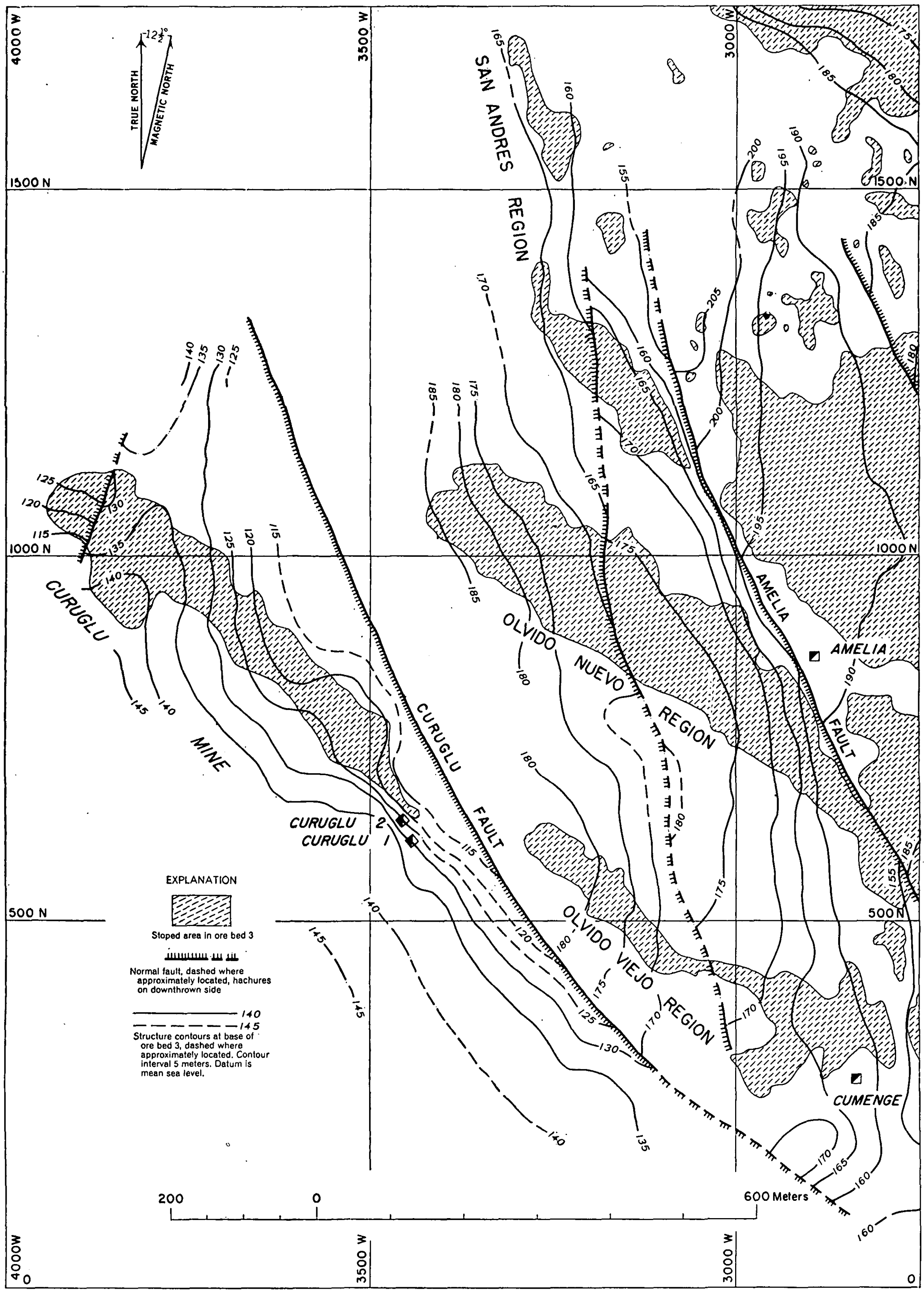

FIGURE 35.—Diagram illustrating distribution of ore shoots in the Amelia and Curuglú mines.

side of Arroyo del Montado, where some high-grade ore was found in a small area directly alongside a projecting hill of the basement rock.

VEINS AND STOCKWORK BODIES IN THE COMONDÚ VOLCANICS

Narrow veins and stockwork bodies of copper and manganese minerals occur in the Comondú volcanics in certain parts of the Boleo district. Although most of these are not considered to be of commercial value, they are described because of their possible genetic significance.

Such veins are associated commonly with fault zones cutting the volcanic rocks. They were noted particularly along the Juanita fault zone which borders the southwest side of Cerro de Juanita, where there are many fractures containing veinlets of copper minerals. They were also noted in some of the volcanic masses in the various branches of Arroyo del Boleo, and along some of the faults that cut the Comondú volcanics in Arroyo del Infierno. Most of these bodies are veinlets a few centimeters thick of jasper or chalcedony, calcite, manganese oxides, and copper minerals, chiefly chrysocolla. In some places a number of reticulating veinlets form a stockwork body in the volcanic rocks. A veinlike mass 1 meter thick of siliceous manganese oxides, accompanied by jasper and copper minerals,

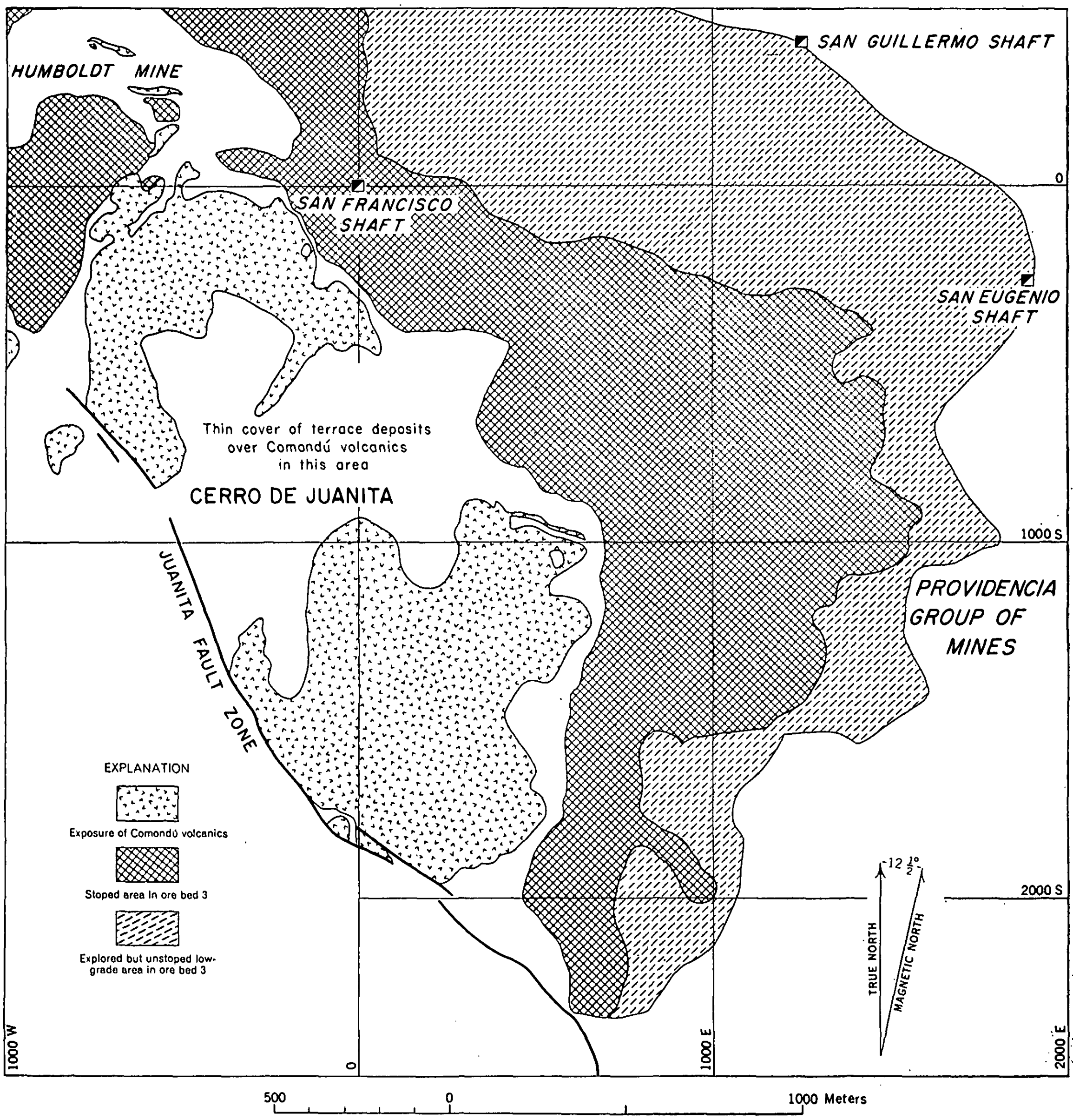

FIGURE 36.—Diagram showing relation of ore deposits in the Providencia group of mines to a former island of Comondú volcanics (Cerro de Juanita).

was noted in the Comondú volcanics near the head of Arroyo del Boleo.

The largest stockwork body observed in the Comondú volcanics is on the southwest side of Cerro de Juanita near the Juanita fault zone. Some prospecting has been done there and a small amount of ore has been sorted out by the *poquiteros* for shipment to the smelter. At that place the stockwork body consists of cupriferous veinlets extending through a brecciated zone as much as 3 meters wide. The copper minerals fill the interstices of the fault breccia and also form definite veinlets cutting the volcanic rock. The individual veinlets are 1 to 10 centimeters thick; they are irregular and reticulating. A sample of ore from this deposit was studied by Charles Milton who describes it as follows:

> This is an aggregate of coarse white calcite, containing amorphous, black, waxy iron and manganese oxides (X-Ray film 5268) and green chrysocolla (X-Ray film 5267). A bluish-green material abundantly present is also chrysocolla, with probably opaline silica, which may have begun to crystallize to quartz (X-Ray film 5266).

Although these veins and stockwork bodies in the volcanic basement rocks are not mentioned in some of the previous reports on the Boleo district, they attracted the attention in particular of Saladin (1892, p. 14). He pointed out the presence of siliceous and cupriferous veinlets on the southwest side of the volcanic ("trachytic") mass of Cerro de Juanita. He also described copper ore in the form of a breccia resting directly against the volcanic mass in the Sontag mine in Arroyo de la Providencia. Tinoco (1885, p. 13) also observed the stockwork body in Cerro de Juanita, and he noted in the Olvido mine (part of the Amelia mine) a true vein containing copper silicates along a fault in sandstone. Evidence that some of the faults in the district have been mineralized was also noted by Bellanger (1931, p. 768).

SPECIAL STRATIGRAPHIC OCCURRENCES OF ORE

In addition to the concentration of ore in regular beds of clayey tuff, and to the subordinate occurrences in the Comondú volcanics that have just been mentioned, ore minerals are found here and there in certain other types of rocks and stratigraphic environments in the Boleo district. Again, these are mentioned not because of their commercial value, which is negligible, but because of their possible genetic significance.

In some places, narrow zones of ore minerals extend into adjoining rocks either above or below the main clayey tuff beds that contain the bulk of the ore. Locally, the ore minerals are found as irregular replacement bodies or fracture fillings in such diversified rocks as sandy tuff, sandstone, conglomerate, limestone, or gypsum.

In particular, the ore bodies that are classified as pertaining to ore bed no. 4 are inclined to be irregular and scattered through a considerable thickness of rock, including not only the usual tuff but commonly also the underlying basal limestone of the Boleo formation. In several parts of the drainage basin of Arroyo del Boleo and Cañada de la Gloria, copper minerals and particularly manganese minerals are found penetrating the impure tuffaceous limestone, and in some places fossils in the limestone were noted to have been replaced by manganese oxides.

RELATION OF FAULTS TO ORE

The relation of faults to the ore bodies of the Boleo district is of both economic and scientific importance. Many of the faults that have been observed to cut the ore beds seem to be postmineral. Their economic effect has therefore been merely to displace the ore beds, without affecting the grade or quantity of ore. The faults are detrimental to mining operations, and where they are very closely spaced they may cause an area of otherwise good ore to be commercially unminable. Most of the faults in the mined areas have displacements of only 10 meters or less; the largest displacement in such an area is along the San Antonio fault, between the San Antonio and Santa Rita mines, where ore bed no. 3 has been displaced vertically as much as 80 meters.

The greatest scientific interest, however, attaches to the premineral faults, which are also of economic significance because of the role they may have played in controlling the distribution of the mineralization. In the discussion on structure, it was pointed out that a period of faulting of pre-Boleo age affected the Comondú volcanics of the district. In places, veins and stockwork bodies of ore minerals occupy these faults.

Some of the faults that show evidence of such mineralization are the Juanita fault zone, several small faults in the drainage basin of Arroyo del Boleo and Cañada de la Gloria, and some faults in Arroyo del Infierno in the manganiferous area of the Lucifer district. Apart from the premineral faults now exposed in the outcrop areas of the Comondú volcanics, it is considered likely that many more faults occur in the basement rocks in the large area covered by the Boleo formation, and these may have served as pathways for the mineralizing solutions.

Aside from the evidence of mineralization along these premineral faults, there appears to be a relation between intensity of mineralization in the ore beds of the Boleo formation and proximity to faults. In some places an ore bed is mineralized on one side of a fault—

in nearly every instance the gulfward side, down the dip of the beds—but is barren or too low in grade to be minable on the opposite side.

Perhaps the best example of this is along the Juanita fault in Arroyo de la Providencia, where commercial ore was exploited in the Carmen mine on the northeast, or gulfward, side of the fault, but only low-grade ore was found on the southwest side, despite exploration in that area. Another possible example is along part of the Santa Agueda fault zone in Arroyo del Montado, where a small amount of good ore was found in the Alhambra mine on the northeast side of the fault, while on the opposite side, drilling shows the ore bed to be too low in grade to be minable. Several smaller examples of apparent relations of intensity of mineralization to faulting were noted in some of the other mines, and similar examples were observed in the manganiferous deposits of the adjoining Lucifer district (Wilson and Veytia, 1949, p. 215).

It should be pointed out that some of the premineral faults were undoubtedly subjected to renewed movements in postmineral time. Such a renewal of movement along old faults is common. The mere fact, therefore, that a particular fault displaces the ore beds and is thus in part postmineral, does not preclude the possibility that the same fault may also be premineral.

MINERALOGY

MINERALS IDENTIFIED IN THE BOLEO COPPER DEPOSITS

The ore beds of the Boleo district have yielded a rich variety of minerals, particularly from the oxidized zone. Altogether some 60 mineral species have been identified from the ore-bearing rocks of the district. Three new minerals that are now generally accepted as valid species were originally described from the district—boléite, pseudoboléite, and cumengite, all oxychlorides of lead and copper. Boléite and pseudoboléite were named for the Boleo district, and cumengite was named for E. Cumenge, one of the French engineers whose detailed study of the district led to the formation of the Boleo company in 1885. Several other rare minerals have been found in the district, including crednerite, phosgenite, rémingtonite, spherocobaltite, and cobaltiferous smithsonite.

Table 14 lists in alphabetical order the minerals that have been described from the ore-bearing rocks of the Boleo district, together with their composition and references to the authorities for the identification of each mineral. References are given, in general, to the first published notice or to publications in which the mineral is described most fully. The references are to publications listed by authors at the end of this report.

TABLE 14.—*Minerals found in the Boleo copper deposits*

Name	*Composition*	*References*
Allophane (?)	$Al_2SiO_5.nH_2O$	This report.
Anglesite	$PbSO_4$	Mallard and Cumenge (1891a, p. 520; 1891b, p. 283); Genth (1893); Lacroix (1895, 1898).
Anhydrite	$CaSO_4$	This report.
Apatite	$(CaF)Ca_4(PO_4)_3$	Touwaide (1930, p. 134).
Aragonite	$CaCO_3$	Inst. geol. México (1923, p. 12).
Atacamite	$CuCl_2.3Cu(OH)_2$	Fuchs (1886a, p. 82; 1886b, p. 415); Lacroix (1895, 1898); Ungemach (1911); this report.
Augite	Silicate of Ca, Mg, Fe, Al	Touwaide (1930, p. 132).
Azurite	$2CuCO_3.Cu(OH)_2$	Fuchs (1886a, p. 82; 1886b, p. 415); Krusch (1899, p. 84); this report.
Barite	$BaSO_4$	Touwaide (1930, p. 134); this report.
Beidellite (?)	$Al_2O_3.3SiO_2.4H_2O$	Touwaide (1930, p. 133).
Biotite	$H_2K(Mg,Fe)_3Al(SiO_4)_3$	This report.
Boléite	$9PbCl_2.8CuO.3AgCl.9H_2O$	Mallard and Cumenge (1891a, 1891b); Mallard (1893); Beaugrand (1894); Lacroix (1895, 1898); Friedel (1906).
Bornite	Cu_5FeS_4	Touwaide (1930, p. 136).
Brewsterite (?)	$(Sr,Ba,Ca)0.Al_2O_3.6SiO_2.5H_2O$	Touwaide (1930, p. 133).
Calcite	$CaCO_3$	Touwaide (1930, p. 132); this report.
Celadonite	Silicate of Fe, Mg, K	This report.
Celestite	$SrSO_4$	Touwaide (1930, p. 134).
Cerussite	$PbCO_3$	Mallard and Cumenge (1891a, p. 520; 1891b, p. 283); Lacroix (1898, p. 44).
Chalcedony	SiO_2	Krusch (1899, p. 84).
Chalcocite	Cu_2S	Saladin (1892, p. 18); Krusch (1899, p. 84); Touwaide (1930, p. 134–136); this report.
Chalcopyrite	$CuFeS_2$	Saladin (1892, p. 18); Touwaide (1930, p. 136); this report.
Chlorite	Silicate of Al, Mg, Fe, H	Touwaide (1930, p. 133).
Chrysocolla	$CuSiO_3.2H_2O$	Hutchings (1876, 1877); Jannettaz (1886); Fuchs (1886a, p. 82; 1886b, p. 415); Krusch (1899, p. 34); this report.
Copper, native	Cu	Saladin (1892, p. 18); Krusch (1899, p. 84); Touwaide (1930, p. 134); this report.
Covellite	CuS	Saladin (1892, p. 18); Krusch (1899, p. 84); Touwaide (1930, p. 136).
Crednerite	$CuMn_2O_4$	Fuchs (1886a, p. 82; 1886b, p. 415); Saladin (1892, p. 18).
Cryptomelane	KR_8O_{16} (?), $R=Mn^{IV}$ chiefly, also Mn^{II}, Zn, Co	This report.
Cumengite	$4PbCl_2.4CuO.5H_2O$	Cumenge (1893); Mallard (1893); Lacroix (1895); Friedel (1906).
Cuprite	Cu_2O	Saladin (1892, p. 18); Lacroix (1898, p. 44); Krusch (1899, p. 84).
Dolomite	$CaMg(CO_3)_2$	This report.
Epidote	$HCa_2(Al,Fe)_3Si_3O_{13}$	This report.
Galena	PbS	Fuchs (1886b, p. 414); Saladin (1892, p. 18).
Garnet	Silicate of Ca, Mg, Fe, Mn, Al	This report.
Gypsum	$CaSO_4.2H_2O$	Lacroix (1895, p. 42; 1898, p. 44); Krusch (1899, p. 84); this report.
Halite	NaCl	Fuchs (1886a, p. 82; 1886b, p. 416).
Halloysite	$Al_2O_3.2SiO_2.nH_2O$	This report.
Hematite	Fe_2O_3	Aguilera (1898, p. 120).
Heulandite	$(Ca,Na_2)O.Al_2O_3.6SiO_2.5H_2O$	Touwaide (1930, p. 132).
Hornblende, "basaltic."	Silicate of Ca, Mg, Fe, Na, Al, Ti, H_2O.	This report.
Hornblende, common.	Silicate of Ca, Mg, Fe, Na, Al, H_2O.	This report.
Kaolinite	$H_4Al_2Si_2O_9$	Touwaide (1930, p. 133).
Limonite	Hydrous iron oxides	Touwaide (1930, p. 132).
Magnesite	$MgCO_3$	Krusch (1899, p. 84).
Magnetite	Fe_3O_4	Touwaide (1930, p. 121).
Malachite	$CuCO_3.Cu(OH)_2$	Fuchs (1886a, p. 82; 1886b, p. 415); Krusch (1899, p. 84); this report.
Melaconite	CuO	Krusch (1899, p. 84).
Montmorillonite	Silicate of Mg, Ca, Al, H_2O	This report.
Opal	$SiO_2.nH_2O$	Jannettaz (1886, p. 211); Krusch (1899, p. 84); this report.
Phosgenite	$(PbCl)_2CO_3$	Mallard and Cumenge (1891a, p. 520; 1891b, p. 283); Lacroix (1895, p. 42; 1898, p. 43).
Plagioclase (andesine-labradorite).	$mNaAlSi_3O_8.nCaAl_2Si_2O_8$	This report.
Pseudoboléite	$5PbCl_2.4CuO.6H_2O$	Lacroix (1895); Friedel (1906).
Pyrite	FeS_2	Saladin (1892, p. 18); Touwaide (1930, p. 136); this report.
Pyrolusite	MnO_2	This report.
Pyromorphite	$(PbCl)Pb_4(PO_4)_3$	Lacroix (1898, p. 43–44).
Quartz	SiO_2	Jannettaz (1886, p. 211); Lacroix (1895, p. 42); Krusch (1899, p. 84); this report.
Rémingtonite	Hydrous cobalt carbonate (?)	Ungemach (1911, p. 161).
Silver, native	Ag	Inst. geol. México (1923, p. 7).
Smithsonite, cobaltiferous.	$(Zn,Mg,Co)CO_3$	Warren (1898).
Spherocobaltite	$CoCO_3$	Lacroix (1898, p. 44).
Sulfur, native	S	Krusch (1899, p. 84).

ORE MINERALS IN THE SULFIDE ZONE

The main primary ore mineral, which accounts for the bulk of the copper in the sulfide zone, is chalcocite. This is found in very small crystals or disseminated grains which are commonly microscopic in size. Scattered through the clayey matrix, these grains give a sooty-black to dusky-blue appearance to the ore.

Detailed microscopic studies of the chalcocite have been made by Touwaide (1930, p. 134–136), who reports that it is found only in the groundmass "and does not penetrate the pseudomorphic areas left by former phenocrysts and rock fragments." He describes the chalcocite as having the form of shapeless grains, fine needles, prismatic crystals, and larger euhedral pseudohexagonal crystals. The latter are due to twinning of orthorhombic crystals and are believed to represent the low-temperature form of chalcocite, formed below 105° C (Buerger, 1941). Touwaide also describes massive secondary chalcocite formed by accretion on the initial grains and needles.

The other copper minerals in the sulfide zone are chalcopyrite, bornite, and covellite, all found in small quantities as fine grains or crystals. Of these, chalcopyrite seems to be most abundant and in some places is in grains large enough to be distinguished with the unaided eye. All these minerals were found by Touwaide (1930, p. 136–137) to replace chalcocite in some places, and the chalcopyrite replaces bornite as well. There is also later chalcocite which replaces chalcopyrite and bornite.

Native copper is found both in the sulfide and oxidized zones. Touwaide (1930, p. 138) found it in the sulfide zone in the Santa Rita mine, associated with zeolites, and in the Montado mine near the oxidation zone as specks on the edge of a grain of bornite. The writers have observed native copper in the oxidized zone as platy crusts in veinlets of gypsum, and in the sulfide zone as plates along slickensided surfaces in the clayey tuff.

Pyrite exists in small crystals in certain parts of the district, but it is generally not common. Galena was noted by the writers to be concentrated in part of the ore from the Carmen mine of the Providencia group. It is probably the source of the secondary lead minerals in the oxidized zone in other parts of the district. No primary zinc minerals have been identified, although considerable quantities of zinc are present in the ore.

ORE MINERALS IN THE OXIDIZED ZONE

The oxidized zone has yielded a wide variety of secondary minerals of copper, lead, iron, and manganese, and to a lesser extent of cobalt, zinc, and silver. The copper minerals include oxides, carbonates, silicates, and oxychlorides, of which the most common are chrysocolla, azurite, malachite, atacamite, melaconite, and cuprite, and the bulk of the oxidized ore consists of mixtures of these minerals.

Several samples of oxidized ore were collected by the writers from the near-surface mines and studied by microscopic and chemical methods by Charles Milton and by X-ray methods by J. M. Axelrod. These samples were collected from the Sin Nombre mine in Arroyo del Montado, from the stockwork deposits in the Comondú volcanics on the southwest side of Cerro de Juanita, from the San Pedro, Santa Teresa, and El Bajío mines in Arroyo del Boleo, and the Dos de Abril, El 160, and La Testera mines in Cañada de la Gloria.

These studies show the dominant oxidized copper mineral to be chrysocolla, accompanied in some specimens by azurite, malachite, and atacamite. The accompanying minerals are principally montmorillonite and oxides of manganese and iron, in addition to calcite, gypsum, barite, and opaline silica, in part crystallized to quartz.

The chrysocolla, present in practically all the samples studied, is green, bluish green, or light blue. It commonly impregnates the montmorillonite clay matrix and also forms thin bluish-green veinlets in the montmorillonite. The atacamite is in part green and massive, and in part occurs as small rosettes 2 to 3 millimeters long coating gypsum. The rosettes have a black exterior, but the interior is the normal bright green. Polysynthetically twinned crystals of atacamite from the Boleo district have been described in detail by Ungemach (1911). Some of the azurite, which is light blue to dark blue, is well crystallized, and some of the crystals are partly altered to green malachite. Cuprite, consisting of small transparent perfect cubes, as well as octahedrons, has been described by Lacroix (1898, p. 44).

Manganese and iron oxides are in nearly all samples of the oxidized ore. The specimens studied by Milton and Axelrod include waxy-black amorphous iron and manganese oxides, hard, heavy, black amorphous manganese dioxide containing a little copper and iron, and soft, black manganese dioxide. In samples from the Dos de Abril mine, manganese dioxide impregnates the green montmorillonite, changing the color to a sharply contrasting lustrous black. Judged from chemical and X-ray studies of the manganese minerals of the adjacent Lucifer district, the principal manganese minerals of the Boleo district are probably cryptomelane, which is massive or fine-grained and incoherent, and pyrolusite, which occurs in minute crystals (Wilson and Veytia, 1949, p. 211). The rare manganese and copper oxide called crednerite has also been reported from the district by Fuchs (1886a, p. 82; 1886b, p. 415) and Saladin (1892, p. 18). Iron oxides are also common in the ore beds, but they have not been studied and have been classified simply on the basis of appearance as hematite and limonite.

Perhaps the most notable minerals are the extremely rare boléite, pseudoboléite, and cumengite, all oxychlorides of lead and copper (with, in addition, some silver chloride in boléite), which were first described from the Boleo district. Boléite has since been found also in Chile and in New South Wales, but pseudoboléite and cumengite have not been identified elsewhere, so far as known.

These minerals occur as small, blue euhedral crystals; cumengite has a tetragonal pyramidal form and boléite and pseudoboléite have an external cubic shape, although the latter two are both tetragonal and owe their pseudocubic appearance to complex twinning. In boléite the center of the crystal is isotropic and the outer part is anisotropic. The minerals commonly occur in parallel intergrowths. Boléite was named by Mallard and Cumenge (1891a, 1891b), cumengite by Mallard (1893), and pseudoboléite by Lacroix (1895). The minerals were described in most detail by Friedel (1906). The very complex nature of the crystals has made them the special object of crystallographic studies by Wallerant (1898), Friedel (1906, 1930), Hadding (1919), Gossner (1928, 1930), Gossner and Arm (1929), Hocart (1930, 1934), and Bellanca (1941).

These minerals were all found in a fairly small area in ore bed no. 3, in the Amelia mine near the Cumenge shaft. The locality was exhausted many years ago and the shaft has long since caved. A few specimens of these minerals may occasionally be found on the dumps, but probably most of the existing specimens are now in museums.

Another unusual mineral from the Boleo district is a pink cobaltiferous smithsonite, described by Warren (1898), which consists of crystalline particles of a delicate pink, embedded in gypsum and associated with atacamite. This mineral was named cobaltsmithsonite by Bilibin (1927, p. 34, 36) and warrenite by Boldyrev (1928, p. 162), although these names have not gained general acceptance. Two other cobalt minerals have been reported from the Boleo district, spherocobaltite and rémingtonite, although it is not certain that the latter is a distinct species.

The lead minerals anglesite, cerussite, phosgenite, and pyromorphite have all been found in association with the boléite group of minerals, but they do not occur in commercial quantities. The anglesite was analyzed by Genth (1893) and was found to be a mechanical mixture of gypsum and anglesite, believed to be pseudomorphic after material having an original composition of $2PbSO_4.CaSO_4$, not yet observed in its original condition. The phosgenite is found in groups of small prismatic crystals (Mallard and Cumenge, 1891b, p. 283). The pyromorphite consists of yellowish-orange crystals surrounded by crystals of gypsum, according to Lacroix (1898, p. 43–44).

A few other minerals that have been listed from Boleo are not generally accepted. Venerite, a cupriferous chlorite reported by Fuchs (1886a, p. 82; 1886b, p. 415), is considered in Dana's "System of mineralogy" (6th edition, p. 711) to be a heterogeneous substance and is not listed in Dana's "Textbook of mineralogy." Bouglisite is a name given by Cumenge (Lacroix, 1895, p. 42) to anglesite impregnated by gypsum, representing the material analyzed by Genth (1893). Percylite was listed by Lacroix (1895) as one of the boléite group of minerals, but work by later investigators (Friedel, 1906, and others) shows that it is distinct from the members of that group occurring at Boleo (boléite, pseudoboléite, and cumengite).

GANGUE MINERALS

The gangue minerals include the normal rock-forming constituents of the tuffaceous ore beds, alteration products of these rock-forming minerals, and extraneous minerals deposited from circulating solutions. In the high-grade ore beds, alteration has proceeded to such an extent that the original rock-forming constituents of the tuff have been almost completely destroyed, although pseudomorphic areas testify to their former presence. In thin-section and mineral grain studies of the tuff and ore, the main rock-forming minerals have been identified as augite, "basaltic" hornblende, common hornblende, biotite, and feldspars, of which the commonest varieties seem to be andesine and andesine-labradorite, along with very sparse quartz and minor apatite, magnetite, and garnet.

The bulk of the gangue is composed of clay minerals, formed by the alteration of the rock-forming minerals and glass of the original tuffaceous rock making up the ore beds. Specimens of clay minerals collected by the writers have been studied microscopically by C. S. Ross, Charles Milton, and Jewell J. Glass, as well as by thermal analysis by George T. Faust, and by X-ray analysis by J. M. Axelrod, all of the U. S. Geological Survey. Although these studies are not entirely conclusive, they indicate that the dominant mineral is a member of the montmorillonite-saponite or montmorillonite-beidellite group, and it is considered most likely to be montmorillonite, according to the studies by Ross and Milton. In the sulfide ore the montmorillonite is generally light to dark gray, but in the samples of oxidized ore studied by Milton it has a variety of colors. It is most commonly cream colored to brown, but is in places also pink, green, buff, or waxy black.

Additional secondary minerals identified by these studies by the Geological Survey are halloysite, celadonite in one sample, allophane (?), calcite, dolomite, gypsum, barite, epidote, chlorite, opal, which is partly crystallized to quartz, and an unidentified material, probably a zeolite. Other minerals reported by Touwaide (1930, p. 132–134) include kaolinite and the zeolites heulandite and brewsterite (?). Krusch (1899, p. 84) described the secondary minerals opal and magnesite, the latter of which he found to contain some strontium, calcium, and copper.

Aside from the clay minerals and the oxides of manganese and iron, the most abundant gangue minerals are gypsum, calcite, chalcedony, and jasper. These occur chiefly in veinlets deposited from circulating solutions, although calcite and chalcedony are also found as alteration products in the groundmass of the tuffaceous ore beds. Gypsum is found not only in veinlets but also in distinct euhedral crystals, which have been described by Lacroix (1898, p. 44). In one of the samples studied by Milton the gypsum is quite pure fibrous selenite, coated with atacamite. Jasper forms fairly large lenslike bodies and veinlets that cut across the beds, and it is found also in veinlets in the Comondú volcanics.

Less common gangue minerals are barite, found by Milton to be occluded in the montmorillonite matrix, and celestite, reported by Touwaide (1930, p. 134). Native sulfur in small crystals and crystalline aggregates associated with melaconite was described by Krusch (1899, p. 84). A peculiar constituent of the ore is halite, which has been found by chemical analyses to be widespread in the tuff and which was recognized also by chemical analyses and X-ray studies in the Lucifer manganese ores (Wilson and Veytia, 1949, p. 212). The halite may have been deposited from the sea water that once permeated the tuffs. Anhydrite is a constituent of the large gypsum masses that in places underlie and are penetrated by the ore beds.

MINERAL GRAIN STUDY

A mineral grain study of three specimens of dominantly sulfide ore from the San Luciano mine was made by Jewell J. Glass of the Geological Survey. Her description of the method of treatment and of the results is quoted below:

> The specimens are dull-gray, very fine grained earthy lumps that appear to be dried-out, silty material. The powdered material bears a strong resemblance to portland cement.
>
> Each of the samples was crushed down to a powder, screened carefully, and separated into heavy and light fractions by use of heavy solutions. Some of the material was studied before washing with water in order to observe any water-soluble minerals present; some was washed with water to remove dust, leaving clean grains for study; some was treated with dilute hydrochloric acid to remove carbonate. The heavy fraction constituted approximately 1 percent of the sample, and all the minerals in this fraction occurred in minute quantities. Much of the material is too fine grained and opaque to be resolved under the microscope; this may account for the source of elements in the chemical analyses otherwise not accounted for. The minerals observed in the light and heavy fractions are listed in table 15.

TABLE 15.—*Minerals identified in mineral grain study of three specimens of ore from San Luciano mine*

[Identification by Jewell J. Glass]

	A	B	C
Light fraction; minerals with specific gravity less than 2.8			
Montmorillonite-beidellite	×	×	×
Halloysite	×	×	×
Calcite	×	×	×
Andesine-labradorite [1]	×	×	×
Quartz [2]	×	----	----
Gypsum [3]	×	----	----
Heavy fraction; minerals with specific gravity greater than 2.8			
"Basaltic" hornblende [4]	×	×	×
Common hornblende	×	×	×
Garnet (n=1.755)	×	----	----
Epidote	×	×	×
Pyrite	×	×	×
Dolomite	×	×	×
Biotite	×	×	×
Chlorite	×	----	----
Magnetite	×	×	----
Copper carbonate [5]	×	×	×
Covellite? [6]	×	×	×
Miscellaneous [7]	×	×	×

[1] Calcic plagioclase (andesine-labradorite). Zoning distinct. Abundant, roughly 10 percent of sample.
[2] Quartz is very sparse. Only a few grains were observed in one sample.
[3] Gypsum occurs in tiny aggregates of fibrous crystals on the surface of specimen A.
[4] Reddish-brown hornblende; reacts for titanium.
[5] Blue carbonate; reacts for copper; appears to be an alteration product of some other mineral.
[6] Indigo-blue, metallic luster; thin plates; reacts for copper.
[7] An unidentified black nonmagnetic mineral was noted in all three specimens. A few black sootlike inclusions in the dry mud of specimen B reacted for MnO.

CHEMICAL COMPOSITION OF THE ORE

CHEMICAL ANALYSES

Chemical analyses of the principal constituents of Boleo copper ores are given in table 16, which is a compilation, from various sources, of 28 analyses made at different times from 1884 to 1946. The earlier analyses given in this table are of samples of high-grade ore—containing more than 15 percent of copper—mined before the advent of the Compagnie du Boléo in 1885, and the later analyses are more representative of the district as a whole. The averages given in the last line of the table are merely the averages of the particular analyses listed and are not necessarily true

TABLE 16.—*Analyses of copper ore from the Boleo district, in weight percent* [1]

No.[2]	Source of sample and year of analysis	SiO_2	Al_2O_3	FeO[3]	MnO	MgO	CaO	CuO	PbO	ZnO	NiO, CoO, ZnO	NaCl	S	SO_3	CO_2[4]	H_2O	Loss on ignition	Total	Cu
1	Olvido mine (1884)	23.00	10.60	10.80	9.66			26.60	tr.	0.60		6.40		0.32			10.00	97.98	21.28
2	Huyar mine (1884)	16.80	8.80	12.60	22.00			15.60	0.25	1.80		.16					20.30	98.31	12.48
3	Sontag mine (1884)	16.30	7.00	7.20	24.00		2.24	15.83				.20			1.76		24.00	98.53	12.66
4	Bompland mine (1884)	22.60	10.00	9.00	11.00		1.68	20.74				.50			1.32		22.00	98.84	15.59
5	Emma mine (1884)	25.00	12.08	3.42	15.00		2.15	15.00				5.10		1.47	.88		10.00	90.10	12.00
6	Prosperidad mine (1884)	28.00	14.30	3.60	7.00		1.66	19.00		1.20		.83		.76	.88		22.00	99.23	15.20
7	Average of 180 samples from all mines (1884)	22.00	10.50	7.78	14.75		1.27	18.45	tr.	.60		2.20		.32	.81		19.55	98.23	15.00
8	Ore mined, of average grade (1886?)	29.34	7.61	5.50	2.47	2.80	2.40	9.28					1.62			25.11	12.58	98.71	7.34
9	Do	25.94	1.76	11.64	12.61	1.89	3.17	9.84					.36			18.35	13.37	98.93	7.86
10	Do	22.85	2.04	12.50	11.08	3.21	3.21	9.86					.62			25.	11.05	101.42	7.89
11	Do	22.80	4.38	10.08	7.20	4.43	6.16	7.50					3.03			20.	14.56	100.14	6.82
12	Typical analysis (1917)	31.1	7.1	6.1	4.0	3.2	2.2	6.7					1.7			28.3	9.4	99.8	5.3
13	Composite of smelting ore (May–August 1923)	27.37	8.21	7.42	3.25	3.02	3.53	6.13			[5] 0.46		1.73	.52		28.00	8.87	98.51	4.90
14	Averages of ore mined (1926)	27.14	8.36	5.96	3.74	3.37	2.99	6.16			.56		1.65	.55		27.00	10.26	97.74	4.92
15	Average smelting ore (August 1931)	25.86	7.17	6.28	4.74	4.46	4.98	6.72					1.09	4.57		24.	10.22	100.09	5.37
16	Sulfide ore (1931)	29.86	8.56	12.21	3.83	4.76	4.12	4.68			.34		1.16	.59		28.00	7.09	105.20	4.68
17	Oxidized siliceous ore (1931)	39.82	.96	17.46	.51	.78	4.54	11.37			.26		.14			22.00	6.85	104.69	9.09
18	Do	33.91	8.10	5.93	4.89	2.42	1.81	6.35			.38		.49			31.00	5.92	101.20	5.12
19	Do	37.20	13.39	5.25	7.17	.66	2.78	2.61			.22					24.00	7.64	100.92	2.10
20	Oxidized ordinary ore (1931)	30.58	11.80	7.41	5.38	1.46	4.87	10.67			.18			.69		21.00	7.74	101.78	8.53
21	Do	21.83	6.56	6.30	4.10	.69	8.42	12.52			.38		.10	3.41		25.00	10.74	100.05	10.01
22	Manganiferous ore (1931)	20.98	2.64	7.00	23.40	1.37	2.69	8.80			1.95		.06	tr.		19.00	10.92	98.81	7.02
23	Sulfide ore (1931)	42.36	12.57	11.82	3.53	4.76	5.57	6.33			.46		1.53	.80			9.58	99.31	5.06
24	Oxidized ore (1931)	51.06	3.24	17.40	.68	3.00	6.83	9.58			.33		.19				8.76	101.07	7.65
25	Manganiferous oxidized ore (1931)	28.89	1.26	4.72	29.21	1.69	3.32	10.87			.40		.07				13.48	93.91	8.68
26	Typical ore (1934)	30.35	9.20	6.57	4.39	7.60	4.44	7.84	none	2.17	(6)		.91	6.03	1.42	13.09		95.46	6.26
27	San Luciano mine, sulfide ore (1946)	34.00	4.80	4.50	2.00	1.30	4.20	5.26					2.50	1.00		29.20	11.50	100.26	4.20
28	San Luciano mine, oxidized ore (1946)	32.00	5.00	6.48	3.00	1.05	2.10	4.76					.20	3.25		26.00	13.40	97.24	3.80
	Average	28.53	7.43	8.32	8.74	2.76	3.59	10.54		1.27	0.49	2.20	1.01	1.73	1.18	24.11	12.29		8.46

[1] Many of the constituents of the original analyses have been recalculated to a uniform basis.

