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GEOLOGY AND MANGANESE DEPOSITS OF THE LUCIFER DISTRICT NORTHWEST OF SANTA ROSALIA BAJA CALIFORNIA, MEXICO

BY
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GEOLOGY AND MANGANESE DEPOSITS OF THE LUCIFER DISTRICT, NORTHWEST OF SANTA ROSALÍA, BAJA CALIFORNIA, MEXICO

By Ivan F. Wilson and Mario Veytia

ABSTRACT

The Lucifer manganese mine is northwest of the town of Santa Rosalía, midway along the Gulf coast of Baja California. Although its development did not begin until late in 1941, it has produced more manganese than any other mine in Mexico. Its total production to May 16, 1948, was 159,718 long tons of ore.

Topographically, the region is characterized by mesas and arroyos. The Lucifer mine lies on the north side of Arroyo del Infierno, 150 meters above the valley floor. Ore is lowered to the arroyo by a gravity tram and is transported by truck and rail to Santa Rosalía. Three shipping routes have been used: across the Gulf of California to Guaymas, Sonora; by steamer to San Pedro, Calif.; and more recently, through the Panama Canal to Atlantic coast ports.

The main mountain range in the region is formed of tilted and faulted volcanic and pyroclastic rocks of the Miocene Comondú formation. This formation is overlain unconformably by the Boleo formation, of lower Pliocene age, consisting of interbedded conglomerate and tuff. The Lucifer manganese deposits and the Boleo copper deposits are within the tuff. The Boleo formation is overlain by middle and upper Pliocene and Pleistocene marine sediments. The mesas are partly covered with lava flows of Pleistocene or Recent age. The main period of deformation was at the close of the Miocene, when the Comondú volcanics were tilted into a series of blocks cut by westward-dipping normal faults having displacements of 50 to 100 meters. The Pliocene and Pleistocene sediments have been gently tilted and faulted, but much of their inclination is due to initial dip and to differential compaction around hills and ridges of the Comondú volcanics. The Pliocene sediments were deposited on a surface of strong relief, and islands and headlands of the Comondú volcanics projected from the Pliocene sea.

The ore at the Lucifer mine forms a gently dipping tabular deposit enclosed in tuff. Its thickness ranges from 1 to 6 meters and averages 2½ meters. In May 1948 a series of intersecting drifts had blocked out ore over an area of 53,000 square meters; scattered outcrops are found as much as 410 meters north of the blocked-out area. The ore lies on a structural terrace trending toward the west-northwest, and it turns steeply upward and pinches out against a projecting ridge of Comondú volcanics in the southwestern part of the mine. As indicated by a map showing structure contours on the base of the ore body and by an isopach map showing the variations in the thickness of the ore, the thickest part of the ore body follows the middle of the structural terrace. The ore is overlain by a nearly flat fault, which may be premineral. The ore body is offset by small normal faults having a maximum displacement of 8 meters.

As the ore is mostly fine-grained and incoherent, it contains a large percentage of "fines." A plant has been installed to sinter the fines for metallurgical purposes. The ore consists of fine-grained cryptomelane and pyrolusite, and contains from 45 to 50 percent of manganese. The content is increased to 52 or 53 percent in the sintered ore. The soft fine-grained ore encloses lenses of a hard siliceous ore and of hematitic and limonitic jasper, but the over-all silica content averages less

than 5 percent. The pyrolusite ore is of chemical grade and is mined selectively.

Small manganese deposits are scattered over an area extending 4 kilometers north and 4½ kilometers southeast of the Lucifer mine, but all of them are thin, of low grade, and unpromising.

The deposits are believed to have been formed by hydrothermal solutions that rose along faults in the Comondú volcanics, spread laterally into the tuff beds of the Boleo formation, and partly replaced the tuff. There is evidence that the deposition of the ore was structurally controlled. These manganese deposits are thought to be closely related in origin to the Boleo copper deposits.

The total size of the Lucifer ore body is of the order of 300,000 tons, of which about half has already been mined, one quarter is expected to be mined in the next 2 or 3 years, and the remaining quarter will probably have to be left in the form of pillars.

INTRODUCTION

FIELD WORK

At the Lucifer mine, northwest of Santa Rosalía in Baja California, Mexico, is a newly discovered deposit of manganese ore. Although this deposit was not actively developed until late in 1941, it has proven to be the largest manganese deposit known in Mexico.

The present report is based upon a cooperative study of the Lucifer deposit and the surrounding area by the Geological Survey, United States Department of the Interior, and the Dirección General de Mines y Petróleo of the Secretaría de la Economía Nacional de México. This study forms a part of a series of geologic investigations in the American Republics, sponsored by the Interdepartmental Committee on Scientific and Cultural Cooperation, which is under the auspices of the United States Department of State.

Parker D. Trask first examined the Lucifer mine on behalf of the Geological Survey in the early part of 1943, and it was his recommendation that a detailed survey be made of the ore deposit and surrounding region. Ivan F. Wilson, of the United States Geological Survey, and Mario Veytia, of the Dirección General de Minas y Petróleo, were assigned to the project. Most of their field work was done in the period October 1943 to January 1944, but Wilson revisited the district at several later dates in 1944, 1945, 1946, and 1948 to bring the maps and data on the mine workings up to date. Most of the development of the mine was during this period, for in 1943 the mine workings had only about one-fourth the extent which they had in 1948. Altogether about 6 months of field work were spent in the district.

Geologic, structure-contour, and isopach maps of the Lucifer mine were constructed on a field scale of 1:500, using as a base a map of the mine workings furnished by the Lucifer company. By plane-table methods a topographic and geologic map, on a field scale of 1:2000, was made of an area 1,200 meters[1] long and 800 meters wide sur-

[1] The metric system of measurement is used throughout this report. A chart of metric equivalents is given at the end of the report.

rounding the Lucifer mine. A smaller-scale geologic map, covering an area of 80 square kilometers, was made on trimetrogon high-oblique aerial photographs, controlled by plane-table triangulation. A planimetric map on a compilation scale of 1:15,000 was converted from the photos by the sketchmaster method in the office of the Geological Survey in Washington, D. C. A geologic map of the Boleo copper district, which adjoins the Lucifer manganese district to the southeast, was made by Wilson and Victor S. Rocha in 1946. This will be published at a later date in a separate report on the Boleo district.

This report was written essentially in its present form in 1944, but the sections concerning history and production, mine workings, extent of ore and related topics have been brought up to date as of May 1948. The most important recent development in the district was an exploratory program of churn drilling carried out from December 1947 to June 1948, by means of which the main ore body of the Lucifer mine was completely delimited. The results of the drilling program have been incorporated in the present report, and the map of the drill holes shows the extent of the mine workings as of May 1948. As the other maps in this report had been finally drafted for publication, however, they show the extent of the mine workings only as of May 1946.

ACKNOWLEDGMENTS

Sr. Ing. P. Mahieux and Sr. Ing. F. L. García Quintanilla put the writers under great obligations by their kind hospitality and assistance during the course of the field work. All the officials of the Compagnie du Boléo at Santa Rosalía were most hospitable and helpful. The Instituto de Geología de México and its director, Sr. Ing. Teodoro Flores, extended full cooperation and provided office facilities in Mexico City. The Dirección General de Minas y Petróleo and its director, Sr. Ing. Germán García Lozano, were most cordial. The staffs of the Foreign Economic Administration and the American Embassy in Mexico City gave us valuable aid. Parker D. Trask gave helpful advice both before and during the investigation. C. A. Anderson kindly lent a copy of his manuscript on the geology of the Gulf of California. Discussions with James A. Noble concerning the geologic problems of the region were very stimulating. James S. Martin was very cooperative during the study of the exploratory drilling program.

Various members of the Geological Survey contributed to the study: Robert L. Smith and Clarence S. Ross examined a number of thin sections; M. K. Carron, R. E. Stevens, and Michael Fleischer made chemical analyses, and Fleischer also identified the ore minerals; J. M. Axelrod made X-ray examinations of some of the manganese minerals; K. J. Murata made a spectrographic analysis of the ore;

and H. E. Vokes identified the fossils collected. Kenneth Segerstrom took the aerial photographs which are reproduced in this report. The manuscript has benefited greatly by the helpful criticism of F. C. Calkins, J. V. N. Dorr 2d, Ward C. Smith, and F. W. Stead. Carl Fries, Jr., gave valuable aid in reviewing the maps. The work was under the general supervision of D. F. Hewett, J. V. N. Dorr 2d, and W. F. Foshag.

GEOGRAPHY

The Lucifer manganese deposit is 17 kilometers by road northwest of Santa Rosalía, which is about midway along the Gulf of California coast of the peninsula of Baja California, Mexico (fig. 15). Santa

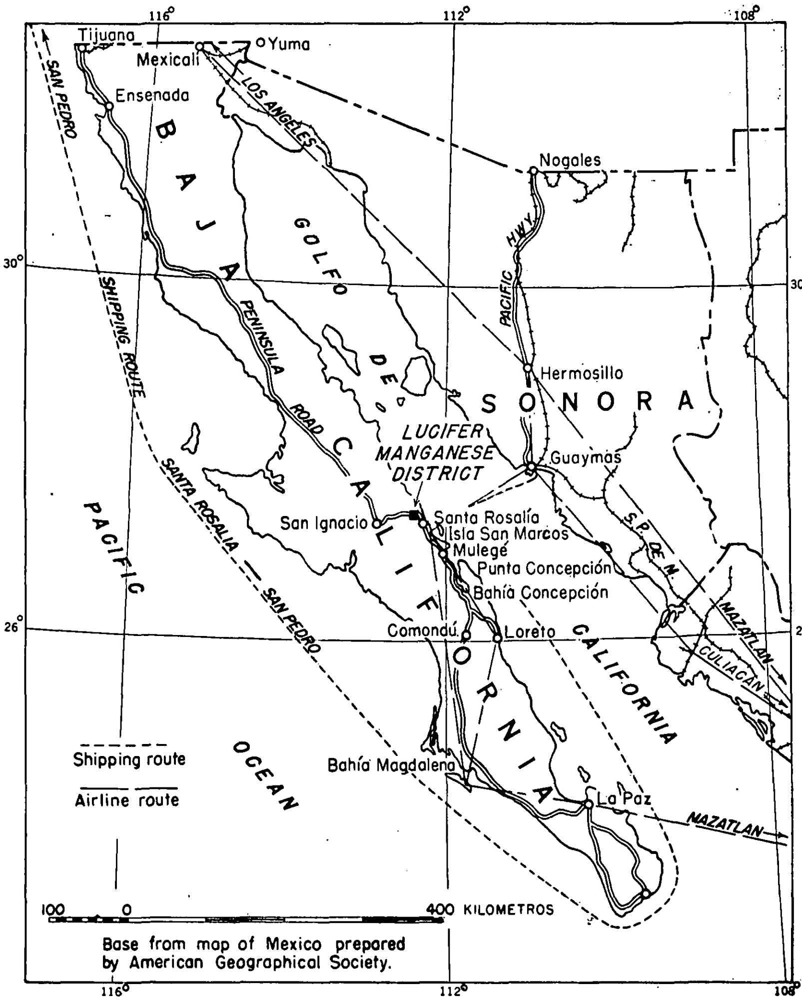


FIGURE 15.—Index map of Baja California, Mexico, showing location and accessibility of the Lucifer manganese district.

Rosalía may be reached by plane from Guaymas, Sonora, or from Mazatlán, Sinaloa; by small boats that cross the Gulf of California from Guaymas, which is reached by automobile, plane, or railroad from Nogales, Ariz.; by ships from San Pedro, Calif.; or by a very poor automobile road extending down the peninsula from Tijuana.

Three routes have been used in shipping ore to the United States. The first, across the Gulf to Guaymas by boat and thence by rail to Nogales, was used for only a short while. During most of World War II ore was shipped to San Pedro, Calif., using ships of the Compagnie du Boléo. Recently shipments have been made to Atlantic coast ports by way of the Panama Canal.

Santa Rosalía, a town of some 6,000 inhabitants, is headquarters for the Boleo copper mines, which have been operated by the French-owned Compagnie du Boléo since 1885. For most of its history the Boleo district has been the second or third largest copper producer in Mexico. The company has constructed an artificial harbor enclosed in a breakwater of furnace slag, a smelter to produce blister copper, and a narrow-gage railroad to some of the copper mines.

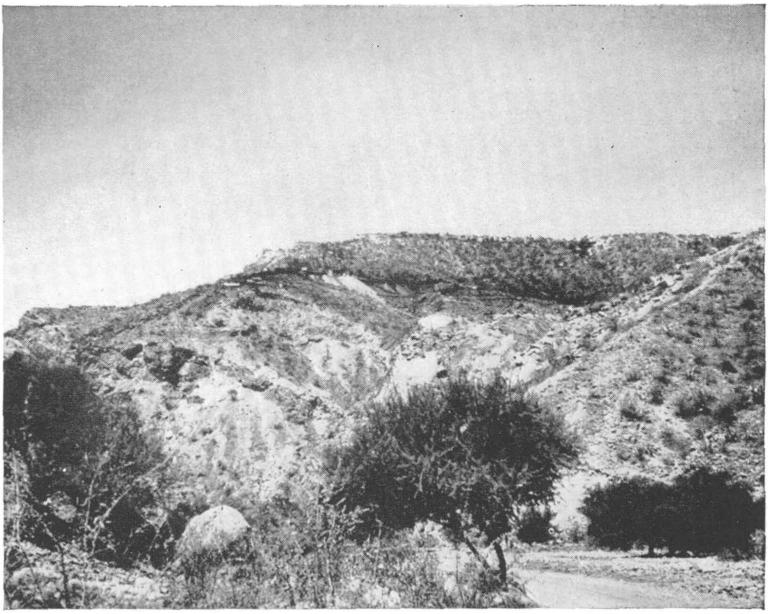
Topographically, the Santa Rosalía area consists of a series of mesas reaching altitudes of 300 to 400 meters, cut by arroyos that drain eastward into the Gulf of California. The mesas slope gradually eastward, ending at the gulf in cliffs bordered by narrow beaches. South of Santa Rosalía the mesas descend gradually to the San Bruno Plain, which is only a little above sea level. On the west the mesas are bordered by the Sierra de Santa Lucía, which is the main mountain range of the peninsula of Baja California in that latitude. The crest of this range lies 20 to 30 kilometers west of the gulf, and 1,500 to 1,600 meters higher. The Tres Vírgenes, three prominent volcanic cones which have erupted within historic times, rise above the mesa 35 kilometers northwest of Santa Rosalía. The highest of them has an altitude of 1,995 meters. Another prominent volcanic mountain, Cerro de Santa María, which is 1,348 meters high, lies 25 kilometers north of Santa Rosalía.

The Lucifer mine lies on the north side of Arroyo del Infierno, at an elevation of 280 to 300 meters above sea level or 150 meters above the valley floor. (See pl. 37.) It is about 8 kilometers inland from the gulf. The town of Lucifer, housing a hundred-odd mine workers and their families, is in the arroyo below the mine. The Santa Rosalía-San Ignacio road crosses Arroyo del Infierno 1½ kilometers east of the mine and proceeds along the top of the mesa 1 kilometer north of the mine. A branch road follows the arroyo to a point directly below the mine, and in 1946 a narrow road was constructed up the side of the arroyo to the main mine entry. Ore is lowered from the mine to the arroyo by a 3-rail gravity tram 350 meters long (pl. 38*A*); it is then trucked 10 kilometers to a railhead in Arroyo del Boleo and carried 7 kilometers by rail to the wharfs at Santa Rosalía.

Small manganese deposits are scattered at wide intervals over an area extending 4 kilometers northward to Arroyo de las Palmas, which

A. AERIAL VIEW OF LUCIFER MANGANESE MINE, LOOKING WESTWARD UP ARROYO DEL INFIERNO.

Black streak near center is outcrop of manganese ore. Town of Lucifer is in bottom of arroyo in lower center.