[2] Analyses Nos. 1 to 7 from Fuchs (1886a, p. 85; 1886b, p. 419); Nos. 8 to 11 from Saladin (1892, p. 22); No. 12 from Duncan (1917, p. 416); No. 13 from Locke (1935, p. 411); No. 14 from Touwaide (1930, p. 129); No. 15 from an unpublished analysis by the Boleo chemical laboratory; Nos. 16 to 22 from Peña (1931, p. 172); Nos. 23 to 25 from Bellanger (1931, p. 772); No. 26 from an unpublished analysis by Abbot A. Hanks, Inc.; Nos. 27 and 28 from Villafaña and others (1947, p. 298). References are to publications, listed by authors, at the end of this report.

[3] Includes Fe_2O_3 calculated as FeO.

[4] CO_2 in analyses 3 to 7 calculated from reported $CaCO_3$.

[5] NiO, CoO, Mo.

[6] Ni, trace; Co, 0.58; As, 0.03; Sb, 0.02.

averages of the general run of ore. Averages based on additional data for some constituents are given later. These analyses are on a wet basis, as are all the ensuing data and analyses, except where otherwise indicated.

A chemical analysis made by the U. S. Geological Survey of a composite sample of low-grade copper ore collected in 1947 from the San Luciano mine, in the sulfide zone of ore bed no. 1, is given in table 17, on a dry basis. A qualitative spectrographic analysis of the same sample is given in table 18.

TABLE 17.—*Analysis of a composite sample of copper ore from San Luciano mine, Boleo copper district*

[Dry basis at 110° C. Analyzed by Israel Warshaw and Charlotte Warshaw, U. S. Geological Survey, 1949]

	Percent		Percent
SiO_2	44.51	K_2O	1.20
Al_2O_3	13.46	TiO_2	.53
Fe_2O_3	1.75	P_2O_5	.08
FeO	2.02	CO_2	6.32
FeS_2	1.37	SO_3 [1]	2.36
MnO	4.18	H_2O+	2.90
CuO	2.28	H_2O- (at 110° C)	[2] 12.22
ZnO	.61		
CaO	7.50	Total	99.66
MgO	6.61	Total S	1.68
Na_2O	1.98	Cu	1.82

[1] Total S as SO_3 exclusive of FeS_2. [2] Not included in total.

TABLE 18.—*Qualitative spectrographic analysis of a composite sample of copper ore from San Luciano mine, Boleo copper district*

[Analyzed by K. J. Murata, U. S. Geological Survey, 1948]

Relative order of percent	Elements
1 percent or more	Si, Al, Ca, Mg, Mn, Fe, Na, and Cu
0.X percent	Ti and Zn
0.0X percent	Sr, Co, Ni, V, and Ba
0.00X percent	Zr, Y, Pb, and Mo
0.000X percent	Cr, Ag, and Be
Looked for but not found	As,[1] Sb,[1] Sn, Tl, Cd, Ga, In, Bi, W, Re, Ge, Au, Pt, Pd, U, and Th

[1] The sample had to be ignited before it could be analyzed; this may have resulted in the loss of As and Sb.

Some samples of ore collected by the senior author in 1948 for the purpose of metallurgical experiments were analyzed by the U. S. Bureau of Mines for copper, lime, manganese, cobalt, nickel, molybdenum, silver, and gold. The results of these analyses are presented in table 19.

Since the gangue or host rock of the Boleo copper ore is a clay composed largely of montmorillonite and related minerals, analyses of the ore were compared with average analyses of the montmorillonite minerals. This comparison has been made in table 20, in which the averages have been calculated of all the available analyses of Boleo copper ore, and an average analysis of montmorillonite has been calculated from 54 analyses of minerals of the montmorillonite-beidellite series published by Ross and Hendricks (1945, table 1, p. 34). The averages have been recalculated to 100 percent to give a better basis for comparison.

TABLE 19.—*Partial analyses of some ore samples for copper, manganese, and certain metals occurring in minor quantities in the Boleo copper district*

[Dry basis. Samples collected by Ivan F. Wilson; analyzed by U. S. Bureau of Mines, Metallurgical Division, Salt Lake City, Utah, 1948]

	Fill in old stopes; ore bed no. 3		Sulfide ore; ore bed no. 3	Low-grade manganese ore; ore bed no. 4	Low-grade manganiferous copper ore; ore bed no. 4	Average smelting ore; May 27, 1948
	Providencia mine	San Fernando mine	La China mine	Dos de Abril mine	El 160 mine	All mines
Cu (percent)	4.9	6.9	4.5		0.63	5.6
Cu as oxides (percent)	4.4	5.2	1.3			
Insoluble (percent)	45.0	47.0	57.3	62.1	13.5	46.1
CaO (percent)	2.3	2.2	1.6			
Mn (percent)	2.8	2.6	1.1	7.6	16.4	3.2
Co (percent)	.10	.12	.15	.071	.075	.13
Ni (percent)	<.01	<.01	.02			.01
Mo (percent)	<.01	<.01	<.01	<.01	<.01	<.01
Ag (grams per ton)	7	10	12			7
Au (grams per ton)	<.2	<.2	<.2			<.2
Specific gravity [1]	2.2	2.1	2.1	2.4	2.5	2.5

[1] Average of Jolley balance and water displacement methods.

The constituents that are most notably higher in the ore than in the montmorillonite minerals are copper and manganese, and to a lesser extent iron. The content of moisture, carbon dioxide, chlorine, sulfur trioxide, zinc, and cobalt is also higher in the ore than in the average montmorillonite. The content of silica and of alumina, however, is considerably lower in the ore than in the clay minerals. The remaining constituents listed in table 20 show no very significant differences in their proportions.

TABLE 20.—*Comparison of analyses of Boleo copper ore with those of minerals of the montmorillonite-beidellite series*

Constituent	Average of analyses of Boleo copper ore	Number of analyses	Average of analyses of minerals of the montmorillonite-beidellite series [1]	Number of analyses
SiO_2	26.39	29	49.22	54
Al_2O_3	6.92	29	19.38	54
FeO [2]	7.46	29	2.86	52
MnO	7.62	35	.08	12
MgO	2.65	22	3.86	54
CaO	3.22	30	1.54	50
K_2O	.96	1	.46	31
Na_2O	1.13	8	.76	33
CuO	5.50	many	.01	1
ZnO	.91	130	.10	1
CoO	.14	126	.12	1
NiO	.05	7	none	1
CO_2	1.64	7	.36	1
TiO_2	.42	1	.34	27
Cl	1.21	7	.28	1
P_2O_5	.06	1	.26	8
SO_3	1.61	16	.28	5
C	.20	5	.18	2
H_2O+	20.98	19	7.96	34
H_2O-	11.22	28	12.02	34
	100.29		100.07	
Less O for Cl	.29		.07	
Total	100.00		100.00	

[1] Averages calculated by the writers from 54 analyses of minerals of the montmorillonite-beidellite series given by Ross and Hendricks (1945, table 1, p. 34).
[2] Includes Fe_2O_3.

The high content of moisture is a notable feature of the ore. In the analyses listed, the content of H_2O ranges from 2.5 to 31 percent and averages 23 percent, besides an average ignition loss of 12 percent, which includes water, carbon dioxide, and carbon. Further data on this subject were obtained from a series of 240 average monthly analyses of the moisture content of the ore shipped from each of the principal mines from 1935 to 1942. The moisture content in these shipments ranged from 12.5 to 32.5 percent and averaged 24.3 percent. It averaged 27.0 percent in the Ranchería mine, 25.8 percent in the San Luciano mine, 23.5 percent in the Santa Rita mine, 21.2 percent in the Purgatorio mine, and 23.4 percent in the ore produced from other mines during that period. The ore loses a considerable part of its moisture upon exposure to the atmosphere, and it is said that the ore as first mined contained at least 5 percent of H_2O more than that indicated by the analyses. In the San Alberto dump, which has been exposed on the surface for more than 30 years, the moisture content averages 19.5 percent.

The content of sodium chloride is exceptionally high in Boleo ores. In the analyses given, the content of NaCl ranges from 0.16 to 6.40 percent and averages 2.20 percent. A high content of sodium chloride was also noted in Lucifer manganese ores, 15 analyses of which showed a trace to 4.85 percent of NaCl and an average of 1.22 percent.

The sulfur content of the ore ranges from 0.06 to 3.98 percent and averages 1.40 percent in the 39 analyses available. The content of sulfur is considerably higher in the sulfide ore than in the oxidized ore. The results of 19 analyses of shipments from different mines in 1940, for example, showed that the mines in the sulfide zone averaged 2.84 percent of sulfur, while those in the oxidized zone averaged 0.63 percent. The content of sulfur trioxide in 16 samples of ore ranged from a trace to 6.03 percent and averaged 1.76 percent. The SO_3, which occurs mostly in gypsum, is more abundant in the oxidized zone than in the sulfide zone. It is particularly abundant in the northern part of the district, in the Santa Rita mine.

The amount of organic carbon in five run-of-mine and general smelter feed samples was determined by the U. S. Bureau of Mines in Salt Lake City. The samples were analyzed by two different methods, to eliminate from the result the carbon present in carbonates. These samples contained 0.12 to 0.37 percent of carbon and averaged 0.22 percent, as indicated below:

	Percent of organic carbon
San Luciano mine	0.19
La China mine	.13
Ranchería mine	.30
General smelter feed, May 27, 1948	.12
General smelter feed, December 29, 1948	.37

These figures contrast with the results obtained by Locke (1935, p. 411), who reported 3 percent of carbon in two analyzed specimens. It may be that the carbon content is quite variable in different parts of the ore beds.

DISTRIBUTION OF ZINC

A special study was made of the distribution of zinc in the Boleo ores. In 1948 the senior author witnessed considerable excitement at Santa Rosalía over the possibility that the Boleo district might become a zinc-producing one. Certain commercial analyses had indicated a phenomenally high content of zinc in the Boleo ores, and the question of whether large quantities of zinc had been overlooked during 60-odd years of mining copper ores, or whether the analyses were unreliable, needed to be resolved.

With the cooperation of H. G. Poole of the U. S. Bureau of Mines, 34 smelter feed samples of Boleo ores were sent to the Bureau in Salt Lake City for analysis.

These samples represented all the mines in the district that were being operated in 1948; they included ore from beds nos. 1, 3, and 4 and from both the sulfide and oxidized zones. Zinc analyses were also obtained for 19 underground samples collected by G. M. Potter of the Bureau of Mines, mostly from fill in the old stopes in ore bed no. 3.

Later, in order to obtain further data on the copper-zinc relationship, the senior author carried out systematic sampling of all the mines that were being operated in the sulfide zone, both in ore beds no. 1 and no. 3, and collected 66 samples from 19 localities. At each locality the ore bed was sampled in 3 or 4 places from bottom to top, including in some localities the adjoining footwall and hanging-wall material.

Altogether, 119 analyses for zinc were made by the Bureau of Mines. These and 11 analyses from other sources give a total of 130 analyses available. S. R. Zimmerley, in charge of the Salt Lake City Branch of the Bureau, who kindly furnished the analyses, states that the Boleo ores presented unusual difficulties for zinc analysis because of the interference of other constituents. This may have led to erratic results of high zinc content in the commercial analyses. Many of the analyses made by the Bureau were checked by two different methods, and the final results are considered to be reliable.

The results of these analyses indicate that zinc is very widely distributed in the Boleo district but is seldom concentrated to the same degree as copper, and very little of the material analyzed could be considered as commercial zinc ore. The average of the 130 analyses was 0.80 percent of zinc, and only 30 samples contained more than 1 percent. The highest content was 6.0 percent and the lowest was <0.05 percent. A sample of the general smelter feed for December 29, 1948, contained 0.50 percent of zinc, and a sample of the smelter slag for the same date contained 0.25 percent. Zinc is concentrated in the flue dust of the smelter—six analyses showed 8.8 to 19.5 percent of zinc—and the possibilities for its recovery there warrant consideration.

This study revealed some relations in the distribution of copper and zinc in the ore beds of the Boleo district which had not previously been known. In most of the localities sampled where a well-defined relation exists between the two metals, the zinc to copper ratio is much higher in the hanging-wall part of the ore bed. At one locality in the Ranchería mine, for example, two samples from the lower part of the ore bed showed 4 to 13 times as much copper as zinc, while two samples from the higher relatively barren hanging wall showed 4 to 7 times more zinc than copper. In a locality in the El Cuarenta mine the main ore bed showed 16 times as much copper as zinc, while the hanging wall contained 11 times more zinc than copper. In part of the San Luciano mine the footwall and main ore bed had 12 to 26 times as much copper as zinc, while the hanging wall had 6 times more zinc than copper.

A similar relation was found in 10 of the 19 localities sampled in detail. Only 1 locality showed the opposite relation, and no definite relation could be observed in 8 localities where the zinc was scattered more or less uniformly through the bed from top to bottom and generally occurred in very small quantities. It is noteworthy also that a composite sample from the San Alberto dump showed 3.22 percent of zinc as compared to 1.45 percent of copper. This dump is composed largely of material from the hanging wall of ore bed no. 3.

The average copper to zinc ratio of 125 recent analyses for both metals is 5.86 to 1, but the extremes are as high as 194 to 1 in the lower part of the ore bed of the San Luciano mine, and as low as 0.09 to 1 (11 times as much zinc as copper) in the upper hanging wall of the El Cuarenta mine. Of the 15 samples that showed more zinc than copper, 12 were in the hanging wall and 3 in the footwall of the ore beds.

All the recent analyses for zinc are assembled in table 21, which gives also the copper content and the copper to zinc ratio for each sample.

TABLE 21.—*Analyses for copper and zinc in ores of the Boleo copper district*

No.[1]	U. S. Bureau of Mines laboratory no.	Percent		Ratio	Locality [2]
		Cu	Zn	Cu : Zn	
			Smelter feed samples		
1	76923	2.90	0.55	5.3	San Agustín mine, ore bed no. 3.
2	76924	3.90	2.20	1.8	Rosalba mine.
3	76925	3.90	1.50	2.6	Alhambra mine, ore bed no. 1.
4	76926	5.70	.35	16	San Fernando mine, ore bed no. 3.
5	76927	5.30	.35	15	Dos de Abril mine, ore bed no. 3 or no. 4.
6	76928	6.45	.50	13	La Testera no. 2 mine, ore bed no. 3.
7	76929	4.00	.80	5.0	Cananea mine.
8	76930	3.25	.35	9.3	San Pedro mine, ore bed no. 3 or no. 4.
9	76931	4.35	.60	7.2	El 160 mine, ore bed no. 4.
10	76932	3.55	.55	6.5	Malibrán mine, ore bed no. 3.
11	76933	4.25	.35	12	Providencia mine, ore bed no. 3.
12	76934	4.05	.45	9.0	San Carlos mine, ore bed no. 3.
13	76935	6.30	.85	7.4	San Luciano mine, ore bed no. 1.
14	76936	4.75	.25	19	La China mine, ore bed no. 3.
15	76937	4.05	.40	10	San Carlos no. 1 mine, ore bed no. 3.
16	76938	6.05	.25	24	San Víctor mine, ore bed no. 3.
17	76939	6.55	.45	15	San Francisco mine, ore bed no. 3.
18	76940	3.15	.20	16	San Fernando mine, ore bed no. 3.
19	76941	3.60	.60	6.0	El Cuarenta mine, ore bed no. 1.
20	76942	6.05	.90	6.7	Ranchería no. 2 mine, ore bed no. 1.
21	76943	3.90	.65	6.0	Ranchería mine, ore bed no. 1.
22	76944	3.80	.85	4.5	Ranchería mine, ore bed no. 1.
23	76945	5.25	.60	8.7	La Testera no. 1 mine, ore bed no. 3.
24	76946	5.10	1.10	4.6	San Porfirio mine, ore bed no. 3.
25	76947	4.65	.35	13	Texcoco mine, ore bed no. 3.
26	76948	4.35	.60	7.2	El 160 mine, ore bed no. 4.
27	76949	3.55	.30	12	El 160 mine, ore bed no. 4.
28	76950	7.65	.60	13	Porvenir mine, ore bed no. 3.
29	76951	4.65	.45	10	San Felipe mine, ore bed no. 3.
30	76952	5.45	.55	9.9	Buenos Aires mine.
31	76953	5.10	.95	5.4	Malibrán mine, ore bed no. 3.
32	76954	6.45	1.45	4.4	Malibrán no. 1 mine, ore bed no. 3.
33	76955	8.60	3.55	2.4	Sin Nombre mine, ore bed no. 1.
34	76956	.48	.25	1.9	Smelter slag from reverberatory furnaces.
35	76957	4.50	.50	9.0	General smelter feed, Dec. 29, 1948.

TABLE 21.—*Analyses for copper and zinc in ores of the Boleo copper district*—Continued

No.[1]	U. S. Bureau of Mines laboratory no.	Percent Cu	Percent Zn	Ratio Cu : Zn	Locality[2]
					Mine samples
					SAN FERNANDO MINE, ORE BED NO. 3
36	76100	19.7	0.35	56	Footwall: thin seam.
37	76101	5.25	.35	15	Fill, 1.65 m.
38	76102	5.45	.15	36	Footwall of old fill, 95 cm.
39	76103	5.9	.15	39	Footwall of old fill, 1 m.
40	76104	2.25	.4	5.6	Sulfide ore, 1.6 m.
41	76105	3.0	.1	30	Old fill, 1.8 m.
42	76106	3.5	.3	12	Old fill, 1.8 m.
43	76107	3.05	3.05	1.0	Old fill, 1.3 m.
44	76108	5.5	.1	55	Old fill, 1.35 m
45	76109	4.3	.45	9.6	Old fill, 1 m.
46	76110	2.2	.15	15	Old fill, 1.3 m.
47	76111	4.25	.25	17	Old fill, 1.5 m.
48	76112	5.0	.2	25	Old fill, 1.0 m.
49	76113	4.4	.1	44	Old fill, 80 cm.
50	76114	4.2	.25	17	Old fill, 85 cm.
					SAN VÍCTOR MINE, ORE BED NO. 3.
51	76115	3.55	.75	4.7	Low-grade sulfide ore, 1.0 m.
52	76116	1.35	1.35	1.0	Low-grade sulfide ore, 1.0 m.
53	76117	3.4	3.4	1.0	Low-grade sulfide hanging wall, 65 cm.
54	76118	2.65	2.65	1.0	Low-grade sulfide footwall, 65 cm.
					RANCHERIA MINE, ORE BED NO. 1.
55	80833	.10	.41	.24	Upper hanging wall, 40 cm.
56	80834	.32	2.30	.14	Lower hanging wall, 40 cm.
57	80835	7.94	.63	13	Upper ore, 40 cm.
58	80836	7.85	1.88	4.2	Lower ore, 40 cm.
					EL CUARENTA MINE, ORE BED NO. 1, 43 M-LEVEL, 206 N., 2573 E.
59	85252	6.38	.4	16	Lower ore, 60 cm.
60	85253	4.75	1.15	4.13	Upper ore, 45 cm.
61	85254	.94	.8	1.2	Hanging wall, 30 cm.
					EL CUARENTA MINE, ORE BED NO. 1, 43 M-LEVEL, 214 N., 2578 E.
62	85255	9.55	.6	16	Main ore, 35 cm.
63	85256	1.09	1.55	.70	Lower hanging wall, 80 cm.
64	85257	.13	1.45	.09	Upper hanging wall, 40 cm.
					LA CHINA MINE, ORE BED NO. 3, 38 M-LEVEL, 344 S., 1433 E.
65	85258	3.82	.1	38	Footwall, 50 cm.
66	85259	8.10	.1	81	Main ore, 40 cm.
67	85260	3.42	.45	7.6	Hanging wall, 90 cm.
					LA CHINA MINE, ORE BED NO. 3, 38 M-LEVEL, 346 S., 1425 E.
68	85261	4.05	.1	40	Footwall, 40 cm.
69	85262	6.25	.1	62	Main ore, 40 cm.
70	85263	1.37	.6	2.3	Hanging wall, 65 cm.
					RANCHERÍA MINE, ORE BED NO. 1, —20 M-LEVEL, 402 N., 2964 E.
71	85264	6.66	1.4	4.8	Footwall, 30 cm.
72	85265	5.35	1.05	5.1	Main ore, 40 cm.
73	85266	.65	5.3	.12	Lower hanging wall, 55 cm.
74	85267	.23	1.3	.18	Upper hanging wall, 50 cm.
					RANCHERÍA MINE, ORE BED NO. 1, —20 M-LEVEL, 412 N., 2963 E.
75	85268	14.3	3.85	3.71	Main ore, 35 cm.
76	85269	5.90	1.25	4.72	Lower hanging wall, 65 cm.
77	85270	6.40	1.85	3.46	Upper hanging wall, 50 cm.
					RANCHERÍA MINE, ORE BED NO. 1, —22 M-LEVEL, 403 N., 2970 E.
78	85271	17.6	6.0	2.9	Lower ore, 25 cm.
79	85272	5.57	1.55	3.59	Upper ore, 40 cm.
80	85273	.24	1.3	.18	Lower hanging wall, 60 cm.
81	85274	.16	1.15	.14	Upper hanging wall, 40 cm.
					RANCHERÍA MINE, ORE BED NO. 1, —5 M-LEVEL, 497 N., 2928 E.
82	85275	.15	.6	.25	Footwall, 40 cm.
83	85276	3.50	1.7	2.1	Lower ore, 35 cm.
84	85277	5.55	.85	6.5	Upper ore, 60 cm.
85	85278	.28	1.3	.21	Hanging wall, 50 cm.
					SAN GUILLERMO MINE, ORE BED NO. 3, 15 M-LEVEL, 71 N., 1470 E.
86	85279	.16	.45	.36	Footwall, 30 cm.
87	85280	5.46	.35	16	Lower ore, 60 cm.
88	85281	2.64	.1	26	Upper ore, 70 cm.
89	85282	.26	.15	1.7	Hanging wall, 50 cm.
					SAN GUILLERMO MINE, ORE BED NO. 3, 15 M-LEVEL, 49 N., 1498 E.
90	85283	.13	.4	.32	Footwall, 35 cm.
91	85284	7.47	.2	37	Lower ore, 50 cm.
92	85285	4.72	.3	16	Upper ore, 65 cm.
93	85286	3.24	.65	5.0	Hanging wall, 60 cm.
					SAN GUILLERMO MINE, ORE BED NO. 3, 15 M-LEVEL, 46 N., 1484 E.
94	85287	.56	.3	1.9	Footwall, 60 cm.
95	85288	4.15	.05	83	Lower ore, 80 cm.
96	85289	8.05	.05	161	Upper ore, 80 cm.
					SAN GUILLERMO MINE, ORE BED NO. 3, 15 M-LEVEL, 56 N., 1525 E.
97	85290	.90	.15	6.0	Footwall, 55 cm.
98	85291	10.4	.15	69	Main ore, 35 cm.
99	85292	4.05	.15	27	Lower hanging wall, 1.0 m.
100	85293	4.20	.1	42	Upper hanging wall, 2.0 m.
					SAN LUCIANO MINE, ORE BED NO. 1, —135 M-LEVEL, 4062 S., 4003 E.
101	85294	.28	.1	2.8	Footwall, 75 cm.
102	85295	16.4	.15	109	Main ore, 40 cm.
103	85296	8.93	.45	20	Hanging wall, 45 cm.
					SAN LUCIANO MINE, ORE BED NO. 1, —135 M-LEVEL, 4058 S., 3990 E.
104	85297	.25	.1	2.5	Footwall, 45 cm.
105	85298	9.70	<.05	194	Lower ore, 40 cm.
106	85299	11.1	.1	111	Upper ore, 40 cm.
107	85300	6.37	.35	18.2	Hanging wall, 45 cm.
					SAN LUCIANO MINE, ORE BED NO. 1, —135 M-LEVEL, 4065 S., 4020 E.
108	85301	2.95	.1	29	Footwall, 45 cm.
109	85302	8.97	.15	60	Main ore, 40 cm.
110	85303	3.97	.4	9.9	Lower hanging wall, 50 cm.
111	85304	.06	.15	.40	Upper hanging wall, 35 cm.
					SAN LUCIANO MINE, ORE BED NO. 1, —135 M-LEVEL, 4040 S., 4010 E.
112	85305	1.28	.1	13	Footwall, 50 cm.
113	85306	5.30	.2	26	Main ore, 50 cm.
114	85307	.22	1.3	.17	Hanging wall, 60 cm.
					SAN VÍCTOR MINE, ORE BED NO. 3, 0 M-LEVEL, 857 S., 1552 E.
115	85308	3.62	.3	12	Lower ore, 60 cm.
116	85309	12.7	.15	85	Upper ore, 70 cm.
117	85310	3.02	.4	7.5	Hanging wall, 75 cm.
					SAN VÍCTOR MINE, ORE BED NO. 3, 0 M-LEVEL, 862 S., 1548 E.
118	85311	3.91	.1	39	Lower ore, 50 cm.
119	85312	8.67	<.05	173	Upper ore, 65 cm.
120	85313	6.35	.05	127	Hanging wall, 60 cm.
121	--------	1.45	3.22	.45	San Alberto dump from ore bed no. 3.
122	--------	9.25	2.91	3.18	Texcoco mine, ore bed no. 3, green oxidized ore on dump.
123	--------	1.66	.62	2.7	Texcoco mine, ore bed no. 3, brown oxidized ore on dump.
124	--------		.62	--------	Dos de Abril mine, ore bed no. 3 or 4, dump.
125	--------	2.60	.62	4.2	San Luciano mine, ore bed no. 1.
126	--------	1.82	.49	3.7	San Luciano mine, ore bed no. 1, composite sample.
Average		4.64	0.79	5.87	

[1] Samples 1 to 120 analyzed by U. S. Bureau of Mines, Metallurgical Division, Salt Lake City, Utah. Samples 121 to 125 analyzed by Comisión de Fomento Minero. Tecamachalco, D. F., Mexico. Sample 126 analyzed by U. S. Geological Survey, Samples 1 to 35, 59 to 120, and 126 collected by I. F. Wilson; samples 36 to 54 collected, by G. M. Potter; samples 55 to 58 and 121 to 125 collected by H. G. Poole and I. F. Wilson.

[2] Thicknesses are in meters (m) or centimeters (cm). Levels are in meters above or below sea level. Coordinates are in meters from San Francisco shaft.

METALS PRESENT IN MINOR QUANTITIES

A number of other metals besides copper and zinc occur in the ore in minor amounts, but no attempt has been made to recover any of them except silver, which is found in very minor quantities in the blister copper. Analyses for many of these minor metals have been made in greater detail on certain of the Boleo smelter products than on the ore itself. Analyses, compiled from different sources, of the principal smelter products are presented in table 22.

TABLE 22.—*Analyses of Boleo smelter products, in percent*

No. of analysis [1]	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Type of material	Blister copper	Black copper		Copper matte		Slag		Old slag dump	Flue dust					
									Near boilers	Flue to stack	No locality given	Near boilers	Half way in dust chamber	Foot of stack
Year of analysis	1934	1901	1892	1901	1892	1892	1934	1948	1932	1932	1940	1948	1948	1948
SiO_2	----	------	----	------	----	41.60	49.10	------	8.78	12.46	------	[2] present	[2] present	[2] present
Al_2O_3	----	------	----	------	----	10.26	13.51	------	3.20	9.59	------	present	present	present
MgO	----	------	----	------	----	6.12	}15	{ ------	2.57	4.89	------	present	present	present
CaO	----	------	----	------	----	5.50		------	3.19	7.43	------	present	present	present
Cu	99.30	91.45	96.25	61.52	73.08	.90	.49	1.5	4.74	5.30	4.43	4.6	3.45	3.2
S	.06	1.00	.767	22.52	19.61	----	.10	------	----	----	------	11.5	15.9	17.8
SO_3	----	------	----	------	----	----	----	------	38.10	30.43	------	--------	--------	--------
Fe	.05	3.52	.83	13.68	4.24	12.10	}16	{ ------	5.02	3.71	------	present	present	present
Mn	----	0	tr.	.938	1.05	15.30		5.2	.96	1.45	2.24	present	present	present
Zn	.03	.7182	----	.2333	----	----	----	------	19.01	13.26	19.52	15.5	10.2	8.8
Co	.08	.6200	----	.4140	----	----	----	.13	----	----	tr.	present	present	present
Ni	.32	.1576	----	.0645	----	----	----	<.01	.50	.42	.31	present	present	present
Pb	.01	.1322	----	.0270	----	----	----	------	----	----	2.20	3.25	1.9	1.8
P	----	.18	----	.019	----	----	----	------	----	----	------	absent	absent	absent
Sb	tr.	.0128	0	.0032	0	----	----	------	----	----	------	<.1	<.1	<.1
As	tr.	.0197	0	.0013	0	----	----	------	----	----	tr.	<.1	<.1	<.1
Bi	tr.	.0030	----	.0008	----	----	----	------	----	----	.27	present	present	present
Ag	.02	.022	----	.0075	----	----	----	<.0003	----	----	.0088	present	present	present
Au	tr.	tr.	----	tr.	----	----	----	<.00002	----	----	.00007	absent	absent	absent
Cd	----	------	----	------	----	----	----	------	----	----	.13	.12	.09	.08
V	----	------	----	------	----	----	----	------	----	----	.06	present	present	present
U	----	------	----	------	----	----	----	------	----	----	------	.05	.04	.04
Cr	----	------	----	------	----	----	----	------	----	----	.03	absent	absent	absent
Tl	----	------	----	------	----	----	----	------	----	----	------	.012	.013	.013
Mo	----	------	----	------	----	----	----	<.01	----	----	.01	present	present	present
Na	----	------	----	------	----	----	----	------	----	----	------	present	present	present
K	----	------	----	------	----	----	----	------	----	----	------	present	present	present
Sn	----	------	----	------	----	----	----	------	----	----	------	present	present	present
Ba	----	------	----	------	----	----	----	------	----	----	------	absent	present	present
Sr	----	------	----	------	----	----	----	------	----	----	------	absent	present	present
Ti	----	------	----	------	----	----	----	------	----	----	tr.	tr.	tr.	tr.
In	----	------	----	------	----	----	----	------	----	----	tr.	present?	present?	present?
Ge	----	------	----	------	----	----	----	------	----	----	tr.	absent	absent	absent
Ga	----	------	----	------	----	----	----	------	----	----	tr.	absent	absent	absent
Miscellaneous	----	(3)	2.153	(3)	2.02	----	----	[4] 76.6	[5] 5.42	[5] 4.20	(6)	(7)	(7)	(7)

[1] Analyses Nos. 1, 7, 9, and 10 by Boleo chemical laboratory; Nos. 2 and 4 from Keller (1901, p. 243); Nos. 3, 5, and 6 from Saladin (1892, p. 41); No. 8 by U. S. Bureau of Mines, Metallurgical Division, of sample collected by Ivan F. Wilson; No. 11 by Abbot A. Hanks, Inc.; Nos. 12, 13, and 14 by U. S. Bureau of Mines, Metallurgical Division, of samples collected by George M. Potter.

[2] Presence or absence of elements in Nos. 12, 13, and 14 determined by spectrographic analysis.

[3] Te and Se determined to be absent.

[4] Insoluble.

[5] Includes C, CO_2, CoO.

[6] Pt group determined to be absent.

[7] Absent, according to spectrographic analysis: Hg, Pt, Hf, Li, Ru, Te, Be, Ir, Cb, Y, Ta, Rh, Zr, W, Th.

Cobalt occurs in noticeable quantities in Boleo ores but has not been recovered. In order to ascertain the distribution of cobalt in Boleo ores, samples 1 to 120 listed in table 21 were analyzed for cobalt by the U. S. Bureau of Mines. These, together with seven previous analyses, indicate a range of less than 0.02 to 0.86 percent of cobalt, averaging 0.12 percent. Two samples of the general smelter feed collected in May and December, 1948, showed 0.13 and 0.12 percent of cobalt. Nineteen samples showed more than 0.2 percent of cobalt, and three samples contained more than 0.5 percent. The highest grade samples were from the Ranchería mine. The two samples that were highest in cobalt were also high in copper, but otherwise no definite relation was found between the amount of cobalt and the amount of copper or zinc.

Analyses of several kinds of smelter products for copper, cobalt, and nickel made by the Boleo chemical laboratory in 1934 are presented in table 23. These, together with several additional analyses, indicate that slag from the reverberatory furnaces contains 0.05 to 0.28 percent of cobalt, flue dust contains 0.03 to 0.53 percent, the copper matte contains 0.40 to 0.43 percent, and the blister copper contains only 0.005 to 0.08 percent.

More recent analyses by the U. S. Bureau of Mines indicate that the converter slag contains 0.5 to 4.0 percent of cobalt, many samples containing between 1 and 2 percent. Also a metallic iron alloy that accumulates in the bottom of the reverberatory furnaces has been found to contain 10 to 20 percent of cobalt. The problem of possible recovery of cobalt in the Boleo smelter is being investigated by the Bureau of Mines at the time of this writing.

TABLE 23.—*Analyses of some Boleo smelter products for copper, cobalt, and nickel, in percent*

[Analysis by Boleo chemical laboratory, 1934]

	Cu	*Co*	*Ni*
Ore in reverberatory furnaces	4.47	0.33	[1] 0.05
Copper matte from reverberatory furnaces	54.24	.40	.32
Blister copper from converters	99.30	.08	.32
Slag from reverberatory furnaces	.20	.28	[1] .05
Flue dust, in boilers	9.35	.53	.22
Flue dust, 30 meters from boilers	4.45	.20	----
Flue dust, half way to stack	2.03	.17	----
Old flue dust, near stack; outside for several years	2.18	.32	----

[1] Estimated.

Very few analyses of Boleo ores are available for *lead*, which is believed to range considerably in amount, for in some analyses it is reported to be absent or present only in traces, and yet in certain ores the lead minerals are conspicuously visible to the unaided eye. The only analyses in table 16 in which lead was analyzed indicate a trace to 0.25 percent of PbO, the latter equivalent to 0.23 percent of Pb.

Nickel occurs only in small quantities in the Boleo ores, but it becomes concentrated in the smelter products. Seven analyses of the ore showed a trace to 0.13 percent of nickel, averaging 0.04 percent; a sample of general smelter feed showed 0.01 percent. Its percent in different smelter products is given in tables 22 and 23. As shown in table 23, the nickel becomes concentrated in the copper matte and blister copper, in both of which it occurs to the extent of 0.32 percent.

Silver is the only element in the Boleo smelter products, besides copper, for which payment is received, but the amount concerned is hardly significant. Four analyses of the ore indicate that the silver content ranges from 7 to 12 grams per ton, and averages 9. The silver becomes concentrated in the blister copper, in which it ranges from 70 to 200 grams per ton. The average of 32 analyses of one shipment of blister copper in 1941 was 87 grams of silver per ton.

Gold is present in the ore and smelter products only in faint traces, well below the minimum quantities necessary for commercial recovery. Four analyses of the ore indicated a gold content of less than 0.2 grams per ton.

Other metals that have been found in the Boleo ores in amounts of hundredths of a percent or less include arsenic, antimony, strontium, barium, vanadium, molybdenum, zirconium, yttrium, chromium, and beryllium. Other elements that have been reported from the flue dust but not analyzed in the ore are bismuth, cadmium, uranium, thallium, tin, and traces of indium, germanium, and gallium.

SUMMARY OF RELATIVE ABUNDANCE OF ELEMENTS

A general summary of the ranges and averages of the available analyses of all constituents known to occur in the Boleo ores is given in table 24, which includes also

TABLE 24.—*Summary of available analyses of all constituents known in Boleo copper ore*

Constituent	Percent			Number of analyses	Remarks
	Range		Average		
	Low	High			
SiO_2	16.30	51.06	28.90	29	Chiefly in clay minerals; also chrysocolla, and some free silica.
H_2O	2.54	31.00	22.98	19	Some loss of moisture before analyses are made.
Ignition loss	5.92	24.00	12.29	28	Includes H_2O, CO_2, C.
MnO	.51	29.21	8.34	35	Highly variable; probably averages 3 to 4 percent in general smelting ore.
FeO	3.80	17.46	8.17	29	Includes Fe_2O_3. Highly variable.
Al_2O_3	.96	14.30	7.58	29	Chiefly in clay minerals.
Cu	.05	35	4.81	many	Average is of total production, 1886 to 1947, weighted for tonnages.
CaO	1.27	8.42	3.53	30	Chiefly in clay minerals and gypsum; also some calcite.
MgO	.66	7.60	2.90	22	Chiefly in clay minerals.
CO_2	.81	5.55	1.80	7	As carbonates.
SO_3	tr.	6.03	1.76	16	Higher in oxidized ores than in sulfide ores; mostly as gypsum.
S	.06	3.98	1.40	39	Averages 0.63 percent in oxidized ores; 2.84 percent in sulfide ores.
Cl	.10	3.88	1.33	7	NaCl 0.16 to 6.40 percent; average 2.20 percent.
Na_2O	.08	3.39	1.24	8	Partly in NaCl; also in clay minerals.
K_2O	-------	-------	1.05	1	Chiefly in clay minerals.
Zn	<.05	6.0	.80	130	Average includes 34 smelter feed and 85 mine samples analyzed by U. S. Bureau of Mines. Flue dust contains 8.8 to 19.5 percent.
TiO_2	-------	-------	.46	1	Trace in flue dust.
C (organic)	.12	.37	.22	5	Based on analyses by Bureau of Mines. Locke (1935, p. 411) reported 3 percent in two specimens. Probably variable.
Co	<.02	.86	.12	126	0.4 percent in copper matte; 0.05 to 0.28 percent in reverberatory slag; 0.03 to 0.53 percent in flue dust; 0.005 to 0.08 percent in blister copper; 0.5 to 4.0 percent in converter slag.
P_2O_5	-------	-------	.07	1	0.019 percent P in copper matte; 0.18 percent in black copper; 0.02 to 0.11 percent in Lucifer manganese ore.
Pb	none	.23	.06	4	1.8 to 3.25 percent in flue dust; 0.01 to 1.74 percent in Lucifer manganese ore.
Ni	tr.	.13	.04	7	0.32 percent in blister copper; 0.22 to 0.50 percent in flue dust.
As	-------	-------	.03	1	Trace in smelter products.
Sb	-------	-------	.02	1	Do.
Sr	-------	-------	[1] .0X	1	Present in flue dust.
Ba	-------	-------	[1] .0X	1	Present in flue dust. 0.05 to 1.45 percent in Lucifer manganese ore.
V	-------	-------	[1] .0X	1	0.06 percent in flue dust. 0.04 to 0.12 percent in Lucifer manganese ore.
Mo	-------	-------	<.01	5	0.00X percent in ore, according to spectrographic analysis. 0.01 percent in flue dust. 0.081 percent in Lucifer manganese ore.
Zr	-------	-------	[1] .00X	1	Absent in flue dust, according to spectrographic analysis.
Y	-------	-------	[1] .00X	1	Do.
Ag	.0007	.0012	.0009	4	In ore: 7 to 12 grams per ton, average 9. In blister copper: 70 to 200 grams per ton, average 87 (in 32 analyses of one shipment). In flue dust: 88 grams per ton.
Cr	-------	-------	[1] .000X	1	0.03 percent in flue dust.
Be	-------	-------	[1] .000X	1	Absent in flue dust, according to spectrographic analysis.
Au	-------	-------	<.00002	4	In ore: less than 0.2 grams per ton. Trace in blister copper. In flue dust: 0.7 grams per ton.
Bi	-------	-------	-------	-------	0.0008 percent in copper matte; 0.003 percent in black copper; 0.27 percent in flue dust.
Cd	-------	-------	-------	-------	0.08 to 0.13 percent in flue dust.
U	-------	-------	-------	-------	0.04 to 0.05 percent in flue dust.
Tl	-------	-------	-------	-------	0.012 to 0.013 percent in flue dust.
Sn	-------	-------	-------	-------	Present in flue dust.
In	-------	-------	-------	-------	Trace in flue dust.
Ge	-------	-------	-------	-------	Do.
Ga	-------	-------	-------	-------	Do.
Miscellaneous	-------	-------	-------	-------	Elements absent in ore, according to spectrographic analysis: W, Re, Pt, Pd, Th. Additional elements absent in flue dust: Hg, Hf, Li, Ru, Te, Ir, Cb, Ta, Rh.

[1] General order of magnitude, according to spectrographic analysis.

some remarks on the occurrence of some of the elements in the different smelter products. This is mainly a summary of the data given in previous tables, but it includes also some additional unpublished partial analyses for certain constituents. The constituents are arranged, insofar as possible, in the order of their abundance in the ore, although the relative rank of the elements listed toward the end of the table, which have been analyzed only in the flue dust, is not known exactly.

TABLE 25.—*Comparison of relative amount of elements in Boleo copper ore with their relative amount in igneous rocks, in percent*

Element	Symbol	Average amount of elements in Boleo copper ore	Average amount of elements in igneous rocks (Rankama and Sahama, 1950)
Silicon	Si	13. 67	27. 72
Manganese	Mn	6. 54	. 10
Iron	Fe	6. 43	5. 00
Copper	Cu	4. 86	. 007
Aluminum	Al	4. 06	8. 13
Hydrogen	H	2. 60	present
Calcium	Ca	2. 55	3. 63
Sulfur	S	2. 13	. 052
Magnesium	Mg	1. 77	2. 09
Chlorine	Cl	1. 35	. 031
Sodium	Na	. 93	2. 83
Potassium	K	. 88	2. 59
Zinc	Zn	. 81	. 013
Carbon	C	. 72	. 032
Titanium	Ti	. 28	. 44
Cobalt	Co	. 12	. 0023
Lead	Pb	. 06	. 0016
Nickel	Ni	. 04	. 008
Phosphorus	P	. 03	. 118
Arsenic	As	. 03	. 0005
Antimony	Sb	. 02	. 0001
Strontium	Sr	. 0X	. 03
Barium	Ba	. 0X	. 025
Vanadium	V	. 0X	. 015
Molybdenum	Mo	<. 01	. 001
Zirconium	Zr	. 00X	. 022
Yttrium	Y	. 00X	. 0028
Silver	Ag	. 0009	. 00001
Chromium	Cr	. 000X	. 02
Beryllium	Be	. 000X	. 0006
Gold	Au	$<2\times10^{-5}$	5×10^{-7}

It seemed of some interest, particularly in relation to the problem of the genesis of the ore, to compare the relative abundance of elements in the Boleo ore with the estimated relative abundance of these elements in igneous rocks. In order to place the Boleo analyses on a comparable basis with tables that have given such estimates, the following procedure was followed: First, the ignition loss, or H_2O-, was eliminated, and the remaining averages of the oxides were recalculated to a total of 100 percent. Then the elements in an oxide form were recalculated to an elemental form. No figure is given for oxygen, as this has not been determined in the ore, nor for the minor elements that are known only in the flue dust.

The resulting average elemental composition of the Boleo copper ore is given in table 25, where it is compared with the average abundance of these elements in igneous rocks, as given by Rankama and Sahama (1950, p. 39–40).

The elements that have a proportion many times higher in Boleo copper ores than their estimated averages in igneous rocks are copper, about 700 times as high; silver, 90 times as high; manganese, 65 times as high; zinc, 60 times as high; cobalt, 50 times as high; lead, sulfur, and chlorine, 40 times as high. All these elements are thought to have been introduced into the Boleo ores by solutions, although some of the chlorine may have been a residual product of sea water. Insufficient data are available for an exact comparison of arsenic and antimony, which also appear to be higher in the Boleo ores than in igneous rocks.

ORIGIN OF THE DEPOSITS

PREVIOUSLY PUBLISHED STATEMENTS ON ORIGIN

The mode of origin of the Boleo copper deposits is controversial, as seems to be true of many copper deposits in sedimentary rocks. Some of the earlier workers believed that the copper was syngenetic—that is, deposited contemporaneously with the enclosing sediments, through the action of warm springs or of "muddy submarine eruptions." Many of the later workers have thought that the copper was introduced into the beds by ascending hydrothermal solutions, although the evidence has never been presented very fully. A contrasting view that the copper was leached out of the overlying rocks and carried downward by descending ground waters has been proposed by one investigator, Touwaide (1930). Because his theory has been widely quoted in different treatises on ore deposits, it will be considered in some detail in the present paper.

The earliest investigator in the district, Tinoco (1885, p. 13), believed that the metalliferous material of the ore beds rose along faults, as indicated by the presence of veins and stockwork bodies, and was then deposited with the surrounding sediments. Martínez Baca and Servín Lacebron (1898, p. 8–9) reviewed the evidence given by Tinoco and differed from him in the sedimentary origin, expressing the opinion that the metalliferous deposits were posterior to the sediments of the ore-bearing formation.

Bouglise and Cumenge (1885) believed that the deposits were formed by hydrothermal submarine emanations, but they do not discuss the mechanism in detail.

Fuchs (1886a, p. 90–91) stated that the deposits were formed by muddy submarine eruptions, and that they have "the double character of eruptivity, with respect to their origin, and of sedimentation, with respect to their form, their mode of deposition and their extent." He suggested that the metals were carried upward by solutions from underlying igneous bodies, which are represented by "materials of emanation of essentially a vein-like origin." In the book on ore deposits by Fuchs and de Launay (1893, p. 351–352), it is stated that a great fracture parallel to the coast (probably the Juanita fault) has served for the passage of waters rich in quartz, which have silicified the rocks at the contact. The three cupriferous beds are attributed to a submarine effusion or discharge of mud which rose to the surface along fractures created by successive dislocations.

Saladin (1892, p. 14–15) states that the copper was probably introduced above ground by mineral springs and by muddy eruptions bursting forth through fissures in the "trachyte." As evidence for the traversing solutions, he cites the siliceous and cupriferous veinlike deposits on the southwest side of the "trachytic" mass of Juanita.

Pošepný (1894, p. 318), who based his interpretation of the Boleo deposits on the description by Fuchs, made the following statement in his treatise on the genesis of ore deposits:

> A periodical metallic precipitation, three or four times repeated, in an open marine basin, is out of the question; and we are forced in this case, even more strongly than elsewhere, to assume a secondary origin for the ores. * * * Certainly the conglomerates underlying the ore-bed must have played an important part, representing, very likely, the channels through which the mineral solutions ascended, to be reduced, probably by the presence of organic matter, in the tufas above.

Krusch (1899) was particularly impressed with the unusual metalliferous combination of copper, manganese, and cobalt in the Boleo deposits. He appealed to the action of siliceous warm springs in forming the deposits.

Weed (1907, p. 246), in a brief description of the Boleo district, made the following statement on origin: "The evidence of silicification and the greater permeability of the conglomeratic beds, resting on impermeable tuff clays, indicates a circulation of mineralizing waters (hot-spring action?) after sedimentation." (It should be noted that the conglomerates rest directly underneath and not on top of the tuff clays.)

De Launay (1913, p. 790–793) states that the sulfide deposits are the result of chemical concentration, and that they were probably derived from the decomposition of igneous rocks or of the ores that these may have contained, unless there has been a subsequent impregnation, which he does not consider very probable. In a classification of copper deposits in sedimentary rocks in another part of his book, de Launay (1913, p. 759) includes the Boleo deposits among ores which are localized in plan view within a restricted radius, which are associated with igneous rocks and lines of dislocation, and which seem to be epigenetic.

Touwaide (1930, p. 140–142) presented a theory of deposition by descending ground waters. He believed that the source of the copper was the tuff itself, which he supposed contained originally 0.2 percent of copper, although it now contains very little. He suggested that connate and ground waters slowly leached the copper from the tuff, and transported the copper as sulfate. He states:

> Downward migration of the copper was hindered by the obstacle of the impervious clay beds but the dip probably allowed sufficient movement to revive constantly the concentration of the solution in contact with the clay beds, in which the copper must have penetrated by diffusion. * * * The initial agent of deposition was probably the organic matter of the beds, which generated hydrogen sulphide, or some organic sulphur compound remaining occluded in the groundmass of the clay.

Bellanger (1931, p. 768) does not give a detailed account of his views on origin, but he states that evidence is present that the metal-bearing solutions came through small fissures caused by faulting and subsidence, and that the solutions apparently traveled through some of the faults themselves. He states: "Association of the ore with the faults indicates that its formation was subsequent to that of the beds."

Peña (1931, p. 164) suggested that the copper was deposited by the circulation of mineralizing solutions at relatively low temperatures, and that the impermeable clayey tuff served to detain the ascending course of the solutions or to confine them to certain horizons. The presence of as much as 3 percent of free carbon, which would act as a reducing and precipitating agent, was cited as one of the factors favoring the precipitation of the copper minerals. Peña pointed out the occurrence of wood fragments that have been silicified or replaced by chalcocite.

Locke (1935, p. 412) briefly discussed Touwaide's theory of leaching by ground waters, remarking that "any such copper content as 0.2 percent in the fresh rocks is unproved," and then presented his own views as follows:

> A satisfactory theory of genesis of these ores must account for the geographic localization as well as the geologic occurrence in small, uniformly dispersed grains of dominant chalcocite in thin clay members interleaved with porous sediments of an igneous basin, as well as the fact that the chalcocite is in the

low-temperature form. I am not ready to advance such a theory but suggest that further study may show that the Boleo copper traveled upward on crosscutting paths renewing those which guided the volcanic rocks, and that the ore bodies spread along porous zones from these paths. There still seems to be room for the bedding ores and the crosscutting ores to be parts of a single genetic system expressed in different rocks and structures.

THE THEORY OF DEPOSITION BY DESCENDING GROUND WATERS

The evidence listed by Touwaide (1930, p. 140–141) that the copper was derived from the overlying tuff is quoted in full as follows:

(1) The tuff is similar in composition to the augite-andesite of the bed rock except that it contains very little copper, whereas the augite-andesite contains 0.2 percent, probably in the pyroxenes.

(2) It is reasonable to suppose that the tuff contained originally also 0.2 percent of copper.

(3) The amount of copper concentrated in the ore beds is exactly what would be expected if the tuff contained originally 0.2 percent of copper. Supposing, very conservatively, that each bed contains two meters of 5 percent ore and was fed by 70 meters of sediments it is found that 0.06 percent copper may still be present in the tuff.

(4) The great uniformity of the mineralization coincides with the uniformity of the sedimentary beds.

(5) Richer ore is found in zones parallel to the facies lines of the conglomerate, that is, parallel to the lines of variation of the tuff.

(6) The deposit is much poorer inland, where the conglomerate prevails over the tuff. The copper was much more easily extracted from the fine grains of tuff than from the pebbles, as the water circulated more easily through the tuff than through the pebbles.

(7) It is easily conceivable that the connate and ground waters could extract the copper from the pyroxenes.

(8) It is equally conceivable that the copper in solution migrated downward to the argillaceous beds and was precipitated as chalcocite. The possibility of primary chalcocite in Red Beds from descending solutions was recognized long ago.

The first point, that the augite-andesite of the bedrock (Comondú volcanics) contains 0.2 percent of copper, was not confirmed. Seven fresh samples of the volcanic rocks collected by the writers and analyzed by E. K. Oslund and S. S. Goldich at the University of Minnesota showed a range from 0.002 to 0.007 percent of copper, averaging 0.004 percent (see table 2).

In order to evaluate the second point, that "it is reasonable to suppose that the tuff contained originally also 0.2 percent of copper," the writers searched the literature for previous analyses for copper in rocks. They received valuable aid from Michael Fleischer and Maryse H. Delevaux, who also provided the results of 160 unpublished analyses made in the laboratories of the U. S. Geological Survey.

The earlier literature was summarized by Clarke and Washington (1924, p. 10, 22), who state that the average of 169 analyses for copper in igneous rocks before 1924 was 0.018 percent of copper. The later analyses that the writers have found, for both igneous and sedimentary rocks, are summarized in table 26.

TABLE 26.—*The copper content of rocks* [1]

Types of rocks	*Number of samples containing the following percentage of copper* *<0.0005*	*0.0005 to 0.001*	*0.001 to 0.01*	*0.01 to 0.1*	*>0.1*	*Total number of samples*
Igneous rocks (including a few metamorphic rocks)	85	[2] 161	[3] 241	100	2	589
Sedimentary rocks	20	151	288	72	5	536
Total	105	312	529	172	7	1,125

[1] A complete list of references on which this table is based will not be cited here, but those giving a large number of analyses for copper (30 or more) include Archangelsky and Rozkova (1932), Broderick (1935) Broderick and Hohl (1935), Kowalski (1936), Sandell and Goldich (1943), Brockamp (1944), Strakhov, Zalmanson, Arestyakubovitch, and Senderova (1944), Lundegardh (1947), Schneiderhöhn and others (1949), and Graf and Kerr (1950).

[2] Includes 6 analyses reported as "<0.001", and 41 analyses reported as "0.0001 to 0.001."

[3] Includes 38 analyses reported as "0.001 to 0.02."

This table, based on more than 1,000 analyses, shows that the largest number of rock samples contain between 0.001 and 0.01 percent of copper. Sandell and Goldich (1943) obtained a weighted average of 0.007 percent of copper from analyses of 73 American igneous rocks, and this figure was accepted by Rankama and Sahama (1950, p. 39) as the best estimate for the relative abundance of copper in igneous rocks.

In addition to the analyses included in table 26, summaries of analyses of nearly 1,000 shales from Germany showed 0.002 to 0.08 percent of copper, averaging 0.0066 percent (Schneiderhöhn and others, 1949); 71 sedimentary rocks of Azerbaijan contained 0.0015 to 0.0064 percent of copper (Itkina, 1946); and many analyses of the alum shales of Sweden gave 0.005 to 0.020 percent of copper (Westergard, 1944).

Among the rocks represented in table 26, the ones whose description most nearly fits that of the tuffs of the Boleo district are some tuffs from the Santa Rita area of New Mexico, described by Graf and Kerr (1950, p. 1033) as "tuff zones partially or completely altered to pink and white montmorillonite . . . interbedded with sand and gravels." Spectrographic analyses of 21 samples of these tuffs showed that 12 contained from 0.0001 to 0.001 percent of copper, and 9 contained between 0.001 and 0.01 percent of copper.

The writers conclude that it is unreasonable to suppose that the tuffs of the Boleo district contained originally 0.2 percent of copper.

The third point made by Touwaide is that the amount of copper contained in the ore beds is exactly what would be expected if they were supplied by 70 meters of sediments containing originally 0.2 percent of copper. It should be pointed out here that the thickness of tuff overlying each ore bed reaches 70 meters in only a few places; the average thickness is 32 meters for the tuff above ore bed no. 1 and 48 meters for the tuff above ore bed no. 3 (see fig. 18). Although the writers do not attribute too much significance to the exact figures, they do believe that, if the copper were derived from the overlying tuff, there should be a correlation between the thickness of overlying tuff and the amount of ore in a particular place. But no such relation appears, as may seen from an analysis of figure 18. Some of the thickest sections of tuff (for example, above ore beds nos. 2 and 4) are underlain by very little ore. In general the tuff thickens toward the gulf where the ore is poorest, and some of the best ore was found directly alongside the volcanic hills where the tuff section has thinned down notably.

Touwaide's fourth point, as to the great uniformity of the mineralization, was not confirmed by the writers, as previously discussed and shown in figures 35 and 36 and table 13. The lack of uniformity was not overlooked by Touwaide, for he states in another part of his paper (1930, p. 128): "In beds 1 and 3 richer zones have been found in the vicinity of the main augite-andesite hills, as for example, the Sombrero Montado and the Cerro Juanita."

The writers agree with Touwaide's fifth point, that "richer ore is found in zones parallel to the facies lines of the conglomerate," but this is regarded as equally compatible with replacement by ascending or descending solutions. Any replacement deposit is likely to show a relation to facies changes in the sediments.

The sixth point, that "the deposit is much poorer inland, where the conglomerate prevails over the tuff," requires some clarification. The deposits are "poorer inland" only on the landward (southwest) side of the main volcanic hills; on the gulfward or northeast side they become better inland, up to the point where they wedge out against the hills. An explanation for this according to the theory of ascending solutions will be discussed later.

Touwaide's seventh and eighth points are that "it is easily conceivable that the connate and ground waters could extract the copper from the pyroxenes" and that "the copper in solution migrated downward to the argillaceous beds and was precipitated as chalcocite." In this connection it will only be pointed out that some of the ore beds and overlying tuff beds were probably well below the water table throughout the time of ore deposition, as also suggested by Touwaide (1930, p. 138). It is difficult for the writers to see why the copper was dissolved, migrated downward, and then precipitated in a tremendously concentrated form, in beds that were saturated with water.

In summary, the principal objections to the theory of deposition by descending ground waters are considered to be these: the improbability that the tuff originally contained enough copper to serve as a source for the deposits; the lack of any correlation between the thickness of the supposed source beds and the distribution of the ore; the difficulty of invoking both solution and deposition of copper in beds lying below the water table; and the inability to explain the vein deposits in the volcanic rocks by such a theory.

THE PREFERRED THEORY: REPLACEMENT BY ASCENDING HYDROTHERMAL SOLUTIONS

STATEMENT OF THE THEORY

The writers believe that the Boleo copper deposits were formed by replacement in favorable beds by ascending solutions of magmatic origin. The solutions were of comparatively low temperature because of their proximity to the surface and their great distance from the magmatic source. A possible interpretation of the mechanism of ore deposition, which could explain the broader pattern of variation in degree of mineralization within the stratigraphic and structural framework, is presented diagrammatically in figure 37.

In this illustration the structural and stratigraphic features are drawn to scale, the only departure from actual conditions being in the elimination of the effects of postmineral faulting, tilting, and erosion. The exact position of the premineral faults shown in the Comondú volcanics is hypothetical, but they are drawn parallel to mineralized faults and fractures that have actually been observed in the surface outcrops of these rocks.

According to this theory, the hydrothermal solutions are considered to have ascended along premineral faults and fractures in the Comondú volcanics. When they reached the contact with the overlying sediments of the Boleo formation, they in part spread outward through the porous beds of this formation and in part ascended along the steep contact bordering the projecting hills and islands of the volcanic basement rocks, since this contact provided a ready channelway for the flow of solutions.

When the solutions came into contact with the relatively impervious clayey tuff beds that overlie porous conglomerate and sandstone, their ascending course was impeded or trapped. The most effective trap was where the clayey tuff beds wedged out against the volcanic hills. The trapped solutions would be backed up underneath the clay and would thus eventually be deflected farther and farther down the dip of the beds; the underlying porous conglomerate (and its gulfward equivalent of sandstone) would serve as a good aquifer for this purpose. Thus any part of the ore bed above the level of the feeder vein and within a reasonable distance from the feeder would be reached by the mineralizing solutions. At least part of the beds were probably already saturated with water, either meteoric or connate. In any event, the mag-

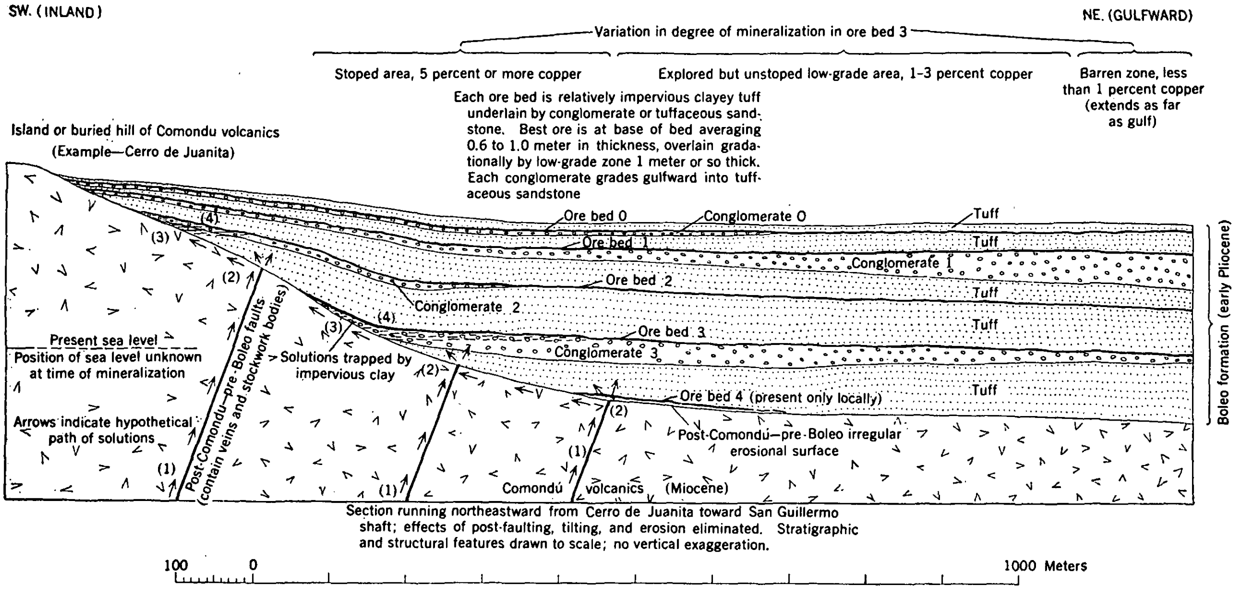

FIGURE 37.—Diagram suggesting a mechanism by which ascending hydrothermal solutions were trapped to form the Boleo copper deposits.

(1) Hydrothermal mineralizing solutions rise from depth along faults and fractures in Comondú volcanics. (2) Solutions ascend along irregular Comondú-Boleo contact and may be dispersed upward and outward through porous beds of Boleo formation. These beds may or may not already be saturated with water; in any event, warmer mineralizing solutions will rise toward top. (3) Solutions are trapped by relatively impervious clayey tuff and back up below the trap in conglomerate (or sandstone) which underlies clay and serves as an aquifer. (4) Constant contact of solutions with clayey tuff permits diffusion of copper into clay, where it is precipitated as chalcocite. Best ore is where most effective trap for ascending solutions exists against volcanic hill. Ore beds become lower grade and eventually barren away from hills. NOTE: In the area of the diagram, bed 3 has best ore; bed 2 is mineralized in a narrow zone, and beds 1 and 0 are practically unmineralized. Assumed reason: Higher beds have very limited contact with volcanic basement rocks, and bed 3 has extensive contact; most of the solutions were trapped by bed 3, and only a small part could reach the higher beds.

matic mineralizing solutions, being warmer and probably also charged with gasses, would tend to rise toward the top, until trapped by the impervious clayey tuff.

Constant contact of the mineralizing solutions with the clayey tuff beds permitted diffusion of solutions bearing copper and other metals, which were precipitated by some unknown chemical agent present in the beds. The mineralizing solutions may have reached the surface in places and issued in the form of springs, but the major deposition of ore is believed to have taken place where the solutions were trapped below the surface.

An outstanding feature of the Boleo deposits is that replacement affected the more nearly impervious rather than the more permeable beds. Concerning this, the recent thought-provoking report by Mackay (1946) about the control of impounding structures on ore deposition is of considerable interest. He maintains "that the relatively impermeable barriers that are common to these structures impounded the solutions in such a manner as to cause the metals to be deposited within the structure and to allow the solvent or ore-carrying fluid to pass on *through* the relatively impermeable barrier."

The copper and other metals probably penetrated the ore beds by diffusion, as suggested by Touwaide (1930, p. 141). The role of diffusion in ore deposition has been discussed by Duffell (1937, p. 509), who states:

> Another case where diffusion probably acts in the distribution of material, is where a solution migrating upwards comes in contact with an impervious layer. * * * When the solution comes in contact with such a barrier conditions will become stagnant and movement of solutions will be very slight. In such cases it seems likely that diffusion will act to a considerable extent, moving material from one place to another.

Since ore was not deposited in the porous rocks of the district, except to a minor degree, the writers believe that the copper was not deposited as a mere result of the effect of decreasing temperature and pressure on a saturated solution, but rather that some particular chemical constituent caused it to be precipitated in the clay. The writers are not yet prepared, however, to state the nature of the chemical agent that might have precipitated the copper.

EVIDENCE FOR ASCENDING SOLUTIONS

The main lines of evidence that the Boleo ore was deposited by ascending solutions, which arose along fractures in the underlying volcanic rocks and then spread outward through the sediments, are believed to be the following:

1. The presence of veins and stockwork bodies in the Comondú volcanics. These bodies seem to point clearly to the fact that mineralizing solutions traversed the volcanic rocks and were localized along faults and fractures. Some of these deposits are in the highest projecting masses and islands of the Comondú volcanics, which were never covered by sediments; hence there was no available source for the solutions from above.

2. The localization of certain high-grade ore bodies along the surface of the Comondú volcanics. In some places, concentrations of ore were found directly against the volcanic surface, even where there was no clayey tuff bed, the usual matrix of the ore. This seems good evidence that mineralizing solutions once flowed along this contact between the Comondú volcanics and the Boleo formation.

3. The areal pattern of variation in grade of ore. The larger bodies of high-grade ore are wrapped around the gulfward side of the projecting masses of Comondú volcanics, as illustrated in figure 36. Toward the gulf from these volcanic masses, the grade of ore decreases gradually, until eventually the stratigraphic equivalents of the ore beds become virtually barren of copper. This relationship seems best explained by the theory that the mineralizing solutions rose along faults and fractures in these projecting masses of Comondú volcanics and then spread out along the tuffaceous beds of the Boleo formation.

4. The relationship of the ore bodies to structural features. In particular, some of the best ore is found where a structural trap would have impeded the flow of ascending solutions, as shown in figure 37. There is also evidence that certain of the deposits are related to premineral faults.

5. The localization of the ore in proportion to the total extent of the tuff. The ore bodies are confined to a narrow, elongated belt occupying only a small part of the large area covered by the tuffaceous beds. This suggests that some special structural conditions were responsible for the localization of the ore, and it is particularly incompatible with the theory that the copper may have been derived from the tuffaceous beds themselves. The ore-bearing zone is elongated parallel to the main projecting masses in the volcanic basement rocks and to the pattern of faults and fractures.

6. The repartition of ore among the different ore beds. It is necessary to explain why ore bed no. 1 is the main ore bed in the southeast part of the district, while it is virtually unmineralized in the northwest part of the district, where ore bed no. 3 is the main bed. The writers' explanation is that ore bed no. 1 lies much nearer the base of the formation in the southeast part of the district (the lower part of the sedimentary section being absent there due to nondeposition) and has extensive contact with the volcanic basement rocks around Cerro del Sombrero Montado. But in the northwest part of the district ore bed no. 1 is much higher and has only a limited contact with the highest parts of the volcanic hills. Thus almost no mineralizing solutions were able to reach it in that area, most of them having been trapped below by ore bed no. 3, and to a lesser degree by ore bed no. 2. This does not deny that the different degree of mineralization in the different ore beds is partly due to original differences in the sedimentary beds themselves, which caused some to be more susceptible to replacement than others.

7. The vertical distribution of ore within a particular bed. Copper is concentrated toward the base of each clayey tuff bed and gives way upward to a low-grade zone in the hanging wall of the bed. Assuming that the copper was distributed by diffusion, as Touwaide suggested and as the writers also consider probable, it seems that the greatest concentration should be where the diffusion began, and that it would gradually decrease outward. Concentration of ore at the bottom would thus indicate that the solutions came from below rather than from above. This question is closely related to the following point.

8. The zonal arrangement of copper and zinc in the ore beds. In most parts of the district where zinc is sufficiently abundant to show a well-defined relationship to the copper, it is relatively concentrated toward the hanging-wall part of the ore bed where copper is relatively scarce. It is well known that in a mixed solution containing salts of copper and zinc, copper is precipitated first. If zinc or zinc sulfide comes into contact with a solution containing copper it will go back into solution and precipitate the copper. Experimental proof of these statements has been presented by Wells (1915, p. 15–16), Zies, Allen, and Merwin (1916, p. 492), and Watanabé (1924a, 1924b). When a solution carrying copper and zinc is diffused through a clay, copper will be precipitated in the zone first penetrated by the solution, and zinc will be precipitated in an adjacent zone farther outward. If a bed of clay were penetrated by solutions migrating downward, copper would be deposited at the top and zinc at the bottom, but if it were penetrated by ascending solutions, copper would be concentrated at the bottom and zinc at the top—the situation found at Boleo.

Interesting experimental evidence for a zonal arrangement of copper and zinc under conditions closely analagous to those at Boleo has been given by Watanabé (1924a, 1924b). He poured a mixed solution of copper and zinc sulfates on a consolidated jelly containing a small amount of sodium sulfide, in a glass tube closed at the lower end. His description of the reaction follows (1924b, p. 497–498):

The deposition of both zinc and copper sulfides commenced immediately as the metallic salts diffused from the overlying solution into the jelly containing sodium sulfide. The precipitation of the two sulfides, however, did not occur in a mixture, but in two different zones, sharply separated from each other. Both zones advanced with time deeper into the jelly, still retaining a sharp boundary between them. The zone of white colloidal zinc sulfide always advanced deeper than that of dark brown copper sulfide, the former being replaced from its rearward side by the latter, while it was advancing deeper on its forward side. In other experiments, the relative concentration of zinc and copper sulfates in the diffusing solution was changed from Cu 95: Zn 5 to Cu 5: Zn 95. In any case, the zone of zinc sulfide advanced at the front of the zone of copper sulfide. The order of these two zones was always constant, independent of the relative concentration of diffusing salts in the overlying solution.

AGE OF THE MINERALIZATION AND RELATION TO IGNEOUS ACTIVITY

The mineralization took place sometime after the deposition of the Boleo formation, but probably not long afterward. It was apparently completed before the deposition of the Gloria formation, for no trace of the effects of mineralization appear in the Gloria or any of the younger formations. The unconformity at the base of the Gloria cuts cleanly across some of the copper ore beds, dividing them into separated segments in places where structural irregularities existed, and the ore bodies were evidently eroded before the Gloria formation was deposited. From what is known of the geologic history of the region, therefore, the time of mineralization was apparently toward the close of the early Pliocene.

The mineralization is believed to have been related to the same period of igneous activity that produced the tuffaceous beds themselves. The underlying igneous bodies regarded as the source of the mineralizing solutions are not exposed and are believed to lie at great depth.

RELATION OF THE BOLEO COPPER DEPOSITS TO OTHER COPPER DEPOSITS OF THE WORLD

The Boleo copper deposits show certain similarities to the following copper deposits of the world:

1. The Kupferschiefer of the Mansfeld district in Germany, in which primary bornite and chalcocite are disseminated over a broad area in an impervious black shale of Permian age;
2. The Corocoro deposits of Bolivia, consisting of native copper and chalcocite deposits localized near a fault in tuffaceous sediments of Pliocene age;
3. The native copper deposits of the Lake Superior region in Michigan, occurring as bedded and fissure deposits in basic lavas and conglomerate, and to a large extent also in sandstone and shale, of late pre-Cambrian age;
4. The "Red Bed" deposits of dominant primary chalcocite in porous sandstones of Permian and Triassic age, widely scattered over the Southwestern United States and through Europe and Asia;
5. The great copper belt of Northern Rhodesia, consisting of tabular-shaped deposits of chalcocite, chalcopyrite, and bornite widely disseminated through particular beds of metamorphosed argillites and quartzites of possible pre-Cambrian age;
6. The Zoutpansberg district of the Transvaal in South Africa (Kent, 1940), consisting of low-temperature chalcocite deposits in quartzitic sandstones and altered andesitic lavas adjacent to a fault.

No one of these deposits duplicates all the pertinent characteristics of the Boleo deposits, such as: the confinement of the mineralization to relatively impervious tuffaceous sedimentary beds; the Pliocene age of the mineralization; the dominance of low-temperature chalcocite as the primary mineral; and the metalliferous combination of copper, manganese, zinc, cobalt, and lead, but with a virtual lack of precious metals.

Perhaps the most similar deposit, considering host rock, primary minerals, and metalliferous combination, is the Kupferschiefer of Germany. This deposit, though not necessarily of the same origin, shares one of the unusual features of the Boleo deposits, in that the ore minerals are found principally in the more impervious rather than in the more permeable beds. It also shows a zonal relation of copper and zinc similar to that of Boleo (Cissarz, 1929; Krüll, 1933).

Many if not most of the copper deposits listed above are of controversial origin, and for some of them at least three different types of theories have been proposed for the origin of the copper: a syngenetic origin, leaching and deposition by descending solutions, and deposition from ascending hydrothermal solutions.[8]

MINING OF THE COPPER DEPOSITS

HISTORY

DISCOVERY AND EARLY OPERATIONS, 1868–85 [9]

The Boleo copper deposits were discovered in the year 1868 by José Rosa Villavicencio, then owner of the Santa Agueda ranch, which is 12 kilometers south-

[8] The literature on the deposits enumerated above is voluminous. Worldwide reviews covering some of these deposits have been published by Iagovkin (1932) and Bastin (1933). Most of the deposits are described in the symposium on "Copper resources of the world" published by the 16th International Geological Congress in Washington in 1935.

[9] The history for the period 1868 to 1885 is taken largely from reports by Tinoco (1874, 1885) and by Bouglise and Cumenge (1885).

west of the present site of Santa Rosalía. This rancher, while searching for a passage across the mesas to reach the port of Santa María, noticed a number of blue and green nodules in Arroyo del Purgatorio. These detrital ball-like fragments composed of copper carbonates and oxides, called *boleos* in Spanish, provided the name that has been used for the district since 1885. Before that it was officially known as the Santa Agueda mining district.

Señor Villavicencio took some of the *boleos*, out of curiosity, to Guaymas, Sonora, where they were recognized to consist of high-grade copper ore. Señores G. Blumhardt and Julio Muller, residents of Guaymas, are said to have purchased Señor Villavicencio's rights to his discovery for 16 pesos, and some time thereafter set out to prospect the region. They first worked an outcrop of copper ore pertaining to ore bed no. 3 near the arroyo level in Arroyo del Purgatorio, and were followed by other prospectors who discovered several outcrops of rich oxidized ore in Arroyo del Boleo. The ore was removed from opencuts along the outcrops and was packed and hauled by wagon to the beach, from where the first shipments of ore to Europe are said to have been made in 1872.

The ore produced by the beginning of the year 1874, the major part of which had been extracted during the previous year, is given by Tinoco (1874) as 6,000 tons, with a value in Europe of 480,000 pesos. It was considered profitable to ship only ore containing more than 20 percent of copper, and lower-grade ore was sorted out and piled on the dumps.

The first underground workings were intersecting drifts following the ore beds inward from the sides of the arroyos. The three principal copper beds were discovered in the earliest years of mining and were numbered 1 to 3 from top to bottom, designations which have been followed ever since, although less important beds were later found both above no. 1 and below no. 3.

In the period from 1875 to 1884, mining operations were continued by several small companies, chiefly under the control of Germans, but beginning in 1879 economic difficulties were encountered, due partly to a sharp drop in the price of copper in England, and to the increasing costs of mining because of greater distance of the ore bodies from the surface and the necessity for sinking deeper shafts for ventilation purposes. Two of the early companies, Camou Hnos. of Guaymas and the J. Kelly Cía. of Mazatlán, failed in the year 1879; by 1884 the principal claims in the district were in the hands of the Cía. Minera Elhuyar y Sontag and of Señores Guillermo Eisenmann and Eustaquio Valle.

The total production through 1884 was about 60,000 tons of ore with an average copper content of 24 percent, according to Tinoco (1885). He states that an additional 120,000 tons of ore with an average grade of 8 percent of copper had been thrown on the dumps or used as fill in the stopes. Tinoco states that by the year 1884 it became evident that investment of considerable capital in the region was needed in order to carry out the mining operations in a systematic manner, and particularly to build a smelter in order to work ores containing less than 20 percent of copper.