B. LUCIFER MINE, AS SEEN FROM BOTTOM OF ARROYO DEL INFIERNO, LOOKING WESTWARD.

is a northern branch of Arroyo del Infierno, and 4½ kilometers southeastward to Arroyo del Boleo and its branch Cañada de la Gloria. (See pl. 39.)

The manganese deposits occur in the geologic formation that contains the Boleo copper deposits. Certain beds in the formation are mainly manganiferous and others are mainly cupriferous, though in some places the manganese and copper deposits occur together. The manganese deposits are found mainly north of Arroyo del Boleo and the copper deposits mainly south of it, though there are small copper deposits in Arroyo del Infierno, east of the Lucifer mine, and low-grade manganiferous beds are found throughout the Boleo copper district. The copper deposits are scattered over an area that extends as far south as Arroyo de Santa Agueda, south of Santa Rosalía, the total area known to contain copper deposits being about 17 kilometers long from northwest to southeast and 1 to 4 kilometers wide.

The climate of the region is warm and extremely arid. The mean temperature of the coldest month is 15.8° C. (60.4° F.) and that of the warmest month 31.0° C. (87.8° F.) (México, Dirección General de Geografía, 1942). The annual rainfall is said to average 138.3 mm. (5½ inches), but it is extremely variable. Rain generally falls only in brief showers occurring three or four times a year, and some years are said to pass without any rain whatever. On the other hand, a few severe storms have caused great damage to habitations in the arroyos. The arroyos are generally dry except for a few small pools of water in rock basins. One such pool, in Arroyo del Infierno 1 kilometer west of the Lucifer mine, yields a supply of water barely sufficient for mining operations and for the domestic needs of the dwellers in the town of Lucifer. The water supply for Santa Rosalía comes partly from Santa Agueda, 12 kilometers to the west, and partly from the deep copper mines. The vegetation in the region consists mainly of cactus and other thorny plants, so that lumber and mining timber all must be imported.

HISTORY AND PRODUCTION

The Lucifer manganese deposit received no attention until the advent of World War II. The deposit is on the former concession of the Compagnie du Boléo, and about 30 years or more ago the company drove two tunnels into the ore body in search of copper ore; these tunnels, however, were soon abandoned. As the ore body has a prominent outcrop 2 to 5 meters thick, it is strange that no mention of it has been made in any of the reports dealing with the Boleo copper district, and it is especially strange that it attracted no attention during World War I, when there was considerable activity at the manganese deposits on Point Concepción, 80 kilmeters to the south.

The Lucifer mine and adjoining deposits are covered by 36 mining claims. These claims are in two groups, the Lucifer group and the Navidad group, and cover a total area of about 10 square kilometers. (See pl. 39.) The Lucifer mine was developed by the partnership of Mahieux y García Quintanilla, S. en N. C., which in 1946 was changed to the Compañía Minera "Lucifer," S. A. de C. V., the officers of which are Ing. F. L. García Quintanilla, president; Ing. Pierre Mahieux, vice president; and Ing. Victor Pierre Mussio, secretary.

Operations began in November 1941, and the first shipment of ore to the United States was made in January 1942. The mine's production in the ensuing 6 years far exceeded the total production of any other manganese mine in Mexico. The total production through May 16, 1948, is reported as 159,718 long tons, distributed as follows:

	Long tons		*Long tons*
1942	10, 412	1946	14, 289
1943	22, 806	1947	37, 185
1944	33, 447	1948 through May 16	21, 213
1945	20, 366		
		Total	159, 718

Some of the early shipments of ore were made to the Metals Reserve Co., but this company later rejected the ore because of the high percentage of "fines." Most of the ore produced until the middle of 1944 was shipped to the Kaiser Co., Iron and Steel Division, at Fontana, Calif. A sintering plant was installed at Santa Rosalía in 1945 in order to eliminate the difficulty of the "fines," and beginning in that year and continuing through 1946 the sintered ore was sold for metallurgical purposes to various consumers in the eastern United States. In 1945 and 1946, part of the ore was shipped for chemical purposes to the Tennessee Eastman Corp. During that epoch the ore was selectively mined and hand sorted into two classes, chemical grade (high in pyrolusite) and metallurgical grade, of which only the latter was sintered. The decline in production in 1945 and 1946 was due mostly to difficulties in marketing the ore. Since 1946 most of the ore has been shipped to the United States Steel Corp. As that buyer made no objection to the "fines" contained in the ore, the sintering plant was shut down because of its high cost of operation.

From December 1947 to June 1948 an exploratory churn-drilling program was carried out to determine the extent of the Lucifer ore body. The results of this program are summarized later in the report.

PREVIOUS GEOLOGIC INVESTIGATIONS

Reconnaissance studies have been made in several parts of Baja California, including the Santa Rosalía area. One of the earliest was made by Gabb (1868, pp. 630–642). Some brief papers on Baja California were published by Lindgren (1889–91). A later report by Darton (1921) shows 21 sections across the peninsula, including one in the latitude of Santa Rosalía. An extensive geographic summary has been given by Nelson (1921). The stratigraphy of the area around La Purísima and Comondú was studied by Heim (1922), and his account of this area has formed the basis for later stratigraphic work in other parts of the peninsula. The stratigraphy was also considered in some detail in an unsigned report on the results of a survey by the Marland Oil Co. of Mexico (1924). This report includes a geologic map of Baja California. Other reports on the oil-producing possibilities of the peninsula that include a description of the Santa Rosalía area have been made by Bustamente (1921), Pastor Giraud (1922), and Hisazumi (1930). A geologic map of Baja California and a general summary of the geology have been given by Flores (1931). The geology of the islands in the Gulf of California has been summarized by Anderson (1941).

Although a number of papers describe the Boleo copper district, not one of them refers to manganese except incidentally, as a constituent of the copper ore. Aside from papers dealing exclusively with some of the rare minerals, the district is described in early reports by Fuchs (1886a, 1886b), Fuchs and de Launay (1893), Krusch (1899), and Saladin (1892); the data from later studies are presented by Touwaide (1930), Peña (1931), and Locke (1935).

GEOLOGY

The mountain range of Baja California consists, in the latitude of Santa Rosalía, of tilted and faulted volcanic and pyroclastic rocks composing the Miocene Comondú formation. The peninsular divide, which lies east of the middle of the peninsula, is bordered on the east by a narrow belt of recently uplifted Pliocene and Pleistocene pyroclastics and sediments dipping gently eastward, and it is in these rocks that the Boleo copper deposits and the Lucifer manganese deposits occur. The Pliocene sediments were deposited on a surface of strong relief, and above them rise many hills of the underlying Comondú, which evidently once formed islands. The mesa that overlooks the Lucifer mine and extends northward from it is covered by lava flows erupted in Pleistocene or Recent time.

ROCK FORMATIONS

GENERAL SEQUENCE

The stratigraphic sequence in the Lucifer manganese district is as follows:

	Meters
Recent:	
Alluvium	0–5
Terrace and talus deposits	0–20
Unconformity.	
Pleistocene or Recent:	
Tres Vírgenes volcanics—latite flows, pumice, and welded tuff; olivine basalt flows, volcanic breccia, and cinder cones	0–30
Unconformity (angular).	
Pleistocene:	
Santa Rosalía formation—fossiliferous sandstone and conglomerate	5–15
Unconformity.	
Upper Pliocene:	
Infierno formation—fossiliferous sandstone	5–10
Unconformity.	
Middle Pliocene:	
Gloria formation—fossiliferous sandstone, gypsiferous silt, and clay	50–150
Unconformity (at least in part of area).	
Lower Pliocene:	
Boleo formation[1]—latitic to andesitic tuff, conglomerate, fossiliferous tuffaceous limestone, fossiliferous sandstone, and gypsum. Ores of manganese and copper occur in the tuff. In the Boleo district five copper-ore horizons have been distinguished, each in a tuff member underlain by conglomerate	100–250
Unconformity (angular).	
Miocene:	
Comondú volcanics—andesitic and basaltic flows, sills, tuff, breccia, agglomerate, volcanic conglomerate, and tuffaceous sandstone	500 ±
Unconformity.	
Age unknown:	
Quartz monzonite.	

QUARTZ MONZONITE

Three small outcrops of quartz monzonite occur in Arroyo de las Palmas. (See pl. 39, near intersection of coordinates 10,000 N. and 10,000 W.) The overlying rock is mostly tuff of the Comondú formation, but part of one outcrop is overlapped by tuffaceous limestone of the Boleo formation. Robert L. Smith, who studied the rock in thin

[1] See chapter on the Boleo formation for a section of the formation at the Lucifer mine.

section, describes it as consisting of quartz, orthoclase, andesine, biotite, and accessory magnetite and sphene. Some of the sphene has altered to leucoxene, but most of it is replaced by calcite.

Granitic rocks are widely exposed in both the northern and southern parts of the peninsula of Baja California, but in the latitude of Santa Rosalía they are buried for the most part under the Comondú volcanics. Their age is known to be pre-Tertiary but has not been determined more accurately. They have generally been regarded as pre-Cretaceous (Darton, 1921, p. 725; Marland Oil Co., 1924, vol. 18, p. 49), but evidence has been given that the granite in northwestern Baja California, near Ensenada, is Cretaceous (Böse and Wittich, 1913, pp. 347–351; Woodford and Harriss, 1938, p. 1328; Woodford, 1940, p. 256).

COMONDÚ VOLCANICS (MIOCENE)

The Comondú volcanics consist of a great thickness of volcanic and pyroclastic rocks, which form the main mountain range of the peninsula in the vicinity of Santa Rosalía and underlie the later sediments containing the ore deposits. The formation was named by Heim (1922, p. 542) for exposures near the town of Comondú (fig. 15). In the Lucifer district the formation is represented by interbedded flows, sills, tuff, breccia, agglomerate, volcanic conglomerate, and tuffaceous sandstone, of andesitic and basaltic composition. These rocks are of many colors, chiefly orange, pink, purple, and brown. The rocks are resistant and form rugged hills with jagged crests and steep slopes.

A specimen from one of the flows, studied in thin section by Robert L. Smith, was classified by him as a hornblende andesite. It contains resorbed phenocrysts of green hornblende and plagioclase in a groundmass of andesine, together with considerable magnetite. Another specimen, classified as basalt, shows an excellent flow structure and consists chiefly of labradorite laths and interstitial augite, but it also contains a few phenocrysts of labradorite, augite, altered biotite, and olivine replaced by iddingsite. A specimen of volcanic breccia was examined by Clarence S. Ross, who describes it as consisting of fragments of andesite enclosed in a fine-grained vesicular groundmass, which originally was partly glass but is similar in composition to the included fragments. The pyroclastic rocks consist mostly of fragments of volcanic rocks, but in a few places they contain much granitic debris. In the upper parts of Arroyo del Infierno and Arroyo de las Palmas volcanic conglomerate and tuffaceous sandstone are intercalated with the volcanic rocks.

Westward the volcanic series grades into sedimentary rocks, mainly sandstone and conglomerate, which form a part of the "mesa sandstone" of Gabb (1868, p. 633) and Darton (1921, pp. 741–742). This term, however, has also been applied to Cretaceous sandstone in Baja California (Willis, 1912, p. 644). At Comondú the formation consists of brownish sandstone and conglomerate, but in Cerro de la Giganta, according to Heim (1922, p. 543) the bulk of the formation is a basaltic volcanic breccia. The series underlies most of the area between Cerro de la Giganta and Santa Rosalía, being overlapped by later sediments near the coast. It makes up most of the Point Concepción peninsula, and also occurs on the neighboring islands in the Gulf of California (Anderson, 1941). It is evident from the eastward coarsening of the beds that the bulk of the formation was derived from the east, the present site of the Gulf of California. This deduction was made by Gabb (1868, p. 634) and Heim (1922, p. 543). The formation is apparently of terrestrial origin.

According to Heim (1922, p. 542) the Comondú overlies, in places with a distinct angular unconformity, the Isidro formation, which is regarded as lower Miocene (Hertlein and Jordan, 1927, pp. 609–618; Loel and Corey, 1932, p. 160; Marland Oil Co., 1924, vol. 17, p. 422). As the Comondú is overlain, in the Santa Rosalía district, with strong angular unconformity by the lower Pliocene Boleo formation, it appears to be limited in age to the middle and upper Miocene.

The Comondú volcanics underlie the minable deposits of manganese and copper near Santa Rosalía, but veinlets of manganese and copper minerals may be seen to cut the formation in many places, and the Gavilán manganese deposits at Point Concepción, 80 kilometers to the south, consist of veinlets of manganese oxide cutting basaltic members of the Comondú.

BOLEO FORMATION (LOWER PLIOCENE)

The Boleo formation, of lower Pliocene age, consists of interbedded latitic to andesitic tuff and conglomerate, fossiliferous tuffaceous limestone, fossiliferous sandstone, and gypsum. The Boleo copper deposits and the Lucifer manganese deposits occur in the tuff members of the formation (pl. 38*B*). In the Boleo copper district five ore horizons have been distinguished—numbered by the company engineers from 0 at the top to 4 at the base—each in a tuff layer underlain by conglomerate.

At the center of the Lucifer mine the ore body is underlain by 4 meters of tuff and 4 meters of conglomerate, but toward the west first the tuff and then the conglomerate wedge out against a projecting ridge of the underlying Comondú volcanics. A similar pinching-out of various members of the Boleo formation against hills and ridges of the Comondú rocks was noted at many places in the district. Some islands of the Comondú were never covered by the Pliocene seas. The strong unconformity between the Comondú and

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Boleo formations is marked in places by angular discordance as great as 35°.

The Boleo formation is here named for the Boleo copper district. It has hitherto been referred to as the Salada formation, which was named by Heim (1922, pp. 544–546) for Arroyo de la Salada, southeast of Magdalena Bay on the Pacific coast of Baja California. The geologists of the Marland Oil Co. (1924, vol. 18, p. 43) put all the marine Pliocene of Baja California into the Salada formation. Touwaide (1930, p. 120) and Locke (1935, p. 410) referred to the ore-bearing rocks in the Boleo district as the "Lower Salada" or "Ore Series." In the vicinity of Santa Rosalía, however, the Pliocene sediments may be divided lithologically and faunally into three formations, separated by unconformities and representing the lower, middle, and upper Pliocene respectively, and the relation of these formations to the type Salada is unknown. The type locality for the Salada is on the opposite side of the peninsula and probably was never directly connected with the embayment at Santa Rosalía. It therefore seems desirable to apply new names to these formations. The lower Pliocene formation is accordingly named the Boleo, the middle Pliocene formation the Gloria, and the upper Pliocene formation the Infierno. Dr. C. A. Anderson noted a similar three-fold division of the Pliocene beds on the islands in the Gulf of California, and in a paper prepared for publication has named the San Marcos, Carmen, and Marquer formations. It seems likely that these are equivalent at least faunally to the Boleo, Gloria, and Infierno formations, respectively. Anderson suggests [2] that his names be used for islands in the Gulf and the writer's names for the Santa Rosalía area. The Boleo, Gloria, and Infierno formations belong to the Salada group in the sense in which that term was used by the Marland Oil Co. (1924, vol. 18, p. 43), but their statement (1924, vol. 17, p. 422) that the Salada (Pliocene) is the marine equivalent of a part of the terrestrial Comondú formation can hardly be credited, in view of the strong angular unconformity between the Comondú and rocks containing lower Pliocene fossils. The same unconformity was found by Anderson (1941) on the islands in the Gulf of California.

The stratigraphic sequence in the Boleo formation in the immediate vicinity of the Lucifer mine is as follows:

Top	*Meters*
Tuffaceous conglomerate	20
Tuff, arenaceous. Fingers out into 2 or 3 thin layers. Small, thin deposits of manganese ore at this horizon, which is above the main Lucifer deposit	0–15

[2] Personal communication, May 17, 1947.

	Meters
Tuffaceous conglomerate	25–30
Tuff, arenaceous; silty to clayey at top (4 meters thick at center of mine). Main Lucifer manganese ore body occurs near top of this member	0–15
Conglomerate. Forms a lens in tuff member listed immediately above. Pebbles better rounded than in basal conglomerate or tuffaceous conglomerate. Probably marine	0–5
Tuffaceous limestone, fossiliferous, marine (average thickness 1 or 2 meters)	0–4
Basal conglomerate (4 meters thick at center of mine). Consists of angular, poorly sorted fragments; probably nonmarine	0–10

Tuff.—The tuffaceous members of the Boleo formation are sandy to silty and clayey and are well stratified. They generally have pinkish to purplish tints, but the main tuff horizon at the Lucifer deposits is buff to nearly white. It grades upward from sandy tuff below the manganese ore to highly sheared silty and clayey tuff overlying the ore.

A thin section of the tuff from below the ore at the Lucifer mine is described by Robert L. Smith as follows:

This rock is a stratified tuff with a composition near that of a latite or an andesite. It contains crystals and fragments of crystals of highly calcic andesine, green hornblende, basaltic hornblende, and biotite, fragments of glassy volcanic rocks with lathlike crystals of plagioclase, and much interstitial montmorillonite.

A specimen of tuff directly overlying the ore was described as a bentonitic tuff consisting largely of montmorillonite, which is mixed with fragments of glass, biotite, feldspar, and other tuffaceous material.

Conglomerate.—The conglomerate members of the Boleo formation are in general poorly sorted, containing pebbles that are mostly subangular, in a sandy tuffaceous matrix. The tuffaceous material has been largely altered to montmorillonite. The pebbles consist almost entirely of various kinds of Comondú volcanic rocks, mostly andesite and basalt, but a few pebbles of quartz monzonite were noted near the outcrop of that rock in Arroyo de las Palmas. The sand grains in the conglomerate have in many places a bluish to purplish coating, probably of opal, which gives a purplish cast to the rock as a whole. The conglomerates are fairly well bedded, and in many places they are strongly cross-bedded. In Arroyo del Infierno east of the Lucifer mine, most of the Boleo formation, which is there at least 150 meters thick, is conglomerate, but toward the east the conglomerate members grade into sandy and silty rocks. This gradation indicates that the source of the sediments lay farther to the west, the opposite condition from that found in the Comondú.

Below the Lucifer deposit the base of the Boleo formation consists of an especially coarse conglomerate, which is distinguished on the larger-scale geologic map (pl. 40) as the "basal conglomerate." It contains boulders up to 1 meter in diameter, and consists so largely of fragments that are almost sharply angular that it resembles a breccia. This basal conglomerate is found only in parts of the district, generally close to projecting hills or ridges of the Comondú volcanics. The basal conglomerate appears to be a nonmarine deposit, perhaps a fanglomerate.

At the north end of the Lucifer mine a lens of conglomerate, distinguished on the larger-scale map (pl. 40), is intercalated with the main ore-bearing tuff bed, lying slightly below the ore horizon. This conglomerate differs from the others in that the pebbles are mostly subrounded and are rather widely scattered through a sandy matrix.

Tuffaceous limestone.—A characteristic member of the Boleo formation is a hard, brown, fossiliferous layer of tuffaceous limestone. Three specimens of this rock were studied in thin section by Robert L. Smith, who describes one as a tuffaceous rock containing much secondary carbonate, and the other two as consisting chiefly of calcite, which has probably replaced tuff. The rock was called a dolomitic limestone by Touwaide (1930, p. 120) and Locke (1935, p. 410), but according to Srs. Mahieux and Quintanilla, analyses show that the content of magnesia is low. It contains numerous poorly preserved casts and molds of pelecypods and gastropods.

This layer is generally 1 or 2 meters thick, though in places it attains a thickness of 4 meters. Though widely distributed, it is far from continuous. It crops out on the slope east of the Lucifer mine, where it overlies the basal conglomerate and is overlain by sandy tuff, but it wedges out toward the west below the mine. It underlies some of the other small manganese deposits in the surrounding district, and in a few places, as on the San Pedro claim, the rock is itself manganiferous and the fossil casts have been replaced by manganese oxide. At many places in the district the tuffaceous limestone rests directly on the underlying Comondú, without any intervening basal conglomerate, and it overlaps one of the quartz monzonite outcrops in Arroyo de las Palmas. The tuffaceous limestone is regarded as the basal marine deposit of the Pliocene seas. Where the bedrock surface is irregular, the limestone may form a continuous mantle on the sloping side of an island of the Comondú rocks, the higher members of the Boleo formation wedging out against it. It is thus overlain in different places by tuff, conglomerate, or gypsum of the Boleo formation, or even by the Gloria formation.

The rock has been quarried to some extent for use as a flux in the Boleo copper smelter.

Fossiliferous sandstone.—In Cañada de la Gloria, near the eastern border of the Santa Gertrudis claim, marine fossils have been found in a small lens of brownish sandstone 5 meters thick that lies a short distance above the tuffaceous limestone. The fossils consist of a number of pectens and a few oysters, which are listed below under "Fossils and age." This sandstone was not identified elsewhere in the district.

Gypsum.—Massive beds of gypsum, some of them as much as 80 meters thick, occur here and there in the Boleo formation (pl. 41*A*). Their distribution is erratic and they wedge out abruptly. No gypsum is exposed near the Lucifer mine, but widely scattered outcrops of it occur elsewhere in the district, particularly in Arroyo de las Palmas and Arroyo del Boleo. The gypsum is massive to thin-bedded and of various colors: brown, white, red, purple, and green. It occurs at several horizons; some rests directly on the Comondú volcanics, some rests on the basal conglomerate of the Boleo formation, and some is intercalated with tuff. In one part of Arroyo de las Palmas there are two layers of gypsum separated by conglomerate; the upper layer wedges out between layers of tuff. (See pl. 39, coordinates 8000 N. and 6500 W.) Gypsum underlies the small manganese deposits at Las Palmas, north of the Lucifer mine, where in one place a 1-meter layer of manganese ore cuts across from tuff into the underlying gypsum for a distance of several meters. The gypsum exhibits a number of wrinkles and folds, particularly of a domelike nature, which are not shared by the surrounding rocks.

Only a little gypsum has been mined in this area for use in the copper smelter at Santa Rosalía, but similar though somewhat purer deposits on nearby San Marcos Island have been mined for several years and the gypsum has been exported to the United States by the Cía. Occidental Mexicana, S. A.

The origin of the gypsum is uncertain; it may have been formed by evaporation in partly enclosed bodies of water, or, as suggested by Touwaide (1930, p. 119), by precipitation from hydrothermal submarine springs.

Fossils and age.—The tuffaceous limestone contains, aside from a cerithiid and some pelecypods and minute gastropods that have not been identified, a new species of *Laevicardium*, described by H. E. Vokes as follows:[3]

> The *Laevicardium* is quite unlike any described species from the west coast fauna, the shell being more quadrate in outline, the radial ribbing heavier, and the smooth posterior area wider and more sulcate. In certain respects it reminds one of the east-coast species *L. serratum* (Linné), but it clearly does not belong to that species.

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[3] From locality F1, San Pedro claim, and locality F5, Legendario claim. Fossil localities are indicated on plate 39

The fossiliferous sandstone in Cañada de la Gloria, at locality F3, near the east border of the Santa Gertrudis claim, contains the following species, identified by Vokes:

Species	*Known range*
Ostrea vespertina Conrad	Lower-upper Pliocene.
Pecten (*Euvola*) *keepi* Arnold	Lower Pliocene.
Aequipecten abietis (Jordan and Hertlein)	Lower-upper Pliocene.
Pecten (*Pecten*) *beali* Hertlein	With lower Pliocene species at type locality.

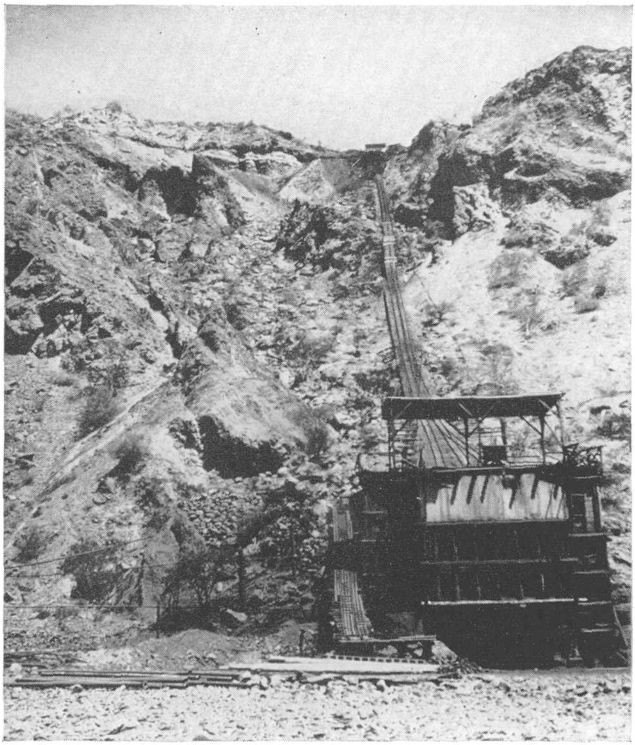
Vokes makes this general comment: "The fauna seems to be of lower Pliocene age, and to be contemporaneous with the Imperial fauna of southern California."

Origin of the Boleo formation.—The bulk of the Boleo formation is probably marine, judging from the presence of definitely marine fossils and from the fact that individual beds are continuous over wide areas. There may, however, be an interfingering of nonmarine beds, particularly toward the west, in which direction the conglomerates thicken. The bulk of the conglomerates and tuffs have yielded no fossils except fragments of petrified wood, which have been reported by Sr. P. Mahieux. The coarse basal conglomerate exposed below the Lucifer mine is of local distribution, being generally found along projecting ridges of Comondú rocks, and it is interpreted as a nonmarine deposit, probably a fanglomerate. The first deposit laid down by the encroaching Pliocene sea is believed to have been the fossiliferous tuffaceous limestone. Repeated explosive volcanic eruptions are indicated by the successive tuff deposits, which were probably laid down in shallow water.

GLORIA FORMATION (MIDDLE PLIOCENE)

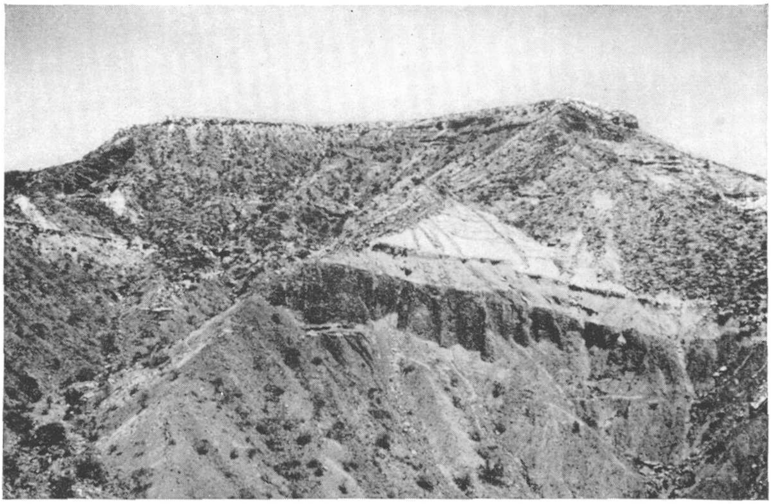
Directly overlying the Boleo formation are gypsiferous silts and clays, white to buff or yellow in color, which grade upward into yellow to brown fossiliferous sandstone containing abundant pectens and oysters. These rocks constitute the Gloria formation, named for Cañada de la Gloria. The silts and clays are soft and form a badlands topography, but the sandstones are more resistant and form cliffs along the edges of the mesas. Occasional conglomeratic layers are found, composed of pebbles of Comondú volcanics, some of which may have been reworked from conglomerates of the Boleo formation.

The Gloria formation is not exposed at the Lucifer mine. Its nearest outcrops are about 2 kilometers to the east, in Arroyo del Infierno; from there it rapidly thickens eastward toward the gulf. The shore line at the time of its deposition was probably not far from the Lucifer mine. In Cañada de la Gloria there is a distinct unconformity at the base of the fossiliferous sandstone, which cuts across



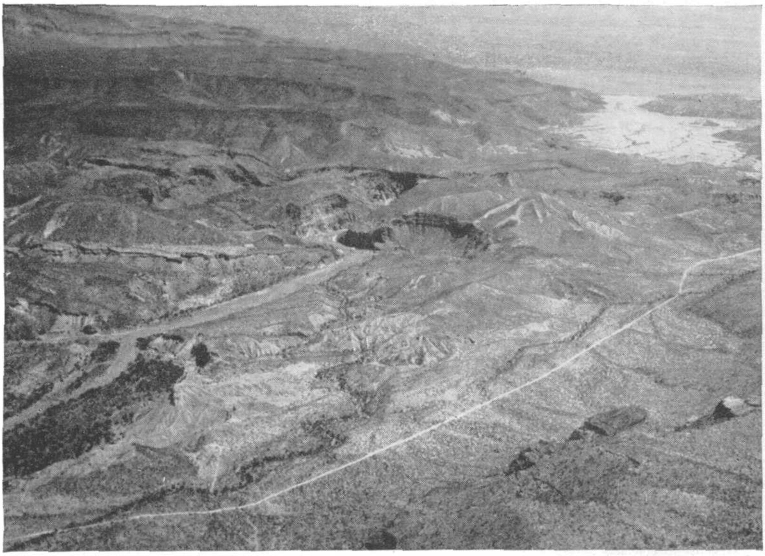
A. GRAVITY TRAMWAY AT LUCIFER MINE.

Outcrop of manganese ore may be seen near top of cliff, near tramway. Volcanic rocks in foreground belong to the Miocene Comondú formation.



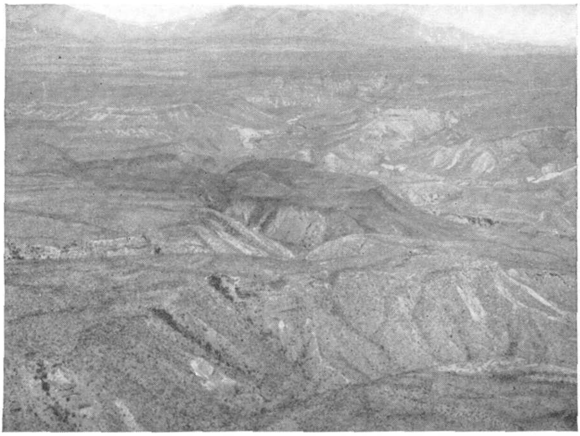
B. SEDIMENTS OF BOLEO FORMATION EXPOSED ON NORTH SIDE OF ARROYO DEL INFIERNO, EAST OF LUCIFER MINE.

Prominent dark-colored cliff in center is formed of conglomerate. A thin tuff layer is intercalated in the conglomerate, below the cliff; and a thin manganese deposit, in which some small openings have been excavated, may be seen in the tuff slightly below center. The moderately dark-colored layer just above the conglomerate is tuff; the lighter-colored beds above this are sandstones and siltstones of the Gloria formation. Lava caps the mesa.



A. AERIAL VIEW EASTWARD, TOWARD MOUTH OF ARROYO DEL INFIERNO.

Prominent cliffs dissected by arroyo in upper central part of photo are formed of gypsum of the Boleo formation. Badlands in foreground formed of the Gloria formation. Dark-colored mesas in upper left are covered by basalt. Gulf of California may be seen at upper right.