OPERATIONS OF THE COMPAGNIE DU BOLÉO, 1885–1938

Several French geologists and engineers visited the region in the year 1884, among them M. Edmund Fuchs of the School of Mines of Paris, and Messrs. G. de la Bouglise and E. Cumenge, who were commissioned by certain French mining interests to make a detailed study of the district. The highly favorable report of Bouglise and Cumenge (1885) led to the formation of the Compagnie du Boléo in Paris on May 16, 1885, backed mainly by the banking interests of the French house of Rothschild. On July 7, 1885, this company, through an agreement with the Mexican Government, purchased all the mining claims then extant in the region and received the concession to an area of some 20,655 hectares (about 80 square miles). The Compagnie du Boléo, later to be known in Mexico as the Compañía del Boleo, S. A., began its operations the same year.

The early years of operation by the Boleo company were devoted not only to organizing a systematic development of the mines, but also the construction of a smelter, the town and mining camps, harbor, railroads, machine shops, a pipeline for water, and all the other facilities needed for large-scale operations in a region that had previously been an uninhabited desert. The first smelter, consisting of small blast furnaces, was finished in 1886, although it was rebuilt toward the close of the century. The smelter produced copper matte and black copper in amounts equivalent to 196 tons of pure copper in 1886 and 1,822 tons in 1887, thereafter increasing each year until a production of 10,537 tons of pure copper was attained in 1894, which was not far from the normal annual production in the ensuing years.

Until 1917 the copper matte and black copper were transported to Europe—to England, France, and Germany. Most of these products were carried directly by ships, but for a time they were transported partly by rail from Guaymas to New Orleans, from where they were shipped as ballast in steamers used in the cotton trade. In 1922 the present smelter was completed, consisting of reverberatory furnaces and converters whose product is blister copper. This product has been shipped to Tacoma, Wash., where it has been refined electrolytically by the American Smelting and Refining Company. In 1924 an electrolytic refinery was installed in Santa Rosalía, but the operation was unsatisfactory and was abandoned after a trial period of about 6 months.

The early mining by the Boleo company was confined largely to the rich oxidized zone of ore bed no. 3, which was mined from three main centers, in Arroyos Providencia, Purgatorio, and Soledad. Eventually the mine workings radiating out from these centers were intercommunicated to form a large area of continuous workings. The dumps and mines of the previous operations were reworked. In turn, some of the early mines of the Boleo company were reworked in a much later epoch, when it was found possible to treat lower-grade ore. Some of the older parts of the mines have in fact been stoped two or three times.

The two decades preceding World War I probably formed the epoch of maximum success of the Boleo operations. The great bulk of underground development in the district was accomplished at that time, as may be seen from a map of the mine workings extant in 1917 (Boletín Minero, 1917, map facing p. 470). All the extensive zone of ore bed no. 3 in the Providencia, Purgatorio, and Soledad groups of mines had been explored and largely stoped out down to the level of 25 meters above sea level, which is approximately the level of the water table in that area. The Ranchería (then called Santa Rosalía) and Montado mines in ore bed no. 1 in the southeast part of the district had also been explored but not yet stoped, except for a rich oxidized zone in the Montado mine adjacent to Cerro del Sombrero Montado.

The history of mining operations since World War I has been one of decreasing grade and thickness of ore and increasing costs due to greater depths of mining. Since 1918 exploitation has been carried out mainly in the sulfide zone of ore bed no. 3, at depths of 25 meters above sea level to 50 meters below sea level in the Purgatorio and Santa Rita mines, as well as in ore bed no. 1 in the Ranchería and Montado mines. Despite the mining of thinner and lower-grade beds, a high production was attained in the period 1926 to 1932, nearly equalling that of the peak epoch of 1906 to 1916. This was made possible by improved stoping methods, particularly the installation of conveyor belts within the mines. The production of copper declined considerably after 1932, as the result mainly of the decreasing grade of the ore mined.

In 1927, as it became evident that the known exploitable ore bodies were rapidly becoming exhausted, an exploratory churn-drilling program was begun. Mainly as a result of this drilling program a new mine, the San Luciano, was opened in Arroyo de Santa Agueda, where the ore body—the sulfide zone of ore bed no. 1—is deeply buried below the surface. Development of this mine began in 1932 with the completion of the William shaft, deepest in the district, which reaches a depth of 255 meters below the surface (199 meters below sea level). An aerial tramway 5 kilometers long was built to transport the ore from the William shaft to Santa Rosalía. Difficulties were experienced in the San Luciano mine because of the heat and water found at depths of 90 to 185 meters below sea level. Additional drilling over an extensive area southeast of the San Luciano mine was continued until 1940, but the ore bed was considered too thin, too low in grade, and too deep to be exploitable in that area.

EPOCH OF THE POQUITEROS, 1938–48

The Compagnie du Boléo went into liquidation in July 1938, and at several times since then it has reportedly been on the verge of ceasing operations altogether, but World War II, with its attendant demand for copper, permitted a temporary prolongation of mining activities. Again definite announcement was made in April 1946 that the smelter would close down, and many of the townspeople of Santa Rosalía emigrated to Ensenada, Mexicali, and other places. As a result of increases in the price of copper about that time, however, together with favorable governmental concessions, this decision was revoked and operations have continued on a reduced scale until the time of writing (1949). The company was reorganized in Mexico in 1948 as Boleo Estudios e Inversiones Mineras, S. A. It was considered then that operations might be continued for several years longer, assuming favorable economic conditions.

In the epoch since 1938 the company gradually gave up most of its mines but continued operating the smelter on ore extracted by the *poquiteros*. These are small, independent operators who have generally from 10 to 20 men working under them and who sell ore to the company at a certain price per ton, depending upon the grade of ore and the current price of copper. The *poquiteros* are in part reworking filled stopes and extracting pillars in the old abandoned mines, and in part working deposits that were never mined by the company because of their small size, low grade, difficulty in exploitation, inaccessibility, or some other reason. Almost all the old mines of the Boleo company have been reentered at some point or another by the *poquiteros*, who in 1948 were working in about 20 different localities. The principal new areas that have been mined are in the northwest part of the district, in the drainage basins of Arroyo del Boleo, Cañada de la

Gloria, and Arroyo del Infierno, areas that were left by the company because of their distance from the railroad.

The last mine that was owned outright by the Boleo company was the San Luciano, which was expected to close down in 1950. After that time it was expected that the entire production of ore would come from the *poquiteros* and that the activities of the company would be confined mainly to operating the smelter and railroad system. The company assists the *poquiteros*, however, by furnishing equipment, electric power, and engineering advice, and by supplying funds for certain exploratory workings that the *poquiteros* would not otherwise be able to undertake.

The Boleo copper district thus has a history of some 80 years as a copper camp, and of more than 60 years of active exploitation by the Boleo company. In total production it ranks second among the copper districts of Mexico, and in total length of underground workings—more than 588 kilometers—it doubtless ranks well up among the metal mines of the world. Apart from its size and production record, however, its picturesque setting and its unusual geologic occurrence should alone assure it a prominent place among the notable copper mines of the world.

PRODUCTION

The total production of the Boleo copper district during its operation by the Compagnie du Boléo from 1886 to June 30, 1947, was 13,622,327 metric tons of ore, from which the equivalent of 540,342 metric tons of metallic copper was recovered. Table 27 gives, for each year from 1886 to June 30, 1947, the production of ore and of copper, as well as other data such as the length of mine workings completed, the average grade of ore, the average yield of ore smelted, the amount of waste extracted, and the production and grade of the smelter products, namely, black copper and copper matte from 1886 to 1922 and blister copper from 1922 to 1947. Following the totals, the same table gives the annual averages of these production figures during different epochs in the company's history; namely, the preliminary period from 1886 to 1893, the epoch of peak production from 1894 to 1916, the period of reduced production from 1917 to 1925, the epoch of renewed high production from 1926 to 1932, and the more recent period of declining production from 1933 to 1947.

The annual production of ore in this period, 1886–1947, averaged 221,504 tons and reached a peak of 371,300 tons in 1913. The production of copper averaged 8,786 tons per year and attained a maximum of 13,000 tons in 1910 and 1913. The average grade of ore for the entire period, weighted for tonnages, was 4.81 percent of copper, and the average yield of ore smelted was 3.98 percent.

The fluctuations in the production of ore and of copper and in the grade of ore through the years are shown in figure 38, which also shows variations in the price of copper over the same period. The prices shown are based on published figures for the average market price in New York for each year, but they are not necessarily the exact price received by the Boleo company. It may be seen from this chart that the fluctuations in production were determined largely by factors other than the price of copper, for there is only a slight relation between the production and price curves. The highest peaks in price of copper, in 1917 and again in 1947, were both times of declining production at Boleo due to other reasons. The very sharp drop in production in 1919 and 1920 is said to have been due largely to the exodus of workers to the cotton fields in the Imperial Valley.

The production of ore from the Boleo district has been tabulated for individual mines and ore beds in table 28. This covers the period 1886 to 1947, but the production from 1886 to 1892 was unclassified as to individual mines, and the ore purchased from 1939 to 1947 from the *poquiteros* was again unclassified as to mines and ore beds. The slight discrepancy in total production as compared with table 27 is due to the fact that table 28 covers the entire year 1947, whereas table 27 ends with June 30, 1947.

Of the total production of ore classified by individual ore beds, ore bed no. 3 is credited with 10,257,824 tons or 83.3 percent, ore bed no. 1 with 2,045,537 tons or 16.6 percent, and ore bed no. 2 with 6,218 tons or 0.1 percent; and 1,412,613 tons of ore is unclassified. This classification is not exact, however, as some of the production listed for ore beds 1 and 3 came from beds 2 and 4 and the Falsa Tercera and Sin Nombre beds. Four individual mines or mining areas have each produced more than a million tons of ore; namely, the San Alberto mine, 1,900,686 tons; the Purgatorio mine, 2,091,141 tons; the California-Lugarda mine, 1,632,909 tons; and the Santa Rita-San Antonio mine, 1,502,773 tons.

Between 1890 and 1899 the Boleo district was the leading copper producer in Mexico. During most of the years since 1900 it has ranked second, having been exceeded by the Cananea district of Sonora, although during a few years it has ranked third, having been surpassed also by the Nacozari district of Sonora. In total production of metallic copper the Boleo district ranks second in Mexico. The rank of the Boleo district in annual production among copper mines of the world was fifteenth in 1912, dropping to twenty-ninth place in 1929 and to thirty-sixth place in 1935, according to data given by Croston (1937, p. 331). The total

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TABLE 27.—*Data on exploration, mine, smelter, and copper production of the Compagnie du Boléo, 1886 to June 30, 1947*

Year	Exploration	Mine production					Smelter production						Copper production	
							Products of blast furnaces (1886–1922)				Products of converters (1922–47)			
	Length of mine workings completed (meters)	Ore extracted (metric tons)	Average grade of ore (percent copper)	Waste extracted (metric tons)	Proportion of waste to total extraction (percent)	Ore smelted (metric tons)	Black copper produced (metric tons)	Average grade of black copper (percent copper)	Matte produced (metric tons)	Average grade of matte (percent copper)	Blister copper produced (metric tons)	Average grade of blister copper (percent copper)	Total production of pure copper (metric tons)	Average yield of ore smelted (percent)
1886	15,439 (1886–88)	10,042	9.58	131,650 (1886–88)	56 (1886–88)	2,826	49		192				196	6.94
1887		40,551	6.88			36,317	554		1,902				1,822	5.02
1888		51,297	7.98			44,180	761		3,018				2,596	5.88
1889	6,928	57,101	7.52	74,250	57	57,208	1,216	92.12	3,560	62.15			3,333	5.83
1890	5,528	57,581	7.19	69,090	55	61,720	926	90.46	4,293	62.02			3,500	5.67
1891	8,819	76,510	8.08	91,810	55	75,106	1,195	93.03	4,485	68.32			4,176	5.56
1892	13,354	98,505	8.08	118,300	55	92,513	2,112	92.82	7,008	63.56			6,415	6.93
1893	13,059	118,020	7.20	140,727	54	117,963	3,089	92.87	8,481	61.76			8,107	6.87
1894	14,343	132,860	8.37	153,340	54	132,235	3,255	94.05	11,292	66.20			10,537	7.97
1895	15,475	150,020	7.92	155,850	51	142,622	3,253	94.92	11,111	67.72			10,612	7.44
1896	16,243	156,010	7.43	196,604	56	155,488	3,184	95.78	9,826	71.67			10,091	6.49
1897	24,276	180,190	6.63	152,059	46	181,520	3,665	94.09	10,297	66.87			10,334	5.69
1898	27,856	192,520	5.90	216,895	53	186,696	2,774	94.20	10,545	66.15			9,588	5.14
1899	26,313	242,325	5.48	188,756	44	243,721	4,342	94.54	9,588	65.52			10,387	4.26
1900	23,249	261,170	5.19	191,360	42	263,073	5,553	93.13	9,877	62.02			11,297	4.29
1901	17,054	275,635	6.02	201,875	42	276,835	5,360	92.30	9,800	61.31			10,956	3.96
1902	9,193	249,895	5.43	157,905	39	249,874	5,319		9,757				10,953	4.38
1903	7,888	230,490	5.59	162,053	41	229,911	4,626	93.21	9,627	64.07			10,480	4.56
1904	10,486	259,870	5.10	158,447	38	260,067	4,672	93.05	10,591	63.97			11,122	4.28
1905	9,638	261,460	4.62	179,559	41	260,694	3,957	92.92	10,318	64.67			10,350	3.97
1906	12,388	304,940	4.27	184,999	38	302,499	3,654	93.00	11,861	64.09			11,000	3.64
1907	16,762	319,850	4.38	211,802	40	321,751	4,144	93.01	11,636	62.70			11,150	3.47
1908	17,294	340,800	4.76	236,128	41	342,334	5,338	93.12	11,975	63.71			12,600	3.68
1909	13,195	330,000	4.99	228,691	41	328,100	5,619	93.73	11,341	63.11			12,425	3.79
1910	19,539	365,000	4.56	305,903	46	366,000	6,038	93.29	11,958	61.61			13,000	3.55
1911	16,902	355,100	4.78	291,700	45	356,700	6,370	93.66	10,296	62.10			12,360	3.47
1912	15,375	364,850	4.49	289,203	44	360,500	5,595	93.83	11,890	62.24			12,650	3.51
1913	18,256	371,300	4.59	267,239	42	374,350	6,426	94.20	11,134	62.40			13,000	3.47
1914	15,194	324,500	4.81	208,605	39	324,800	5,232	93.60	10,299	63.92			11,480	3.53
1915	13,784	316,800	4.71	192,794	38	317,000	4,972	93.48	10,612	64.56			11,500	3.63
1916	15,801	290,000	4.84	188,113	39	290,100	4,011	92.83	11,474	63.42			11,000	3.79
1917	14,448	258,400	4.93	208,090	45	259,000	4,179	92.99	8,410	63.49			9,225	3.56
1918	10,504	263,700	4.61	194,300	42	263,700	2,803	93.50	10,859	62.44			9,400	3.56
1919	11,940	194,800	4.61	194,800	50	195,500	1,974	92.13	10,004	61.79			8,000	4.09
1920	3,919	96,900	5.65	96,900	50	97,300	518	93.76	6,776	59.97			4,550	4.68
1921	4,584	99,000	5.50	127,020	56	95,970	386	94.16	7,650	53.95			4,490	4.68
1922	6,998	143,400	5.37	163,962	53	145,300			797	51.67	6,172	99.45	6,550	4.51
1923	7,197	171,700	4.92	189,420	52	172,100					7,586	99.47	7,545	4.38
1924	5,454	193,000	4.85	183,816	49	185,900					6,497	99.43	[1] 7,865	4.23
1925	4,238	167,400	5.03	164,143	50	174,050					7,732	97.65	7,550	4.34
1926	3,431	247,800	4.84	164,125	40	245,800					10,243	98.70	10,110	4.11
1927	5,527	266,500	4.48	202,700	43	261,900					10,535	99.43	10,475	4.00
1928	9,302	284,400	4.50	226,320	44	289,000					11,665	99.44	11,600	4.01
1929	10,633	311,800	4.33	228,830	42	307,100					11,776	99.40	11,705	3.81
1930	9,327	333,600	4.31	204,400	38	338,900					12,675	99.41	12,600	3.72
1931	5,911	278,700	4.74	171,275	38	275,700					11,626	99.43	11,560	4.19
1932	3,554	267,000	4.47	121,345	31	263,500					10,483	99.40	10,420	3.95
1933	3,073	216,800	4.37	60,935	22	219,500					8,621	99.41	8,570	3.90
1934	3,712	193,200	4.48	80,620	29	198,800					8,253	99.36	8,200	4.12
1935	3,799	204,300	4.40	84,750	29	202,200					7,924	99.26	7,865	3.89
1936	2,043	203,900	3.98	81,900	29	204,200					7,146	99.28	7,095	3.47

1937	5, 201	269, 400	3. 74	97, 000	26	266, 800	---------	---------	---------	---------	8, 343	99. 31	8, 285	3. 11
1938 [2]	1, 864	116, 100	3. 86	47, 356	29	117, 900	---------	---------	---------	---------	4, 310	99. 31	4, 280	3. 63
1938–39	3, 808	245, 500	3. 49	77, 422	24	245, 900	---------	---------	---------	---------	7, 753	99. 25	7, 695	3. 13
1939–40	3, 872	255, 300	3. 10	73, 229	22	254, 300	---------	---------	---------	---------	6, 739	99. 27	6, 690	2. 63
1940–41	1, 773	247, 100	3. 69	41, 131	14	249, 100	---------	---------	---------	---------	7, 470	99. 26	7, 415	2. 98
1941–42	775	233, 200	3. 60	59, 648	20	232, 600	---------	---------	---------	---------	7, 052	99. 27	7, 000	3. 01
1942–43	518	274, 900	3. 27	52, 670	16	272, 500	---------	---------	---------	---------	7, 359	99. 27	7, 305	2. 68
1943–44	1. 018	261, 400	3. 36	38, 215	13	261, 440	---------	---------	---------	---------	8, 057	99. 29	8, 000	3. 06
1944–45	62	216, 900	3. 70	31, 519	13	219, 450	---------	---------	---------	---------	7, 557	99. 37	7, 510	3. 42
1945–46	---------	166, 980	4. 39	13, 001	7	164, 700	---------	---------	---------	---------	6, 422	99. 34	6, 380	3. 87
1946–47	---------	154, 055	4. 05	---------	---------	151, 000	---------	---------	---------	---------	5, 426	99. 33	5, 390	3. 57
Totals and averages [3]	588, 114	13,622,327	4. 81	9, 026, 549	40	13,585,813	127, 121	93. 45	324, 540	63. 61	215, 422	99. 27	540, 342	3. 98
Annual averages during various periods														
1886–93	7, 891	63, 701	7. 81	78, 228	55	60, 979	1. 238	92. 26	4, 117	63. 56	---------	---------	3, 768	6. 09
1894–1916	16, 370	272, 859	5. 43	205, 212	43	272, 473	4, 668	93. 63	10, 744	64. 27	---------	---------	11, 255	4. 43
1917–25	7, 698	176, 478	5. 05	169, 161	50	176, 535	1, 972	93. 31	7, 416	58. 88	6, 996	99. 00	7, 242	4. 23
1926–32	6, 812	288, 114	4. 52	188, 427	39	283, 128	---------	---------	---------	---------	11, 286	99. 32	11, 210	3. 97
1933–47	2, 174	224, 761	3. 83	57, 889	20	224, 854	---------	---------	---------	---------	7, 478	99. 31	7, 426	3. 36
Annual average 1886 to June 30, 1947	9, 563	221, 504	5. 19	146, 773	40	220, 907	3, 531	93. 37	8, 771	63. 19	8, 448	99. 26	8, 786	4. 31

[1] Includes 1,405 metric tons of copper anodes refined in an electrolytic plant built at Santa Rosalía. This plant was abandoned the same year.

[2] First six months only of 1938. Succeeding data are given for fiscal years, as from July 1, 1938 to June 30, 1939.

[3] The averages given on this line are weighted for tonnages, while the annual averages given on the last line are merely the averages for each year, regardless of tonnage.

TABLE 28.—*Production of ore, in metric tons, from the Boleo copper*

Year	Ore bed no. 1					Ore bed no. 2	Ore bed no. 3					
							Providencia group				Purgatorio group	
	San Luciano	Montado	Ranchería or Santa Rosalía	Cinco de Mayo	Total	Mines in ore bed no. 2	San Alberto	Carmen	Sontag	Total	Purgatorio	California-Lugarda
1886–1892												
1893								48,085		48,085		2,445
1894							515	61,385		61,900		1,370
1895							45	72,015		72,060		9,705
1896		190			190		55,070			55,070		36,300
1897		989			989	545	48,577			48,577		33,662
1898		710			710		55,425			55,425		27,810
1899		150			150		68,390			68,390		12,041
1900						180	64,700			64,700		735
1901							62,000		3,070	65,070		32,763
1902							47,580		920	48,500	22,280	88,310
1903							28,490		5,950	34,440	34,950	69,560
1904							43,840		590	44,430	42,670	62,070
1905							63,000		530	63,530	38,790	61,750
1906							63,810		11,720	75,530	44,660	74,000
1907							72,170		12,250	84,420	51,611	77,030
1908							86,030		6,040	92,070	51,020	75,190
1909							92,640		4,000	96,640	45,990	71,520
1910							114,190		1,470	115,660	51,260	63,960
1911						(3)	109,083		7,097	116,180	50,010	55,840
1912							107,540		18,430	125,970	53,290	61,130
1913			1,730		1,730		119,680		2,800	122,480	45,590	67,880
1914						5,443	109,557			109,557	33,770	69,850
1915							119,180			119,180	560	88,480
1916							104,670			104,670	5,170	77,750
1917			17,820		17,820		83,010			83,010	(5)	70,860
1918		[6] 33,275	2,910		36,185		42,220		[6] 33,275	75,495	(5)	72,140
1919		[6] 32,400	(7)		32,400		12,020		[6] 32.400	44,420	(5)	54,060
1920		[6] 14,455	(7)		14,455				[6] 14,455	14,455	(5)	35,820
1921		[6] 17,155	(7)		17,155				[6] 17,155	17,155	14,440	44,120
1922		[6] 26,310	(7)		26,310				[6] 26,310	26,310	43,750	46,160
1923		[6] 31,080	(7)		31,080				[6] 31,080	31,080	59,310	40,130
1924		80,480	(7)		80,480						46,550	32,510
1925		57,610	5,340	487	63,437						42,430	14,658
1926		68,540	33,220	3,080	104,840						75,940	
1927		70,214	44,230	4,636	119,080						67,660	
1928		56,000	59,450	1,970	117,420						57,370	1,300
1929		58,210	78,960	720	137,890	50					60,930	
1930		60,480	82,350		142,830						94,970	
1931		27,040	81,770		108,810						78,270	
1932	60		58,690		58,750						95,830	
1933	1,540		600		2,140						130,130	
1934	910				910						108,960	
1935	2,830				2,830						108,790	
1936	15,000		6,040		21,040						98,090	
1937	4,740		52,440		57,180		[8] 53,020			53,020	95,460	
1938	22,990		44,910		67,900		[8] 11,470			11,470	88.780	
1939	26,520		46,400		72,920		[8] 24.165			24.165	88,630	
1940	46.420		62,280		108,700		[8] 9,239			9,239	63,230	
1941	68,030		69,930		137,960							
1942	72,620		59,340		131,960		[8] 29,360			29,360		
1943	86,690		57,790		144,480							
1944	75,000		46,520		121,520							
1945	57,386				57,386							
1946	5,900				5,900							
1947												
Total	486,636	635.288	912,720	10.893	2,045,537	6.218	1,900,686	181,485	229,542	2,311,713	2,091,141	1,632,909

dollar value of the metallic copper produced from the Boleo district is estimated to be about $166,000,000.[10]

MINING CLAIMS

Before the Compagnie du Boléo was formed, some 77 mining claims of varying size, shape, and orientation were scattered about the district, according to a map by Tinoco (1885).

These early claims and a large additional area were included in the original Boleo concession, granted in 1885, which covered an area of 20,655 hectares. This concession was divided into 11 claims numbered I to XI, a twelfth unnumbered claim that covered more than half the total area, and two additional claims called Santa Rita and Santa Rosalía del Carmen (Barrios, 1886). The concession extended from Arroyo de las Palmas on the northwest beyond Arroyo de Santa Agueda on the southeast (see pl. 2).

The greater part of this concession was given up in later years, and in 1936 the Boleo company took up 22 claims, designated by roman numerals I to XXII, covering an area of 1,791 hectares (see pl. 2). These claims were divided into two main groups. A northern group extended from the Ranchería mine northwestward across the Purgatorio mine to the Santa Rita mine. The southern group covered the San Luciano mine and

[10] This is an approximation based on the average New York market price of copper for each year; it does not indicate the amount of money actually received by the Boleo company for its copper.

district, 1886 to 1947, tabulated by ore beds and individual mines

Ore bed no. 3											Unclassified		Total, all mines and ore beds
Purgatorio group			Soledad group						Infierno	Total, ore bed no. 3	Miscellaneous mines	Ore purchased from *poquiteros*	
San Francisco	Humboldt	Total	Santa Rita, San Antonio, Santa Marta	Amelia	San Agustín	San Luis	Curuglú	Total					
											[1] 391,587		391,587
10,715	9,600	22,760	1,020	8,840		37,315		47,175		118,020			118,020
13,075	8,565	23,010	1,720	9,700		36,520	10	47,950		132,860			132,860
11,215	810	21,730	80	17,970		38,120	60	56,230		150,020			150,020
7,945		44,245	110	13,685		42,540	170	56,505		155,820			156,010
24,235		57,897	137	19,362		52,638	45	72,182		178,656			180,190
48,310		76,120	540	23,045		31,300	5,380	60,265		191,810			192,520
41,870	26,049	79,960	760	16,170		72,540	4,355	93,825		242,175			242,325
51,800	67,070	119,605	1,605	13,030	62,050		(2)	76,685		260,990			261,170
46,625	41,467	120,855	820	29,000	59,890			89,710		275,635			275,635
		110,590	230	38,685	51,890			90,805		249,895			249,895
		104,510	1,380	39,940	50,220			91,540		230,490			230,490
		104,740	880	51,430	58,390			110,700		259,870			259,870
		100,540	780	57,520	39,090			97,390		261,460			261,460
		118,660	35,350	62,810	12,590			110,750		304,940			304,940
		128,641	27,531	45,169	34,089			106,789		319,850			319,850
		126,210	16,730	42,980	62,810			122,520		340,800			340,800
		117,510	27,230	32,920	55,700			115,850		330,000			330,000
		115,220	23,180	49,770	61,170			134,120		365,000			365,000
		105,850	19,820	60,800	52,450			133,070		355,100			355,100
		114,420	20,760	46,810	56,890			124,460		364,850			364,850
		113,470	22,280	44,570	66,770			133,620		369,570			371,300
		103,620	(4)	41,250	64,630			105,880		319,057			324,500
		89,040	4,420	35,530	68,630			108,580		316,800			316,800
		82,920	46,820	31,600	23,990			102,410		290,000			290,000
		70,860	46,080	26,080	14,550			86,710		240,580			258,400
		72,140	57,960	21,920				79,880		227,515			263,700
		54,060	56,650	7,270				63,920		162,400			194,800
		35,820	32,170					32,170		82,445			96,900
		58,560	6,130					6,130		81,845			99,000
		89,910	870					870		117,090			143,400
		99,440	10,100					10,100		140,620			171,700
		79,060	23,200			[8] 10,260		33,460		112,520			193,000
		57,088	40,290			[8] 6,585		46,875		103,963			167,400
		75,940	53,530			[8] 13,490		67,020		142,960			247,800
		67,660	71,390			[8] 8,370		79,760		147,420			266,500
		58,670	95,230			[8] 13,050		108,280	30	166,980			284,400
[8] 4,210		65,140	87,060			[8] 19,890		106,950	1,770	173,860			311,800
[8] 6,300		101,270	84,310			[8] 890		85,200	4,300	190,770			333,600
		78,270	89,340					89,340	2,280	169,890			278,700
		95,830	112,420					112,420		208,250			267,000
		130,130	84,530					84,530		214,660			216,800
		108,960	83,330					83,330		192,290			193,200
[8] 24,770		133,560	67,910					67,910		201,470			204,300
[8] 28,170		126,260	56,600					56,600		182,860			203,900
[8] 700		96,160	63,040					63,040		212,220			269,400
		88,780	26,450			[8] 42,795		69,245		169,495	[9] 305		237,700
[8] 3,403		92,033				[8] 14,026		14,026		130,224	[9] 6,575	35,281	245,000
		63,230								72,469		78,931	260,100
												96,040	234,000
										29,360		104,780	266,100
											[9] 31,290	93,030	268,800
											[9] 8,956	101,024	231,500
											[9] 15,534	123,850	196,770
												139,830	145,730
												185,600	185,600
323,343	153,561	4,200,954	1,502,773	887,856	895,799	440,329	10,020	3,736,777	8,380	10,257,824	454,247	958,366	13,722,192

[1] Before 1893, records are not available for individual mines. The production from 1886 to 1892 probably came largely from the Carmen, California-Lugarda, San Francisco, Humboldt, Amelia, and San Luis mines.
[2] Production included in figure for Amelia mine.
[3] Some production from Margarita mine, ore bed no. 2, included in figure for Purgatorio mine, ore bed no. 3.
[4] Production included in figure for San Agustín mine.
[5] Production included in figure for California-Lugarda mine.
[6] From 1918 to 1923 the records for the Montado and Sontag mines were combined, although the Montado mine is in ore bed no. 1 and the Sontag is in ore bed no. 3. The figures for these years are arbitrarily divided equally between the two mines.
[7] Production included in figure for Montado mine.
[8] Production from dumps.
[9] Includes production from slag dumps.

an additional area southeast of Arroyo de Santa Agueda where exploratory drilling was carried out. By 1948 all these claims had likewise been given up, with the exception of those covering the San Luciano mine.

With the growth of mining by *poquiteros* since 1938, the Boleo district has again been covered by a large number of claims of many sizes and shapes. The principal claims in existence in 1948 are shown in plate 2, but it should be pointed out that these are in a constant state of flux in respect to number, name, location, and ownership.

MINING METHODS

The mining methods in the Boleo district are similar to those sometimes used in mining thin coal seams and are quite distinct from those used in most metal mines. The most unusual problems are occasioned by the nature of the soft clay comprising the ore beds, which is under strong pressure that gives the workings a tendency to close in from the roof, floor, and sides shortly after they are opened. This is true particularly of the deeper mines below the water table. As a result, an abnormal amount of timbering is required, and it is

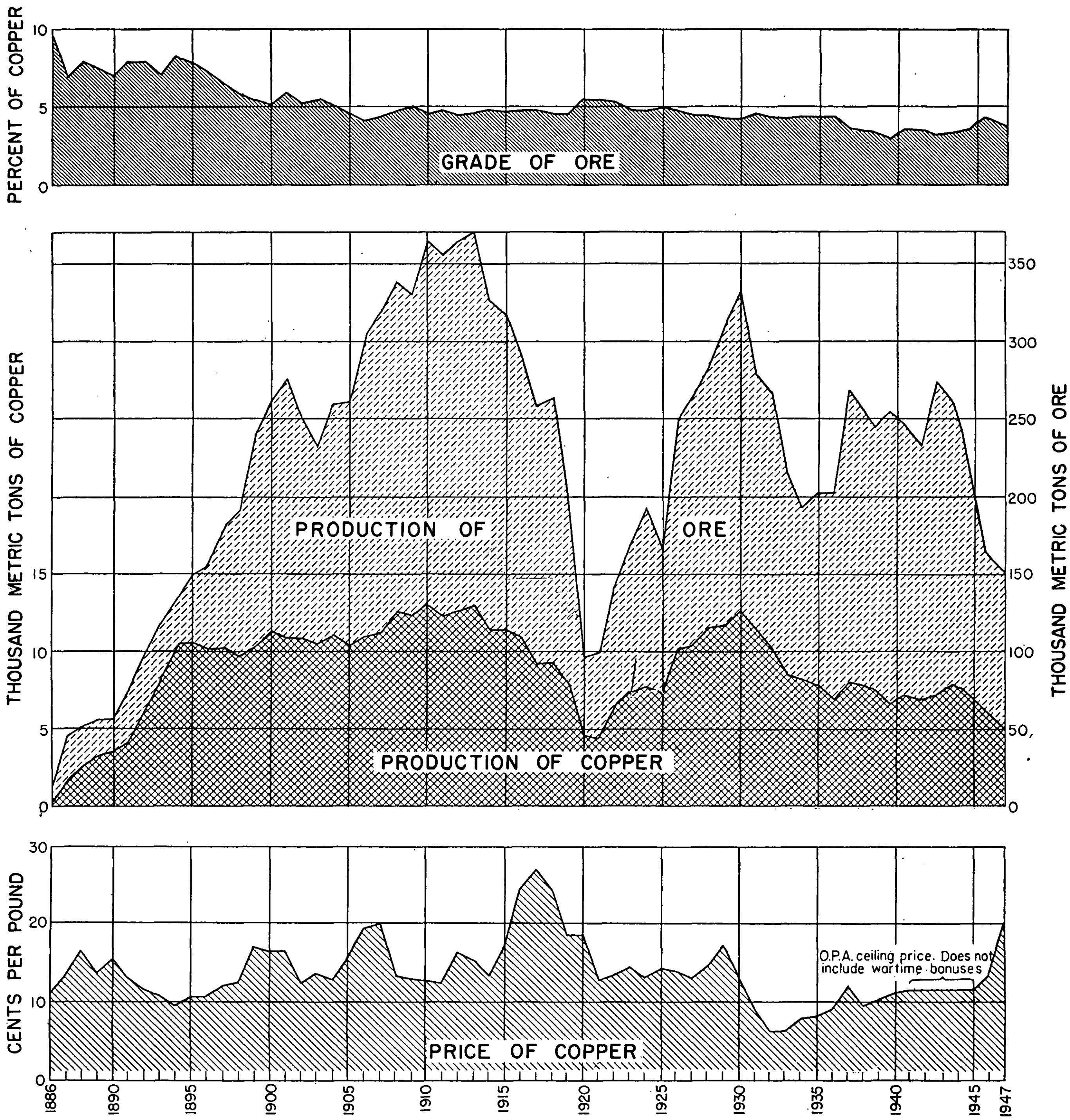

FIGURE 38.—Trends in price of copper, production of ore and of copper, and grade of ore in the Boleo copper district, 1886 to 1947.

commonly necessary to retimber a given working two or three times before the adjoining area can be stoped out. For this reason, very few of the several hundred kilometers of workings made in the district are now accessible, except those that are currently being worked. Other problems in the deeper mines are the heat and high humidity. The temperature gradient has been determined as 1° C per 15 meters of depth, or more than twice the usual rate. Because of the excessive humidity the miners customarily wear nothing but a loin cloth and a hat while at work.

In the earliest years of mining, the ore bed was followed by irregular drifts and was stoped out according to a modified room-and-pillar system, and this method is still used by the *poquiteros* in the smaller mines. In the larger mines, however, the Boleo company has followed in general a method called locally the system of *tallas*, in which the ore bed is completely stoped out along an advancing face and the waste from the hanging wall is used as fill in the stopes. Since 1927, conveyor belts along the stoping faces have been used as an integral part of this method. This system is called by Bellanger (1931, p. 769) the shortwall method; it is similar to the longwall method of the coal-mining industry, except for the shorter length of the faces.

The mines are generally developed by two intersecting sets of workings: a set of horizontal drifts following the strike and a set of inclined workings following the dip of the ore bed, which ranges from 3° to 15° in most of the mines. In plan view the horizontal drifts are irregular in detail, as they follow the structure contours of the ore bed, whereas the inclined workings are commonly driven along straight lines. The main haulageways are commonly driven in the footwall conglomerate or sandstone, which stands better than the ore beds, and they follow a straighter course than the drifts in ore. They are driven with a grade of 0.5 to 1 percent to favor the transportation of loaded ore cars.

In preparing for stoping, a block is outlined by two major inclined workings commonly 100 to 120 meters apart, and by two horizontal drifts following the strike, generally 100 to 180 meters apart, the exact spacing depending upon structural features, faults, or other local conditions. These major blocks are divided into smaller sections by temporary horizontal drifts spaced 20 to 30 meters apart, and each of these sections forms a stoping unit called a *talla*. The stoping face is along the dip of the ore bed, parallel to the inclined workings and between two of the horizontal drifts, and the stoping advances inward along the strike.

Miners are stationed along the face of each *talla*, and each miner is assigned a working portion, generally 2.2 meters wide. An electrically driven conveyor belt is placed parallel with the face and the ore is shoveled onto the belt. Because of the soft character of the ore, the stoping is done with pick and shovel. Only rarely is blasting necessary, as when jasper or some other hard rock is encountered. Since the ore is nearly always thinner than the necessary working height, a variable thickness of wall rock from the hanging wall is removed and shoveled as fill into the stoped area behind the conveyor belt. Common proportions are 60 to 80 centimeters of ore plus 1.2 to 1.0 meters of wall rock, to make a total working height of 1.8 meters. After the face has advanced an average of 1.1 meters, the stoping is halted temporarily while the conveyor belt is moved forward to a new position, a process that requires about 2 hours. As the face advances, the partially filled stope behind is abandoned and soon caves in.

It is necessary to timber the area being stoped, keeping up with the advancing face, for otherwise caving takes place very rapidly. Very little of the timber is salvaged. Bellanger (1931, p. 769) states:

> As subsidence is greater ahead than behind the working face, only advance methods can be used at the Boleo mines. In bad ground, to keep a drift open ahead of the face is practically impossible. The change of equilibrium is felt as far as 100 meters ahead of the advancing face.

Supporting pillars are left adjacent to the principal galleries and inclined workings. Aside from these pillars, the ore is stoped out completely, except for those areas where the ore bed is considered too thin or too low in grade to be exploitable, or where it cannot be stoped conveniently because of faulting, structural irregularities, or some other reason. The coefficient of exploitability—that is, the percent of total area in a given mine that can actually be stoped—averaged about 35 percent for the mines as a whole during the 1930's, and ranged from as little as 24 percent in the Ranchería mine to as much as 59 percent in the Purgatorio mine.

Three sets of conveyor belts are commonly used: one set along the stoping face, another along the horizontal drift adjoining the stope, and a third along the major inclined working bordering the general block being stoped. The last belt dumps the ore into a chute, from which it is loaded into ore cars in the main haulageway, usually situated about 6 meters below the level of the ore bed. The main haulageways are provided with double tracks, along which trains of ore cars are pulled by mules. The subsidiary workings are provided with single tracks along which the ore cars are propelled by hand. The small ore cars, made locally, are of 400 kilograms capacity.