B. AERIAL VIEW NORTHWEST TOWARD HEAD OF ARROYO DE LAS PALMAS.

Dark-colored areas in center and upper right are formed of basalt, of the Tres Vírgenes volcanics. Light-colored areas on the mesa are formed of latite. Terraces along sides of arroyo may be seen.

tuff and conglomerate layers of the Boleo formation. In Arroyo del Infierno, however, there is no visible unconformity between the Boleo formation and the overlying silt and clay, and none between the silt and clay and the fossiliferous sandstone. Where the silt rests directly on the tuff the contact is not well marked, being distinguished mainly by a difference in color; the tuff is pinkish and the silts and clays white to buff or yellowish green. In many parts of plate 39 the mapping of the Boleo-Gloria contact is only approximate.

A fossil collection from locality F7, on the western border of the Agua Azul claim, north of Cañada de la Gloria, is listed by H. E. Vokes as follows:

Species	*Known range*
Ostrea megodon Hanley	Lower and middle Pliocene; Recent.
Ostrea vespertina Conrad	Lower-upper Pliocene.
Anomia sp. indet.	
Aequipecten n. sp. Durham manuscript (A)	Middle Pliocene.
Aequipecten aff. n. sp. Durham manuscript (B).	Middle Pliocene.
Aequipecten n. sp.	
Patinopecten bakeri (Hanna and Hertlein) n. subsp. Durham manuscript.	Middle Pliocene.
Patinopecten n. sp.	
Turritella aff. *T. gonostoma* Valenciennes	Lower Pliocene, Pleistocene-Recent.
Balanus sp.	

Vokes adds:

> The new species described by Durham are clearly recognizable in the present fauna, and there is no doubt that it is of middle Pliocene age, in terms of Durham's age assignments.

The following forms were identified in a collection from locality F8, on the south side of Arroyo del Infierno:

Species	*Known range*
Ostrea megodon Hanley	Lower and Middle Pliocene; Recent.
Ostrea cf. *O. angelica* Rochebrune.	
Aequipecten abietis (Jordan and Hertlein)	Lower-upper Pliocene.
Patinopecten bakeri var. (Hanna and Hertlein).	
Patinopecten cf. *P. stearnsii* (Dall)	(*P. stearnsii* is middle Pliocene).

Vokes regards this fauna as probably middle Pliocene.

No manganese or copper deposits are known to occur in the Gloria formation or in any of the overlying formations.

INFIERNO FORMATION (UPPER PLIOCENE)

On the south side of Arroyo del Infierno the fossiliferous sandstone at the top of the Gloria formation is unconformably overlain by another sandstone, here named the Infierno formation, which is somewhat softer, finer-grained, and even more abundantly fossiliferous. The type locality is at fossil locality F10 (pl. 39, coordinates 6300 N. and 4400 W.). At one place the unconformity is marked by an angular discordance of 5°, but it cannot be traced far along the strike. A similar unconformity was observed on the south side of Arroyo de las Palmas, but there the rocks were not definitely identified by faunal evidence. Elsewhere the Gloria-Infierno contact is so obscure that it could not be located accurately without collecting many fossils, which there was not time to do in the course of the present study. The same is true of the contact between the Infierno and the overlying Santa Rosalía formation, and on part of the small-scale geologic map (pl. 39) these two formations are shown as "undifferentiated upper Pliocene and Pleistocene beds." The Infierno formation is cut out by an unconformity at the base of the Santa Rosalía formation both west and south of the type locality.

H. E. Vokes has identified the following forms from locality F10, directly above the unconformable contact with the underlying Gloria formation:

Species	*Known range*
Ostrea fischeri Dall	Lower Pliocene-Recent.
Aequipecten abietis (Jordan and Hertlein)	Lower-upper Pliocene.
Patinopecten n. sp. (described in Durham manuscript).	Upper Pliocene.
"*Pecten*" sp.	
Crucibulum sp. cf. *C. spinosum* (Sowerby).	

Vokes regards this fauna as upper Pliocene.

SANTA ROSALÍA FORMATION (PLEISTOCENE)

The highest marine sediments, which are probably of Pleistocene age, consist mainly of fossiliferous sandstone and coarse-grained conglomerate. They include some beds so highly fossiliferous that they might be called coquina. These sediments are named the Santa Rosalía formation, for the town of Santa Rosalía, but the type locality is at fossil locality F9, on the south side of Arroyo de las Palmas, just below the top of the mesa, on Lucifer claim 6. An unconformity marked by slight angular discordance may be noted in places at the base of the Santa Rosalía formation, which overlies different rocks in different places. At locality F6, on the south side of Arroyo del Infierno, the beds descend from near the top of the mesa for a considerable distance down the slope of the arroyo, having apparently been deposited in an embayment cut into the Boleo formation. The base of the formation was not located with certainty in all parts of the area, and further collecting of fossils would be necessary to locate its boundaries precisely.

The beds at locality F9 contain, in addition to a number of microscopic gastropods which have not been studied, the following forms identified by H. E. Vokes:

Species	*Known range*
Anadara (Larkinia) multicostata (Sowerby)	Upper Pliocene-Recent.
Aequipecten sp.	
Americardia biangulatum (Sowerby)	Middle Pliocene-Recent.
Divaricella eburnea (Reeve)	Upper Pliocene-Recent.
Dosinia (Dosinidia) n. sp.	
Chione succincta (Valenciennes)	Pliocene-Recent.
Chione sp. aff. *C. kellettii* (Hinds).	
Megapitaria squalida (Sowerby) (immature specimen).	
Megapitaria aurantiacus (Sowerby) n. subsp.	
Pitar n. sp.	
Oliva cf. *O. venulata* Lamarck.	
Olivella n. sp.?	
Paramentaria coniformis (Sowerby).	
Cerithium uncinatum Gmelin.	
Nassarius sp. (immature specimen).	
Terebra variegata Gray.	
Crepidula sp. (fragments).	
Bullaria sp. (fragments).	
Balanus sp.	

In Vokes' opinion the traces of color patterns preserved in a number of the specimens, together with the known range of the few forms previously reported, which have been listed by Durham, suggest a Pleistocene age for the fauna. He remarks that the unusually large number of new species (or subspecies) must be attributed to some unusual ecologic conditions.

Fossils from locality F6 on the south side of Arroyo del Infierno were identified as follows:

Species	*Known range*
Ostrea cummingiana Dunker	Uppermost Pliocene-Recent.
Ostrea fischeri Dall	Lower Pliocene-Recent.
Aequipecten circularis (Sowerby)	Uppermost Pliocene-Recent.
Indeterminate echinoid fragments.	

Vokes adds that the fauna is of uppermost Pliocene or of Pleistocene age, and that dim remnants of color patterns preserved on some of the specimens of *A. circularis* favor an assignment to the Pleistocene.

TRES VÍRGENES VOLCANICS (PLEISTOCENE OR RECENT)

Most of the mesa extending north and west of Arroyo del Infierno is covered with volcanic rocks, which consists of latite flows, pumice and welded tuff, later olivine basalt flows, volcanic breccia, and cinder cones. These rocks are named the Tres Vírgenes volcanics, after the three volcanic cones to the northwest, which probably formed the main center of eruption. Another center was around Cerro de Santa María to the north, and there were subsidiary centers within the mapped area surrounding the Lucifer deposit. The lava did not completely cover the mesas, for several ridges of the underlying rocks project above the flows. The volcanic rocks attain their greatest thickness in former small valleys in the mesas. South of Arroyo del Infierno the lava covered only small areas.

In many places two separate flows of latite may be observed, each with a thin layer of welded tuff at the base. In a few places there is a thin layer of gravel between the two flows. The lower flow is less extensive than the upper and is generally found only in former valleys in the mesa. The welded tuff is black and glassy, resembling obsidian in its field appearance, but a thin-section studied by Robert L. Smith is described by him as follows: "This rock contains phenocrysts of oligoclase and augite in a groundmass of glass. The glass has formed by refusion of tuff fragments." In places the welded tuff is overlain by a thick layer of pumice, a specimen of which is described by Smith as follows:

> This specimen is a pumiceous-textured rock which contains phenocrysts of oligoclase and some augite in a groundmass of feldspar and devitrified glass. It contains what appears to be alkalic feldspar and considerable tridymite as late-phase constituents. Numerous inclusions of tuffaceous material are also present.

A specimen from one of the flows is classified by Smith as a porphyritic tridymite latite, and is described as containing phenocrysts of hypersthene and oligoclase in a groundmass consisting mainly of alkalic feldspar, accompanied by considerable tridymite.

Olivine basalt flows, younger than the latite, are exposed on the sides of Arroyo de las Palmas (pl. 41*B*). A specimen studied in thin section is described by Smith as containing phenocrysts of labradorite, olivine, hypersthene, and augite in a groundmass of labradorite. Another contains a few large phenocrysts of olivine in a groundmass of labradorite laths, augite, and some second-generation olivine; this specimen shows a well-developed flow structure.

Arroyo de las Palmas has cut through one side of a volcanic center, which is designated as the Las Palmas volcano on the accompanying map (pl. 39, coordinates 9,000 N. and 9,000 W.). The lowest volcanic rock here exposed is a breccia, which is overlain by a thick accumulation of olivine basalt, scoriaceous at the top. Some of the basalt is intruded into the older latite. A basaltic cinder cone rests on top of the basalt flows. Two prominent red basaltic cinder cones lie north of Arroyo de las Palmas (pl. 39, coordinates 11,000 N. and 5,000 W.). In the latite flows south of Arroyo de las Palmas there is a large crater, surrounded by an area covered with basaltic cinders and bombs (pl. 39, coordinates 8,000 N. and 10,000 W.). A few pieces of manganese oxides were blown out from this crater.

As the Tres Vírgenes volcanics overlie Pleistocene sediments, they must be either Pleistocene or Recent. Some of the basaltic flows around the Tres Vírgenes were probably erupted during historic times; fumaroles are still active near the bases of the cones. Grewingk (1848, pp. 143–144) says that the volcanoes erupted in 1746, and Nelson (1921, p. 60) gives the same date for the last eruption, but according to Russell (1897, p. 190) an eruption occurred in 1857. None of these authors gives the original source of his information.

TERRACE AND TALUS DEPOSITS (RECENT)

Terrace and talus deposits line the sides of the arroyos, the underlying geology being obscured in many places by accumulations of gravel 1 to 20 meters thick. Some of the older terrace deposits in Arroyo de las Palmas consist of well-cemented conglomerate. Most of the deposits, however, consist of unconsolidated gravel, which overlies the ore at the main Lucifer mine. Most of these deposits were evidently formed during an earlier cycle of erosion, for they are now being dissected by the arroyos and side canyons. Three or four different terrace levels may be distinguished in many places.

ALLUVIUM (RECENT)

Recent alluvium, consisting of poorly sorted boulders, gravel, sand, and silt, is limited mainly to the bottoms of the arroyos. On top of the mesas are a few dry-lake beds containing thin deposits of silt and clay.

STRUCTURE

The effects of two main periods of deformation can be distinguished in the region. The earlier deformation caused steep tilting and normal faulting of the Comondú rocks before the deposition of the Boleo formation, and it may thus be dated as late Miocene. In the later period of deformation, the Pliocene sediments were subjected to gentler tilting and to further normal faulting. Most of this deformation occurred during the late Pliocene or Pleistocene, before the eruption of the Tres Vírgenes volcanics. The volcanic rocks are cut, however, by a few faults, which indicates a renewal or continuance of faulting in late Pleistocene or Recent time. Slight unconformities at the top of the lower Pliocene, of the middle Pliocene, and particularly of the upper Pliocene beds give evidence of at least three stages of gentle warping and perhaps tilting.

The Comondú volcanics in the vicinity of Arroyo del Infierno have been tilted to the east at angles ranging from 20° to 45°, and have been offset by a series of "compensating" normal faults, downthrown on the west, having displacements of 50 to 100 meters. (See west part of section, pl. 39.) Most of the faults strike northwest and dip 40° to 50° SW. At the head of Arroyo del Infierno and farther west the Comondú volcanics dip more gently (see extreme west end of section, pl. 39), as they also do in the western part of Arroyo de las Palmas; and Darton's (1921, p. 723, sec. 11) cross sections indicate a gentle westerly dip between the peninsular divide and the Pacific coast. The zone of strong tilting and faulting thus appears to be limited to a narrow belt along the Gulf coast.

The gentle dips of the later sediments are in part initial dips, reflecting the irregular underlying surface developed in the Comondú rocks. Superposed upon these initial dips, however, are the effects of tilting and faulting. The general dip of the younger sediments is 5° to 10° E., toward the Gulf of California, but in some places, near buried hills or irregular projections of the underlying Comondú the sediments dip in various directions at angles as high as 30°. The dips particularly of the higher beds have probably been accentuated by differential compaction. The tuffaceous limestone member of the Boleo formation, usually the basal bed on these buried hills, shows the steepest dips.

In places the Pliocene sediments wedge out abruptly against cliffs of the Comondú. The steep east side of the northernmost outcrop of quartz monzonite in Arroyo de las Palmas is overlapped by the tuffaceous limestone generally present near the base of the Boleo formation. The limestone cuts across the contact between quartz monzonite and the Comondú, which here has a westerly dip. At the time of the submergence recorded by the fossils in the limestone, the shore line appears to have been irregular and of strong relief, showing headlands, promontories, and islands; it probably had the same bold character as the present shore line of Concepción Bay, 80 kilometers south of Santa Rosalía. A similar irregular surface below Pliocene sediments was found by Anderson (1941) on the islands of the Gulf of California.

The Boleo formation is cut by a few normal faults that dip westward like those in the Comondú but have less displacement. One with a displacement of 15 to 20 meters is visible in the side canyon just east of the Lucifer mine. (See pl. 40, sec. A–A′.) Most of the faults, however, that cut the Pliocene sediments in the vicinity of the Lucifer mine dip eastward, and their downthrow, which is to the east, ranges from less than 1 meter to about 20 meters. In the Lucifer mine the ore zone is cut by a few such faults, the largest having a displacement of 8 meters and another a displacement of 4 meters. The ore is also cut by a westward dipping normal fault with a displacement of 6 meters. A nearly flat fault above the ore can be seen at many places in the Lucifer mine; in some places it limits the ore at the top, though elsewhere it lies a short distance above the ore. This flat fault and the faults offsetting the ore body are discussed in more detail in the section on structure of the Lucifer deposit.

Most of the faults cutting the Pliocene sediments are older than the Tres Vírgenes volcanics, but in two or three places the lava is offset 2 to 5 meters by small faults.

MANGANESE DEPOSITS

GENERAL FEATURES

The Lucifer deposit is a gently dipping tabular body of high-grade manganese oxide ore enclosed in tuff. The main ore body is 1 to 6 meters in thickness, averaging 2½ meters; in May 1948 it had been blocked out by a series of intersecting drifts over an area of 53,000 square meters. The ore is mostly fine-grained and incoherent, and gives rise to a large percentage of "fines." It consists chiefly of fine-grained cryptomelane and pyrolusite. Its average manganese content is between 45 and 50 percent. Its silica content averages less than 5 percent, but within the soft fine-grained ore there are lenses of a hard siliceous ore or "hueso," and occasional lenses of hematitic and limonitic jasper. Some of the ore is of chemical grade, and occurs in such a way that it can be mined selectively. The ore body's axis of maximum thickness extends toward the west-northwest along a structural terrace. Outcrops of thinner and poorer ore continue 410 meters north-northwest of the northernmost part of the area of blocked-out ore (pl. 42). The ore is believed to have been deposited by hydrothermal solutions rising along faults and spreading out along tuff beds. Other manganese deposits are scattered over an area extending 4 kilometers north and 4½ kilometers southeast of the Lucifer mine, but all of them are small and of lower grade than the Lucifer.

OCCURRENCE

The ore lies near the top of a bed of tuff intercalated in conglomerate of the Boleo formation. The ore zone roughly follows the bedding of the tuff, but locally it cuts across the bedding. In the outcrop at the southeast end of the Lucifer mine, the ore is underlain by 4 meters of tuff and that in turn by 4 meters of conglomerate, which rests on the underlying Comondú volcanics (pl. 43). Toward the west the tuff pinches out and the ore rests directly on conglomerate. Within the mine the conglomerate likewise wedges out against a projecting ridge of the Comondú volcanics, so that in the southwestern part of the mine the ore rests directly on agglomerate and vesicular volcanic rocks of the Comondú. A short distance farther south the ore pinches out against the Comondú.

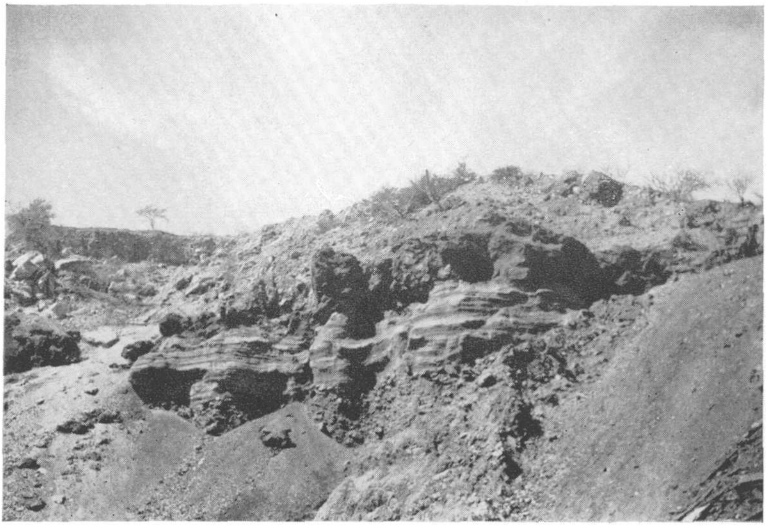
The boundaries of the ore are sharply defined in many places, but in some places, particularly at the base, they are gradational. In places the ore grades down into a zone of tuff containing only stringers and irregular spots and pockets of manganese oxide. Tuffaceous layers or thin lenses that may be traced for several meters are intercalated with the ore. In the western part of the mine, where the ore rests directly on the basal conglomerate, some manganese oxide extends down and surrounds the pebbles of the conglomerate. Manganese oxide also extends down into the agglomerate of the Comondú where the ore body rests on that rock. In a ventilation tunnel through the Comondú volcanics at the south end of the mine (pl. 44, southeast of intersection of coordinates 5,000 N. and 8,400 W.), veinlets of manganese oxide penetrate the agglomerate. Patches and veinlets of manganese oxide also extend into the overlying conglomerate in other parts of the mine. In places there appears to have been selective replacement of certain constituents of the conglomerates. In many of the smaller deposits surrounding the Lucifer mine the ore is not a solid body but an irregular network of stringers, patches, and pockets of manganese oxide in tuff.

In the surrounding area, veinlets of manganese oxide, accompanied by jasper and by copper minerals, cut the tuff and conglomerate members of the Boleo formation and also the underlying Comondú volcanics. Many of these veinlets extend along faults: the fault in the side canyon east of the Lucifer mine is followed by a series of such veinlets, and a number of others were found along the faults mapped in Arroyo del Infierno west of the mine. Although most of the veinlets are only 1 to 10 centimeters in thickness, there is a veinlike mass 1 meter thick of jasper, manganese oxide, and copper minerals in the Comondú volcanics near the head of Arroyo del Boleo (pl. 39, coordinates 3400 N. and 5400 W.).

STRUCTURE OF THE LUCIFER DEPOSIT

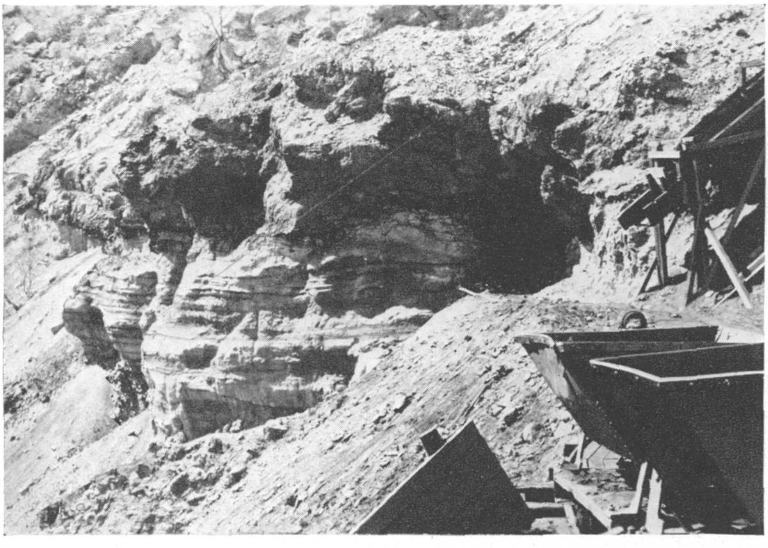
STRUCTURE CONTOURS

The thickest part of the ore body extends along a structural terrace that dips 5° to 10° NE. The beds turn sharply upward to dips as high as 45° at the southwest, and turn steeply downward to the northeast. A structure contour map (pl. 45) has been constructed with contours drawn along the base of the ore bed at intervals of 2 meters, and an isometric block diagram (pl. 46), drawn by means of elevated structure contours, shows the relation between structure and thickness of ore.



A. OUTCROP AT SOUTH END OF LUCIFER MINE.

From top to bottom are exposed terrace gravels, the prominent black outcrop of manganese ore, well-stratified tuff, basal conglomerate, and Comondú volcanic rocks, which form the small ridge in foreground slightly to right of center.



B. MINE ENTRY AT SOUTHEAST END OF LUCIFER MINE.

Shows prominent outcrop of manganese ore underlain by thin light-colored layer of sheared clayey tuff. Light-colored cliff below ore is 4-meter layer of well-stratified sandy tuff, underlain by basal conglomerate.

A. OPEN-CUT AT NORTHEAST END OF LUCIFER MINE.

Shows flat fault overlying ore. The workings are in ore; a thin wedge of tuff and tuffaceous conglomerate occurs between top of ore and fault, and a narrow zone of ore occurs above fault. Terrace gravels at top.

B. OUTCROPS OF MANGANESE ORE ON DIP SLOPE NORTHEAST OF LUCIFER MINE.

View south toward Arroyo del Infierno. Ore has been mined from outcrops by means of open-cuts. In background, on south side of Arroyo del Infierno, may be noted the rounded foothills of Cerro del Infierno, composed of Comondú volcanics, which rise above the general mesa level.

A striking feature shown by the structure contour map is the rapid steepening of the dip along the southwest side of the mine. This steepening is due to a projecting ridge or hill of the Comondú volcanics (pl. 45, southeast of intersection of coordinates 5000 N. and 8400 W.); the contours curve around the nose of this ridge, the strike changing from N. 30° W. along the outcrop to nearly due west in the western part of the mine.

The broad structural terrace may be seen to extend from southeast to northwest across the central part of the map. In the western part of the mine is a syncline that plunges northwest, and a northwestward-plunging nose lies north of the syncline. There is also a small trough or syncline at the extreme eastern end of the mine. The structure contours are modified by faults, the most important of which are shown on the map.

Aside from the modifying influences of the faults and possible later tilting, the major features revealed by the structure contours are believed to reflect irregularities in the surface of Comondú volcanics on which the later sediments were deposited. The structure contours on the base of the ore do not, however, represent exactly the contours on the Comondú surface except at the southwest end of the mine, where the ore rests directly on the Comondú. Between the ore and this surface is a wedge of sediments that thins to nothing at the southwest end and thickens to 8 meters or more to the northeast, so that the surface of the Comondú is steeper than the base of the ore.

The structure of a broader area surrounding the Lucifer mine is shown by the structure contours, drawn at an interval of 5 meters, on the map of the drill holes. (See pl. 52.) The structural terrace on which the Lucifer deposit lies is seen to merge toward the west into an eastward-plunging syncline. There seems to be little doubt that this syncline reflects an eastward flowing valley in the buried topographic surface of the Comondú volcanics; the structure contours have all the aspects of topographic contours except for slight complications due to faulting. The valley or syncline splits into two branches on either side of drill hole 1. Northwest of this valley the structure takes the form of a broad dome reaching a high point in drill hole 8. Minable manganese ore occurs only on the south flank of the valley or syncline mentioned; where the dip turns up to the north the ore bed terminates and gives way to a zone only slightly replaced by manganese oxides. This is revealed in the northernmost mine workings and in the holes drilled north of the Lucifer mine.

FAULTS

A nearly flat fault lies immediately upon the ore body or at a short distance above it through a large part of the Lucifer mine. This fault may be observed in the outcrop at the southeast end of the mine, in the open-cut at the northeast end (pl. 47*A*), and at many places in the mine where the top of the ore has been broken through in the back of the drifts. This fault cannot be shown on the mine map, but it is indicated on the sections wherever possible. (See pl. 48.) The fault surface is in part nearly horizontal, but in most places it dips 10° to 30° NE. It closely parallels the ore body. It is followed by smooth slickensided surfaces, which are mostly in tuff though in some places they are bordered on one or both sides by conglomerate. The fault is composite in many places, and steeper faults of small displacement branch from its lower side, some of them gradually curving into it. The displacement of the fault cannot be measured, as the movement nearly parallels the bedding, but it probably is not very great. It seems possible that this fault may have resulted from slumping or sliding of the sediments away from the adjoining ridge of Comondú volcanics.

The top of the ore generally lies a little below this flat fault but joins it at iregular intervals; there is in many places a zone of sheared tuff as much as half a meter thick between the ore and the fault. Above the fault there may be another thin layer of tuff, or of conglomerate. In many places the conglomerate above the fault is permeated with manganese oxide for a height of a few tenths of a meter, and in some places a lens of solid ore lies above the fault, separated from the main ore body below by tuff.

The ore body is cut by a few steeply dipping faults of northwesterly strike and small displacement. The largest of them is a fault zone, composed of several branching fractures, in the southwest part of the mine. (See pl. 44, coordinates 5000 N., 8440 W.) The fault zone strikes northwest, and the southwest side has been upthrown. At the southeast end the displacement is 8 meters or more, but it gradually decreases toward the northwest. The main fracture strikes N. 45° W. and dips 65° SW. to 85° NE. Striae on the fault surface pitch 10° to 15° NW., indicating a large horizontal component. Another fracture, 2 to 5 meters northeast of the main one, strikes N. 42° to 43° W. and dips 80° SW. to vertical. Another branch fracture lying southwest of the main fault is exposed in the raise at the west end of section IV–IV′. (See pl. 48.) In the raise both the ore and the flat fault on top of the ore have been upthrown between two branches of the fault. The ore body has been upturned to a vertical position along part of the fault zone. The various branches of this fault zone cannot be classified strictly either as normal or as reverse faults, because their dips change in direction along the strike and are for the most part nearly vertical.

In the eastern part of the mine there is a fault having a displacement of about 4 meters. (See pl. 44, just west of coordinate 8300 W. and on both sides of coordinate 5000 N.) This fault strikes N. 10° E., dips 60° to 65° E., and is normal, with the east side downthrown. A southwest-dipping fault, with a downthrow on the southwest of as much as 6 meters, is exposed in the central part of the mine. (See pl. 48, near west end of section II–II′.) This fault strikes N. 65° W. and dips 65° S. Most of the other faults shown on the map (pl. 44) are of even smaller displacement, and many are branches of the flat fault overlying the ore.

A small fault is exposed on the surface at the east end of the southern outcrop of ore, near the head of the gravity tram. The ore has been downdropped on the east side and was eroded immediately adjacent to the west side before the deposition of the overlying terrace gravels.

THICKNESS OF ORE

The thickness of ore within the blocked-out area of the Lucifer mine ranges from 1 meter to more than 6 meters and probably averages about 2½ meters. A mathematical average from about 320 measurements is 2.4 meters, which is probably a minimum figure, because in many parts of the mine the workings have not been extended either to the top or to the bottom of the ore. In the area of 36,000 square meters that had been blocked out by May 1946, the average thickness was 2.8 meters. In the additional 17,000 square meters blocked out between May 1946 and May 1948 however in an area west of the mine workings shown in plate 44, the average thickness was only 1.5 meters, bringing the average in general, weighted for areas, down to 2.4 meters.

An isopach map has been constructed to show the variations in thickness of ore in the area that had been blocked out by May 1946, using an isopach interval of 1 meter. (See pl. 49.) From this map it is seen that almost throughout the mine, as developed in May 1946, the thickness is greater than 2 meters, and in nearly half the area it is greater than 3 meters. The relation of thickness to structure is clearly shown by comparing the isopach map with the structure contour map (pl. 45), and also by the block diagram (pl. 46), which shows the thickness of ore by means of sections superposed on the structure contours. Thickness-structure relations are also shown on the structure sections of the areas explored by drill holes (pl. 53). The most marked change in thickness is found along the steep dip bordering the ridge of Comondú volcanics in the southwestern part of the mine, where the ore rapidly pinches down to a meter or half a meter in thickness. The greatest thickness occurs where the dip flattens out along the slope of this ridge. Wherever the bed turns up again to the north it rapidly decreases in thickness.

The major axis of maximum thickness of ore runs in a westerly dirction, closely following the trend of the structural terrace. The ore has its greatest observed thickness of over 6 meters in a syncline in the central part of the mine—coordinates 5050 N. and 8430 W. The axis of maximum thickness also branches off into the syncline found at the east end of the mine. The northwestward-trending nose in the vicinity of coordinates 5060 N. and 8400 W. is paralleled by an axis of minimum thickness. Some of the minor axes of maximum and minimum thickness have not been definitely related to the structure.

In the western part of the mine, developed between May 1946 and May 1948, the thickness of ore decreases. In most of this area the ore has a thickness between 1 and 2 meters, only locally reaching 3 to 4 meters, and over a considerable area northwest of the Lucifer shaft the thickness is only 0.6 to 0.7 meter.

EXTENT OF ORE

In May 1948, the ore had been blocked out by intersecting drifts over an area of 53,000 square meters, having a maximum length of 590 meters in a westerly direction and a width of 50 to 130 meters. The ore body is bounded to the southeast and northeast by outcrops, to the southwest by wedging out against a buried ridge of Comondú volcanics, and to the northwest and north by "assay walls". To the southeast the outcrops have been cut off abruptly by erosion. To the northeast the ore bed spreads down a dip slope over a broad area, and recently the ore has been mined in open-cuts from some of the outcrops in this area. (See pl. 47*B*.) This dip slope is covered with terrace gravel; on some parts of the slope the ore has been largely eroded, but elsewhere there is ore left below the gravel. To the southwest the ore pinches out against a projecting ridge of Comondú volcanics. The elevation at which the ore wedges out against this ridge ranges from 320 meters in certain parts of the mine to 340 meters in the southwesternmost outcrop. The line of wedging out is indicated on the map of the area explored by drill holes (pl. 52); it has a general westerly trend, although it is irregular in detail.

To the northwest and north the ore body gives way to a zone which is too thin and low in grade to be minable; the boundaries in those directions may thus be classified as "assay walls". The ore-bearing zone crops out discontinuously for at least 410 meters north-northwest of the mine, and it continues beneath the lava-covered mesa northwest of the mine for at least 850 meters, as shown by drill holes, but over most of this distance it is a thin, low-grade bed or merely a zone of tuff slightly or partially replaced by manganese oxides.

In the northern outcrops and short mine workings the ore is generally not more than 1 meter thick, is discontinuous, and contains many inclusions of tuff. It seems unlikely that much of this zone could be mined. A description of the ore zone found in the drill holes northwest of the Lucifer mine is given in a later section on the exploratory drilling program.