In the mines below the arroyo levels, the ore is brought to the surface either by inclined entries or by vertical shafts. The inclined entries, which are locally called *chiflones*, have been very commonly used in the Boleo district. They generally have an inclination of 15 to 30 percent, the inclination varying along the length in the form of a curve concave upward, to allow for sagging of the cables. They commonly have a three-rail track, providing for ascending and descending trains of cars, which are pulled by electrically operated hoists locally called "donkeys."

Some of the extraction has also been by vertical shafts, of which the only one still in use at the time of writing was the William shaft of the San Luciano mine. In places where the ore bed lies above the arroyo levels, the ore has been extracted from adits.

At the surface the ore has generally been dumped from the mine cars onto a sorting belt, where the obvious pieces of wall rock are discarded, although the finer waste can not be sorted out. The ore is then dumped into loading bins, for transportation by railway, aerial tramway, or truck to the smelter. Any waste rock not used as fill in the stopes is disposed of at the surface in the form of conical dumps. Cars loaded with waste are pulled by a winch along tracks leading to the apex of the cone, where the material is dumped. These cone-shaped dumps, some of which are very large, are characteristic of the Boleo district.

Artificial ventilation is required in nearly all the mines. The larger mines have had one or more shafts equipped with electric ventilators for this purpose. In addition, portable blowers and canvas tubing are used to supply air to the working faces. All the mines below the water table are equipped with electrically operated pumps.

For a more detailed account of the mining methods and equipment used, as well as a statement of operating costs, the excellent report of Bellanger (1931) is recommended. Similar data will also be found in the reports by Huttl (1931), Peña (1931), and Cárdenas (1939).

EXTENT OF EXPLORATION AND DEVELOPMENT

UNDERGROUND WORKINGS

The length of underground workings in the Boleo district was recorded through the year 1945 as having reached a total of 588 kilometers. At one time, practically the entire system of mines was intercommunicated; it was possible to enter the Montado mine near the southeast end of the district and proceed entirely underground through the Providencia and Purgatorio mines to the northwest end of the Santa Rita mine, over an air-line distance of 10 kilometers (a much longer distance by way of the underground workings). At present, however, the great majority of the underground workings are caved. Most of the old mines have more recently been reentered at a number of scattered localities by the *poquiteros*.

The areas stoped in ore beds nos. 1 and 3 are separate, although they were formerly intercommunicated by haulageways. The area of workings in ore bed no. 1 extends from Arroyo de Santa Agueda on the southeast to Arroyo de la Providencia to the northwest, and includes the San Luciano, Montado, and Ranchería mines. A smaller isolated area is in the Cinco de Mayo mine farther north in Arroyo del Purgatorio. The area of workings in ore bed no. 3 begins to the southeast in Arroyo de la Providencia, farther inland from the no. 1 workings, and extends northwestward across Arroyos Purgatorio and Soledad to Arroyo del Boleo. A few small isolated workings in ore bed no. 3 are also farther northwest, in the drainage basin of Arroyo del Boleo, Cañada de la Gloria, and Arroyo del Infierno.

Some relatively small workings in ore bed no. 2 are superimposed upon the no. 3 workings in Arroyos Providencia and Purgatorio. Small workings in the Falsa Tercera ore bed are superimposed upon the no. 3 workings on the south side of Arroyo del Boleo. A small area of workings in the Sin Nombre ore bed slightly overlaps at a lower level the area of workings in ore bed no. 1 in the Montado mine. A few small workings in ore bed no. 4, which are of slight importance, are below or to one side of the no. 3 area. In general, with the exceptions noted above, in any particular area only one ore bed has been worked and there is accordingly only one level of workings, except for haulageways or entries at a higher or lower level; but from one area to another the levels of workings change constantly according to the dip of the ore beds.

SHAFTS

About 56 vertical shafts have been sunk in the district. Their depths average 90 meters, and some are as deep as 255 meters. The total combined depth of the principal shafts is 5,047 meters, excluding several smaller shafts of only a few meters depth. These shafts have been sunk for extraction, ventilation, or exploration purposes. Among the latter may be mentioned the San Agustín, Amelia, La Ley, San Eduardo, and San Alejandro shafts, which explore ore bed no. 4; the Santa Marta, San Enrique, San Roberto, San Alfonso, and Falla shafts, which explore ore bed no. 3 outside the limits of the area mined; and the San Julio, Santa Agueda, and San Luciano shafts, which explore ore bed no. 1 beyond the limits of the area mined. Data concerning the location, elevations, and depths of the shafts and of the principal ore beds cut therein are presented in table 29. Columnar sections of the rocks exposed in the shafts for which data are available are given in plates 5 and 6.

DRILL HOLES

An extensive exploratory drilling program was carried on by the Boleo company from 1927 until 1940, during which period 46 vertical holes were made by churn drilling. The holes were drilled to depths ranging from 19 to 398 meters, the average depth having been 222 meters. The aggregate total of drilling was 10,237 meters. Records were kept of the elevations at which different lithologic units and ore beds were penetrated, and assays were made of the more important ore beds. Data on location, elevations, and depth of the holes as well as elevations, depth, thickness, and grade of ore bed no. 1, the principal ore bed found in the holes, are given in table 30.

TABLE 29.—*Shafts in the Boleo copper district*

[Measurements are in meters]

Name of shaft	Coordinates, based on San Francisco shaft: North-south	Coordinates, based on San Francisco shaft: East-west	Altitude at surface	Distance of bottom above or below sea level	Total depth of shaft	No. of the principal ore bed exposed	Distance of ore bed above or below sea level	Depth of ore bed below surface	Main purpose of shaft	Remarks
Amelia	863 N.	2894 W.	205.24	46.45	158.79	3 4	190.17 49.15	15.07 156.09	Exploration of ore bed no. 4; extraction of ore bed no. 3.	Ore bed no. 4: 0.14—1.74 percent Cu. Comondú volcanics at 49.15 m. Formerly an important extraction shaft.
Boleo	3584 N.	2717 W.	80.36	5.36	75.00	4 (?)	5±	75±	Exploration of ore bed no. 4 (?).	Used as a water well for many years. Now caved.
Bompland	108 N.	221 W.	73.77	61.82	11.95	3	62±	12±	Ventilation	
California	255 N.	1583 W.	182.50	148.52	33.98	3	149±	34±	Ventilation	
Carmen	1573 S.	794 E.	107.05	53.17	53.88	3	53±	54±	Extraction	
Carré	1887 S.	696 E.	112.92	62.26	50.66	3	62±	51±	Ventilation	
Central	180 S.	863 E.	185.10	28.95	156.15	1 (barren)	151.42	33.68	Ventilation	Bottom of shaft approximately at depth of ore bed no. 3.
Conchas	554 N.	1093 W.	140.00	111.57	28.43	3	112±	28±	Ventilation	
Cumenge	283 N.	2838 W.	259.53	168.36	91.17	none			Extraction, ventilation.	Bottom of shaft 5± m above ore bed no. 3.
Curuglú no. 1	608 N.	3440 W.	204.32	130.15	74.17	3	130.66	73.66	Extraction	
Curuglú no. 2	635 N.	3455 W.	202.01	125.58	76.43	3	125.58	76.43	Ventilation	
De Gaulle	4935 S.	3869 E.	62.31	−106.89	169.20	1	−95.26	157.57	Ventilation	Most recent shaft; completed in 1944, to ventilate San Luciano mine.
Falla	2136 S.	246 E.	121.44	23.00	98.44	(?)	(?)	(?)	Exploration	Lies inland from mined area; ore bed probably found, but not considered exploitable.
Indios	1728 N.	382 W.	162.91	34.42	128.49	2 3	77.66 41.06	85.25 120.85	Ventilation	
La Ley (surface shaft)	170 S.	1743 W.	176.37	141.22	35.15	3	141±	35±	Ventilation	
La Ley (interior shaft)	195 S.	1760 W.	141.20	60.40	80.80	3 4	134.40 93.71	41.97 82.66	Exploration of ore bed no. 4.	Comondú volcanics at 78± m.
Mars	680 N.	577 E.	60.50	−3.00	63.50	3	−3±	63±	Exploration of ore bed no. 3.	Used as water well.
Niña	81 S.	82 W.	87.80	61.96	25.84	3	62±	26±	Ventilation	
Pablito	412 N.	427 W.	78.49	67.19	11.30	3	67±	11±	Ventilation	
Purgatorio	350 N.	134 E.	79.01	24.95	54.06	none			Extraction	Bottom of shaft is above ore bed no. 3. Formerly an important extraction shaft.
San Agustín	1989 N.	2054 W.	155.43	26.93	128.50	3 4	139.93 37.13	15.50 118.30	Exploration of ore bed no. 4; extraction of ore bed no. 3.	Ore bed no. 4 not exploitable. Formerly an important extraction shaft.
San Alberto	553 S.	1258 E.	81.06	24.02	57.04	3	24±	57±	Extraction	Formerly an important extraction shaft.
San Alejandro	395 N.	197 W.	79.37	−58.30	137.67	3 4	41.97 −55.30	37.40 134.67	Exploration of ore bed no. 4; ventilation.	Ore bed no. 4: 2.3—5.1 percent Cu. Comondú volcanics at −55.30 m.
San Alfonso	2426 S.	33 W.	140.80	28.46	112.34	(?)	(?)	(?)	Exploration	Lies inland from mined area; ore bed probably found, but not considered exploitable.
San Diego	1068 S.	2943 E.	126.38	−43.08	169.46	1	9.16	117.22	Ventilation	
San Eduardo	276 N.	994 W.	87.12	1.86	85.26	4	9.62	77.50	Exploration of ore bed no. 4.	Comondú volcanics at 1.86 m.
San Enrique	2877 N.	826 W.	88.64	47.87	40.77	3	47.87	40.77	Exploration, ventilation.	Ore not exploitable.
San Eugenio (or Malibrán).	260 S.	1912 E.	81.34	−4.90	86.24	none (?)			Exploration	
San Felipe	966 N.	1863 W.	237.44	164.01	73.43	none			Ventilation	Bottom of shaft is above ore bed no. 3.
San Francisco	0	0	78.17	37.75	40.42	3	38±	40±	Extraction	Formerly an important extraction shaft; now caved. Center of coordinates.
San Gregorio	181 N.	2569 E.	127.29	55.03	72.26	none			Ventilation	Bottom of shaft is above ore bed no. 1.
San Guillermo	402 N.	1243 E.	129.68	−13.15	142.83	3	−13.15	142.83	Exploration, ventilation.	
San José	2050 N.	1064 W.	152.94	32.63	120.31	2	52.03	100.91	Ventilation	Bottom of shaft approximately 25 m above ore bed no. 3.
San Juan	2849 N.	2262 W.	164.09	79.34	84.75	none			Ventilation	Bottom of shaft is slightly above ore bed no. 3.
San Julio	1324 S.	2343 E.	166.42	6.42	160.00	0 (?) 1 (?) 2 (?)	85.37 57.27 21.07	81.05 109.15 145.35	Exploration	Ore beds not considered exploitable. Comondú volcanics at 6.42 m.
San Luciano	3821 S.	3275 E.	142.70	37.80	104.90	0 (?) 1 (?)	80.80 46.30	61.90 96.40	Exploration of ore bed no. 1.	Ore beds not considered exploitable. Comondú volcanics at bottom.
San Luis	1643 N.	2376 W.	168.52	150.96	17.56	3	160±	8±	Extraction, ventilation.	Formerly an important extraction shaft.
San Marcelo	547 S.	2572 E.	184.92	−21.19	206.11	0 1 2	81.88 42.50 −21.19	103.04 142.42 206.11	Exploration, ventilation.	
San Pablo	370 N.	216 W.	77.05	48.62	28.43	3	49±	28±	Ventilation	
San Pedro	639 N.	545 E.	64.33	20.93	43.40	none			Exploration of ore bed no. 2.	
San Porfirio	1497 N.	1603 W.	198.92	103.56	95.36	3	103.56	95.36	Ventilation	
San Roberto	1365 N.	1285 E.	55.21	−9.89	65.10	2 3	17.51 −9.89	37.70 65.10	Exploration of ore bed no. 3.	Ore beds no. 2 and no. 3 not considered exploitable.
Santa Agueda	3371. S.	4489 E.	43.43	−139.92	183.35	0 1	−99.07 −136.42	142.50 179.85	Exploration of ore bed no. 1.	Ore bed no. 1: 3.8 percent Cu. Not considered exploitable.
Santa Bárbara	1183 S.	1351 E.	109.32	26.59	82.73	none			Ventilation	Bottom of shaft is above ore bed no. 3.
Santa María	1995 N.	484 W.	142.51	42.81	99.70	2 (barren)	88.61	53.90	Ventilation	Bottom of shaft about 22 m above ore bed no. 3.
Santa Marta	3260 N.	256 W.	85.34	0.87	84.47	none			Exploration, ventilation.	Lies seaward from mined area.
Santa Natalia no. 1	3155 N.	1671 W.	111.99	83.43	28.56	none			Ventilation	Not deep enough to reach ore beds.
Santa Natalia no. 2	3113 N.	1697 W.	113.41	27.06	86.35	3a	54.67(?)	58.74(?)	Ventilation	Reached Falsa Tercera ore bed.
Santa Rita no. 1	2635 N.	1516 W.	115.28	19.28	96.00	3	19.96	95.32	Extraction	Manganiferous beds found above ore bed no. 3. Formerly an important extraction shaft.

323059—55——8

TABLE 29.—*Shafts in the Boleo copper district*—Continued

[Measurements are in meters]

Name of shaft	Coordinates, based on San Francisco shaft		Altitude at surface	Distance of bottom above or below sea level	Total depth of shaft	No. of the principal ore bed exposed	Distance of ore bed above or below sea level	Depth of ore bed below surface	Main purpose of shaft	Remarks
	North-south	East-west								
Santa Rita no. 2	2615 N.	1495 W.	115.62	18.23	97.39	3	19.37	96.25	Ventilation	Manganiferous beds found above ore bed no. 3.
Santiago	1491 N.	358 E.	117.70	5.46	112.24	None			Ventilation	Bottom of shaft 50± m above ore bed no. 3, west of Santiago fault.
Solitario	1483 N.	871 W.	187.42	68.03	119.39	3	68±	119±	Ventilation	
Sombrero Montado no. 1.	2593 S.	2596 E.	132.48	34.34	98.14	(?)	(?)	(?)	Ventilation	Ore beds no. 1 and Sin Nombre near bottom of shaft.
Sombrero Montado no. 2.	2555 S.	2638 E.	130.90	34.31	96.59	0 (?)	75.47	55.43	Ventilation	Bottom of shaft 7± m above ore bed no. 1.
Sontag	1000 S.	763 E.	118.03	59.69	58.34	3	60±	58±	Extraction	
William	4040 S.	4086 E.	55.60	−199.45	255.05	0	−105.30	160.90	Extraction	Deepest shaft in district; used for extraction from San Luciano mine.
						1	−149.27	204.87		

Columnar sections of the rocks cut in the drill holes, arranged roughly in geographic order from northwest to southeast, are presented in plates 5–8. In these columnar sections the data on elevations, thicknesses, and grade of ore have been taken from the company's records, but the correlations of the lithologic units and the assignments to geologic formations are interpretations of the writers, based on their stratigraphic studies in the region. Certain of the driller's lithologic terms have also been reinterpreted in the light of the writers' observations. The locations of the drill holes have been indicated on the mine map of the district, plate 9.

TABLE 30.—*Drill holes in the Boleo copper district*

[Measurements, except as noted, are in meters]

Drill hole no.	Coordinates, based on San Francisco shaft		Altitude at surface	Distance of bottom below sea level	Total depth of hole	Distance of ore bed no. 1 below sea level	Depth of ore bed no. 1 below surface	Thickness of ore bed no. 1[1]	Grade of ore bed no. 1 (percent copper)[1]	Remarks
	South	East								
1	3469	4499	33.90	−210.10	244.00	−159.16	193.06	0.62	1.71	Comondú volcanics at −236.45 meters, below gypsum.
2	3552	4318	42.32	−247.12	289.44	−160.20	202.52	0.30	0.97	
3	4308	3586	62.42	−116.92	179.34	−53.78	116.20	1.65	0.65	Comondú volcanics at −112.34 meters.
4	4209	4171	37.68	−242.31	279.99	−168.65	206.33	0.76	20.85	Gypsum at −241.09 meters.
5	4197	4691	35.01	−262.20	297.21	−200.14	235.15	0.55	1.85	Gypsum at −260.37 meters.
6	4596	4537	34.42	−281.40	315.82	−201.65	236.07	?	?	Gypsum at −279.57 meters.
7	4286	4102	39.23	−156.88	196.11	−155.05	194.28	0.50	5.59	
8	4138	4249	35.66	−172.65	208.31	−169.60	205.26	0.51	5.72	
9	4081	4348	33.56	−182.99	216.55	−181.16	214.72	0.15	1.29	
10	4263	4219	37.21	−172.32	209.53	−169.27	206.48	0.55	7.23	
11	4418	4358	37.50	−189.11	226.61	−187.89	225.39	0.40	2.11	
12	4062	4036	56.39	−138.81	195.20	−137.59	193.98	0.70	6.09	
13	3915	3904	65.70	−83.44	149.14	−82.22	147.92	0.50	6.96	
14	3883	4039	57.25	−116.60	173.85	−115.38	172.63	0.75	7.20	
15	4056	3900	64.80	−101.52	166.32	−99.90	164.70	0.45	4.81	
16	4349	4435	37.36	−186.20	223.56	−185.59	222.95	0.70	1.57	
17	4273	4576	35.53	−208.30	243.83	−206.48	242.01	0.55	3.62	
18	4485	4284	37.99	−181.47	219.46	−179.64	217.63	0.65	6.54	
19	1637	4275	36.00	−151.45	187.45	−90.18	126.18	0.55	1.63	Comondú volcanics at −146.88 meters.
20	4672	4276	54.75	−179.95	234.70	−178.12	232.87	0.40	4.04	
21	1648	3728	57.47	−56.52	113.99	−55.91	113.38	0.55	3.18	
22	5153	4727	125.92	−265.75	391.67	−201.43	327.35	0.60	2.40	Gypsum at −264.22 meters.
23	1168	3561	60.80	−50.76	111.56	−48.93	109.73	0.60	3.60	
24	5266	4558	134.61	−141.72	276.33	−141.72	276.33	0.42	4.81	
25	730	4975	6.60	−12.90	19.50	--------	--------	--------	--------	Comondú volcanics at −10.15 meters.
26	5353	4482	136.36	−125.63	261.99	−125.63	261.99	0.40	4.69	
27	1281	4322	26.35	−76.67	103.02	--------	--------	--------	--------	Comondú volcanics at −72.71 meters, below gypsum.
28	5425	4416	139.87	−139.33	279.20	−117.68	257.55	0.57	1.29	Comondú volcanics at −138.72 meters.
29	845	3529	70.13	−78.40	148.53	−28.99	99.12	0.80	7.48	
30	5205	4630	130.97	−229.61	360.58	−223.51	354.48	0.65	4.16	
31	839	3412	77.22	−20.62	97.84	−18.79	96.01	1.07	6.08	
32	5435	4650	131.74	−192.26	324.00	−154.16	285.90	0.45	3.76	
33	3254	5026	26.14	−305.09	331.23	−291.67	317.81	0.40	0.08	Gypsum at −304.48 meters.
34	5532	4580	134.27	−135.48	269.75	−134.56	268.83	0.49	4.22	
36	5680	4717	122.58	−84.07	206.65	([2])	--------	--------	--------	Comondú volcanics at −81.64 meters.
38	5540	4850	114.11	−223.30	337.41	−221.17	335.28	--------	0	Comondú volcanics at −221.17 meters.
40	4949	4413	56.27	−158.00	214.27	−151.91	208.18	0.60	4.4	
42	5038	4297	57.30	−145.39	202.69	−143.87	201.17	--------	0	Comondú volcanics at −143.87 meters.
44	5135	4162	59.49	−109.98	169.47	−95.04	154.53	--------	0	Comondú volcanics at −109.06 meters.
46	4864	4472	55.15	−185.95	241.10	−162.78	217.93	0.50	3.69	
48	4312	3844	46.49	−128.16	174.65	−112.01	158.50	0.55	6.6	
49	910 North	920	51.00	−114.51	165.51	([3])	([3])	--------	--------	Comondú volcanics at −113.59 meters.
50	5920	5155	99.72	−89.26	188.98	--------	--------	--------	--------	Not deep enough to penetrate ore beds.
52	5790	5363	74.78	−322.98	397.76	−319.93	394.71	1.11	0.25	
56	4586	3709	60.09	−174.00	234.09	−113.65	173.74	--------	0	
58	4774	3799	43.67	−115.44	159.11	−115.44	159.11	1.10	3.55	

[1] Thickness and grade of ore bed refer in general only to the exploitable part, if any.

[2] Boleo formation is missing in hole 36, probably because of lack of deposition over a buried hill of Comondú volcanics.

[3] Hole 49 was drilled to explore ore bed no. 3, which was penetrated at −25.20 meters, or 76.20 meters below the surface. The bed was very thin and barren.

With the exception of a single hole (no. 49) drilled to explore ore bed no. 3 in Arroyo del Purgatorio, all the holes were drilled in the southeast part of the district, where ore bed no. 1 is the most important ore bed and is generally buried rather deeply below the surface. Seven holes were drilled in Arroyo del Montado, 27 holes in and near Arroyo de Santa Agueda, and 11 holes on the mesas southeast of Arroyo de Santa Agueda.

Most of the holes penetrated a considerable thickness of the fossiliferous sandstone and conglomerate of the Gloria and Infierno formations, before striking the ore-bearing beds of the Boleo formation. Eleven holes were drilled entirely through the Boleo formation and reached the Comondú volcanics (uniformly designated by the drillers as "trachyte") at depths of 10 to 236 meters below sea level. In two of these holes gypsum was found to lie directly on the Comondú volcanics. Five additional holes were drilled as far as the gypsum, at depths of 242 to 305 meters below sea level, and then stopped, for it was considered likely that the Comondú volcanics would be found directly below. Most of the other holes were terminated after reaching ore bed no. 1, although a few continued down into ore bed no. 2.

It was demonstrated that ore bed no. 3 is missing over the entire area covered by the drill holes. Ore bed no. 2 was found in 11 of the holes, but without exception it was considered to be unexploitable. Seven additional holes were deep enough to demonstrate the absence of ore bed no. 2. Ore bed no. 1 was found in all but three of the holes—nos. 25, 27, and 36—where its absence is evidently due to nondeposition over buried hills of Comondú volcanics. Ore bed no. 0 was found in all but four of the holes, but it is extremely low in grade and was considered unexploitable throughout.

One of the results of the drilling program was to block out the exploitable ore body of the San Luciano mine, the most recent mine in the district, developed deep below the surface in Arroyo de Santa Agueda. In the vicinity of the San Luciano mine, 12 drill holes outlined an area in which ore bed no. 1 lies between 82 and 180 meters below sea level (148 to 233 meters below the surface), and was shown by the drill-hole samples to have an average thickness of 62 centimeters and an average grade of 7.1 percent of copper. (These figures compare with averages of 76 centimeters in thickness and 6.0 percent of copper determined by later sampling involving 2,301 measurements in the mine.)

An additional 18 holes south and east of the San Luciano mine explore an area in which the ore bed has an average thickness of 50 centimeters, an average grade of 3.3 percent of copper, and lies at depths of 118 to 224 meters below sea level. The grade decreases farther down the dip to the northeast, for in drill hole 33, the most northeasterly hole in Arroyo de Santa Agueda, ore bed no. 1 lies at 292 meters below sea level and was found to have a thickness of 40 centimeters and a grade of only 0.08 percent of copper. The lack of commercial possibilities in the most southeasterly holes, nos. 36, 38, and 52, indicates that the southeastern limit of possible exploitability of marginal reserves is formed by holes nos. 32 and 34, in which ore bed no. 1 has a grade of 3.76 and 3.31 percent of copper, respectively.

Two of the holes in Arroyo del Montado—nos. 31 and 29—cut ore bed no. 1 at depths of 19 to 29 meters below sea level (96 to 99 meters below the surface), where it has a thickness of 107 and 80 centimeters in the two holes, respectively, and a grade of 6.07 and 7.48 percent of copper. As the depth, thickness, and grade were considered to be favorable, the workings of the Ranchería mine were extended to the area covered by these holes. Three additional holes in Arroyo del Montado—nos. 19, 21, and 23—outline an area southeast of the Ranchería mine, in which ore bed no. 1 lies at depths of 49 to 90 meters below sea level (110 to 126 meters below the surface), has an average thickness of 57 centimeters, and contains an average of 2.80 percent of copper.

Holes 25 and 27, near the mouth of Arroyo del Montado, reached the Comondú volcanics at shallow depth without penetrating any ore beds. They apparently struck the western slope of a buried ridge of Comondú volcanics that reaches the surface along the sea coast near the mouth of Arroyo del Montado. The entire Boleo formation is missing in hole 36, which seemingly passed from the Gloria formation directly into the Comondú volcanics at a depth of 81 meters below sea level. The Comondú lies at a higher position in this hole than in localities nearby, and the absence of the Boleo formation is attributed to nondeposition over a buried hill.

A stereogram showing the structural and stratigraphic relations in the area explored by drill holes in the vicinity of Arroyo de Santa Agueda is presented in plate 10. This stereogram shows the irregularities in the surface of the Comondú volcanics, which reaches a high point (46 meters above sea level) in the San Luciano shaft to the northwest and a low point (more than 305 meters below sea level) in drill hole 33 to the northeast. The buried hill penetrated by hole 36, at the southernmost corner of the diagram, is also shown.

The stereogram illustrates the manner in which beds of the Boleo formation wedge out against the irregularities of the surface of the Comondú volcanics. It also illustrates the local distribution of the gypsum and the lenticular character of the conglomerates in the Boleo formation, as well as the facies changes in the Gloria formation (seaward thickening of sandstone and landward thickening of conglomerate). Interfingering of sandstone and conglomerate in the Gloria formation is well shown by the cross section running northwest from drill hole no. 38 through no. 22 to no. 6.

METALLURGICAL TREATMENT OF ORE[11]

The Boleo copper ore is smelted directly after crushing and drying. Before 1922 the ore was smelted in blast furnaces, from which two products were obtained simultaneously: black copper, averaging 93.4 percent of copper, and copper matte, averaging 63.6 percent of copper. The two products were in an average ratio of 1 ton of black copper to 2.5 tons of copper matte. These products were shipped to Europe for further refining. The slag from the blast furnaces was comparatively high in copper content, much of it containing about 1 percent. The average recovery from 1886 to 1922 was 79.5 percent.

Since 1922 the ore has been smelted in reverberatory furnaces, producing a relatively high-grade copper matte which contains from 60 to 65 percent of copper. The matte is treated in a converter, the product of which is blister copper containing an average of 99.3 percent of copper. The blister copper is shipped to Tacoma, Wash., where it is refined electrolytically by the American Smelting and Refining Company. An electrolytic refinery was installed at Santa Rosalía in 1924 but was abandoned after about 6 months of operation.

The smelter capacity since 1922 has been about 12,000 tons of blister copper per year, although it was reduced in 1948 to about 7,000 tons, because of a decrease in the number of reverberatory furnaces in operation. In 1948 the daily capacity was about 600 tons of ore, yielding about 20 tons of blister copper. The average smelter recovery from 1922 to 1947 was 87.4 percent. Most of the loss is in the slag, which contains about 0.4 percent of copper, but some is in the flue dust.

Both oxidized ores and sulfide ores have been treated together in the Boleo smelter. The ore is deficient in sulfur which must be added to the furnace charge, either as imported pyrite or locally mined gypsum. Carbon is also added to the charge, in order to reduce the copper oxides and the sulfur contained in the sulfates. The source of the carbon has been coal, either bituminous or anthracite, coal dust, or coke breeze. Other materials added to the furnace charge are a siliceous slag and a calcareous flux, such as gypsum or rocks containing a high proportion of calcium carbonate. The source of the latter has been a shell-bearing calcareous sandstone of the Infierno formation, or the impure limestone of the Boleo formation.

The Boleo smelter is near the northwest end of the harbor at Santa Rosalía. The smelter building contains space for 6 reverberatory furnaces, 4 rotary driers, 2 converters, crushing equipment, a flue system, and a slag disposal plant. It also houses a powerplant which utilizes waste heat from the furnaces.

Bins and elevated railroad platforms provide for stockpiling large tonnages of ore north of the smelter. The ore is hauled by bottom-dump 6-ton railroad cars to a loading platform, where it is weighed and dumped into loading bins, having automatic samplers. The ore is conducted by a metallic conveyor to hammer crushers, which deliver a ½-inch product, and is thence conducted by conveyor belts to the driers. Four Allis-Chalmers rotary driers, each of 300 tons per day capacity, utilize waste heat provided by gasses from one of the reverberatory furnaces.

The dried ore, mixed with the other materials composing the furnace charge, is side fed through hoppers into the reverberatory furnaces. A maximum of 6 reverberatory furnaces have been operated, but in 1948 3 furnaces were in operation, having a capacity of about 250 tons per day of solid charge each. The furnaces are fired by fuel oil, mostly imported from California. The hot gasses from the furnaces are conducted through Stirling waste-heat boilers, which provide steam for the powerplant, and are then discharged through a flue 600 meters long. The slag is tapped continuously from the end of the furnaces, and is granulated by flowing into a trough of running sea water. The granulated slag is carried by a drag conveyor to a loading bin beside the harbor, and disposed of by barges or by trucks.

The copper matte is tapped once in 24 hours, from one side of the furnace, into 5-ton cast iron ladles and transported by overhead crane conveyors to the converters. Two basic-lined converters are available, with a capacity of about 32 tons of blister copper per day each, although generally only one is in use. The converters are charged with molten copper matte and a flux consisting of silica, silica brick, and slag. The converter slag, which contains 1.5 to 3.5 percent of copper, is crushed and charged back into the reverberatory furnaces.

Molten copper from the converters is poured by a ladle into 24 anode molds mounted on a track car and quenched by a spray of sea water. After cooling, the rectangular anodes of blister copper, which weigh approximately 140 kilograms each, are removed from the molds and stored for shipment.

[11] Assistance in the preparation of this part has been provided by Alan Probert of the U. S. Bureau of Mines, and by J. Ranc, Boleo smelter superintendent, who kindly guided the writers through the smelter. Descriptions of the smelter have been published by Huttl (1931) and Bellanger (1931).

The direct smelting method results in a comparatively high cut-off grade for ore, which must contain at least 3 to 3.5 percent of copper to be commercial. In the past the Boleo ores have not been considered amenable to concentration, mainly because of the extremely fine size of the ore minerals and the close association of these minerals with the clayey matrix. The matrix has the swelling properties of a bentonitic clay, which makes filtration of the pulp almost impossible in ore-dressing experiments. The ore is not of the type amenable to preliminary heavy media separation, nor would the commonly known methods of gravity concentration be expected to be satisfactory.

One means of prolonging the life of the Boleo district would be the development of some ore-dressing process that would make possible commercial exploitation of the lower grade ores. With this view in mind, the senior author collected several large samples in 1948 which were sent to the U. S. Bureau of Mines in Salt Lake City for ore-dressing tests. Later, George M. Potter of the Bureau of Mines collected other samples. The work on these samples was carried out in cooperation with the Comisión de Fomento Minero of Mexico.

Some preliminary results of these experiments indicate that the Boleo ores pose difficult problems for ore-dressing, but that a method that might be applicable is a combination leach and flotation process. Although moderately good results were obtained by this method, the leaching process would be expensive because of high acid consumption, and the sulfides respond poorly to flotation. S. R. Zimmerley, chief of the Salt Lake City Branch, Metallurgical Division of the Bureau of Mines, states: "The problem of milling and leaching the ores has by no means been solved but neither do we believe that the problem is hopeless."

DESCRIPTION OF PRINCIPAL MINES

NOMENCLATURE OF MINES

The nomenclature of the mines in the Boleo district is subject to confusion because an area has sometimes been given two or three different names, and many of the mines merge into one another without any definite boundaries. In the early years of the Boleo company the mine workings in ore bed no. 3 radiated from three main centers, established in Arroyo de la Providencia, Arroyo del Purgatorio, and Arroyo de la Soledad. The three main groups of mines were named after the arroyos and called the Providencia, Purgatorio, and Soledad groups. Within each group different mines were named according to the centers of extraction used, as for example the Amelia, San Luis, San Agustín, and Santa Rita mines in the Soledad group. In later years these different mines and groups were nearly all intercommunicated underground and the mine workings in ore bed no. 3 covered one large continuous area; on the mine maps it is often difficult to find any exact dividing lines between the groups. Some areas have, moreover, been served at different times by different centers of extraction, thus causing added confusion in the nomenclature and in the production records for individual mines.

The principal individual mine workings have been named according to their elevation in meters above or below sea level and the name of the mining area or the geographic "band" in which they occur. For this purpose the district has been divided into east-west bands 500 meters wide, each named after some prominent feature within the band (see pl. 9). A working termed "Nivel 25 Indios", then, means a mine level at 25 meters above sea level in the band called Indios; "Nivel—10 Carmen" means a mine level at 10 meters below sea level in the band called Carmen. The principal types of workings named are *nivel*, meaning level; *tiro*, meaning shaft; *chiflón*, a name applied specifically in the Boleo district to a gently inclined entry from the surface, although this does not correspond to the Spanish usage of this term everywhere; *inclinado*, an inclined working; and *travers-bancs*, a French term for crosscut.

The principal mines are described in the succeeding sections primarily in the order of the ore beds which have been exploited, beginning with ore bed no. 1, and secondarily in geographic order, beginning at the south end of the district and proceeding northward. The mine workings and drill holes of the district are shown on a general mine map (pl. 9).

SAN LUCIANO MINE (ORE BED NO. 1)

The San Luciano mine is in Arroyo de Santa Agueda, 4.5 kilometers inland from the mouth of the arroyo, at the southeast end of the Boleo district. It is communicated underground with the Montado mine to the northwest, but the exploited ore bodies of the two mines are separated by a gap of roughly 300 meters. The San Luciano is the deepest mine in the district, extending to a depth of 185 meters below sea level in the lowest drifts and to 199 meters below sea level in the William shaft.

The San Luciano is the newest of the large mines in the district and is the only important mine that was not discovered during the early years of operations. It was outlined entirely by exploratory churn drilling, for the ore bed does not crop out anywhere in the vicinity of the mine. Production from the San Luciano mine began in 1932, with the completion of the William shaft, and operations were continuing in 1949, but the mine was expected to be closed down in 1950 because the area of exploitable ore would then be largely exhausted.

Ore bed no. 1 has provided all the ore produced from the San Luciano mine. Ore bed no. 2 was followed in two places in the minus 60-meter level at the northwest end of the mine, but it was not considered exploitable. The ore bed has a fairly uniform dip of 10°–12° E. The structure contours show a broad arcuate curve in strike, concave eastward (see pl. 4). At the south end of the mine the strike is N. 50° W.; it swings around to north in the central part and to N. 15° E. at the north end. The elevations of the workings that are in ore range from 59 meters below sea level at the northwest end of the mine to 182 meters below sea level at the east end. Most of the stoping has been confined to the levels ranging from 70 to 170 meters below sea level. Several minor faults were exposed in the mine, closely paralleling the general strike of the beds, some dipping westerly and others dipping easterly, but in general they have only a few meters of displacement.

Data on thickness and grade of ore in the San Luciano mine are given in table 12. Monthly smelter returns indicate that the average grade of ore actually shipped from the mine has ranged from 2.9 to 6.3 percent of copper, staying mostly between 4.0 and 4.5 percent. The ore in the San Luciano mine is practically all of the sulfide type, although oxidized copper minerals appear in places as thin films along fractures.

The entire mine is below the water table, which was originally at an elevation of about 8 meters above sea level. The San Luciano mine has probably offered the greatest engineering difficulties of any of the Boleo mines, mainly because of its great depth below sea level and the consequent problems of water, heat, and keeping the workings open. The mine has been highly mechanized, however, and all the stoping has been done according to the shortwall system, using conveyor belts along the stoping faces.

The San Luciano mine has about 15 kilometers of underground workings. It extends 1,200 meters from north to south and 700 meters from east to west. The limits of the stoped areas are determined nearly everywhere by assay walls.

All the extraction from the San Luciano mine has been from the William shaft, 255 meters in depth, which is the deepest and best equipped shaft in the district. It is a two-compartment circular shaft 4.25 meters in diameter, and is lined with cement, to prevent the influx of water. Details of the construction of this shaft have been published by Peña (1932). For ventilation purposes the De Gaulle shaft, 169 meters deep, was sunk at the south end of the mine in 1944. Ventilation is also provided by an inclined entry at the north end of the mine, called Chiflón —40 Pedregoso, which communicates with both the San Luciano and Montado mines.

Ore is transported within the mine first by inclined workings running down the dip to the east, and thence by a series of haulageways in the footwall that run northward and communicate at various levels with the William shaft. The principal levels used for haulageways are at approximate elevations of 60, 90, 135, 160, and 185 meters below sea level. An aerial tramway nearly 5 kilometers long was installed to transport ore from the William shaft to the railhead at the Ranchería mine, on the south edge of the town of Santa Rosalía.

The production of the San Luciano mine from 1932 to April 1948 was 587,502 tons of ore. Extraction of waste from 1932 to the first part of 1946 amounted to 307,608 tons, or 39 percent of the total extraction for that period.

The ore body of the San Luciano mine is outlined on nearly all sides by drill holes. Toward the west, the ore bed was found to be barren in hole no. 56, to contain only 0.65 percent of copper in hole no. 3, and to be unexploitable in the San Luciano shaft, which is an exploratory shaft 500 meters northwest of the mine, sunk in 1905–06. To the east and southeast, drill holes indicate that the ore bed continues, but with reduced thickness and grade. If a commercial method were found to utilize the lower-grade ores of the district, this could be considered an area of marginal reserves, but a major disadvantage is the great depth of the ore bed in this area—from 118 to 224 meters below sea level—and the consequent high cost of mining.

Exploration was carried out from 1925 to 1927 in the Santa Agueda shaft, 550 meters northeast of the San Luciano mine. Drifts at a level of 136 meters below sea level explored ore bed no. 1 through a length of 200 meters. The ore bed was found from a series of 99 samples to have an average thickness of 58 centimeters and an average grade of 3.3 percent of copper, or 2.5 percent after reduction by a dilution factor of 25 percent. If ore of this thickness and grade should someday become exploitable, a substantial area between this shaft and the San Luciano mine to the southwest, as well as the Montado mine to the northwest, might warrant further exploration.

MONTADO MINE (ORE BED NO. 1 AND SIN NOMBRE ORE BED)

The Montado mine is in Arroyo del Montado and its branches, 3.5 to 4 kilometers inland from the coast, on the east flank of Cerro del Sombrero Montado. It is adjoined by the San Luciano mine to the south and the Ranchería mine to the north.

Work began at the Montado mine as early as 1894 or perhaps before, but the principal productive period was between 1918 and 1931. The mine was abandoned after the great cloudburst of September 12, 1931, which flooded many of the workings. Some ore was later extracted through the Ranchería mine to the north and also through the San Luciano mine to the south. A part of the mine was being reopened by the *poquiteros* in 1948 and 1949 under the name of the Sin Nombre mine, and the ore was being hauled by truck from Arroyo del Montado to the smelter.

Ore bed no. 1 in the Montado mine has been followed in a long, narrow, sinuous belt, which runs northward from the San Luciano mine for 700 meters, swings around to the west for an additional 700 meters, and then continues to the north and northeast for 1,500 meters where it merges into the Ranchería mine. The strike in these different segments ranges from due north to due west and back to due north, swinging around locally to N. 40° E. at the north end of the mine. The dip ranges from 5° to 12° E. The structure contours reveal a broad northeast-trending structural trough near the Sombrero Montado shafts, bordered to the south by a northeast-plunging anticlinal nose (see pl. 4). These structural features are believed to be related to the buried topography of the bedrock surface on the eastern slope of Cerro del Sombrero Montado.

The beds in the Montado mine have been offset by a number of faults, most of which are of minor displacement. Near the north end of the mine is the Montado fault, which strikes N. 50° W. and has dropped the beds downward about 30 meters on the southwest side. The dip of the beds is such that the minable belt has been displaced a considerable distance to the northwest on the southwest side of the fault. In the south central part of the mine is another fault in which the southwest side has been downthrown as much as 20 meters.

Elevations of the mine workings that are in ore range from 59 meters above sea level at the west end, where the ore bed is present on the surface of the Comondú volcanics southwest of the Sombrero Montado shafts, to as low as 28 meters below sea level at the southeast end of the mine.

The ore beds do not crop out anywhere in the general vicinity of the Montado mine, as they are buried below Arroyo del Montado by the Gloria and Infierno formations. The principal ore bed was discovered at an early date, however, by the first Sombrero Montado shaft, and it was followed by exploratory workings driven from the shaft. This ore bed was for many years considered to be ore bed no. 3—the same ore bed that was being exploited in the Providencia group and the other principal mines to the northwest. One of the Boleo engineers concluded on the basis of stratigraphic studies, however, that the bed was more likely correlative with no. 1, and this was eventually proved beyond a doubt when the mine was intercommunicated along the ore bed with the Ranchería mine in Arroyo de la Providencia to the north, which is in ore bed no. 1, about 115 meters stratigraphically above ore bed no. 3 in that arroyo. Ore bed no. 3 wedges out against a buried ridge of Comondú volcanics southeast of Arroyo de la Providencia and does not extend southeast as far as the Montado mine.

Although the principal ore bed mined has been ore bed no. 1, in a small part of the mine south of the Sombrero Montado shafts another ore bed was mined that is called the Sin Nombre. This bed lies about 3 meters stratigraphically below ore bed no. 1, although the interval increases to as much as 10 meters in some localities and locally the two beds join. The Sin Nombre ore bed was apparently exceptionally rich in places, but it was found only over a fairly small area. It was mined for a length of 350 meters and width of 50 to 100 meters, between levels of 37 and 57 meters above sea level.

The Sin Nombre ore bed was followed in exploratory drifts for an additional distance of 425 meters to the east and 400 meters to the north of the mined area, but over those areas it was not considered exploitable. The stoped area in the Sin Nombre ore bed lies in general to the west of that in ore bed no. 1, although in places the two overlap. Ore bed no. 0 was encountered in two workings at the southeast end of the Montado mine but was not considered exploitable.

The Comondú volcanics were exposed in several of the workings of the Montado mine, particularly at the southwest end where the ore beds wedge out against the rising surface of Cerro del Sombrero Montado. The long haulageway called Travers-Bancs Montado, which extends to Arroyo de la Providencia, went through Comondú volcanics for much of its length, beginning about 100 meters northwest of the main Montado mine at an elevation of 34 meters above sea level. The Comondú volcanics were also penetrated for a distance of 100 meters by a haulageway called Travers-Bancs 34 Santa Agueda, lying at an elevation of 39 meters above sea level in the south central part of the mine.

Data on thickness and grade of ore, calculated from assay maps of the Montado mine, are given in table 12. The assay maps do not represent the older part of the mine which contained richer ore. The highest grade ore appears to have been found where the beds wedge out toward the bedrock surface in the western extremity of the mine. The average grade of ore shipped from the Montado mine was recorded in 1909 as 5.96 percent of copper, in 1919 as 5.59 percent, and in 1926 as approximately 5.5 percent. The Sin Nombre ore bed is said to have contained about 7 percent of copper, but this provided a relatively small proportion of the total production of the mine. Some oxidized ore was found in the higher levels of the mine, particularly in the stoped areas of the Sin Nombre ore bed south of the Sombrero Montado shafts. Much of the ore shipped from the Montado mine, however, is said to have been of the sulfide type.

The underground workings of the Montado mine have an aggregate length of more than 33 kilometers. The ore has been mined only in a fairly narrow belt having a length of 2.4 kilometers and a width of 200 to 300 meters. Exploration has been carried out for an additional 100 to 200 meters down the dip to the east, but the ore bed in that area was considered too low in grade to be mined.

The main entry for extraction was the haulageway known as Travers-Bancs Montado, which extended for a distance of 1.5 kilometers to Arroyo de la Providencia, where it communicated with the Providencia group of mines and was entered by the Yaqui inclined shaft. Ore cars were pulled through this haulageway by electric locomotives. The principal haulageways within the mine were at levels of 34, 20, and 5 meters above sea level, and 10 meters below sea level. The mine workings communicated to the northeast with the Ranchería mine, through which some ore was extracted after the Travers-Bancs Montado was abandoned in 1931. After completion of the William shaft of the San Luciano mine in 1932, ore from a small area at the southeast end of the Montado mine was extracted through the San Luciano mine.

The only vertical shafts in the Montado mine are the two Sombrero Montado shafts in Arroyo del Montado, which were used for ventilation. Ventilation, as well as extraction of waste, was also provided by several gently inclined shafts.

The Montado mine is recorded as having a total production of 635,288 tons of ore, although this figure is not exact because for many years the production figures were lumped with those of the Sontag mine of the Providencia group. Some 748,425 tons of waste is recorded as having been extracted, giving a ratio of waste to total extraction of 54 percent—the highest ratio for any of the Boleo mines.

The Montado mine contains some relatively large explored but unstoped areas of low grade marginal ore, particularly in the central and eastern parts of the mine, at levels ranging in general from 20 meters above sea level to 5 meters below sea level.

Also, the mine is believed to offer good possibilities for the recovery of some ore of currently minable grade. The mine was never stoped out completely, but was abandoned after flooding of the main haulageway in 1931, and in later years the central part of the mine was considered too distant from either of the extraction centers of Ranchería to the north or of San Luciano to the south to warrant further exploitation.

RANCHERIA MINE (ORE BED NO. 1)

The Ranchería mine, also formerly known as the Santa Rosalía mine, is on the south side of Arroyo de la Providencia near the mouth of the arroyo. The main entries are near the south edge of the town of Santa Rosalía. The mine extends from the arroyo southward for a distance of about 2 kilometers, where it adjoins and intercommunicates underground with the Montado mine. The Ranchería mine has been worked intermittently from 1910 until the present time. Production was very small before 1925, however, and the main productive periods of the mine have been from 1926 to 1932 and again from 1937 to 1944. Different parts of the mine have been worked since 1944 by the *poquiteros*.

All the production of the Ranchería mine has been from ore bed no. 1. This bed crops out along the south side of Arroyo de la Providencia, and a number of the mine workings follow the ore bed into the hill from the outcrops. Toward the east the bed dips down below the arroyo level, however, and in that part of the mine the ore bed has been reached by inclined entries. The elevations of workings in ore range from 124 meters above sea level at the west end of the mine to 64 meters below sea level at the east end.

Ore bed no. 1 in the Ranchería mine has a general northerly strike and easterly dip, but the structure is locally complicated by gentle flexures and by faults. In the south central part of the mine, between the San Marcelo and San Diego shafts, is a conspicuous eastward-trending structural trough, bordered to the south by an eastward-plunging anticlinal nose. Farther north in the central part of the mine is a broad, irregular, dome-shaped structure, resulting in a wide flattish area lying 43 to 44 meters above sea level west of the San Marcelo shaft. Near the outcrops at the north end of the mine the structure has many local complications, as shown on the structure contour map (pl. 4). Aside from the areas just mentioned, where the strike is highly variable and the dip is in places reversed, the usual strike is due north to N. 25° W. and the average dip is about 12° E., ranging in general from 8° to 28° E.

Faults are particularly numerous in the Ranchería mine, with the result that exploitation in many parts of the mine has been confined to narrow strips. Altogether, about 20 faults in this mine have offset the ore bed by significant amounts. Most of the faults strike north to northwest, and the west side is generally downthrown, although in some the east side is downthrown. The Ranchería fault, whose southwest side has been downthrown 35 meters, terminates the workings in the deepest part of the mine at the northeast end.

Most of the other faults have displacements that do not exceed 10 to 15 meters.

The Ranchería mine has been rather thoroughly sampled, except for the older highest levels in the west part of the mine. The results of thickness and grade of ore determined from this sampling are given in table 12. Smelter records indicate that the actual average grade of ore shipped from the Ranchería mine was 5.6 percent of copper in 1919, 4.3 percent in 1926, 3.9 percent from 1937 to 1942, and 4.0 percent from 1946 to 1948. The ore in the Ranchería mine is mostly of the oxidized type down to levels of 25 to 40 meters above sea level, whereas in the lower levels it is largely of the sulfide type.

Ore bed no. 2 was explored in two separate parts of the Ranchería mine. In the vicinity of the San Marcelo shaft a working followed that bed for a distance of 450 meters down the dip in an easterly direction, at elevations of 8 to 50 meters below sea level and at depths of 53 to 60 meters below ore bed no. 1 in the same area. The average thickness was shown by 14 determinations to be 63 centimeters and the average grade was 1.3 percent of copper—too low in grade to be exploitable. An ore bed probably correlative with no. 2 was also found in Chiflón 30 Santa Rosalía at the north end of the mine. This working penetrated an ore bed containing less than 1 percent of copper at a level of 11 meters below sea level, whereas ore bed no. 1 lies at 39 meters above sea level at this point.

An exploratory working east of the San Marcelo shaft was extended downward from ore bed no. 2 to a depth of 84 meters below sea level for the purpose of exploring ore bed no. 3, which, however, was found to be absent in this area. Gypsum was found between 67 and 81 meters below sea level, and it in turn was underlain by conglomerate. A black cupriferous unit a few centimeters thick found in one place at the base of the gypsum was determined to have a grade of 3 percent of copper. Ore bed no. 0, lying above ore bed no. 1, was penetrated by several of the inclined workings from the surface, but in all places it was considered unexploitable.

The Ranchería mine has more than 36 kilometers of workings. The mine has been explored for 2 kilometers in a northerly direction, and from 1.5 kilometers at the north end to 0.5 kilometer at the south end. The proportion of stoped area to explored area is one of the lowest of any of the Boleo mines and reflects the low grade and thinness of the ore bed over much of the explored area. The limits of the individual stoped areas are determined mainly by assay walls, although some of them are outlined by faults, and the mine is limited to the northwest by outcrops.

The Ranchería mine has several entries, but the principal entries for extraction were three workings which enter at nearly the same place on the side of the arroyo at the north end of the mine, at an elevation of 30 meters above sea level. The westernmost of these is an adit 1 kilometer long called Travers-Bancs 30 Ranchería; the middle entry, Chiflón 0 Santa Rosalía, is an inclined working that goes down to sea level; and the easternmost entry, Chiflón −35 Santa Rosalía, extends to 35 meters below sea level.

The principal haulageways within the mine, which run in general in a northerly direction and are driven in the footwall of the ore bed, are at levels of 95, 70, 50, 43, 30, and 0 meters above sea level, and 35 and 55 meters below sea level. Communication between these levels is provided by inclined workings running downward to the east. There are about 25 entries along the outcrop of the ore bed on the southeast side of Arroyo de la Providencia, which were made for purposes of exploration and ventilation, but they have been used for extraction only to a limited extent, mainly in the recent period of exploitation by the *poquiteros*. Ventilation has been supplied also by two vertical shafts, the San Marcelo shaft near the center of the mine and the San Diego shaft in the south-central part, as well as by half a dozen inclined shafts in the southern part of the mine. The San Julio shaft, situated inland from the Ranchería mine workings, was for purposes of exploration, but the ore beds were not considered exploitable in that area.

Production of the Ranchería mine during its period of operation by the Boleo company through 1944 totaled 912,720 tons of ore. In the same period 581,182 tons of waste was extracted—a proportion of waste to total extraction of 39 percent. Since 1944 the mine has been operated by the *poquiteros*, and the total production has probably reached about a million tons of ore.

The *poquiteros* have been working mainly in the upper levels of the mine, in areas near the outcrops along the side of Arroyo de la Providencia, where considerable ore was left by the company. The lower levels of the mine are flooded. The *poquiteros* have worked different parts of the mine as separate units called by different names. The name Ranchería is now confined mainly to workings reached from the 30-meter level or lower; an area served by the 40-meter level is called El Cuarenta; an area reached by the 50-meter level is called El Cincuenta; and an area above the 70-meter level at the west end of the mine is called Himalayo.

The ore in the Ranchería mine was not so rich or thick in general as that of the older mines in ore bed no. 3, and there would probably be little profit in reworking the filled stopes or the dumps, as has been possible in the older mines. If thinner and lower grade ores should ever become exploitable in the Boleo district, however, large unstoped areas remaining in the Ranchería mine might become of commercial value.

CINCO DE MAYO MINE (ORE BED NO. 1)

The Cinco de Mayo mine is one of the smaller mines of the Boleo district, and it is not communicated with the main groups of mines. It is the northernmost of the mines in ore bed no. 1. The mine is on the southeast side of Arroyo del Purgatorio, 1.5 kilometers inland from the mouth of the arroyo, on the northwest slope of Cerro de la Calera. It is separated by a distance of 1.5 kilometers from the Ranchería mine in the same ore bed to the southeast, and by a like distance from the Purgatorio mine in ore bed no. 3, exploited farther inland to the southwest in the same arroyo. The mine has been known since the earliest years of the district, but it was operated by the Boleo company mainly from 1925 to 1929, and it has been operated more recently on a small scale by the *poquiteros*.

The Cinco de Mayo mine is entirely above the arroyo level and consists of many short workings that have followed the outcrops of ore bed no. 1 into the slope to the southeast. The ore bed lies at elevations ranging from 152 meters above sea level at the south end of the mine to 66 meters above sea level at the north end. The bed strikes N. 45°–60° W. and has an average dip of about 12° NE., although in part of the mine the dip is comparatively flat. The bed is offset by several small faults, some of which have displacements downward to the southwest and others to the northeast.

The ore bed is comparatively thin and averages half a meter or less in thickness. The grade is quite variable but averages probably between 3 and 5 percent of copper. Some shipments of ore from the Cinco de Mayo mine in 1926 contained about 7 percent of copper. Ore shipped by the *poquiteros* in 1946 from outcrops near the Cinco de Mayo mine averaged 3.13 percent of copper. The limits of mining have been determined by assay walls and recent erosion. The ore is of the oxidized type and lies entirely above the water table.

The workings consist of about 25 entries distributed along the outcrop over a length of 500 meters from south to north. Some of these entries intercommunicate inward, and irregular stopes have been opened in the form of a room-and-pillar system. The principal workings are levels that follow the bed along the strike to the southeast and are communicated by inclined workings that follow the dip downward to the northeast. The extent of the workings into the hill averages about 100 meters and reaches a maximum of 200 meters. The ore was extracted from different entries and then lowered by tracks a distance of 400 meters to the railroad in Arroyo del Purgatorio below.

The Cinco de Mayo mine has a recorded production of 10,893 tons of ore in the period 1925–1929. These figures are believed to be incomplete, however, and the total production is probably somewhat greater than this. The mine has not been greatly developed because of the thinness and spotty nature of the ore. It has the advantage, however, of ready accessibility, being situated above the arroyo level and close to a railroad, and it might be a source of reserves in the event thinner and lower grade beds should become exploitable.

SMALLER MINES IN ORE BED NO. 1

Several small mines and prospects have been made in ore bed no. 1 in the drainage areas of Arroyos Santa Agueda and Montado, northeast of the Santa Agueda fault zone.

Alhambra.—One of the more important of these is the Alhambra mine, situated on the northeast side of one of the branches of Arroyo del Montado, 2 kilometers inland from the arroyo mouth and about 10 meters above the arroyo level. This mine is about 400 meters east of the nearest workings of the Ranchería mine, but it is at a much higher level and is not communicated with that mine. The Alhambra is a new mine developed in recent years by the *poquiteros*.

Ore bed no. 1, which is 20 meters below sea level in the nearest workings in the Ranchería mine to the west, has been brought up on the northeast side of the Santa Agueda fault to elevations of 40 to 53 meters above sea level in the Alhambra mine. The bed crops out at the south end of the mine and is cut off by the fault at the northwest end of the mine. Ore bed no. 1 strikes N. 45°–65° W. and has an average dip of 2° NE. in this area. The ore shipped from the Alhambra mine from 1946 until April 1948 averaged 3.64 percent of copper. The ore is of the oxidized type and lies above the water table.

The mine workings consist of about 10 entries that follow the outcrop inward toward the north and are intercommunicated to form a blocked-out area about 150 meters wide from east to west, and 175 to 285 meters long from north to south. The ore has been extracted from different entries and then hauled by truck down Arroyo del Montado and thence to the smelter.

Production from the Alhambra mine during its operation by the *poquiteros* from 1946 until April 1948 was recorded as 11,425 tons of ore. Production was continuing and the limits of the ore body had not been reached in 1948, but the grade of ore was comparatively low.

East and southeast of the Alhambra mine, a few prospects have been opened in scattered outcrops of ore bed no. 1 along both sides of Arroyo del Montado between the Santa Agueda fault and the mouth of the arroyo, as well as along the south side of Arroyo de Santa Agueda, but the results have not been encouraging.

El Crestón.—An ore bed which probably corresponds to no. 1 has also been found along the southwest side of a ridge of Comondú volcanics that crops out here and there along the coast northwest of the mouth of Arroyo de Santa Agueda. Some ore was mined there in the earliest years, before the formation of the Boleo company, in the El Crestón mine, situated in a locality later called Lazareto. This is on the northwest side of Arroyo del Montado, 500 meters inland from the coast and at an elevation of 10 meters above sea level (see pl. 1, coordinates 600 S., 5350 E.). The ore was in tuff which wedged out against the ridge of Comondú volcanics. The mine workings have long since caved and no map of them has been found, but they are believed to have been comparatively shallow and of small extent. The ore reportedly has been worked out, but some of it was high in grade, judging from some material left on the dump and later hauled to the smelter at Santa Rosalía. Prospects have been opened in other localities farther northwest along the same volcanic ridge, but no minable ore bodies have been found.

MINES IN ORE BED NO. 2

The mines in ore bed no. 2 are all fairly small compared to those in beds 1 and 3. They are mainly in areas superimposed on the workings of ore bed no. 3. Some of the mines in ore bed no. 2 were worked in the earliest years of mining, and they were later worked for a few years by the Boleo company, but over most of the company's history this ore bed has not been exploited because of its thinness. Some small mines in ore bed no. 2 have been worked recently by the *poquiteros*. Production figures for the mines in this ore bed have generally not been recorded separately.

Providencia-Purgatorio Second Bed.—The principal mine in ore bed no. 2 has been called the Providencia-Purgatorio Second Bed mine. This is a continuously mined area extending northwestward from Arroyo de la Providencia to the southeast side of Arroyo del Purgatorio, which overlies parts of the Providencia and Purgatorio mines in ore bed no. 3. This is one of the oldest mining areas in the district, but it has been abandoned for many years, although some of the workings near the outcrops have been reexplored recently by the *poquiteros*. An old name applied to part of the mine on the side of Arroyo del Purgatorio is Escondida.

Ore bed no. 2 in the Providencia-Purgatorio mine dips northeastward from the mass of Comondú volcanics called Cerro de Juanita. As the ore bed rises against the basement rocks to the southwest, it rests directly on the surface of the volcanics for some distance before wedging out, as may be observed in the outcrops in both arroyos. The ore bed ranges in elevation from 164 meters above sea level at the southwest end of the mine to 98 meters above sea level at the northeast end, although the principal workings lie between 100 and 128 meters above sea level.

The strike of the ore bed averages N. 50° W., but it curves from nearly west at the south end of the mine to N. 30° W. in the central part and back to N. 60° W. at the northwest end. The dip averages 8°–12° NE. in the area covered by the mine workings, but it becomes steeper farther southwest. Only a few small faults were exposed in the mine.

The ore bed is comparatively thin, probably averaging only half a meter in thickness. The grade is variable, but some ore of comparatively high grade is known to have been shipped. The ore is all of the oxidized type and lies high above the water table. The ore bed is limited by surface erosion to the northwest and southeast, by assay walls down the dip to the northeast, and in part by wedging out against the basement rocks of Comondú volcanics to the southwest.

The mine was explored by a series of entries along the outcrops on the northwest side of Arroyo de la Providencia and the southeast side of Arroyo del Purgatorio. There are about ten entries in each arroyo. These workings followed the strike of the ore bed inward to the northwest and southeast, respectively, and are intercommunicated below the ridge that separates the two arroyos.

The total length of the mine in a northwesterly direction is 1 kilometer, and the width explored down the dip to the northeast averages about 150 meters in the center of the mine, and is as much as 400 meters in Arroyo del Purgatorio and 600 meters in Arroyo de la Providencia. The principal levels that extend from one end of the mine to the other are at elevations of 108 and 128 meters above sea level. The workings in ore bed no. 2 are communicated with the underlying workings of the Providencia mine in ore bed no. 3, 65 meters lower in elevation, in an inclined working near the southwest end of the mine.

Margarita.—The Margarita mine is a small mine in ore bed no. 2 on the northwest side of Arroyo del Purgatorio, across the canyon and 500 meters northwest of the mine that has just been described. The name Margarita has also sometimes been applied to the underlying mine in ore bed no. 3, which is referred to in this report as the Purgatorio mine.

In the Margarita mine the outcrop of ore bed no. 2 has been penetrated by six entries distributed over a width of 75 meters, and the bed has been followed inward along the strike to the northwest for a length of 275 meters. The ore bed lies at elevations of 79 to 90 meters above sea level, and has an average strike of N. 30° W. and average dip of 5° E. The ore is similar to that found in the Providencia-Purgatorio Second Bed mine. The Margarita mine was recently reopened by the *poquiteros*, but little exploitation was carried on because of the thinness of the ore bed.

A short distance to the northeast of the Margarita mine, ore bed no. 2 descends below the level of Arroyo del Purgatorio. The bed was followed along the dip in a northeasterly direction in this area by an exploratory working 240 meters long, lying at elevations of 46 to 61 meters above sea level. This working was reached by an inclined shaft at the southwest end and by the Mars vertical shaft at the northeast end. The bed explored by this working was considered to be unexploitable.

Artemisa.—The Artemisa mine is a small mine recently worked by the *poquiteros* in ore bed no. 2 on the southeast side of Arroyo de la Soledad, 300 meters southeast of the San Agustín shaft. It is 50 meters above workings in ore bed no. 3 pertaining to the San Agustín mine, which is below the arroyo level in that area. The Artemisa mine is above the arroyo level, in a small ridge between Arroyo de la Soledad and a small branch arroyo to the southeast.

Outcrops of ore bed no. 2 have been entered on both sides of the ridge by intercommunicating workings, which follow the strike of the bed in a northwesterly direction. The length of the mine between the two outcrops is only 200 meters, and the width down the dip to the northeast is 125 meters. Ore bed no. 2 lies at elevations of 177 to 193 meters above sea level in this area, strikes N. 35° W., and dips 9° NE. The ore bed is cut off to the northeast by a fault, which has the northeast side downthrown. The same fault was exposed in the underlying mine in ore bed no. 3.

Prosperidad.—The Prosperidad mine is another small mine in ore bed no. 2, recently worked by the *poquiteros*. It is below a long, narrow, northwesterly trending ridge between two small unnamed southeasterly branches of Arroyo del Boleo. The mine is 700 meters south of the Texcoco mine and 700 meters northwest of the San Luis shaft. It is above workings in ore bed no. 3 that belong to the San Luis mine of the Soledad group.

Outcrops along the strike of the ore bed on both sides of the ridge have been entered by mine workings that intercommunicate under the ridge in a northeasterly direction. The bed has a general northerly strike, which is irregular in detail, and has an easterly dip averaging 7°. The ore bed lies at elevations ranging from 224 meters above sea level in the west part of the mine to 199 meters above sea level in the east part. Th3 stratigraphic interval between ore beds nos. 2 and e has lessened in this area, for the workings in ore bed no. 3 lie at a level of only 35 meters below those in ore bed no. 2 in this mine. This may be due to the influence of a projecting ridge in the basement rocks of Comondú volcanics, which come to the surface only 200 meters northwest of the mine. The length of the mine workings toward the northwest is 250 meters, and the width between the two outcrops on the southwest and northeast sides is 160 meters.

A few other prospects and short workings have been made in ore bed no. 2 in different parts of the district, all of which are of small extent and appear to be of slight importance.

PROVIDENCIA GROUP OF MINES (ORE BED NO. 3)

The Providencia group of mines is in ore bed no. 3 in Arroyo de la Providencia, 2.5 to 4.5 kilometers inland from the town of Santa Rosalía. Different centers of mining have been given different names, but the workings form a continuously mined zone in which the individual mines cannot be delineated. The Providencia group merges to the northwest into the Purgatorio mine, which was exploited from Arroyo del Purgatorio. It is adjoined to the northeast by the Ranchería mine, which, however, is in ore bed no. 1 and is not communicated with the Providencia group.

Carmen, La China, San Alberto, San Carlos, San Víctor, and *Sontag.*—The Providencia group was one of the first areas mined before the advent of the Boleo company in 1885, after which it was worked by the company until 1923, when it became the first of the large mining groups to be abandoned. The Carmen mine, at the south end of the group, was operated from the earliest years until 1895 and was replaced by the San Alberto mine, near the north end, which was operated from 1894 until 1919. The Sontag mine, near the center, was operated from 1901 until 1923. Later, the dumps of the San Alberto mine, which are among the largest and richest in the district, were reworked intermittently from 1937 until the present. In recent years the *poquiteros* have reopened parts of the Providencia group and have been mining old filled stopes and pillars that were left in the early operations. Three principal mines opened by the *poquiteros* are called the San Carlos mine in the west central part of the area, the San Víctor mine in the east-central part, and the La China mine in the northeast part.

The Providencia group follows a belt in ore bed no. 3 that is wrapped around the east and northeast flanks of a mass of Comondú volcanics known as Cerro de

Juanita. This is one of the best areas in which to observe the influence of the topography of the basement rocks on the structure and distribution of the ore bed. The bed strikes north to slightly northeast at the south end of the mine, and then swings around to northwest and nearly west at the north end. Many local irregularities in strike are revealed by the structure contour map (see pl. 4). A northeastward-plunging nose is found at the north end of the mine, northeast of the San Alberto shaft. A notable feature shown by the structure contours is the rapid steepening of dip at the west end of the mine, as the ore bed rises up against the surface of the volcanic rocks. In the westernmost 100 meters the dip steepens to 24° E., whereas over the rest of the mine the average dip is 5° E., and it is as little as 2° NE. in a structural terrace in the north-central part.

A few relatively small faults were exposed in the Providencia group of mines. The principal one is a fault that cuts through the northeast part of the mine, from near the Santa Bárbara shaft northward past the San Alberto shaft. This fault strikes N. 0°–25° W. and dips southwest; its southwest side has been downthrown an average of 10 meters and a maximum of 15 meters. Several smaller faults were found that strike north to northwest and have their east sides downthrown. The Carmen mine is terminated to the southwest by the Juanita fault zone, which is one of the more important faults in the district and has its southwest side downthrown as much as 60 meters. Exploration has been carried on southwest of this fault, but no exploitable ore bodies have been found.

The workings in ore in the Providencia group range in elevation from 116 meters above sea level along the west side of the mine to 33 meters below sea level at the east end. The largest part of the stoped area lies between 25 and 60 meters above sea level. The ore bed is entirely concealed below the surface in this area, though at comparatively shallow depths, and was explored by vertical and inclined shafts from the bottom of the arroyo.

The ore in the Providencia group was comparatively thick and high in grade. Assay maps are not available for most of these mines, but the thickness of minable ore is believed to have averaged about 1 meter, and the grade of ore mined averaged probably 5 to 6 or more percent of copper. Ore produced from the San Alberto mine in 1909 averaged 5.20 percent of copper. Higher grade ore was mined in the earlier years, and according to early reports, the highest grade ore was found in northwest-trending ribs.

The fill in the old stopes, now being extracted by the *poquiteros*, contains from 3.5 to 4 percent of copper. Shipments of ore from the San Carlos mine, consisting largely of fill, averaged 3.53 percent of copper from March 1947 to April 1948. Shipments from La China mine, partly of fill and partly of solid ore down the dip from the previously stoped areas, averaged 4.04 percent of copper from 1946 to April 1948. Shipments of material from the San Alberto dump from 1937 to 1942 averaged 1.72 percent of copper.

Most of the ore in the Providencia group of mines was of the oxidized type, although sulfides appear in the lower levels at the north and east edges of the mine. In some places the base of the ore bed consists largely of sulfides, and the higher part is oxidized. A majority of the workings are above the water table, which was originally at an elevation of about 25 meters above sea level.

The limits of ore in the Providencia group are determined in part by the termination of the ore bed against the basement of Comondú volcanics, and in part by assay walls. Toward the west, at elevations of 110 to 116 meters above sea level, the ore bed wedges out against the old island of Comondú volcanics that makes up Cerro de Juanita. Toward the east the bed also wedges out down the dip against a buried ridge of Comondú volcanics—a ridge that seems to be a buried northeastward branch of Cerro del Sombrero Montado. Some workings that penetrated the Comondú volcanics are listed in table 5.

To the east and northeast, however, mining was not carried on to the end of the ore bed, and the limits of stoping in those directions were determined by assay walls. Assay maps of the easternmost lowest workings of the mine, beyond the limits of the stoped area, indicate an average thickness of 64 centimeters and an average grade of 2.8 percent of copper, based on 39 samples.

The mine is bordered to the northeast by an area which has been explored but in which no stoping has been done. This area, known as the San Guillermo region of low-grade ores, is one of the largest explored areas of marginal reserves in the district. It extends from the San Eugenio shaft at the east edge, northwestward between the Central and San Guillermo shafts to the Purgatorio and Mars shafts, where it joins the Purgatorio mine to the northwest. The ore bed probably has an average grade of 2 to 3 percent of copper throughout much of this area, although local areas of higher grade ore might be found. A series of 32 thickness and grade determinations made along one of the principal exploratory drifts in this area indicates an average thickness of 69 centimeters of ore and an average grade of 3.3 percent of copper, which, reduced 25 percent for dilution, would indicate an average grade of about 2.5 percent for minable ore.

The total length of underground workings in the

Providencia group of mines amounts to 84 kilometers, of which 12 kilometers pertain to the Carmen mine, 15 kilometers to the Sontag mine, and 57 kilometers to the San Alberto mine. The area mined extends over a length of 2.2 kilometers from south to north and a width ranging from 500 meters at the south end to 1 kilometer in the central part of the mine.

The principal centers of extraction in the Providencia group of mines were the Carmen and Sontag shafts, used in the very early years, and the San Alberto shaft, which was one of the more important extraction shafts in the district. Extraction was also carried out by a number of inclined shafts or *chiflones*, and the mining now being done by the *poquiteros* is by means of inclined shafts. The Central and Santa Bárbara shafts have provided ventilation, and the San Guillermo and San Eugenio or Malibrán shafts were made primarily for exploration.

The principal haulageways for ore in the Providencia group were at levels of 25 to 26 meters above sea level. An important haulageway at this general level ran southward from the San Alberto shaft to the southeast end of the Carmen mine, and was connected to the east with the Santa Bárbara shaft and with the Travers-Bancs Montado at the foot of Chiflón Yaqui. Other levels are at elevations of 90, 70, 60, 54, 50, 40, 37, and 34 meters above sea level, and, at the east end of the mine, at elevations of 15 and 5 meters above and at 5 meters below sea level.

The total recorded production of the Providencia group of mines, including the mine production from 1893 to 1923 and the production from dumps between 1937 and 1942, is 2,311,713 metric tons of ore, of which 181,485 tons is recorded from the Carmen mine, 229,542 tons from the Sontag mine, and 1,900,686 tons from the San Alberto mine. The total would be increased probably on the order of 100,000 tons or so, by the unrecorded production before 1893 and the production of the *poquiteros* in recent years. The amount of waste extracted from 1893 to 1923 was 1,542,613 tons, equivalent to 40 percent of the total extraction.

The future possibilities of the Providencia group of mines are considered as good as for any of the old mines of the district. Much of the material discarded in the stopes was high enough in grade to serve as minable ore at the present time. There are also unstoped areas which contain minable material, particularly in the northeast area, in the vicinity of the San Víctor mine. It is said that mining in this area was stopped because of flooding after a cloudburst, leaving small unexploited areas which had previously been prepared for stoping. In addition, the largest explored area of low-grade ore lies in the San Guillermo region north of the Providencia group. An advantage of mining in that area is that the ore bed does not lie at great depths below the surface, as it does in the areas of marginal reserves adjacent to the San Luciano and Montado mines. In the San Guillermo area the ore bed lies in general at elevations of 5 to 25 meters above sea level.

CALIFORNIA-LUGARDA MINE (ORE BED NO. 3)

The California-Lugarda mine is on the northwest side of Arroyo del Purgatorio, 4.5 to 6 kilometers inland from the coast. It is part of the continuously mined area of ore bed no. 3 that lies between Arroyos Purgatorio and Boleo, and it communicates with other mines on all sides, except to the southeast, where the ore bed crops out along the side of Arroyo del Purgatorio.

The name California-Lugarda was generally applied to that part of the area mined on the northwest side of Arroyo del Purgatorio in which the ore was extracted from surface adits. It is bordered on the northeast by the Purgatorio mine, situated farther down the dip where the ore bed has gone below the arroyo level and where the extraction was from vertical and inclined shafts. It is bordered on the north by the Santa Rita mine, on the northwest by the San Augustín mine, and on the west by the Amelia mine, all of which were worked from centers in Arroyo de la Soledad.

In the early years three names were applied to different parts of this mining area—the La Ley mine near the La Ley shaft at the southwest end; the California mine, around the California shaft; and the Lugarda mine, toward the northeast. In general, however, the records of these mines have been combined under the name of California-Lugarda. This was one of the earliest areas in the district to be chosen for mining, because of the conspicuous outcrops of ore bed no. 3 on the side of the arroyo. The mine was exploited by the Boleo company from 1886 until 1925, after which mining in Arroyo del Purgatorio was confined to the area lying farther down the dip in the Purgatorio mine. The California-Lugarda area was rather thoroughly mined out and has not been reopened in recent years.

The structure of ore bed no. 3 in the California-Lugarda mine consists of a fairly regular northeast-dipping bed stepped up repeatedly to the northeast by small faults. The ore bed has an average strike of N. 10–30° W. and an average dip of 7° NE. The faults have a northwest trend roughly paralleling the general strike of the beds, although in detail they cut obliquely across the structure contours of the ore bed (see pl. 4). Most of the faults displace the ore bed downward from 5 to 20 meters on their southwest side, although a few faults displace it downward on their northeast side, particularly the La Ley fault at the west end of the mine, whose northeast side has been downthrown as much as 35 meters. Altogether about 20 faults in the

California-Lugarda mine have offset the ore bed significant amounts.

In the northeast part of the mine, between the Solitario and San Porfirio shafts, is a northeast-trending nose, bordered to the northwest by a structural trough which also plunges northeastward. In this area the structure contours swing around from N. 30° W. to due west and even southwest before regaining their normal northwest strike. Elevations along the ore bed in the California-Lugarda mine range from 165 meters above sea level at the west end of the mine to 42 meters above sea level at the east end. The majority of the workings are between 65 and 150 meters above sea level.

Outcrops of ore bed no. 3 were originally fairly conspicuous along the northwest side of Arroyo del Purgatorio, but the ore from the outcrops was extracted in the early years and later the area of the outcrops was largely obscured by dumps. The ore bed rises as much as 35 meters above the arroyo level at the northwest end of the mine and descends about 20 meters below the arroyo level at the northeast end.

No assay maps are available for this mine, but the average thickness and grade of ore are believed to have been at least as high as the average for the district. Scattered records of ore produced from the California-Lugarda mine during 1909, 1919, and 1926 indicate that the average grade of ore produced during those years was about 5 percent of copper. The ore in this mine lies entirely in the oxidized zone, well above the water table.

A total of 78 kilometers of underground workings was made in the California-Lugarda mine. The mine extends for 1.6 kilometers along the dip in a northeast direction and for 1.0 to 1.5 kilometers along the strike to the northwest. The unstoped areas remaining in the mine are irregular in shape and are mostly small scattered patches in which the ore decreased in grade and thickness, or became difficult to mine locally because of faulting.

The ore was developed by irregular-shaped levels which followed the strike to the northwest, and by long straight inclines which followed the dip to the northeast. The extraction was mainly by horizontal adits along the northwest side of Arroyo del Purgatorio, and by an inclined entry at the east end of the mine. Some of the more important haulageways within the mine were at levels of 147, 140, 134, 123, 102, 99, 90, and 70 meters above sea level.

Ventilation inside the mine was provided by three shafts between Arroyos Purgatorio and Soledad—the San Felipe, San Porfirio, and Solitario, all of which were equipped with ventilators. Some smaller ventilation shafts along Arroyo del Purgatorio were the La Ley, California, Conchas, and Pablito shafts. The La Ley interior shaft and the San Eduardo shaft were sunk for exploration below the arroyo level of ore bed no. 4, which was not considered exploitable in that area.

The California-Lugarda mine had a total recorded production of 1,632,909 tons of ore. The amount of waste extracted is recorded as 959,614 tons, or 37 percent of the total material extracted. As the mine has been almost entirely stoped out, its only possibilities seem to lie in mining small pillars and perhaps some of the filled stopes.