MINERALOGY

The ore in the Lucifer deposit consists chiefly of manganese oxides, which J. M. Axelrod has identified by X-ray examination as cryptomelane [4] and pyrolusite (MnO_2). In one sample he found an unidentified mineral that showed "a weak pattern similar to that given by a fluffy unidentified material from Embreeville, Tenn.", and an unnamed hydrous manganese oxide was noted in another sample.

The cryptomelane is mostly fine-grained and incoherent, although in places it is massive or occurs in rodlike or platy forms. The pyrolusite occurs in minute crystals, which form coatings on massive cryptomelane and also make up aggregates of considerable size. The ore encloses lenslike bodies consisting mainly of pyrolusite that are large enough to be mined selectively, and some ore mined from such bodies has been shipped for chemical use.

A large part of the ore is so fine-grained, earthy, and incoherent as to make a high percentage of "fines." Fines below 20-mesh have averaged about 30 percent and have run as high as 43 percent. This is the only distinctly troublesome feature of the ore, and early in 1945 a sintering plant was installed to correct it.

Within the normal fine-grained ore are lenses of hard, massive, tough, siliceous ore which the miners call "hueso." The hueso may contain 20 to 30 percent of silica and less than 40 percent of manganese, whereas the general run of ore contains less than 5 percent of silica and more than 45 percent of manganese. An X-ray determination by J. M. Axelrod of a sample of hueso revealed opal, pyrolusite, and a trace of an unnamed hydrous manganese oxide. The hueso probably constitutes about 10 percent of the volume of the ore deposit. It would be possible to sort out the hueso, and that was actually done during the early operations, but in 1944 and 1945 the hueso was being shipped with the higher-grade ore.

Associated with the hueso in some places and occurring separately in others are lenses of red or brown jasper mixed with the iron oxides hematite and limonite. An analysis of red hematitic jasper showed it to contain 10.13 percent of manganese, 24.76 percent of silica, and

[4] Composition KR_8O_{16} (?), $R=Mn^{IV}$ chiefly, also Mn^{II}, Zn, Co. See Fleischer and Richmond (1943, pp. 273-274).

37.71 percent of iron; an analysis of brown limonitic jasper showed 4.62 percent of manganese, 52.15 percent of silica, and 21.94 percent of iron. The jasper makes up only a small part of the ore body and is sorted out in the mine. The principal occurrences are indicated on the map and sections of the underground workings. (See pls. 44 and 48.) It has been noted that jasper accompanies manganese deposits in many places, as for example in Washington (Park, 1942b, p. 442), California (Trask and others, 1943, pp. 62–63), Cuba (Park, 1942a, pp. 81–82; Park and Cox, 1944, p. 315), and Costa Rica (Roberts, 1944, p. 389), to mention only a few.

Few minerals other than the manganese oxides, jasper, and iron oxides are visible in the ore. A few thin veinlets of calcite and of chalcedony were seen. Halite, though nowhere visible, was identified by X-ray methods, and from 1 to nearly 5 percent was found in some samples by chemical analysis. Copper stains were noted in one of the drifts north of the blocked-out area and also in some of the smaller outlying deposits, but none was seen in the main Lucifer ore body. Gypsum also is found in some of the smaller deposits, especially at the Las Palmas mine, but it was not observed at the Lucifer mine.

The specific gravity, which is difficult to determine on most of the fine-grained incoherent ore, varies greatly with the type of ore, depending especially on whether the ore is massive or fine-grained and porous. Some determinations by the Section of Chemistry and Physics of the Geological Survey follow:

Specific gravity	*Nature of ore*
2.7	Fine-grained cryptomelane; typical ore.
2.2	Fine-grained cryptomelane; typical ore.
3.5	Crystalline pyrolusite and massive cryptomelane.
3.4	Massive siliceous ore ("hueso").
1.6	Fine-grained, earthy, porous ore.
1.7	Do.
1.7	Do.

GRADE AND CHEMICAL COMPOSITION OF ORE

Analyses of samples taken by the writers indicate that the manganese content ranges from 37 to 57 percent and averages close to 47 or 48 percent. The richest material consists of crystalline pyrolusite, and the leanest of hard siliceous ore or hueso. The fine-grained cryptomelane that makes up a large part of the ore body contains between 45 and 50 percent of manganese. Tests on the sintered ore, made since installation of the sintering plant in early 1945, are said to indicate a manganese content of 52 or 53 percent.

Determinations of some constituents of the ore follow:

Chemical determinations on Lucifer manganese ores,[1] in percent

Sample No.	Mn	SiO_2	Fe	Pb	Cu	BaO	V_2O_5 [2]	NaCl [3]	O [4]
1a	52.5	0.27	-------	0.49	0.11	0.50	0.16	4.85	-------
1b	51.3	[5] 1.34	-------	.12	.16	.06	.22	4.08	-------
A14	57.7	.40	-------	.05	.13	1.18	.16	.10	-------
J1	44.1	1.63	-------	.15	.71	1.62	.12	.11	-------
M12	54.2	.42	-------	.01	.18	.80	.10	.02	-------
3	57.1	.60	-------	.51	.70	.89	.11	trace	-------
6 [6]	37.0	[5] 31.3	-------	.05	.12	.94	.08	.08	-------
11	53.17	.92	1.06	.78	.30	-------	-------	.92	14.82
15	48.34	2.98	1.36	.74	.24	-------	-------	1.89	12.93
18	49.98	1.67	.92	.78	.25	-------	-------	.85	14.50
23	53.91	1.40	.87	.98	.30	-------	-------	.87	14.47
25	51.99	1.37	.75	1.74	.30	-------	-------	.46	14.63
37	48.56	11.12	.90	.62	.28	-------	-------	1.08	13.80
40	49.57	7.52	.83	1.02	.19	-------	-------	1.46	13.41
48	49.91	4.28	2.12	.82	.26	-------	-------	1.49	13.60

[1] Analyses of first seven samples by Michael Fleischer, of samples 11 to 37 by R. E. Stevens, and of samples 40 and 48 by M. K. Carron.
[2] All determinations of V_2O_5 were made by M. D. Foster.
[3] Calculated from water-soluble chloride.
[4] Available oxygen.
[5] Insoluble.
[6] Hueso.

The range and average of these constituents in percent is summarized below:

	Range	Average	Number of analyses
Mn	37.00 to 57.70	49.03	51
SiO_2	0.27 to 31.3	[1] 4.47	15
Fe	.75 to 2.12	1.10	8
Pb	.01 to 1.74	.59	15
Cu	.11 to .71	.28	15
BaO	.06 to 1.62	.86	7
V_2O_5	.08 to .22	.14	7
NaCl	trace to 4.85	1.22	15
O (available)	12.93 to 14.82	14.02	8

[1] Excluding the sample of "hueso," No. 6, the average SiO_2 content is 2.57 percent.

No WO_3 was found in any of the samples.

According to analyses made available to the writers by Srs. Mahieux and García Quintanilla, some additional constituents of the ore range as follows:

	Range	Average	Number of analyses
H_2O	0.16 to 13.60	8.21	30
Al_2O_3	.13 to 4.21	1.73	23
CaO	.25 to 2.10	1.10	9
MgO	.18 to 1.50	.83	5
Zn	.01 to .19	.11	44
S	.02 to .20	.11	25
P	.02 to .11	.05	49
CO_2	.65	----------	1
Co	none to .098	----------	3
Mo	.081	----------	1
Sb	.024	----------	1
Ni	none to .003	----------	3
As	trace to .01	----------	2
Ag	trace	----------	1

Spectrographic examination by K. J. Murata of a composite sample of the manganese ore, made up of 8 samples collected from various parts of the mine, gave the following results:

Spectrographic analysis of composite sample, Lucifer manganese ore

1 percent and more	Mn, Si, K, Na, Fe, Ba.
.X percent	Pb, Cu, Ca, Al, Mg.
.0X percent	V, Mo, Co, Sr.
.00X percent or less	Tl, Ti, Cr, Li.
Looked for but not found	As, Sb, Bi, Zn, Cd, Rb, Cs, Ni, Ga, In, Sn, Ge, Au, Pt, Pd, W, Ag, Re, Th, Cb, Ta.

The high percentage of NaCl is noteworthy. It is regarded as an original constituent of the tuff, derived from sea water, for Weed (1908, p. 245) reports that the tuff associated with the Boleo copper ore contains 0.1 to 6 percent of NaCl.

USES OF ORE

The Lucifer ore by its chemical composition is well suited for metallurgical purposes. The bulk of the ore will meet the usual peacetime standard for high-grade metallurgical ore of a manganese content of 48 percent. The sintering plant furnishes a product containing about 52 or 53 percent of manganese, and eliminates the problem of excessive "fines." The percentages of silica and iron are well below the maxima generally allowed. The only constituents that might draw penalties under peacetime specifications are lead and copper, whose content appears to vary in different parts of the ore body.

The Tennessee Eastman Corp. has found the pyrolusite ore suitable for chemical purposes in the photographic industry. For this use a large amount of available oxygen is the main requisite, and the specifications are based on the percentage of MnO_2 in the ore. The Lucifer ore that has been sorted out for this purpose has had a content of MnO_2 ranging from 76 to 82 percent. Perhaps one-third of the ore body, the part consisting largely of pyrolusite, could be selectively mined for chemical ore. For use in batteries, the lead and copper content of the Lucifer ore exceed the maximum amounts usually allowed, although the exact requirements of manganese ore for battery purposes do not yet appear to be well established.

DEPOSITS OTHER THAN THE LUCIFER

Small deposits of manganese ore occur in tuff at several places near the Lucifer mine. Some are above and north of the Lucifer deposit, at a higher stratigraphic level, and scattered outcrops are found at two different horizons in the canyon east of the Lucifer mine and along the slope just below the mesa north of the mine (pls. 40 and 42).

These deposits are generally less than 1 meter thick and are mostly of low grade, being mixed with considerable tuff. In one of the deposits near the mesa north of the mine (pl. 40, east of coordinate 8400 W. near north end of map) the manganese oxide appears to have spread out along a tuff bed from a small fault. Along the fault the manganese oxide is concentrated in a zone about 2 meters wide and is cut by a number of vertical ribs of calcite. Toward the east the deposit thins out rapidly, separating into three or four layers of manganese oxide a few centimeters thick, and disappears entirely within a few meters. Some of the other deposits wedge out into thin streaks of ore. In the side canyon east of the Lucifer mine (pl. 40, near east edge of map, between coordinates 5100 and 5500 N.), there is ore overlain by a nearly flat fault, as at the Lucifer mine.

Deposits are also scattered over an area extending north to Arroyo de las Palmas, 4 kilometers from the Lucifer mine, and southeast to Cañada de la Gloria and Arroyo del Boleo, 4½ kilometers from the mine. The outcrops of ore and the location of the mining claims are shown in plates 39 and 54. In many places these deposits have been developed by open-cuts and short drifts, and some ore has been extracted from them by gambusinos—individual prospectors. So far as developed, however, all the deposits are small, irregular, and discontinuous, and mostly of lower grade than the Lucifer ore body. On the whole they show little promise. The production from all these outlying deposits to 1944 was about 1,100 tons, but, as the gambusinos sold the ore to the operators of the Lucifer mine, it was included in the total production reported for the Lucifer. Some of the ore from these deposits contained gypsum and hence added to the sulfur content of the Lucifer ore. In 1945 these deposits were no longer being developed, and many of them had been completely worked out.

These deposits illustrate, more clearly than the Lucifer deposit, crosscutting relations to the bedding and extreme localization of the manganese oxides. Many of them contain much intercalated tuff, and some consist of an irregular patchwork of manganese oxide in tuff or, at a few places, in tuffaceous conglomerate. In one of the deposits on the Las Palmas claim, on the south side of Arroyo de las Palmas, a body of manganese ore 1 meter thick cuts across from tuff into underlying massive gypsum for a distance of several meters.

The deposits occur in tuff, at two or possibly three horizons. On parts of the Neptuno and San Pedro claims, ore occurs in the fossiliferous tuffaceous limestone that lies at the base of the Boleo formation in this area. The manganese oxide has impregnated and apparently replaced fossil molds in the limestone.

Siliceous manganese oxide accompanied by jasper and copper minerals forms a veinlike mass, 1 meter thick, in the Comondú volcanic rocks near the head of Arroyo del Boleo (pl. 39, coordinates 3400 N. and 5400 W.). Veinlets of manganese oxide, accompanied by jasper and copper minerals (probably chrysocolla for the most part), were observed at a number of places in the Comondú volcanics.

RELATION TO COPPER DEPOSITS

The manganese deposits occur in the same group of rocks that contains the Boleo copper deposits. Manganese oxides are found throughout the Boleo copper district, as a matter of fact, either intimately mixed with the copper minerals or occurring in separate beds. The major manganese deposits, however, are north of Arroyo del Boleo, whereas the major copper deposits are found south of this arroyo.

Copper stains are noted in some of the manganese deposits, particularly in one of the short drifts at the north end of the Lucifer mine. The analyzed samples of the Lucifer ore contain 0.11 to 0.71 percent of copper. Copper stains are visible in the agglomerate of the Comondú volcanics just below the southernmost outcrop of the Lucifer ore body, and copper minerals, probably chrysocolla for the most part, along with manganese oxides, jasper, and chalcedony form veinlets in the Comondú volcanics in many places. Manganese oxide is found in nearly all the copper-bearing beds. In seven analyses of the copper ores given by Fuchs (1886a, p. 85, 1886b, p. 419) the manganese oxide content ranges from 7 to 24 percent, and Saladin (1892, p. 22) gives four analyses in which it ranges from 3.3 to 15.4 percent. Touwaide (1930, p. 129) gives the average percentage of MnO in the copper ore mined in 1926 as 3.74, remarking that it is "very variable," and Locke (1935, p. 411) gives the MnO in a composite analysis of smelting ore taken from May to August 1923 as 3.25 percent. The manganese-copper oxide crednerite ($Cu\ Mn_2O_4$) has been noted in the oxidized portion of the copper ore (Krusch, 1899, p. 86).

The copper ore occurs in beds of clay derived from altered tuff and containing 30 percent of water. The principal copper mineral is chalcocite, but bornite and chalcopyrite are present in minor quantity, forming particles rarely larger than a pin head and commonly microscopic (Locke, 1935, p. 410; Touwaide, 1930, p. 128). The average copper content of the ore does not exceed 5 percent. In the oxidized zone several rare copper minerals were discovered, such as boleite, pseudoboleite, and cumengite.

Five copper horizons are recognized in the Boleo district, each at the base of a tuff member underlain by conglomerate; the Lucifer manganese deposit, it will be remembered, is near the top of a tuff member. The horizons are numbered by the engineers of the Compagnie du Boléo from 0 at the top to 4 at the bottom. Although these five horizons cannot be definitely identified in the area mapped north of Arroyo del Boleo, the company engineers believe that the Lucifer manganese-ore horizon is stratigraphically equivalent to copper horizon 4, a conclusion that seems likely.

It seems probable that the manganese and copper deposits had a similar origin. Two theories have been advanced as to the origin of the copper deposits. A general theory of hydrothermal solutions rising along fissures and spreading along the beds has been invoked by Fuchs (1886a, p. 92; 1886b, p. 425), Krusch (1899, pp. 85–86), Peña (1931, p. 164), and Weed (1908, p. 266), and tentatively supported by Locke (1935, p. 411). Touwaide (1930, pp. 140–141), on the other hand, assumes that the copper was extracted from the tuff by subsurface waters, carried into the clay by diffusion, and precipitated as chalcocite. It may be said that we favor a hydrothermal origin for the copper deposits, but the evidence will not be discussed in detail here, except as it relates to the origin of the manganese deposits considered below.

ORIGIN OF THE MANGANESE DEPOSITS

The manganese ore is thought to have been deposited by hydrothermal solutions that rose along faults through the Comondú volcanic rocks and spread out along the bedding planes of the tuff members of the Boleo formation, impregnating and replacing the tuff. Structural control of deposition appears to have played a large part in localizing the main Lucifer ore body and some of the smaller deposits. Among the lines of evidence favoring this theory are the following:

1. Veinlets of manganese oxide—accompanied in various places by copper minerals, iron oxides, and jasper—occur in the underlying Comondú volcanics. They are localized especially along faults, one of which occurs just east of the Lucifer deposit. A veinlike body 1 meter thick in the Comondú volcanics near the head of Arroyo del Boleo has been described.

2. The ore is accompanied by jasper. The jasper is clearly not a sedimentary deposit, for it cuts across the bedding; it transgresses the Comondú volcanics and locally cuts across the conglomerate both above and below the tuff member enclosing the Lucifer deposit. Wherever found, it is commonly accompanied by manganese oxide.

3. In many places the manganese oxide transgresses from tuff into the overlying or underlying conglomerate. Some of this crosscutting could be explained by secondary migration. In Arroyo de las Palmas,

however, a 1-meter layer of manganese ore transgresses from tuff into underlying gypsum for a distance of several meters, and this transgression appears to be a primary feature of the ore body.

4. The distribution of the deposits is irregular, and when the total area covered by the tuff layers of the Boleo formation is considered, the manganese deposits are seen to be highly localized. The great thickness of the Lucifer deposit is not even approached in any of the other beds of tuff, which are exposed for an aggregate length of several kilometers. In most of the small deposits the ore consists of small bodies that wedge out abruptly along the length or pinch down into thin sheets; many of them consist merely of patches or of a complex of veinlets, pockets, and irregular masses of manganese oxide in tuff. Some of these deposits, such as the one that crops out just below the mesa north of the Lucifer deposit, appear to be related to faults.

5. The deposition of the main Lucifer deposits appears to have been structurally controlled. The close relation between structure and thickness shown by the structure contour and isopach maps has been pointed out. The gently dipping fault overlying the ore may be premineral and may have influenced ore deposition. Like the ore, it has been offset by later faults.

As no manganese deposits are known in the middle Pliocene or later sediments, it seems likely that the mineralization occurred near the close of the lower Pliocene, perhaps as a late phase of the vulcanism represented by the tuffs of the Boleo formation. The manganese deposits on Point Concepción, together with some between that place and the Lucifer mine, and some that lie south of Point Concepción, may have been formed at the same time. The main deposit on Point Concepción consists of veinlets of manganese oxide cutting basaltic members of the Comondú formation. Such veinlets also cut volcanic conglomerate that may be equivalent to the Boleo formation.

The deposits were probably formed close to the surface, for it seems unlikely that the Boleo formation in the vicinity of the Lucifer deposit ever had a very thick cover. No evidence has yet been found of the presence of any manganese minerals other than oxides.

Numerous channels along which the mineralizing solutions could have ascended cut across the Comondú volcanic rocks underlying the Boleo formation, the Comondú rocks having been tilted and faulted before the Boleo formation was deposited. The mineralizing solutions may have risen along fissures through the Comondú and then followed the irregular contact with the Boleo formation before spreading out along the tuff beds.

Compared with other manganese deposits that have been described from various parts of the world, the Lucifer deposits seem to resemble most closely some of the deposits occurring in tuff in Cuba. The Cuban deposits are commonly accompanied by jasper, as are the Lucifer deposits. Park (1942a, p. 84) describes the Cuban "tuff ores" as consisting of "grains, nodules, pockets, and veinlets of manganese oxides irregularly distributed through beds of altered tuff. Their form is essentially tabular." This description would fit many of the outlying deposits in the Lucifer district, but the main Lucifer deposit appears to be a thicker and more concentrated body of high-grade ore than those commonly found in Cuba. Park (1942a, p. 93; Park and Cox, 1944, pp. 315–317) attributed the Cuban deposits to ascending warm waters, from which the manganese was deposited in part as sedimentary beds and in part as replacement bodies.

MINING METHODS

The ore body has been developed by means of a series of intersecting drifts, forming a room-and-pillar system. In general, one set of drifts has fairly closely followed the strike of the ore body to the northwest, and another set has been driven to the southwest, rising upward along the dip of the body. Some of the latter workings are inclined, but others rise upward by steps 3 to 4 meters high, generally provided with ore chutes. Many of the workings are of irregular level. The attempt has been made to keep the floor of the workings at the base of the ore bed, but in many places the roof has not been extended upward to the top of the ore body. Most of the workings are in solid ore, except for a ventilation entry at the south end of the mine and a main haulageway at the north end of the mine.

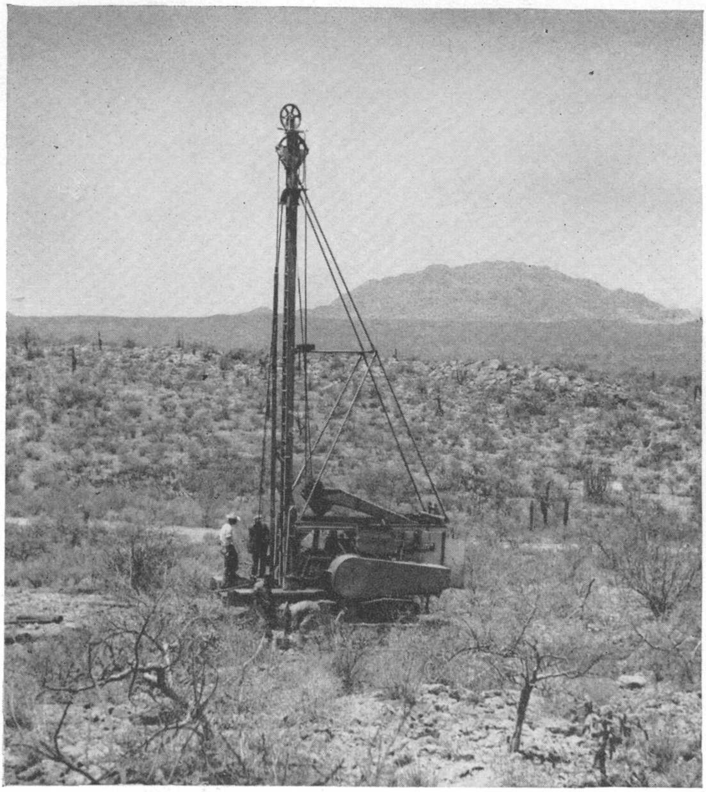
Development started at the south and east ends of the mine and has gradually progressed northwestward. Since 1946 the main haulageway has been the northernmost mine entry (pl. 44, coordinates 5150 N. and 8420 W.), which has several branches inside the mine. This haulageway and its branches are driven principally in Comondú volcanics and in conglomerate. Formerly all haulage was done by cars propelled by hand, but recently the cars have been hauled by mules along the main haulageways and also outside the mine, from the main entry to the head of the gravity tram. A sorting belt has been installed at the mouth of the main haulage tunnel. (See pl. 50*B*.) Here the obvious pieces of waste are discarded, and for a time the ore was sorted into two classes, chemical grade—consisting mainly of pyrolusite, recognized by its crystalline form—and metallurgical grade. In 1948, however, only ore of metallurgical grade was being shipped.

Ventilation in the mine was satisfactory in the early workings, because of the many entries from the southeast and northeast. In the newer (western) part of the mine the ventilation has been poor, however, and in 1946 a shaft was sunk on the mesa west of the mine to provide ventilation in that area (pl. 44, coordinates 4982 N. and 8910 W.).

In general no timbering has been done where the workings are in solid ore, but timbering has usually been necessary where the roof is in tuff, gravel, or conglomerate. The zone of sheared tuff that commonly overlies the ore is particularly susceptible to caving. In December 1945 a large cave-in occurred, affecting an area about 110 meters long and 30 to 70 meters wide, in the central part of the mine. The approximate boundary of this caved area is shown on plate 44. In 1948 this area was being reentered from workings driven in wall rock at a lower level.

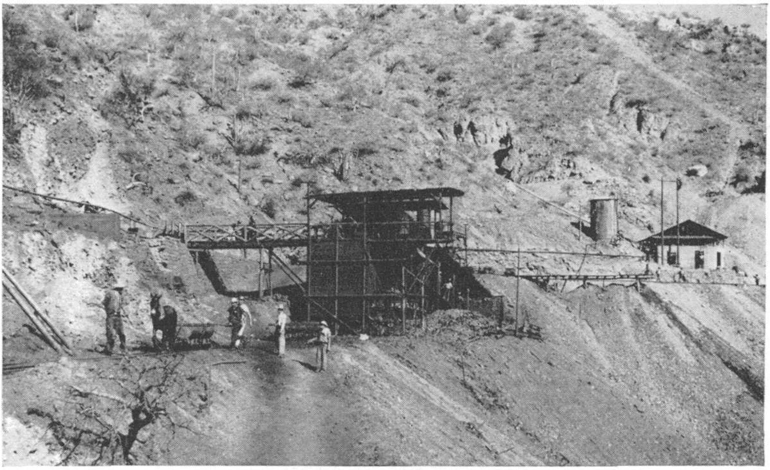
In 1948 two other mining methods were being employed in addition to the room-and-pillar system described above. In the southeast part of the mine near the outcrops the surface was being stripped by drag lines and the manganese ore was being removed from open-cuts. (See pl. 51 *A*, *B*.) Plate 51*B* shows one of these open-cuts from which the overburden has been stripped away. The original intersecting drifts of the room-and-pillar system in the manganese ore bed may still be seen. This stripping will be carried out only in the eastern part of the mine where the ore body has a shallow cover consisting largely of loose gravel. Probably a maximum thickness of 15 meters of overburden can profitably be removed in this area. In the western part of the mine, where the overburden reaches 60 to 70 meters, stripping is considered to be out of the question.

In the extreme western part of the mine where the ore bed is only 0.6 to 1.0 meter thick over a broad area, a stoping method has been employed similar to the one used in the Boleo copper mines. This is called locally the system of "tallas," and is similar to the longwall method of the coal-mining industry. The ore is stoped out completely along an advancing face, and at the same time an equal or somewhat greater thickness of wall rock above the ore is removed and shoveled back into the stopes to serve as fill. Timbering is necessary at the time of stoping, but after the stopes are filled with waste the roof is allowed to cave. This method is considered practical only where the ore bed has a thickness of about 1 meter or less; where the bed is thicker it is not considered economical to mine enough wall rock to fill the stopes. In a few places where the ore is about 2 meters thick stoping has been accomplished by using a square set system of timbering. In most of the mine, however, the room-and-pillar system has been followed, and no method has been devised for the removal of pillars without great danger of caving. Because of



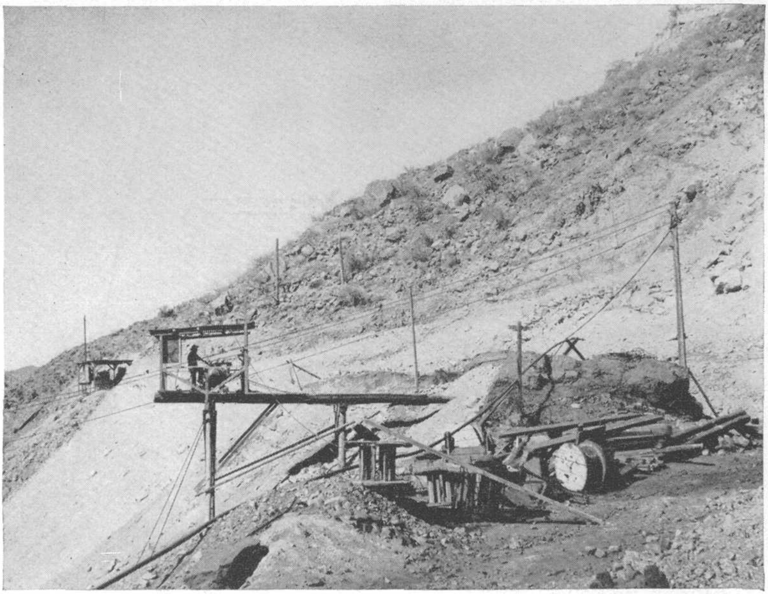
A. CHURN DRILLING RIG USED FOR EXPLORATORY DRILLING IN 1948.

This is on lava-covered mesa northwest of Lucifer mine, looking northward toward Cerro de Santa Maria.



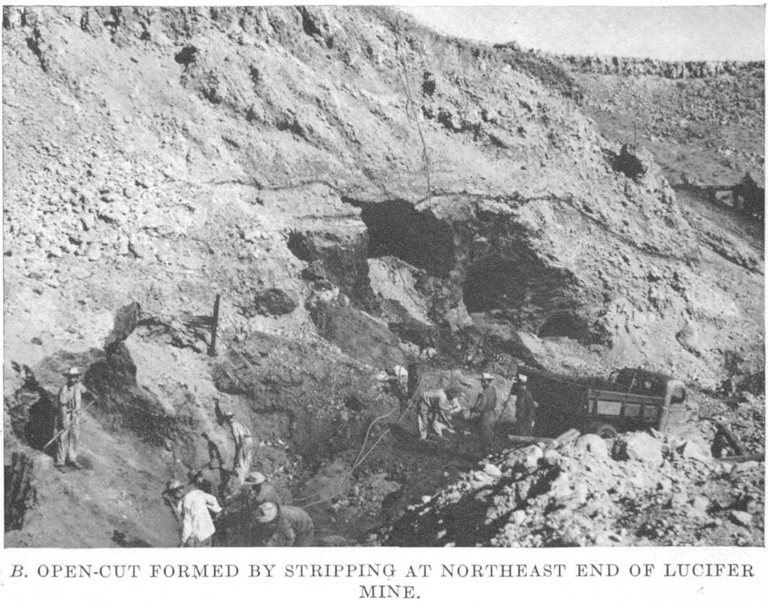
B. SORTING BELT AND LOADING BIN AT MOUTH OF MAIN LUCIFER MINE ENTRY IN 1948.

Tracks to left lead to head of gravity tramway.



A. DRAG LINE USED IN STRIPPING OVERBURDEN FROM OUTCROP AT SOUTHEAST END OF LUCIFER MINE.

This photo, taken in 1948, shows same general area as in plate 43*B*, which was taken in 1943.



B. OPEN-CUT FORMED BY STRIPPING AT NORTHEAST END OF LUCIFER MINE.

Original underground workings made by room-and-pillar system in manganese ore bed may still be seen. Flattish fault appears above ore in center, running off into conglomerate at right-hand side.

the large size of pillars left under the present methods it is very doubtful if the total extraction of ore from the mine will exceed 75 percent of the tonnage existent in the ore body.

EXPLORATORY DRILLING PROGRAM

An exploratory churn-drilling program was carried out in the Lucifer district from December 1947 until June 1948. Altogether 31 holes were drilled, of which 29 were situated on the mesa west and northwest of the Lucifer mine, and two were drilled in the bottom of the arroyo east of the mine. The holes ranged in depth from 56 to 160 meters, averaging 98 meters. The total depth of drilling amounted to 3,037 meters. A table showing the results of drilling, including location, elevations, and depth of holes, and data on the ore beds encountered, is presented herewith. A map showing the location of the drill holes, as well as structure contours at the base of the principal manganese ore bed in the area drilled, is given in plate 52. This map also shows the extent of the Lucifer mine workings as of May 4, 1948. Structure sections showing the ore beds and structure encountered by the drill holes are given in plate 53. A photograph of the drilling rig is given in plate 50*A*, which also shows the typical topography and vegetation of the lava-covered mesa northwest of the Lucifer mine.

Although nearly all the drill holes penetrated the principal manganese ore horizon, they revealed that it is too thin and low in grade to be minable over most of the area that was explored. In many of the holes, indeed, there was no solid ore bed but rather a zone of tuff or tuffaceous conglomerate only slightly or partially replaced by manganese oxides. An idea of the degree of replacement represented in the various holes is given in the accompanying table.