HUMBOLDT MINE (ORE BED NO. 3)

The Humboldt mine is a fairly small but comparatively rich mine on the southeast side of Arroyo del Purgatorio, opposite the California-Lugarda mine, 5 kilometers inland from the coast. It is in an isolated area on the northwest flank of Cerro de Juanita where ore bed no. 3 lies fairly close to the surface, and it is not communicated with the other mines of the district.

The mine was almost completely surrounded by conspicuous outcrops of ore, and it was one of the first mines to be worked in the district. Two early claims in this area were known as Tamberlick and Humboldt. Probably a considerable production from this mine was attained before the formation of the Boleo company in 1885. The mine was worked by the Boleo company until 1901, when it was abandoned, having been considered mined out. Recently some of the filled stopes have been reworked on a small scale by the *poquiteros*.

The Humboldt mine is in an area where ore bed no. 3 lies close to and in part directly upon the basement of Comondú volcanics. This relation may clearly be observed in outcrops at the southwest end of the mine, where, going southward toward Cerro de Juanita, conglomerate no. 3 of the Boleo formation wedges out, and the ore bed rests directly on the surface of the volcanic rocks for some distance before also wedging out. In plan view the ore body is semicircular, and is bounded by outcrops on the west, northwest, and northeast, and by the line of wedging out to the southeast. Farther east, a few small patches of ore are found lying on irregularities in the surface of the Comondú volcanics.

The structure of ore bed no. 3 in the Humboldt mine is that of a structural trough plunging north to northeast, rather broad and gentle in the middle but steepening rapidly along the sides (see pl. 4). The dip steepens to as much as 30° E. along the west side of the trough, but decreases to 7° toward the middle. This structural trough is considered most likely to be an initial structure, somewhat modified by later tilting and faulting, reflecting a buried valley in the surface of the underlying basement rocks.

A conspicuous fault near the west side of the mine strikes N. 10° W. and drops the ore bed downward as much as 30 meters to the west. A few small faults were exposed in the mine. Elevations of the ore bed range from as much as 144 meters above sea level along outcrops at the west end of the mine to 80 meters above sea level in the structural trough at the northeast end. The ore bed is above the arroyo level throughout most of the area mined, but it descends slightly below the arroyo level at the north end of the mine.

No data are available on the thickness or grade of ore in the Humboldt mine, but as this was one of the earliest mines to be worked, the grade is believed to have been considerably higher than the average for the district. The ore was entirely of the oxidized type.

The length of underground workings recorded in the Humboldt mine is 5.7 kilometers, but this does not include the workings made before the operations of the Boleo company. The mine has a length of 700 meters from north to south and a width of 300 meters. The unstoped areas consist of only a few small scattered pillars and some ground made unexploitable by faulting.

The ore was extracted from about 35 small surface entries, mostly horizontal adits but also a few inclined entries, which are found on all sides of the mine. These entries provided sufficient ventilation so that no shafts were needed.

The production of the Humboldt mine recorded by the Boleo company from 1893 to 1901 was 153,561 tons of ore, but there was also a considerable production before 1893. The total might be closer to 200,000 tons. Considering the small area of this mine, the production was comparatively large. The recorded extraction of waste was 39,766 tons, or 21 percent of the total extraction—the lowest figure of any of the mines for which records have been kept.

As the Humboldt mine has been almost completely stoped out, its possibilities are confined mainly to reworking the filled stopes, as has been done to a small extent in recent years by the *poquiteros*.

PURGATORIO MINE (ORE BED NO. 3)

The Purgatorio mine is on both sides of Arroyo del Purgatorio, 3 to 4 kilometers inland from the coast. It is down the dip from the California-Lugarda mine, in an area where ore bed no. 3 lies mainly below the arroyo level and in part below sea level.

The Purgatorio mine communicates with other mines on all sides except the northeast or gulfward side, where the ore bed pinches out or becomes too low in grade to be minable. To the northwest it is bordered by the Santa Rita and San Antonio mines, the dividing line being near the Santa María shaft. The boundary with the California-Lugarda mine to the southwest is in part a fault between the 60- and 70-meter levels, extending from near the Pablito shaft northwestward toward the Solitario shaft. To the southeast the Purgatorio mine joins the Providencia group of mines about 500 meters southeast of Arroyo del Purgatorio.

Part of the southeast area in the vicinity of the San Francisco shaft was early known as the San Francisco mine. Some of the old workings southeast of the arroyo, reopened by the *poquiteros* in recent years, are called the San Fernando mine. The Purgatorio mine has also commonly been known as the Margarita mine, although this name referred originally to workings in ore bed no. 2 in Arroyo del Purgatorio.

Different parts of the Purgatorio mine have been worked almost throughout the mining history of the Boleo district. The part known as the San Francisco mine, where the ore bed is fairly close to the surface, was one of the earliest mines to be opened and was worked until 1901. The higher levels of the Purgatorio mine on the northwest side of the arroyo were worked from 1902 until about 1920. The lower part of the mine, below the 25-meter level, was worked from about 1920 until 1940, when the mine was abandoned by the Boleo company. The period of peak production was during the decade from 1930 to 1940, when the Purgatorio mine was the largest producer in the district. Part of the mine has been reworked recently by the *poquiteros*.

Ore bed no. 3 has a general northeast dip over most of the Purgatorio mine, although the structure becomes complicated locally by faulting (see pl. 4). A northeast-trending nose lies between the Indios and Santa María shafts, and another is found just northwest of the Santiago shaft. The two noses are separated by a northeast-plunging structural trough, and a smaller trough lies just south of the Santiago shaft. A rather broad sweeping curve in the structure contours is found in the vicinity of Arroyo del Purgatorio; southeast of that arroyo the average strike is N. 65° W., whereas northwest of the arroyo it swings around to N. 30° W. Near the arroyo the dip averages 4° NE., but farther northwest between the Santiago and Indios shafts it steepens to 15° NE. Southwest of the San Francisco shaft the ore bed rises up steeply and pinches out against the northeast flank of Cerro de Juanita—a continuation of the same structural feature that was described for the Providencia group of mines. Locally alongside the basement of volcanic rocks the dip reaches 30° NE.

The principal fault is the Santiago fault, near the northeast edge of the mine, along which the ore bed has been downthrown to the southwest as much as 60 meters. Several other faults of smaller displacement were observed, some of which are downthrown to the northeast and others to the southwest. Some of these faults cut across the structure contours at a considerable angle.

In that part of the mine lying on the northwest side of Arroyo del Purgatorio, the position of the ore bed ranges from 76 meters above sea level to 73 meters below sea level. The deepest place is in the structural trough 300 meters northwest of the Santiago shaft. In the smaller trough 200 meters southwest of the shaft the ore bed descends to 53 meters below sea level. On the southeast side of the arroyo elevations range from 4 to 109 meters above sea level in the mine workings, but reach 135 meters above sea level in some of the surface outcrops.

The only outcrops of ore bed no. 3 in the vicinity of the Purgatorio mine are a few scattered patches where the bed rises up alongside Cerro de Juanita southwest of the San Francisco shaft. Elsewhere the ore bed lies below the arroyo level throughout the area mined.

Mine workings in ore bed no. 2 overlie part of the area of the Purgatorio mine, as already described. This bed was also penetrated in Travers-Bancs Santiago-San Porfirio along two short stretches at distances of 100 and 250 meters southwest of the Santiago shaft. Ore bed no. 4 was explored in some small workings extending from the bottom of the San Alejandro shaft.

Assay maps cover only the lower parts of the Purgatorio mine, below the 25-meter level, and the older, higher levels are not represented. The average thickness and grade of ore indicated by this sampling is shown in table 12. The actual grade of ore produced from the Purgatorio mine averaged 5.8 percent of copper in 1909, representing ore from the higher levels, but it dropped to 4.5 percent in 1926 and averaged also 4.5 percent in the period from 1935 to 1940. Ore shipped by the *poquiteros* from old filled stopes in the San Francisco region from 1946 to April 1948 had an average grade of 3.63 percent of copper. Ore produced from the filled stopes of the San Fernando mine averaged 3.22 percent of copper during the same period. Material shipped from the San Francisco dump from February to June 1936 averaged 2.10 percent of copper.

The ore in the Purgatorio mine was mainly of the oxidized type above the 25-meter level, but it was chiefly of the sulfide type below that level, which was approximately the height of the water table.

The total length of underground workings in the Purgatorio mine is 79 kilometers. The mine extends over a length of 2.2 kilometers in a northwest direction and has an average width of 1 kilometer along the dip to the northeast.

The northwest part of the mine has been rather thoroughly stoped as far northeast as the Santiago fault. To the southeast is the San Guillermo region of low-grade ores, already described. Northeast of the Santiago fault the ore bed pinches out or becomes virtually barren. To the northeast in Arroyo del Purgatorio, ore bed no. 3 was penetrated by drill hole no. 49 and was explored also in some workings at the bottom of the San Roberto shaft, but in both localities the bed was considered unexploitable.

The principal centers of extraction for the Purgatorio mine have been the vertical Purgatorio shaft and the inclined entries nearby known as Chiflón 50 Purgatorio, Chiflón Margarita, and Chiflón 5 Mars, all of which emptied alongside the railroad line in Arroyo del Purgatorio. The old San Francisco mine was entered by the vertical San Francisco shaft and also by some surface entries along the slope of Cerro de Juanita.

Ventilation in the Purgatorio mine was provided by Chiflón 5 San Porfirio and by the Indios, Santa María, Santiago, and San Guillermo shafts, all equipped with ventilators. Some smaller shafts that also provided ventilation were the Pablito, San Pablo, Bompland, and Niña shafts. The San Alejandro shaft was sunk mainly to explore ore bed no. 4, the San Pedro shaft to explore ore bed no. 2, and the Mars shaft was also for exploration, although it was later used as a water well. The principal haulageways inside the Purgatorio mine were at levels of 50, 25, 10, and 0 meters above sea level, and at levels of 30 and 60 meters below sea level.

Production figures have been kept separately for the San Francisco and Purgatorio mines. Production from the San Francisco mine from 1893 until 1901, together with some production from dumps between 1929 and 1939, totaled 323,343 tons of ore. Production from the Purgatorio mine, excluding the San Francisco mine, from 1901 until 1940 totaled 2,091,141 tons of ore—the highest figure for any of the mines in the district. The combined production of the two mines totals 2,414,484 tons of ore. In addition, there was some unrecorded production from the San Francisco mine before 1893 and also some recent production by the *poquiteros* from parts of the Purgatorio mine. The amount of waste extracted from the San Francisco mine was recorded as 128,579 tons, or 28 percent of the total extraction, and the waste extracted from the Purgatorio mine proper was 1,563,396 tons, or 43 percent of the total extraction.

The future possibilities of the Purgatorio mine are believed to lie largely in the explored but unstoped area in the southeast part of the mine, known as the San Guillermo region of low-grade ores and previously discussed in connection with the Providencia group of mines. The northwest part of the mine has been almost completely stoped out, and as the lower levels were stoped during a comparatively recent epoch of operations when the cut-off grade was low, it is doubtful that it would be profitable to rework the filled stopes in that area. The older higher levels of the mine, however, particularly those in the San Francisco region, contain filled stopes and pillars that are higher in grade and that in some places have been reentered and profitably worked by the *poquiteros* in recent years.

AMELIA AND CURUGLÚ MINES (ORE BED NO. 3)

The Amelia mine is a part of the large area mined in ore bed no. 3 near the head of Arroyo de la Soledad. The mine is bordered on the east by the California-Lugarda mine in Arroyo del Purgatorio, the approximate boundary being the line of the La Ley fault, and on the northeast by the San Luis mine in Arroyo de la Soledad, the boundary being about midway between the Amelia and San Luis shafts. On the west and northwest the Amelia mine is terminated by outcrops of ore bed no. 3 along the sides of Cañada de Curuglú and other branches of Arroyo del Boleo. The Curuglú mine is in a downfaulted segment of ore bed no. 3 on the west side of Cañada de Curuglú, separated from the Amelia mine by the Curuglú fault. Different areas of the Amelia mine have been given different names, including Olvido Viejo, Olvido Nuevo, San Andrés, San Jorge, and Fortuna. The north end of the Curuglú mine has been called Santa Teresa.

The Amelia mine is one of the oldest in the Boleo district, the prominent outcrops along Cañada de Curuglú and vicinity having attracted prospecting soon after the discovery of the district. Operations in the Amelia mine were carried on by the Boleo company from 1886 until 1919, when the mine was abandoned. The Curuglú mine was worked from 1894 until 1906. Recently, small parts of the Amelia and Curuglú mines have been reworked by the *poquiteros*.

Ore bed no. 3 in the Amelia and Curuglú mines has a fairly regular strike of N. 5°–35° W., averaging about N. 20° W., and a dip of 3°–10° NE. The ore bed is repeatedly upthrown to the northeast by a series of northwest-trending normal faults, so that in spite of the northeast dip of the ore bed, the elevations of the ore are nearly the same along the northeast border of the mine as along the outcrops at the southwest side. The more important faults are the Curuglú in Cañada de Curuglú, with a maximum displacement of 60 meters, and the Amelia near the Amelia shaft, with a maximum displacement of 40 meters. A few faults with their downthrown sides to the northeast are of slight importance.

Outcrops of ore bed no. 3 are fairly extensive along the east side of Cañada de Curuglú and in the next side canyon of Arroyo del Boleo to the east. On the west side of Cañada de Curuglú the ore bed has been dropped below the canyon level by the Curuglú fault. The ore bed lies below the level of Arroyo de la Soledad in the Amelia mine. Ore bed no. 4, found 141 meters below ore bed no. 3 in this area, was explored by the Amelia shaft, but it was considered unexploitable.

Elevations of the ore bed in the Amelia mine range from a maximum of 209 meters to a minimum of 144 meters above sea level. Elevations in the Curuglú mine range from 146 to 117 meters above sea level.

A notable feature of the Amelia and Curuglú mines is the concentration of the ore in definite shoots, which are elongate, northwest-trending, subparallel, riblike bodies, as shown in figure 35.

No assay maps are available for the Amelia and Curuglú mines. The only definite figures found on the grade of ore shipped from the Amelia mine were for the year 1909, when the grade averaged 4.79 percent of copper, and for 1919, when it averaged 6.72 percent of copper. The ore from these mines was all of the oxidized type, lying entirely above the water table. The area around the Cumenge shaft is of interest as being the type locality for the rare minerals boléite, pseudoboléite, and cumengite.

The length of underground workings in the Amelia mine totals 44 kilometers and in the Curuglú mine 5.7 kilometers. The Amelia mine extends over a length of 2 kilometers in a northwest direction and has a maximum width of 1 kilometer. The stoped area of the Curuglú mine forms a single, narrow belt extending for 600 meters to the northwest and having a width of 50 to 150 meters. A pair of exploratory workings, from which no stoping was done, extends an additional 500 meters along the strike to the southeast and 300 meters up the dip to the southwest.

Extraction from the Amelia mine was accomplished mainly from the vertical Amelia shaft and from the inclined entries nearby known as Chiflón 186 Amelia and Chiflón Cumenge. The Cumenge shaft was used for ventilation. There was also a number of surface entries, to the south in Arroyo del Purgatorio, to the west in Cañada de Curuglú, and to the north in branches of Arroyo del Boleo, which were used mainly for ventilation and disposal of waste. Some of the principal haulageways were at levels of 190, 186, 180, 172, 170, and 158 meters above sea level.

Extraction from the Curuglú mine was provided first by one of the Curuglú shafts, the other being used for ventilation, and later by the inclined entry called Chiflón 120 Curuglú. Ventilation was provided also by Chiflón 142 Curuglú and by several surface entries at the north end of the mine. The principal levels in this mine were at 131 and 120 meters above sea level.

In order to transport ore from the Curuglú mine out to the railroad in Arroyo de la Soledad, the Curuglú tunnel, 437 meters long, was driven through the ridge at the head of Arroyo de la Soledad, from near the Amelia shaft to Cañada de Curuglú. A bridge 137 meters long and 35 meters high was constructed across Cañada de Curuglú, and electric locomotives pulled ore cars across the bridge and through the tunnel to the former railhead near the Amelia shaft.

Production records indicate a total production of 887,856 tons of ore from the Amelia mine and 10,020 tons from the Curuglú mine, although neither figure is complete. The total waste extracted from the two mines was recorded as 459,030 tons, or 34 percent of the total extraction.

Comparatively large unstoped areas and pillars remain in the Amelia and Curuglú mines. Although these areas were considered too low in grade to be mineable at the time of original exploration, some of them might now be exploitable by the type of operations recently carried on by the *poquiteros* elsewhere in the district. At the time of this writing, only small parts of these mines had been reentered by the *poquiteros*, mainly a small area known as the Santa Teresa mine, at the north end of the Curuglú mine.

SAN AGUSTÍN AND SAN LUIS MINES (ORE BED NO. 3)

The San Agustín and San Luis mines are part of the large area mined in ore bed no. 3, whose centers of extraction were in Arroyo de la Soledad, 4 to 5 kilometers inland from the coast. These mines are surrounded by others on all sides, except to the northwest, where ore bed no. 3 reaches the surface along some of the branches of Arroyo del Boleo. San Luis was the name given to workings around the San Luis shaft, the first sunk in this area. Later, the San Agustín shaft was sunk farther northeast in Arroyo de Soledad, and it came to be used for extraction not only from the new area but also from the area formerly served by the San Luis shaft, which was abandoned.

The boundaries of the San Agustín and San Luis mines with the other mines were purely administrative and artificial, and they are difficult to fix exactly. Roughly, these mines were separated from the Amelia mine to the southwest by a line running about midway between the Amelia and San Luis shafts. They were divided from the California-Lugarda mine to the southeast by a line running approximately through the San Felipe and San Porfirio shafts. The boundary with the Santa Rita mine to the northeast and north was a line running northward from the San Porfirio shaft, crossing Arroyo de Soledad about 200 meters northeast of the San Agustín shaft, and then proceeding northwest and west to the outcrops in the drainage basin of Arroyo del Boleo, approximately at coordinate 2500 N.

The San Luis mine was worked from the earliest years of operation of the Boleo company until 1899. The San Agustín mine was operated from 1900 until 1917. Parts of these mines have been reworked in recent years by the *poquiteros*.

The structure of ore bed no. 3 in the San Agustín and San Luis mines is that of a rather broad structural nose, trending northeast. Southeast of Arroyo de la Soledad the average strike of the ore bed is about N. 10° W., whereas on the northwest side it swings around to N. 70° W. and is in places due west. The average dip is only 3° NE. between the San Luis and San Agustín shafts, but northeast of the San Agustín shaft the dip steepens locally to 23° NE.

The structural nose is paralleled to the northwest by a conspicuous northeast-plunging structural trough, which produces a distinct U-shaped bend in the structure contours (see pl. 4). The axis of this trough lies about 500 meters northwest of the San Luis shaft; from there it trends northeast and then swings around to the east, reaching Arroyo de la Soledad about 400 meters northeast of the San Agustín shaft. The ore bed is offset by a few faults in the San Agustín and San Luis mines, but none is of great importance.

Ore bed no. 3 crops out in a small erosional window in Arroyo de la Soledad, 100 to 400 meters southwest of the San Luis shaft, at elevations of 170 to 180 meters above sea level. Elsewhere the ore bed lies below the arroyo level in the area covered by the San Agustín and San Luis mines. Prominent outcrops of ore are found at the northwest end of these mines, along some of the branches of Arroyo del Boleo. In places the ore bed covered dip slopes and thus formed extensive superficial deposits which were mined in the earliest days by open cuts. An interesting feature in one small canyon (pl. 1, coordinates 2000 to 2500 N., 2850 W.) is that the ore bed was displaced by a small fault in such a way that it crops out in two different belts, one slightly above the other, on the same slope.

Elevations of ore bed no. 3 in the area of these mines range from 197 meters above sea level in some of the outcrops to 88 meters above sea level along the boundary with the Santa Rita mine. Most of the mine workings are at elevations of 135 to 160 meters above sea level. Ore bed no. 4 was explored in the San Agustín shaft, where it lies 103 meters below ore bed no. 3, but it was considered unexploitable.

No exact data are available on the thickness and grade of ore in the San Agustín and San Luis mines, but they are believed to be at least as great as or greater than the general averages for the district as a whole. The only precise figure found was for the year 1909, when the average grade of ore produced from the San Agustín mine was 5.43 percent of copper. The ore mined by the *poquiteros* in Arroyo de la Soledad from 1946 to April 1948, mainly from filled stopes in the old San Agustín, San Luis, and Amelia mines, averaged 3.47 percent of copper. Material that was shipped from the old dump of the San Luis mine averaged 2.6 percent of copper in 1926 and 2.1 percent in 1938. The ore found in these mines was nearly all of the oxidized type.

The length of underground workings was recorded as 37 kilometers for the San Luis mine and 40 kilometers for the San Agustín mine, or a total of 77 kilometers for the two mines. The mines cover an area that extends for about 1.5 kilometers to the northwest and about 1 kilometer to the northeast.

Extraction from the San Luis mine until the end of 1899 was from the vertical San Luis shaft and an adit nearby at the 168-meter level. In 1900 extraction was diverted to the vertical San Agustín shaft and to several inclined entries nearby. Two adits on the southeast side of the arroyo also served for extraction. Many entries along the outcrops in the drainage area of Arroyo del Boleo at the northwest end of the mine served for ventilation and dumping of waste. Ventilation in the southeast part of the mine was provided by the San Felipe and San Porfirio shafts. Some of the major levels in the San Luis mine were at elevations of 180, 168, and 162 meters above sea level, and in the San Agustín mine at elevations of 160, 158, 150, 138, 136, and 131 meters above sea level.

The total recorded production of the San Luis mine, including mine production from 1893 to 1899 and dump production from 1924 to 1930 and 1938 to 1939, was 440,329 tons of ore. The production of the San Agustín mine from 1900 to 1917 was 895,799 tons of ore. The combined total for the two mines is 1,336,128 tons of ore. In addition, there was some production from the San Luis mine before 1893 and some production by the *poquiteros* in recent years. The waste extracted from the two mines amounts to 961,415 tons, or 42 percent of the total extraction.

Some of the filled stopes and unmined areas of the San Agustín and San Luis mines are believed to offer good possibilities for the type of small-scale mining operations recently carried on by the *poquiteros* in the Boleo district. These mines have been reentered by the *poquiteros* at half a dozen scattered localities, both in Arroyo de la Soledad and also near the outcrops in the drainage basin of Arroyo del Boleo.

SANTA RITA, SAN ANTONIO, AND SANTA MARTA MINES (ORE BED NO. 3 AND FALSA TERCERA ORE BED)

The Santa Rita and associated mines are in the northeasternmost part of the large area mined in ore bed no. 3, extending from Arroyo de la Soledad to Arroyo del Boleo. Different parts of this area have been given different names, but the production records have generally been combined. The name Santa Rita was used for the older part of the mine, lying above the 25-meter level, mainly northwest of Arroyo de la Soledad. The name San Antonio was applied to the workings in an upfaulted segment northeast of the San Antonio fault, on the southeast side of Arroyo de la Soledad, where ore bed no. 3 was brought up from below sea level to above the arroyo level. The name Santa Marta has been applied to the newer workings on the southeast side of Arroyo de la Soledad, below the 25-meter level of the Santa Rita mine and below the 50-meter level of the San Antonio mine.

Some smaller mined areas with different names include the San Juan mine, in outcrops on the northwest side of Arroyo de la Soledad, northeast of the San Antonio fault; the Buena Suerte mine in the Falsa Tercera ore bed on the southeast side of Arroyo del Boleo; and the Boleo mine, referring to exploratory workings on the northwest side of Arroyo del Boleo. Several small new mines, including the Texcoco, Anahuac, and Mangle have been opened by the *poquiteros* along outcrops on the southeast side of Arroyo del Boleo.

The Santa Rita mine is bordered to the southeast by the Purgatorio mine, to the south by the California-Lugarda mine, and to the southwest by the San Agustín mine. The approximate boundaries have been given in connection with those mines. On the northwest of the Santa Rita ore bed no. 3 crops out on the side of Arroyo del Boleo; on the northeast it pinches out down the dip.

Some of the outcrops along Arroyo del Boleo were probably worked at an early date. Work in the Santa Rita mine proper began in 1893 or earlier and continued until the 1920's. The Buena Suerte mine was worked from 1899 to 1908. The San Antonio mine was operated mainly from 1906 to 1913. Work in the Santa Marta mine was conducted mainly from 1923 to 1938, after which the entire area was abandoned by the Boleo company. The peak production was in the years 1926 to 1937. Work in the Texcoco, Anahuac, and Mangle mines and a few other parts of the Santa Rita mine has been carried out recently by the *poquiteros*.

The area covered by the Santa Rita mine provides some of the best examples in the district of initial structures formed over irregularities in the basement topography. In the northern part of the mine, particularly, are several eastward-plunging anticlinal noses and synclinal troughs formed over buried ridges and valleys. Proceeding from north to south, there are at least four conspicuous synclinal troughs, separated by anticlinal noses: one north of the Boleo shaft, one in the Mangle mine, one between the Texcoco and

Anahuac mines, and one south of the Texcoco mine.

Because of the initial structures the strike of the ore bed is quite variable in different parts of the Santa Rita mine, ranging anywhere from due west to northwest or northeast. Away from the structural irregularities, however, the average strike is about N. 25° W. The dip ranges from 5° to 27° E., reaching a maximum on the flanks of some of the structural troughs.

The most important fault in this area is the San Antonio, which separates the lower levels of the Santa Rita mine from the San Antonio mine. This fault has the southwest side downthrown as much as 80 meters. An interesting feature is the abruptness with which the fault dies out to the southeast near the Santa María shaft. Several other faults of lesser displacement have been found in the Santa Rita mine.

Ore bed no. 3 crops out extensively along the southeast side of Arroyo del Boleo, extending as far northeast as the Buena Suerte mine, where the ore bed goes below the arroyo level. On the northwest side of Arroyo del Boleo, outcrops are found only in a small area. In Arroyo de la Soledad, ore bed no. 3 is below the arroyo level throughout the area under discussion, except for a short distance northeast of the San Antonio fault.

The positions of the ore beds range from 148 meters above sea level in outcrops alongside Arroyo del Boleo to 31 meters below sea level along the southwest side of the San Antonio fault. In the upfaulted area northeast of the San Antonio fault the elevations of the ore range from 112 meters above sea level in outcrops to 3 meters above sea level in the northeasternmost level of the Santa Marta mine.

The Falsa Tercera ore bed was mined at the north end of the Santa Rita mine, in the Buena Suerte region; it was followed in exploratory workings southeastward to the Santa Natalia shafts and was also exposed in a few other places farther south. This bed lies 1 to 9 meters above ore bed no. 3, with which it locally coalesces. Outcrops of the Falsa Tercera ore bed are conspicuous in parts of Arroyo del Boleo. The stoped areas in the Falsa Tercera ore bed lie in general to the northeast of those in ore bed no. 3, but in part they overlap. The principal area mined in the Falsa Tercera ore bed lies at elevations of 123 to 38 meters above sea level, but in one working southeast of the Santa Rita shaft the bed was found as low as 7 meters above sea level.

Ore bed no. 2 was cut by some of the inclined workings in the Santa Marta area, namely Chiflón San José and Chiflón Santa María, but it was considered unexploitable. Ore bed no. 4 was explored at the bottom of Chiflón Santa Natalia, where it lies about 95 meters below ore bed no. 3, but it was too low in grade to be exploitable. Ore bed no. 4 is said to have been found also in the bottom of the Boleo shaft, an old shaft in Arroyo del Boleo which was once used as a water well but which has been completely covered by alluvium for many years.

The ore is rather sporadic over much of the Santa Rita mine, which has one of the lowest ratios of stoped areas to explored areas in the district. In part the ore is concentrated in two elongate ore shoots, which have a northwest trend and cut obliquely across structural features. One shoot averaging 200 meters in width begins in outcrops in the Texcoco mine and extends for 1.5 kilometers S. 75° E. to the area south of the Santa Rita shaft. This shoot is separated from the stoped area of the San Agustín mine to the southwest by a comparatively barren zone about 2 kilometers long and 300 meters wide. Another fairly definite shoot is farther north in the Buena Suerte area, involving stoped areas both in ore bed no. 3 and in the Falsa Tercera ore bed. This shoot extends from outcrops along Arroyo del Boleo for 800 meters S. 50° E. It is separated from the shoot first described by a comparatively barren zone 300 meters wide. Down the dip at the northeast end of the San Antonio and Santa Marta mines the ore bed is said to give way to material composed largely of gypsum and iron oxides.

Assay maps are available for the lower levels of the Santa Marta and San Antonio mines, but the older part of the Santa Rita mine is represented only by very few assays. Data on thickness and grade of ore determined from this sampling are given in table 12. Data on the actual grade of ore shipped to the smelter from the Santa Rita and associated mines show an average of 7.39 percent of copper in 1909, 3.88 percent in 1919, 4.7 percent in 1926, and 4.08 percent from 1935 to August 1938. Ore shipped by the *poquiteros* between 1946 and April 1948 from the Texcoco mine averaged 3.95 percent of copper. Ore that has been produced from the Falsa Tercera ore bed is said to have averaged about 5 percent of copper.

The water table as originally found in the Santa Rita mine was about 25 meters above sea level. Above that level the ore was largely of the oxidized type, and below that level mainly of the sulfide type, although there was no sharp dividing line between the two.

The total length of underground workings in the Santa Rita, San Antonio, and Santa Marta mines amounts to 77.5 kilometers. The mining area extends for 2.5 kilometers to the northwest and has a width of 1 kilometer to the northeast. Some exploratory workings in the Santa Marta area extend an additional kilometer to the northeast. The Falsa Tercera ore bed has been explored for a length of 1 kilometer and stoped for a length of 500 meters and average width of 100 meters.

The principal centers of extraction from the Santa

Rita mine were the vertical Santa Rita shaft and the inclined entries nearby called Chiflón 75 Santa Rita and Chiflón 50 Santa Rita, which emptied alongside the railroad in Arroyo de la Soledad. Originally an extraction center was planned also in Arroyo del Boleo, but the railroad running up that arroyo was washed out in 1898 and never replaced. All the ore alongside Arroyo del Boleo was extracted toward the southeast, in Arroyo de la Soledad. A number of entries along Arroyo del Boleo served for exploration, ventilation, and disposal of waste. The main extraction center for the Santa Marta mine was Chiflón 10 Santa Rita, which emptied near the Santa Rita shaft. Extraction from the San Antonio mine was mainly from an adit at the 97-meter level and from an inclined entry which connected with the 80-meter level.

Shafts equipped with ventilators in the Santa Rita area included the San Juan, San José, and Santa María shafts. Others that served for exploration and ventilation included the Santa Natalia, San Enrique, and Santa Marta shafts. Ventilation in the Santa Marta mine was also provided by two inclined shafts.

Some of the main haulageways in the Santa Rita mine were at levels of 102, 75, 50, and 25 meters above sea level. The main levels in the San Antonio mine were at elevations of 97, 80, and 50 meters above sea level. The principal haulageways in the Santa Marta mine were at levels of 25 and 10 meters above sea level, and 0 to 5, 20, and 35 meters below sea level.

The total production of the Santa Rita, San Antonio, and Santa Marta mines is recorded as 1,502,773 tons of ore. This does not include some production by the *poquiteros* in recent years. The waste extracted amounted to 1,054,524 tons, or 41 percent of the total extraction.

The northwest end of the Santa Rita mine, along the outcrops in Arroyo del Boleo, has provided one of the most profitable fields for activity of the *poquiteros* in recent years. Large areas in that region were left unmined by the Boleo company, owing to local structural irregularities that caused difficulties in mining, and also to the great distance of that area from the extraction centers in Arroyo de la Soledad. A considerable amount of ore has been taken out by the *poquiteros*, particularly from the Texcoco, Anahuac, and Mangle mines, using short surface entries from Arroyo del Boleo and hauling the ore out that arroyo by truck. Several areas are believed to remain in the Santa Rita region that could be mined by the present methods of the *poquiteros*.

MINES IN ARROYO DEL BOLEO AND CAÑADA DE LA GLORIA (ORE BEDS NO. 3 AND NO. 4)

A number of small mines are in the drainage of Arroyo del Boleo and Cañada de la Gloria, northwest of the main mining area in the Boleo district. Only a small amount of work was done in that area by the Boleo company, but in recent years several small mines have been worked by the *poquiteros*, and the ore has been hauled out by truck to the railhead at El Yeso, in the lower part of Arroyo del Boleo.

The structure is highly irregular in this area, owing to the proximity of several buried ridges and valleys in the topography on the basement rocks along the outskirts of Cerro del Infierno. For this reason the individual mining areas are rather small, irregular, and difficult to mine by the regular stoping methods of the Boleo company, but they are well adapted to the small-scale operations of the *poquiteros*.

The Texcoco, Anahuač, and Mangle mines along the southeast side of Arroyo del Boleo have already been mentioned in connection with the Santa Rita mine. These were areas in ore bed no. 3 that had been left near the outcrops in Arroyo del Boleo. The Texcoco mine in particular was one of the best mines that has been developed by the *poquiteros*. This mine had a production of 116,043 tons of ore from December 1945 to April 1948.

The old Macheteros mine on the south side of Arroyo del Boleo, between coordinates 3100 and 3300 W., consists of a few scattered workings in ore bed no. 4, which dips steeply north and lies between 82 and 155 meters above sea level. The workings extend over a length of 275 meters and a width of 75 meters. Only a few small stopes were made there.

The Los Altos mine consists of some very old scattered workings in ore bed no. 4 on the south side of Arroyo del Boleo, extending from coordinates 3500 to 4200 W. The ore bed there lies at elevations of 110 to 155 meters above sea level. Practically no stoping has been done in that area.

The El Bajío mine is a small new mine on the south side of Arroyo del Boleo just west of the Los Altos mine, between coordinates 4200 and 4400 W., where both ore beds no. 3 and no. 4 have been explored. Ore bed No. 3 lies above the arroyo level, on top of a thick conglomerate, at elevations of 172 to 189 meters above sea level. A small amount of stoping was done in this bed. Ore bed no. 4 was found directly on the edge of the arroyo and was followed a short distance below the arroyo level. It lies below the thick conglomerate mentioned above, in tuff only a short distance above the Comondú volcanics. Workings in this ore bed are at elevations of 123 to 130 meters above sea level. This is a rather irregular bed, in which nodules and pockets of high-grade oxidized copper minerals, including some fine euhedral crystals of azurite, are scattered through a massive clay.

The Neptuno and La Testera mines were recently opened by the *poquiteros* on the north side of Arroyo del Boleo, between coordinates 4300 and 4600 W. The Neptuno is on a small hill almost completely surrounded by outcrops of ore bed no. 3, which lies at elevations of 179 to 199 meters above sea level. The mine was opened by numerous surface entries, and the intervening area, measuring about 175 by 100 meters, has been almost completely stoped out.

Adjoining the Neptuno mine to the north, beyond a small saddle, is the La Testera mine, where ore bed no. 3 goes into the slope to the northwest at elevations of 155 to 184 meters above sea level. Several entries in the outcrops on the southeast side of this mine have followed the ore bed inward, and an area of 300 by 50 to 100 meters has been stoped out. The bed is cut off by a fault to the southwest and crops out to the southeast and northeast, but it may continue for some distance farther under the slope to the northwest. From December 1945 to July 1947 the production of the La Testera mine was 2,307 tons of ore, which had an average grade of 4.22 percent of copper.

The El 160 mine is a new mine of the *poquiteros* in ore bed no. 4 on the southwest side of Cañada de la Gloria, half a kilometer north of the La Testera mine. The ore bed lies close to the surface of a steep dip slope over much of this area and has been removed in open cuts and shallow workings. To the southwest the ore bed goes deeper under the slope. Elevations of the ore range from 193 meters above sea level at the west end of the mine to 125 meters above sea level at the east end. The mine workings are scattered at intervals over an area of 300 by 150 meters. Shipments of ore from the El 160 mine from September 1946 to July 1947 totaled 2,028 tons with an average grade of 3.80 percent of copper. Low-grade manganese oxides are prevalent in the vicinity of the El 160 mine, in places mixed with copper ore and elsewhere occurring in separate beds.

The Dos de Abril mine is a promising new mine opened by the *poquiteros* in Cañada de la Gloria, 1.5 kilometers northwest of the El 160 mine. The ore bed, which is of uncertain correlation, crops out on both sides of the arroyo. On the south side, elevations range from 236 to 299 meters above sea level, increasing toward the west, and on the north side they range from 238 to 252 meters above sea level. The ore is a rather thin bed of clay from 40 to 50 centimeters thick, penetrated by oxidized copper minerals, which are mainly green to blue chrysocolla. The ore tends to pinch out on the south side of the arroyo, but on the north side it appears to continue under the slope to the northwest. Ore shipped from the Dos de Abril mine from April 1947 to April 1948 totaled 3,997 tons and had an average grade of 3.80 percent of copper.

A low-grade manganese-oxide bed as much as 2 meters thick crops out on the north slope of Cañada de la Gloria, 6 to 7 meters stratigraphically above the copper ore bed of the Dos de Abril mine. The bed is a sandy tuff replaced partially by manganese oxides; it is coarser grained than most of the manganiferous beds found in the district. This manganiferous tuff has been explored in open cuts and short workings scattered at intervals over a length of 900 meters. A sample of this material collected by the writers contained 7.5 percent of manganese.

Several other prospects and shallow workings are scattered around the area between Arroyo del Boleo and Cañada de la Gloria, both in outcrops of copper ores and in low-grade manganese oxide beds. In some of these localities the possibilities seem favorable for the development of small mines. Because of structural irregularities, however, all the mining areas are likely to be of comparatively small size.

MINES IN ARROYO DEL INFIERNO (ORE BED NO. 3)

Some small copper mines are in Arroyo del Infierno, the next main arroyo northwest of Cañada de la Gloria, northwest of the principal area mined in the Boleo district. The geology of this arroyo is shown on the geologic map of the Lucifer manganese district (Wilson and Veytia, 1949, pl. 39). The copper mines are on both sides of the arroyo about 1.5 kilometers northeast of the Lucifer manganese mine, at a higher stratigraphic horizon than the manganese ore bed.

Some prospecting and mining were done along outcrops in that area at an early date, before the operations of the Boleo company. Some mining was done there by the Boleo company in 1928 to 1931, but in general the company took little interest in that area because of its distance from the smelter and the lack of transportation facilities. The mines in Arroyo del Infierno have been reopened by the *poquiteros* in recent years, and the ore has been hauled by truck to the mouth of the arroyo and thence along the coast to the railhead at El Yeso—the same route used since 1941 for transporting manganese ore from the Lucifer mine.

The Infierno mine consists of three separate groups of workings and some other small isolated workings on the north side of Arroyo del Infierno, besides another set of workings on the south side of the arroyo. The principal group of workings covers an explored area of about 300 by 200 meters, of which about one-third has been stoped. In this area the ore bed, believed to be no. 3, lies at elevations ranging from 123 to 164 meters above sea level. Two other groups of workings, one to the southwest and the other to the northeast of the principal group, have explored areas of about 175 by 50 meters each. In these workings the ore bed has elevations of 116 to 190 meters above sea level.

On the south side of the arroyo, 200 meters southeast of the principal group of workings, is a scattered group of workings covering an area of about 200 by 75 meters. Very little stoping has been done in that area, where the ore bed ranges in elevation from 120 to 143 meters above sea level.

Data on thickness and grade of ore shown by assay maps of the Infierno mine are given in table 12. The only data found on the actual grade of ore shipped to the smelter were for February and March 1947, when the average grade was 4.86 percent of copper. The production from 1928 to 1931 was 8,380 tons of ore. This figure does not include the early production from this area, nor the more recent production of the *poquiteros*.

The Noche Buena mine is on the south side of the arroyo, higher up the slope and about 600 meters south of the workings just described. A few exploratory workings have followed the ore bed, which is of uncertain correlation, for about 175 meters to the southeast. The bed there lies at elevations ranging from 281 meters above sea level along the outcrops, to 274 meters above sea level farther southeast.

The area of Arroyo del Infierno is believed to offer good possibilities for the discovery of additional ore bodies, since it has been very little explored to date except directly adjacent to the outcrops.

RESERVES AND POSSIBILITIES

RESERVES

The Boleo district, after more than 60 years of mining resulting in the production of more than half a million tons of copper, is rapidly approaching the end of its reserves of currently minable ore. The known reserves of high-grade ore amount to only a few hundred thousand tons, although there exist several million tons of marginal reserves which contain significant amounts of copper but which are not commercially minable at present because of low grade, thinness, or great depth below the surface.

It is not practical to list reserves of currently minable ore in this report. Any reserves that might be listed at the time of this writing would probably be mined out by the time this report is published, but meanwhile new reserves would probably have been found. At no time since the senior author first visited the district in 1943 have the reserves been considered sufficient for more than 1 or 2 years of operations; yet in 1950 the estimated reserves were not greatly different from those of the earlier year, despite the intervening production.

Aside from the areas of currently minable ore, the Boleo district contains large marginal reserves which are not considered to be a profitable source of ore at present, but which nevertheless constitute a reserve of copper that might be available under some future combination of economic conditions, scarcity of copper, and improved methods of mining and treatment. Whether these reserves may ever mined, it seems desirable to record their presence.

The general order of magnitude of marginal reserves, in beds having a minimum thickness of 50 centimeters and minimum grade of 2 percent of copper, is estimated to range somewhere between 2 and 5 million tons. The figure of 2 million tons could be considered as "indicated ore," fairly well blocked out by drill holes and mine workings, and the figure of 5 million tons as "inferred ore," involving incompletely explored areas. If the grade were lowered somewhere below 2 percent of copper, the reserve figure would be considerably larger.

Although ore of 50 centimeters thickness containing 2 percent of copper is not now commercially minable in the Boleo district because of the high cost of mining and treating the ore, it does not seem inconceivable that such ore might become minable at some time if more economical methods of mining or metallurgy are developed or if the price of copper is greatly increased. In this connection it might be mentioned that one of the most nearly similar copper deposits in the world to the Boleo deposit, the Kupferschiefer or copper-shale in Germany, which has been mined for 750 years, contains only 20 to 30 centimeters of minable ore averaging 2.5 to 2.8 percent of copper. Neither the mining nor metallurgical problems, however, are so severe in the Kupferschiefer as in the Boleo deposits.

All four of the principal ore beds are considered as potential sources of marginal reserves. In ore bed no. 1, a considerable area has been blocked out by exploratory drilling east of the San Luciano and Montado mines. An area explored by 18 drill holes showed an average thickness of 50 centimeters with an average grade of 3.3 percent of copper, and an exploratory working in the Santa Agueda shaft showed an average thickness of 58 centimeters and average grade of 3.3 percent of copper. A disadvantage is the great depth of the ore bed: 118 to 224 meters below sea level in that area.

Ore bed no. 2 contains fairly large areas of low-grade ore which could be considered as marginal reserves, particularly between Arroyos Providencia and Boleo, where the bed lies close to the surface and thus could be readily mined. Parts of the bed are highly manganiferous, and this would be of interest in the event any metallurgical process could be developed for recovering both manganese and copper.

One of the largest and most favorable areas of marginal reserves is in ore bed no. 3, in the San Guillermo area between Arroyos Providencia and Purgatorio. This area was partially explored at an early date, and one long working showed an average thickness of 69 centimeters and average grade of 3.3 percent of copper.

Ore bed no. 4 is another manganiferous bed, like ore bed no. 2, which has been exploited only in small areas and can be considered a potential source of marginal reserves. This bed was explored by several shafts in Arroyos Soledad and Purgatorio, and although it was considered unexploitable at the time of exploration, some spotty concentrations of high-grade ore were found, and in places the low-grade ore extends over a considerable thickness. In a drift at the bottom of the San Alejandro shaft the ore bed had an average thickness of 61 centimeters and average grade of 4.1 percent of copper. It should be minable under present conditions.

DUMPS AND SLAG PILES

Dumps from the richer and older mines have provided ore for the smelter in recent years. The recorded dump production through 1947 amounts to 324,163 tons, which includes 127,254 tons from the San Alberto mine, 67,553 tons from the San Francisco mine, and 129,356 tons from the San Luis mine.

TABLE 31.—*Grade and amount of copper ore in certain dumps that have been sampled in the Boleo district* [1]

Location of dump	Grade of dump (percent of copper)		Estimated amount of ore contained in dump (metric tons)
	Wet	Dry	
Arroyo del Montado			
Chiflón −30 San Alberto	1.28	1.39	3,000
Arroyo de la Providencia			
Chiflón Juanita	1.13	1.25	100
Above Chiflón 54 Sontag	2.18	2.42	20,000
In front of Chiflón 54 Sontag	2.67	3.10	2,000
Providencia, ore bed no. 2	1.68	2.10	1,000
Chiflón Yaqui	1.12	1.24	1,000
Conical dump, Yaqui	3.00	3.24	10,000
San Víctor	3.04	3.38	2,000
Entrance to level 70 Ranchería	2.86	3.32	1,000
Entrance to second level 70 Ranchería	2.24	2.46	1,000
Level 50 Ranchería	1.37	1.50	10,000
Flat dump, level 30 Ranchería	2.35	3.50	5,000
Conical dump, level 30 Ranchería	.88	1.16	40,000
San Alberto dump	1.80	2.40	100,000
Arroyo del Purgatorio			
Below Lugarda cemetery	0.41	0.51	5,000
Level 147 California	.81	1.01	10,000
Level 90 Lugarda	1.27	1.74	10,000
Dump below Margarita conical dump	1.17	1.52	60,000
Upper Margarita conical dump	1.17	1.52	60,000
Six small dumps at Cinco de Mayo	2.92	3.32	500
Arroyo de la Soledad			
Curuglú	1.50	1.95	5,000
Large San Agustín dump	.72	.83	140,000
Amelia	1.19	1.52	5,000
San Jorge	2.19	2.46	2,000
San Luis	1.71	1.92	1,000
Chiflón 75 Santa Rita	.73	.79	2,000
Chiflón Santa María	2.34	2.78	1,000
Level 80 San Antonio	2.10	2.44	1,000
Averages and total weighted for tonnages [2]	1.26	1.58	498,600

[1] Grade and tonnage determined by engineering department of the Cía. del Boleo, May 29, 1946.

[2] By eliminating the relatively large but low grade San Agustín dump (140,000 tons) and the conical dump, level 30 Ranchería (40,000 tons), the remaining total would be 318,600 tons, with an average copper content of 1.55 percent wet and 1.96 percent dry.

Several dumps have been sampled recently by the Boleo company, and the results are indicated in table 31. This table lists only a part of the dump material of the district, inasmuch as 9 million tons of waste is recorded as having been extracted from the Boleo mines. Some of the waste has been lost by erosion, and many of the dumps consist of barren waste material.

In addition to the dumps, some old slag piles from the early blast furnaces are fairly high in copper, and this material has been used from time to time in the reverberatory furnaces of the present smelter. The slag piles northwest of the Boleo smelter, called the Terrero Bleichert, were estimated by the Boleo company on May 21, 1943, to amount to 436,985 cubic meters of material averaging 1.3 percent of copper. About 5,000 tons of slag has been exploited since the date indicated above. An analysis of this old slag by the U. S. Bureau of Mines, showing 1.5 percent of copper, is given in table 22 (see analysis 8). The volume and grade of the four different slag piles of the Terrero Bleichert, as calculated by the Boleo company, are listed below, from south to north.

No. of slag pile	*Volume (cubic meters)*	*Grade (percent of copper)*
1	171,744	1.32
2	41,696	1.35
3	114,512	1.48
4	109,033	1.19
Total volume and average grade	436,985	1.33

RECOMMENDATIONS OF AREAS FOR EXPLORATION

The best area for discovering new deposits of currently minable ore is considered to be the northwest region, in the drainage basins of Arroyo del Boleo, Cañada de la Gloria, and Arroyo del Infierno. This area was largely neglected by the Boleo company, because of its comparatively great distance from the smelter. Recently the *poquiteros* have opened several small new deposits in that area which have provided ore of good grade. As the structure in the northwest area is irregular, individual minable areas are not likely to be of great extent, but several minable areas of comparatively small size, adaptable to the present small-scale mining methods, may still be found.

A concealed area 1 kilometer wide in which some minable ore bodies could very likely be found by drilling lies between Cañada de la Gloria and Arroyo del Infierno. Another possible area for the discovery of new ore bodies by drilling—either of copper or of manganese ore—is believed to be in the lava-covered mesa northwest of Arroyo del Infierno and also possibly north of Arroyo de las Palmas, where the geology throughout a large area is obscured by recent lava flows. Possibly by some geophysical method the structure of the basement rocks could be discerned in that area, revealing conditions that may have been favorable for ore deposition according to the theory outlined in this report.

Among the old mines in the district, those with the most favorable possibilities for yielding continued production of currently minable ore are considered to be the Montado and Providencia mines. Both mines were abandoned because of flooding before the explored ore bodies had been completely stoped out, and both are believed to contain fair-sized areas of ore of minable grade. The mines between Arroyos Soledad and Boleo in ore bed no. 3 are also believed to contain some minable ore in pillars and small unmined areas, such as those recently exploited by the *poquiteros* in the Texcoco and adjacent mines.

Some ore of currently minable grade could probably also be found in the so-called San Guillermo area of low-grade ores, in ore bed no. 3 between Arroyos Providencia and Purgatorio. An unexplored area in ore bed no. 1 between the Cinco de Mayo mine in Arroyo del Purgatorio and the Ranchería mine in Arroyo de la Providencia might also warrant exploration.

The best areas for exploiting filled stopes are considered to be the older mines in ore bed no. 3, such as the Providencia, California-Lugarda, San Francisco, Humboldt, Amelia, San Luis, San Agustín, and the higher parts of the Santa Rita mine.

The area lying near the coast is not regarded as favorable for further exploration, with the possible exception of the immediate vicinity of some of the buried hills of Comondú volcanics, such as the one adjoining the old El Crestón mine north of Arroyo del Montado.

OTHER MINERAL DEPOSITS IN THE REGION

MANGANESE DEPOSITS

The most important mineral deposits that have been exploited in the region thus far, aside from those of copper, are deposits of manganese oxides. The deposit of greatest importance so far discovered is a single large high-grade ore body developed in the Lucifer mine, in Arroyo del Infierno, 17 kilometers by road northwest of Santa Rosalía. This deposit has been described in detail in the report by Wilson and Veytia (1949). The total production of the Lucifer mine from 1942 until January 1, 1950, amounted to 215,981 long tons of ore, which greatly exceeds the production of any other manganese mine in Mexico. On that date the reserves in sight were considered sufficient for about 2 more years' production or perhaps longer, and it was considered likely that some more exploratory drilling would be done besides that already described in the report by Wilson and Veytia.

Manganiferous beds have also been found throughout the Boleo copper district, but no thick bodies of high-grade ore have been discovered such as that in the Lucifer mine. There are, however, extensive beds that contain from 5 to 20 percent of manganese. The principal manganiferous beds observed in the field are indicated on the geologic map (pl. 1). Some of these correspond to the regular numbered copper beds, but others are unnumbered beds that occur in tuff between the copper ore beds. Nearly all the copper ore contains a certain amount of manganese; the average smelting ore contains probably 3 to 4 percent of MnO, and the 28 analyses of copper ores given in table 21 show a range from 0.5 to 29 percent and an average of 8.74 percent of MnO.

Probably the most highly manganiferous of the numbered copper beds is ore bed no. 4, as exposed in parts of Arroyo del Boleo and Cañada de la Gloria. In places the copper and manganese minerals are intermixed in the same bed, as on the El 160 claim; in other places a manganiferous bed is found a short distance below a copper bed, as on the Neptuno claim, and elsewhere a manganiferous bed lies a few meters stratigraphically above a copper bed, as on the Dos de Abril claim. In certain places ore beds no. 1 and no. 2 are highly manganiferous, and in places other manganiferous beds are found between ore beds nos. 1 and 2 and also between ore beds nos. 2 and 3.

As the Lucifer high-grade ore body is approaching exhaustion, the future of manganese mining in the district will depend either upon finding another high-grade body of the Lucifer type, or upon the development of a commercial process for concentrating the lower-grade ores of the district, either in conjunction with or separately from the copper mining.

The possible application of the dithionate process for the recovery of manganese from low-grade ores, as described by Ravitz, Wyman, Back, and Tame (1946), is of interest in this regard. This is a process of leaching by sulfur dioxide (which might be furnished by waste gas from the Boleo smelter) in a suspension of the ore in calcium dithionate (CaS_2O_6) solution. The manganese is precipitated as manganese hydroxide, which is sintered or nodulized to produce a high-grade manganese-oxide product. (A sintering plant is already available at Santa Rosalía.) Copper and zinc may be recovered in the same process—a feature of interest in regard to the low-grade manganiferous and zinciferous copper ores of the Boleo district.

Additional manganese deposits along the east side of Baja California, including deposits on San Marcos

Island, near Mulegé, near Point Concepción, and southeast of Concepción Bay, have been described by Wilson and Veytia (1948) in the general report on manganese deposits of Mexico published by Trask and Rodríguez Cabo. None of these deposits appears to offer very favorable commercial possibilities. The one of the largest potential tonnage—the Gavilán deposit on Point Concepción peninsula—is a very low-grade deposit consisting of thin veinlets of manganese oxides scattered through a basalt unit of the Comondú volcanics. It was planned to strip a large tonnage of the basalt and to extract the manganese oxides by wet jigging with sea water. A plant was constructed for this purpose in 1944, but successful operations were not attained and by 1948 the project had been abandoned.

METALS PRESENT IN MINOR QUANTITIES IN THE COPPER ORE

A number of metals besides copper and manganese occur in Boleo ores, but only one—silver—is recovered in the blister copper, and this only in minor amounts. The amount of silver in the blister copper ranges from 70 to 200 grams per ton, whereas its content in the ore ranges from 7 to 12 grams per ton. Other valuable metals that are found in the Boleo ore or smelter products in noticeable amounts, but which have not been recovered, include zinc, cobalt, lead, and nickel. The only one of these metals that concentrates in the blister copper is nickel, which is present to the extent of 0.32 percent, according to one analysis, although samples of the ore show only a trace to 0.13 percent of nickel.

Zinc is present in the ore in amounts that average 0.80 percent and are as much as 6.0 percent. The zinc becomes concentrated in the flue dust, which contains 8.6 to 19.5 percent. Other potentially valuable constituents of the flue dust, not so far recovered, include copper, 3.2 to 4.6 percent; lead, 1.8 to 3.25 percent; cobalt, 0.03 to 0.53 percent; nickel, 0.22 to 0.50 percent; bismuth, 0.27 percent in one sample; and silver, 88 grams per ton.

Cobalt is widely distributed in the Boleo district, but commercial ore bodies have so far not been found. The average cobalt content of the ore is 0.12 percent, ranging from 0.02 to 0.86 percent, according to 126 analyses. In the Boleo smelter, the cobalt becomes concentrated in the converter slag, which contains 0.5 to 4.0 percent of cobalt, and in a metallic iron alloy, containing 10 to 20 percent of cobalt, which collects in the reverberatory furnaces. As an outgrowth of the present study, the possibilities for the recovery of cobalt from the Boleo smelter products are now being investigated by the U. S. Bureau of Mines.

Lead appears to be concentrated in certain parts of the Boleo district, notably in part of the Carmen mine, where galena appears, and in the vicinity of the Cumenge shaft, where the lead-bearing boléite group of minerals was discovered. The ore samples that have been analyzed from other parts of the district, however, show only a trace to 0.23 percent of lead. A vein deposit of galena has been reported from the northwest side of Cerro de Santa María, about 25 kilometers northwest of the copper district.

GYPSUM

Gypsum is present in enormous quantities in the Boleo district. It occurs in beds as much as 80 meters thick intercalated near the base of the Boleo formation. The gypsum is found in two general areas: in the northwest part of the district from Arroyo del Boleo northwestward to Arroyo del Infierno and Arroyo de las Palmas, and in the southeast part of the district from Arroyo del Montado southeastward beyond Arroyo de Santa Agueda. The most extensive exposures are in the northwest area, particularly in the vicinity of Arroyo del Boleo. In the southeast area the gypsum is largely buried, although there is a small exposure near the mouth of Arroyo de Santa Agueda. Lithologic descriptions, as well as stratigraphic information and details about the surface and subsurface distribution of the gypsum, have already been given in the description of the Boleo formation.

A chemical analysis of the gypsum is given in table 5. If we assume that all the sulfur trioxide reported in that analysis is present in gypsum, the proportion of pure gypsum would be 95.61 percent. Anhydrite is present only in minor quantities in the outcrops, although it was found in large masses in the deeply buried bodies penetrated by drill holes. In some places seams of tuff or clay are intercalated in the gypsum, and these would need to be sorted out in any mining operation.

The gypsum has been mined thus far only for use in the Boleo smelter, as a combination flux and source of sulfur. It has been so used during two periods: from 1920–36 and 1939–44. At other times the flux used in the smelter has been calcareous sandstone or limestone, obtained locally, and the source of sulfur has been imported pyrite. Figures available for various years on the production of gypsum, as well as of calcareous sandstone and limestone, are presented in table 32. According to these figures the total production of gypsum in the Boleo district has amounted to 266,573 tons. The maximum annual production was 36,656 tons, attained in 1925.

The gypsum produced for use in the smelter was obtained principally from localities along the south side of Arroyo del Boleo, near the railway loading point known as El Yeso (Spanish for gypsum). There

TABLE 32.—*Production of gypsum, calcareous sandstone, and limestone for use in the Boleo smelter, 1909 to May 1948, in metric tons*

	Gypsum	*Calcareous sandstone*	*Lime-stone*
1909	-------	12,700	-------
1910	-------	33,800	-------
1911	-------	29,530	-------
1912	-------	31,850	-------
1913	-------	35,750	-------
1914	-------	22,654	-------
1917	-------	1,100	-------
1918	-------	245	-------
1919	-------	565	-------
1920	212	955	-------
1921	819	1,625	-------
1922	5,911	850	-------
1923	28,009	1,281	-------
1924	35,766	1,040	-------
1925	36,656	580	-------
1926	26,213	385	-------
1927	17,556	365	-------
1928	21,474	37	-------
1929	26,467	631	-------
1930	12,240	535	-------
1931	6,523	466	-------
1932	3,091	645	-------
1933	205	-------	-------
1934	66	-------	-------
1935	2,127	-------	-------
1936	536	-------	-------
1939–40 [1]	[2] 3,815	-------	-------
1940–41	9,220	-------	-------
1941–42	6,280	-------	-------
1942–43	10,420	-------	[3] 13,325
1943–44	10,652	-------	28,046
1944–45	[4] 2,315	-------	19,960
1945–46	-------	-------	11,760
1946–47	-------	-------	10,855
1947–May 1948	-------	-------	14,105
Total, 1909 to May 1948	266,573	177,589	98,051

[1] Succeeding data are for fiscal years, from July 1 to June 30.
[2] Production began in August 1939.
[3] Production began in February 1943.
[4] Production ended in September 1944.

natural cliffs of gypsum 10 to 20 meters high have been quarried from the arroyo level—a situation ideally suited for economical mining (see fig. 14). The gypsum is trucked a short distance to the railhead and thence shipped by rail a distance of 6 kilometers to the smelter at Santa Rosalía. The known exposures of gypsum, as well as the areas thought to be underlain by gypsum, based upon exposures and subsurface information, are shown in plate 11.

Deposits of gypsum on the southeast end of San Marcos Island have been mined for a number of years for export to the United States by the Cía. Occidental Mexicana, S. A., which was a former subsidiary of the Pacific Portland Cement Co., but which was purchased during World War II by the Henry J. Kaiser interests. The gypsum on San Marcos Island has the same stratigraphic relations and is evidently of the same age as that in the Boleo district. It is of somewhat greater purity, however, and has in general a whiter color than that of the Boleo district. The gypsum occurs in a thick bed which has been mined in opencuts and shallow underground workings; it is carried in small rail cars to a loading platform on a wooden pier constructed along the southwest side of the island. From there it is taken by chartered ship to California ports. The reserves of gypsum on San Marcos Island are very large.

It is probably because of the readily available source of high quality gypsum on San Marcos Island that no attempt has been made to exploit the gypsum of the Boleo district, except for local use in the smelter. In the event it should ever be desired to augment the production from San Marcos Island, or if some additional local industrial use for the gypsum could be found, almost inexhaustible supplies are readily available in the Boleo district.

LIMESTONE AND CALCAREOUS SANDSTONE

To serve as fluxes in the Boleo smelter, limestone from the Boleo formation and calcareous sandstone from the Infierno formation have been mined. The calcareous sandstone was mined from the early years until 1932, and the limestone from February 1943 until the present time. Production figures for these materials are given in table 32. They indicate a total production of 177,589 tons of calcareous sandstone from 1909 to 1932, and 98,051 tons of limestone from February 1943 to May 1948. The figures for the production of calcareous sandstone are incomplete, however, as there is believed to have been a substantial production before 1909, and no data are available for 1915 and 1916.

The limestone is mined from the basal marine limestone of the Boleo formation, described in the section on stratigraphy in this report. The material is referred to locally as dolomite, but since the magnesia content revealed by an analysis is only 1.65 percent, limestone is evidently a more appropriate term. This rock has been mined principally in a large open cut on a hill slope in a small northerly branch of Arroyo de Santa Agueda, 1300 meters inland from the gulf (pl. 1, coordinates 1700 S., 5250 E.), where it forms a steep dip slope inclined 39° E. The limestone at that locality is thicker and purer than average and is in a favorable place for quarrying. It is trucked to the smelter at Santa Rosalía, a distance of about 5 kilometers by road.

The limestone has also been mined in a few other places, as near the mouth of Arroyo del Purgatorio and near the El 160 claim in Cañada de la Gloria. The different exposures of limestone are indicated on the geologic map (pl. 1). Although the limestone is generally thin, the supply is sufficient to meet all the foreseeable needs of the region.

An analysis of the limestone from the quarry in the branch of Arroyo de Santa Agueda is presented in table 3 in another part of this report. From the content of calcium oxide and carbon dioxide indicated by this analysis, the proportion of calcium carbonate present is estimated to be about 80 percent.

The calcareous sandstone mined comes from a sandstone unit of the Infierno formation, which is locally so tightly packed with comminuted shell fragments as to provide a usable source of calcium carbonate. The rock has been mined at a locality known as the Calera mine or the Buena Vista mine, on the northwest side of Arroyo de la Providencia 1 kilometer inland from the gulf (pl. 1, coordinates 1100–1300 N., 2250–2400 E.). The mine is along a steep arroyo wall, at elevations of 150 to 160 meters above sea level, or 120 to 130 meters above the arroyo level. The sandstone bed is nearly flat-lying at that place and has been mined by a room-and-pillar system from a number of entries that extend over a length of about 250 meters. The drifts are fairly large, averaging 3 or 4 meters in width and 4 or 5 meters in height. The sandstone is 30 meters thick at that locality, but the mine workings are confined to the lowermost 5 to 10 meters of the bed.

The sandstone was lowered by a gravity tram down a terrace-covered slope northeast of the mine, and thence was carried by rail a distance of less than 1 kilometer to the smelter. The production of calcareous sandstone from the Calera mine ranged from 20,000 to 30,000 tons a year through 1914, but then dropped to 1,000 tons or less a year until 1932, when the deposit was abandoned. Large quantities of this type of material remain, in the event any commercial use should be found for it.

SULFUR

Deposits of native sulfur have been found in the vicinity of the Tres Vírgenes volcanoes. They were not visited by the writers, but judging from accounts of them, both published and unpublished, they are believed to be small and of little potential value. The deposits were first described by Castillo (1870, p. 50), who states that a vent emitting sulfurous vapors is surrounded by an area about 50 meters across containing numerous fractures along which native sulfur has condensed in crystalline forms. A mesa northeast of the volcano is also described as being traversed by numerous veinlets of sulfur. A few tons of sulfur are said to have been exported in early years by some merchants from Guaymas, but no work has been done on the deposits in recent years.

BUILDING STONE, PUMICE, AND PERLITE

The chief source of building stone in the region consists of the massive, resistant basaltic layers of the Comondú volcanics. Rocks of this type were quarried from near the top of Cerro del Sombrero Montado, for use as a foundation in building the breakwater of the Santa Rosalía harbor.

Extensive pumice deposits are found in the vicinity of the Tres Vírgenes volcanoes, 30 to 35 kilometers northwest of Santa Rosalía. They are crossed by the main road between San Ignacio and Santa Rosalía. Some of the pumice has been carried by truck to Santa Rosalía and fashioned into special bricks, which have the advantage of being very light in weight though comparatively strong. Pumice bricks have been used for insulating the outside of the reverberatory furnaces at the smelter, and they have also been used recently in other construction work, including a new refrigeration plant for the fishing industry.

Perlite deposits exist near Cerro de Santa María, north of Santa Rosalía, but they have not been exploited. Perlite is coming into increasing industrial use because of its property of great expansion upon the sudden application of heat, forming an artificial pumice having several advantages over natural pumice, especially as a lightweight aggregate in concrete. The perlite near Santa Rosalía has not yet been tested for its expansion properties, and hence its potential value as a lightweight aggregate is not known.

LIST OF FOSSIL-COLLECTING LOCALITIES

Fossil localities F1 to F10 are plotted on plate 39 of U. S. Geological Survey Bulletin 960–F; localities F11 to F28 are plotted on plate 1 of this report. The localities are also plotted on figure 3 of the paper by Wilson (1948). The fossil collections in the following list (table 33) are deposited in the U. S. National Museum.

TABLE 33.—*List of fossil-collecting localities*

Field no.	U. S. National Museum no.	Coordinates, in meters from San Francisco shaft		Formation, age, and description of locality
		N.-S.	E.-W.	
F1	15442	3950 N.	4350 W.	Boleo formation, early Pliocene. Brownish basal limestone overlying Comondú volcanics. Northern branch of Arroyo del Boleo, on San Pedro claim.
F2	15443	3310 N.	4560 W.	Boleo formation, early Pliocene. Brownish basal limestone overlying Comondú volcanics. Contains only unidentified poorly preserved casts and molds of pelecypods. North side of Arroyo del Boleo, on Neptuno claim.
F3	15444	4230 N.	4240 W.	Boleo formation, early Pliocene. Brownish sandstone overlying basal limestone. South side of Cañada de la Gloria, just east of Santa Gertrudis claim.

TABLE 33.—*List of fossil-collecting localities*—Continued

Field no.	U. S. National Museum no.	Coordinates, in meters from San Francisco shaft		Formation, age, and description of locality
		N.-S.	E.-W.	
F4	15445	4200 N.	4260 W.	Boleo formation, early Pliocene. Brownish basal limestone, below the sandstone of locality F3. Contains unidentified minute gastropods, abundant but poorly preserved. South side of Cañada de la Gloria, on Santa Gertrudis claim.
F5	15446	5150 N.	8220 W.	Boleo formation, early Pliocene. Brownish limestone overlying basal conglomerate. North side of Arroyo del Infierno, slope just below and to east of entries to Lucifer manganese mine, on Legendario claim.
F6	15447	5780 N.	6490 W.	Santa Rosalía formation, Pleistocene. Fossiliferous sandstone. South side of Arroyo del Infierno, east of Infierno claim, about midway up slope between road to San Ignacio and lava-covered mesa to south.
F7	15448	4640 N.	4770 W.	Gloria formation, (type locality), middle Pliocene. Fossiliferous gray sandstone, lying unconformably on Boleo formation. North side of Cañada de la Gloria, at west edge of Agua Azul claim, about midway up steep slope between road and top of mesa to north.
F8	15449	6360 N.	4420 W.	Gloria formation, middle Pliocene. Fossiliferous sandstone forming steep cliffs below the Infierno formation of locality F10 (see fig. 21; locality is in steep cliffs near middle of left side of photograph). South side of Arroyo del Infierno, along cliffs just above the prominent terrace followed by road to San Ignacio.
F9	15450	8410 N.	8370 W.	Santa Rosalía formation (type locality), Pleistocene. Thin fossiliferous sandstone and conglomerate unconformably overlying Gloria formation. South side of Arroyo de las Palmas, just below top of lava-covered mesa on Lucifer claim no. 6.
F10	15451	6260 N.	4410 W.	Infierno formation (type locality), late Pliocene. Highly fossiliferous sandstone unconformably overlying the Gloria formation of locality F8 (see fig. 21; bench on top of cliff just below top of mesa, slightly to left of center of photograph). South side of Arroyo del Infierno, bench above sandstone cliffs of the Gloria formation, below top of mesa.
F11	16053	2670 N.	2260 E.	Gloria formation, middle Pliocene. Fossiliferous sandstone unconformably overlying tuffs of the Boleo formation, just southwest of a small fault (see fig. 27; sandstone cliff to right of fault). South side of Arroyo del Purgatorio, near mouth, 80 m above sea level.
F12	16054	810 N.	1390 E.	Infierno formation, late Pliocene. Fossiliferous soft fine-grained sandstone overlying conglomerate of Gloria formation. South side of Arroyo del Purgatorio, south of San Roberto shaft, near top of ridge, 180 m above sea level.
F13	16055	1410 N.	650 E.	Gloria formation, middle Pliocene. Fossiliferous gray calcareous sandstone, rich in echinoids, unconformably overlying conglomerate no. 1 of the Boleo formation. Northeast side, near mouth, of Cañada Santiago, a northern branch of Arroyo del Purgatorio, 100 m above sea level.
F14	16056	1530 N.	370 E.	Infierno formation, late Pliocene. Thick fossiliferous sandstone overlying conglomerate of the Gloria formation. East side of Cañada Santiago, a northern branch of Arroyo del Purgatorio, just northeast of Santiago shaft and southwest of Santiago fault, 140 m above sea level.
F15	16057	1550 N.	700 E.	Gloria formation, middle Pliocene. Fossiliferous sandstone unconformably overlying tuff above ore bed no. 1 of the Boleo formation. North side of Arroyo del Purgatorio, in small side canyon 200 m northeast of Cañada Santiago, 110 m above sea level.
F16	16058	1660 N.	580 E.	Infierno formation, late Pliocene. Fossiliferous massive buff sandstone overlying conglomerate of the Gloria formation. On slope above locality F15, 150 m above sea level.
F17	16059	1870 N.	20 E.	Santa Rosalía formation, Pleistocene. Thin fossiliferous gray conglomeratic sandstone overlying conglomerate of the Infierno formation. Head of Cañada Santiago, a northern branch of Arroyo del Purgatorio, at top of mesa, 230 m above sea level.
F18	16060	1310 N.	670 E.	Gloria formation, middle Pliocene. Fossiliferous sandstone rich in echinoids, same as locality F13. Southwest side, near mouth, of Cañada Santiago, a northern branch of Arroyo del Purgatorio, 80 m above sea level.
F19	16061	1930 N.	700 E.	Gloria formation, middle Pliocene. Fossiliferous sandstone unconformably overlying tuff above ore bed no. 1 of Boleo formation. Side canyon on northwest side of Arroyo del Purgatorio, opposite San Roberto shaft, 110 m above sea level.
F20	16062	2600 N.	430 W.	Gloria formation (?). Conflicting evidence for age; middle or late Pliocene. Soft light-colored fossiliferous sandstone near top of a thick cliff-forming sandstone overlying tuff of Boleo formation, below a conglomerate. Southeast side of southern branch of Arroyo de la Soledad, southeast of San Enrique shaft, 165 m above sea level.
F21	16063	2650 N.	1840 W.	Infierno formation, late Pliocene. Thick fossiliferous sandstone, overlying thick conglomerate of Gloria formation and underlying thin conglomerate mapped as Santa Rosalía formation. Top of ridge on northwest side of Arroyo de la Soledad, west of Santa Rita shaft, 220 m above sea level.
F22	16064	3880 N.	3920 W.	Age doubtful. Classified in field as Boleo formation, early Pliocene, but fossils more closely related to Gloria formation, middle Pliocene. Dark-brown coarse-grained fossiliferous sandstone directly overlying basal limestone of the Boleo formation. Northern branch of Arroyo del Boleo, on Hugo claim, 170 m above sea level.
F23	16065	3430 N.	3100 W.	Boleo formation, early Pliocene. Brownish fossiliferous sandstone in tuff below ore bed no. 3 of Boleo formation. North side of Arroyo del Boleo, opposite Texcoco mine, 90 m above sea level.
F24	16066	2240 S.	5100 E.	Infierno formation, late Pliocene (?). Thick fossiliferous sandstone southwest of Santa Agueda fault zone. Northwest side of Arroyo de Santa Agueda, opposite point where road to Mulegé leaves arroyo, 20 m above sea level.
F25	16067	3160 S.	5170 E.	Infierno formation, late Pliocene. Thick fossiliferous buff sandstone. Southeast side of Arroyo de Santa Agueda, below road to Mulegé, 55 m above sea level.
F26	16068	2990 S.	5060 E.	Infierno formation, late Pliocene (?). Thick fossiliferous sandstone; same as at locality F25 but 25 m lower. Southeast side of Arroyo de Santa Agueda, below road to Mulegé, small knob on side of arroyo, 30 m above sea level.
F27	16069	2950 S.	6380 E.	Gloria formation (?), middle Pliocene. Thick fossiliferous sandstone. A single echinoid collected; not certain that it was in place. Along coast, south of Arroyo de Santa Agueda, on top of a small knob below mesa level, 110 m above sea level.
F28	16070	2700 S.	6240 E.	Infierno formation, late Pliocene. Thin gray calcareous fossiliferous sandstone, unconformably overlying sandstone of the Gloria formation. South side of Arroyo de Santa Agueda, near mouth, on narrow ridge just below top of mesa, 150 m above sea level.
SI	15616	---------	---------	Isidro formation, middle Miocene. Gray fossiliferous sandstone. Arroyo de San Ignacio, bottom of arroyo, approximately 5 km southwest of town of San Ignacio, which in turn is 77 km by road west of Santa Rosalía.

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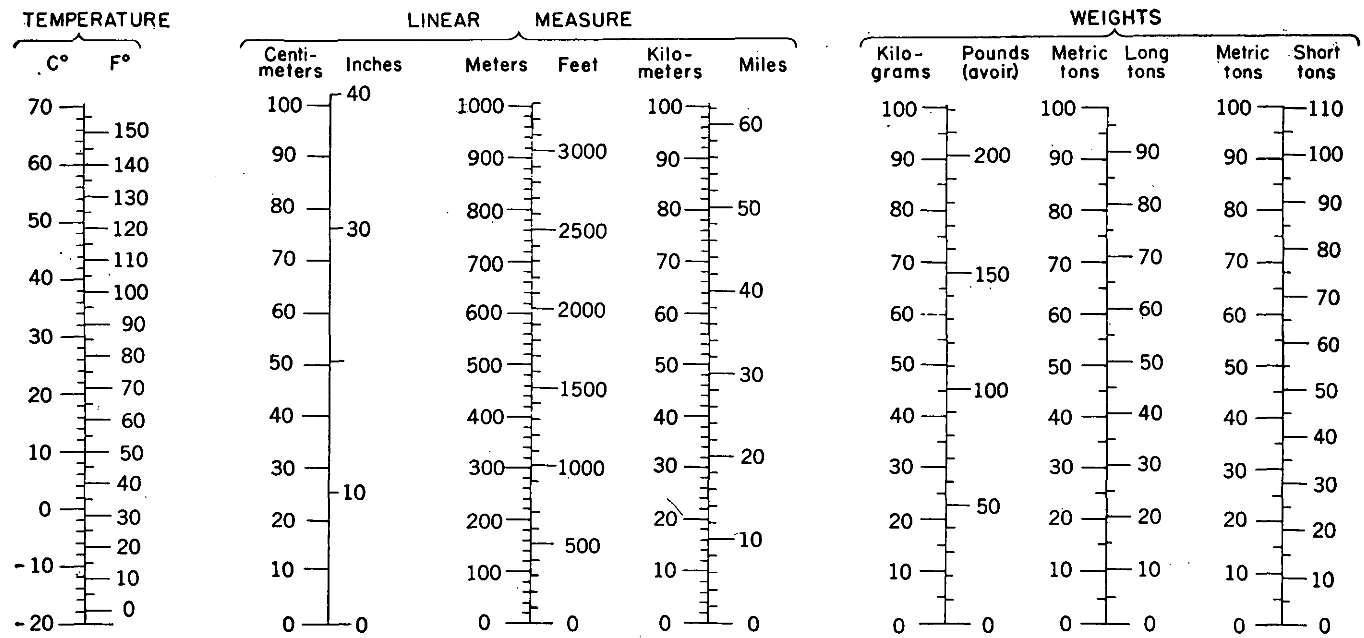
METRIC EQUIVALENTS



1 cm. = 0.3937 in.
1 in. = 2.5400 cm.

1 m. = 3.2808 ft.
1 ft. = 0.3048 m.

1 km. = 0.6214 mile
1 mile = 1.6093 km.

1 sq. m. (m2) = 1.20 sq. yd.
1 hectare (100x100m.) = 2.47 acres
1 cu. m. (m3) = 1.31 cu. yd.

1 kg. = 2.2046 lb.
1 lb. = 0.4536 kg.

1 metric ton = 0.9842 long ton
1 metric ton = 1.1023 short tons
1 metric ton = 2,205 lb.
1 long ton = 1.0161 metric ton
1 short ton = 0.9072 metric ton

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