Drill holes in the Lucifer manganese district

No. of drill hole	Coordinates in meters from San Francisco shaft		Altitude at surface (meters above sea level)	Altitude at bottom (meters above sea level)	Total depth of hole (meters)	Data on principal manganese ore bed encountered in drill holes				Altitude of top of Comondú volcanics (meters above sea level)	Nature of ore and remarks
	North	West				Altitude at base of bed (meters above sea level) [1]	Depth of base of bed below surface (meters)	Thickness of ore bed (meters) [2]	Grade of ore (percent manganese) [3]		
1	5, 059. 02	8, 819. 57	387. 95	320. 65	67. 30	322. 95	65. 00	1. 0	----------	----------	No sample available.
2	5, 060. 86	8, 924. 76	381. 37	284. 37	97. 00	----------	----------	----------	----------	357. 87	Ore beds lacking because of nondeposition over a ridge of Comondú volcanics. Manganese oxide stringer zone in Comondú volcanics at 315.87 meters.
3	5, 062. 14	9, 024. 76	380. 91	289. 51	91. 40	----------	----------	----------	----------	346. 71	Ore beds lacking because of nondeposition over a ridge of Comondú volcanics. Manganese oxide stringer zones in Comondú volcanics at 318.71 and 293.71 meters.
6	5, 159. 41	8, 822. 64	390. 80	305. 40	85. 40	316. 80	74. 00	{1. 0 . 6 1. 0}	28. 1 30. 1 47. 6	----------	High-grade ore bed. Lucifer mine workings extended in this direction upon completion of the drill hole. Tuffaceous limestone directly underlies the ore bed.
7	5, 259. 52	8, 820. 72	393. 81	233. 71	160. 10	348. 21	45. 60	----------	----------	323. 71	Tuffaceous conglomerate slightly replaced by manganese oxides, 3.1 meters thick. Also a higher bed of same nature, 1.5 meters thick, at 368.01 meters.
8	5, 359. 45	8, 819. 00	392. 88	299. 88	93. 00	351. 38	41. 50	----------	----------	321. 88	Tuffaceous conglomerate slightly replaced by manganese oxides, 4.0 meters thick. Also a higher bed of same nature, 3.1 meters thick, at 365.38 meters.
9	5, 459. 39	8, 817. 22	391. 94	238. 64	153. 30	343. 74	48. 20	. 15	----------	315. 64	Ore bed 0.15 meter thick, underlain by tuff partially replaced by manganese oxides. Also a higher bed of tuffaceous conglomerate slightly replaced by manganese oxides, 3.1 meters thick, at 366.04 meters.
11	5, 659. 60	8, 820. 12	380. 82	275. 72	105. 10	327. 02	53. 80	----------	----------	----------	Tuff and tuffaceous conglomerate very slightly replaced by manganese oxides, 2.1 meters thick.
13	5, 859. 32	8, 820. 14	381. 58	297. 78	83. 80	322. 48	59. 10	----------	----------	----------	Tuff partially replaced by manganese oxides, 3.2 meters thick. Underlain by unmineralized tuff.
16	5, 459. 91	8, 910. 74	384. 00	227. 00	157. 00	347. 60	36. 40	----------	----------	318. 50	Tuffaceous conglomerate very slightly replaced by manganese oxides, 1.5 meters thick. Also manganese oxide stringers in Comondú volcanics at 309.20 and 263.40 meters.
17	5, 459. 15	9, 018. 78	381. 29	304. 99	76. 30	336. 19	45. 10	----------	----------	310. 79	Tuff very slightly replaced by manganese oxides, 3.5 meters thick. Underlain by unmineralized tuff.
18	5, 458. 16	9, 124. 11	389. 02	312. 82	76. 20	336. 32	52. 70	----------	----------	----------	Small stringers of manganese oxides in tuff at 336.32 meters and 346.02 meters.
19	5, 458. 30	9, 220. 98	404. 63	322. 93	81. 70	333. 93	70. 70	1. 3	40. 7	----------	Regular ore bed 1.3 meters thick, underlain by 3.2 meters and overlain by 2.9 meters of tuff partially replaced by manganese oxides.
20	5, 456. 11	9, 317. 86	405. 14	304. 24	100. 90	338. 64	66. 50	. 3	----------	----------	Ore bed 0.3 meter thick, underlain by 3.6 meters of tuff partially replaced by manganese oxides.

21	5,869.99	8,974.00	390.60	241.90	148.70	301.90	88.70	.6	34.7	249.40	Ore bed overlain by 7.3 meters of tuff partially replaced by manganese oxides and limonite; underlain by 0.7 meter of tuff partially replaced by manganese oxides, then 3.6 meters of limonitic tuff, then 22.9 meters of sandy tuff with particles of manganese oxides, copper minerals, and limonite. Also a higher bed of tuff partially replaced by manganese oxides at 366.70 meters.
23	5,874.43	9,123.36	381.67	287.47	94.20	296.37	85.30	.7	43.6	----------	Hard ore bed 0.7 meter thick; another manganese oxide bed 0.4 meter thick at 301.87 meters, separated by tuff. Ore bed underlain by 4.8 meters of tuff partially replaced by limonite. Also a higher bed of tuffaceous conglomerate slightly replaced by manganese oxides, 0.9 meter thick, at 355.77 meters.
26	5,552.40	9,157.09	399.07	314.27	84.80	335.47	63.60	----------	----------	----------	Tuff partially replaced by manganese oxides, 0.5 meter thick.
27	5,359.03	9,264.69	414.37	316.77	97.60	337.37	77.00	----------	----------	----------	Tuff partially replaced by manganese oxides, 4.7 meters thick.
28	5,455.62	9,539.96	380.42	221.92	158.50	331.42	49.00	----------	----------	273.32	Tuff very slightly replaced by manganese oxides, 3.2 meters thick.
29	5,457.60	8,717.24	400.04	325.94	74.10	332.29	67.75	.35	37.4	----------	Ore bed 0.35 meter thick, overlain by 1.25 meters of tuff partially replaced by manganese oxides, then a manganese oxide bed 0.25 meter thick, then 2.1 meters of unmineralized tuff, then 1.9 meters of tuff partially replaced by manganese oxides.
30	4,957.37	8,827.40	386.15	310.95	75.20	316.65	69.50	1.1	11.4	----------	Low-grade ore bed in tuff. Also a higher tuffaceous conglomerate partially replaced by manganese oxides, 2.9 meters thick, at 323.25 meters.
31	5,976.92	8,962.00	382.89	259.19	123.70	283.99	98.90	----------	----------	----------	Tuff partially replaced by manganese oxides, 0.6 meter thick, underlain by 1.2 meters of tuff slightly replaced by manganese oxides, limonite, and copper minerals. Also a higher tuffaceous conglomerate slightly replaced by manganese oxides, 0.9 meter thick, at 287.39 meters.
32	5,769.17	9,056.28	395.95	279.04	116.90	310.40	85.55	.3	----------	----------	Ore bed 0.3 meter thick, in a tuff 1.8 meters thick, partially replaced by manganese oxides. Farther down, at 299.45 meters, is a tuff 5.8 meters thick partially replaced by manganese oxides and limonite. Also a higher tuffaceous conglomerate slightly replaced by manganese oxides, 4.5 meters thick, at 356.45 meters.
33	5,853.23	8,683.37	381.76	300.96	80.80	314.46	67.30	----------	----------	----------	Tuff very slightly replaced by manganese oxides, 2.3 meters thick. Same at 318.86 meters, overlain by 0.9 meter of tuffaceous conglomerate slightly replaced by manganese oxides. Also a lower tuffaceous conglomerate slightly replaced by manganese oxides, 3.3 meters thick, at 305.46 meters.
34	5,562.55	8,714.50	398.98	327.38	71.60	337.18	61.80	.4	----------	----------	Ore bed 0.4 meter thick, overlain by 1.6 meters and underlain by 5.4 meters of tuff slightly replaced by manganese oxides.
35	5,305.40	8,697.96	391.04	335.24	55.80	336.74	54.30	----------	----------	----------	Tuff partially replaced by manganese oxides, 2.1 meters thick, overlain by 3.0 meters of tuffaceous conglomerate with a little manganese oxide. Also a higher bed of tuffaceous conglomerate with a little manganese oxide, 3.9 meters thick, at 352.84 meters.

See footnotes at end of table.

Drill holes in the Lucifer manganese district—Continued

No. of drill hole	Coordinates in meters from San Francisco shaft		Altitude at surface (meters above sea level)	Altitude at bottom (meters above sea level)	Total depth of hole (meters)	Data on principal manganese ore bed encountered in drill holes				Altitude of top of Comondú volcanics (meters above sea level)	Nature of ore and remarks
	North	West				Altitude at base of bed (meters above sea level) [1]	Depth of base of bed below surface (meters)	Thickness of ore bed (meters) [2]	Grade of ore (percent manganese) [3]		
36	5,177.10	8,688.99	388.25	290.65	97.60	300.45	87.80	----------	----------	----------	Tuff partially replaced by manganese oxides, 4.3 meters thick.
37	5,298.44	9,007.86	381.00	282.50	98.50	----------	----------	----------	----------	303.70	Ore bed lacking, probably due to erosion in a valley before deposition of Tres Vírgenes volcanics. Just below Tres Vírgenes volcanics, at 336.40 meters, is a tuffaceous sandstone believed to be stratigraphically below the principal manganese ore horizon.
38	5,208.28	8,895.73	389.93	301.23	88.70	346.63	43.30	----------	----------	302.93	0.6 meter of tuff partially replaced by manganese oxides, overlain by 1.0 meter of tuffaceous conglomerate with a little manganese oxide, overlain by 0.6 meter of tuff partially replaced by manganese oxides. Also a higher bed of tuff partially replaced by manganese oxides, 2.2 meters thick, at 355.53 meters.
39	5,469.53	7,622.36	122.88	66.68	56.20	----------	----------	----------	----------	----------	Hole drilled in arroyo east of Lucifer mine. No ore bed found. All conglomerate except a sandy tuff from 70.43 to 75.18 meters.
40	6,200.17	6,883.27	107.90	22.50	85.40	----------	----------	----------	----------	----------	Hole drilled in arroyo east of Lucifer mine. No ore bed found. All conglomerate down to 45.40 meters; then gypsum to bottom.

[1] In many of the holes there was no distinct ore bed but rather a zone of tuff or tuffaceous conglomerate in varying degree replaced by manganese oxides, as indicated in the column headed "Nature of ore and remarks." For these holes the altitude above sea level is given for the manganiferous zone thought to be stratigraphically equivalent to the manganese ore bed of the Lucifer mine.

[2] Thickness is given only where there was a fairly well defined ore bed. Thickness of the zones that are only partially replaced by manganese oxides is indicated in the column headed "Nature of ore and remarks."

[3] Grade of ore is given only where a sample was assayed. In most of the other holes the ore zone was considered to be of no commercial value, with the possible exception of hole No. 1.

A definite solid ore bed of measurable thickness was found in 11 holes, but in only a few of them were the thickness and grade sufficient to be minable. The best showing was in hole 6, which revealed 1.0 meter of ore containing 47.6 percent of manganese, overlain by an additional 1.6 meters containing 28 to 30 percent of manganese. As this bed was considered to be of minable quality and thickness, the Lucifer mine workings were directed toward this hole shortly after its completion, and they were being communicated with the drill hole in June 1948.

In hole 1 an ore bed 1 meter thick was found which may also be of minable quality, but unfortunately no sample was obtained because the coring technique had not yet been perfected at the time this hole was drilled. Another hole revealing ore of possible minable quality and thickness is hole 19, 500 meters northwest of hole 6, in which an ore bed 1.3 meters thick had a manganese content of 40.7 percent. As this hole was completely surrounded by four other holes in none of which minable ore was found, however, it appears that the ore bed in hole 19 is a pocket or lens of small extent, which would probably not be economically exploitable because of its isolated position. In hole 23 an ore body 0.7 meter thick was found to have a grade of 43.6 percent of manganese. As this was the northwesternmost hole drilled the possibility was not eliminated that a minable ore body might extend northwest of that hole.

In only three of the holes drilled on the mesa was the ore horizon not found at all. In holes 2 and 3 the drill went directly from the Tres Vírgenes volcanics into the Comondú volcanics, and it seems clear that the absence of the ore horizon is due to nondeposition over a ridge of Comondú volcanics—the same ridge against which the ore pinches out along the southwest border of the mine. The ore evidently wedges out between holes 1 and 2, as is indicated in section D–D′ of plate 53. In hole 37, in the middle of the dry lake bed on top of the mesa northwest of the Lucifer mine, the absence of the ore horizon is evidently due to erosion in an old valley that was filled in with the Tres Vírgenes volcanics, as is shown in section C–C′ of plate 53. Holes 39 and 40, drilled in the arroyo east of the Lucifer mine, failed to strike the ore horizon. These two holes are not shown on the map because of their distance from the other holes, but they are listed in the table. Hole 40 struck gypsum at an altitude of 45 meters above sea level, possibly representing a continuation of the same gypsum body found in Arroyo de las Palmas, although its presence in this part of Arroyo del Infierno had not previously been known.

Among the purely geologic results of the drilling program should be mentioned the striking picture it reveals of two buried erosion surfaces—that on top of the Comondú volcanics, which is closely paralleled by the structure of the principal manganese ore bed in the Boleo formation, and an entirely discordant erosion surface carved in the Boleo formation at the base of the Tres Vírgenes volcanics. The filling in of valleys by Tres Vírgenes volcanics had been noted in outcrops, but the magnitude of the buried valley underlying the dry lake bed northwest of the Lucifer mine had not been suspected; this valley was filled in by lava flows and cinder beds to depths of 30 to 40 meters. (See sections, pl. 53.)

RESERVES AND FUTURE POSSIBILITIES

The total size of the Lucifer ore body, as outlined by mine workings and drill holes, has proved to be about 300,000 tons. Of this amount approximately half has already been mined, one-quarter is expected to be mined in the next 2 or 3 years, and the remaining quarter will probably have to be left in the form of pillars, unless a more complete system of extraction can be devised than that used to date. As compared with other manganese deposits of the world, it may be said that the Lucifer deposit is by far the largest in Mexico; it is also larger than any of the high-grade manganese oxide deposits known in the United States, although it is not so large as the manganese carbonate deposits of Butte, Mont. It does not compare in size with the deposits of Brazil, India, the Gold Coast, and Russia, however, which are measured in millions of tons.

Although the drill holes completely outlined the Lucifer ore body proper, they did not eliminate the possibility that additional ore bodies might be found elsewhere in the general region. The drilling was confined to a relatively small area adjacent to the Lucifer mine, but there remain large areas extending from the Lucifer mine northward to Arroyo de las Palmas and farther west, in which the underlying geology is concealed by lava flows and where additional manganese deposits might be discovered by drilling. That manganiferous beds exist in this area is revealed by the fact that pieces of manganese oxides were blown out by the volcanic crater on the mesa south of Arroyo de las Palmas, northwest of the Lucifer mine. The unanswered question, however, is as to whether there may be a minable ore body in this area or whether the manganese oxides are merely scattered through replacement zones, as in most of the area that has been drilled and as in the outcrops that are known to occur in Arroyo de las Palmas. The relative apparent promise of various areas in which drilling might lead to the discovery of unknown deposits of manganese is shown in plate 54, on which the known outcrops of manganese ore also are plotted.

Extensive low-grade manganiferous beds occur in the Boleo copper district, south of the Lucifer manganese mine, and also in the area between Arroyo del Boleo and Arroyo del Infierno. No high-grade concentrations of importance have been noted in this area, however, and probably the only means of working such beds would be by some type of leaching operation. Metallurgical tests are being conducted on these low-grade ores in connection with experiments on the low-grade Boleo copper ores.

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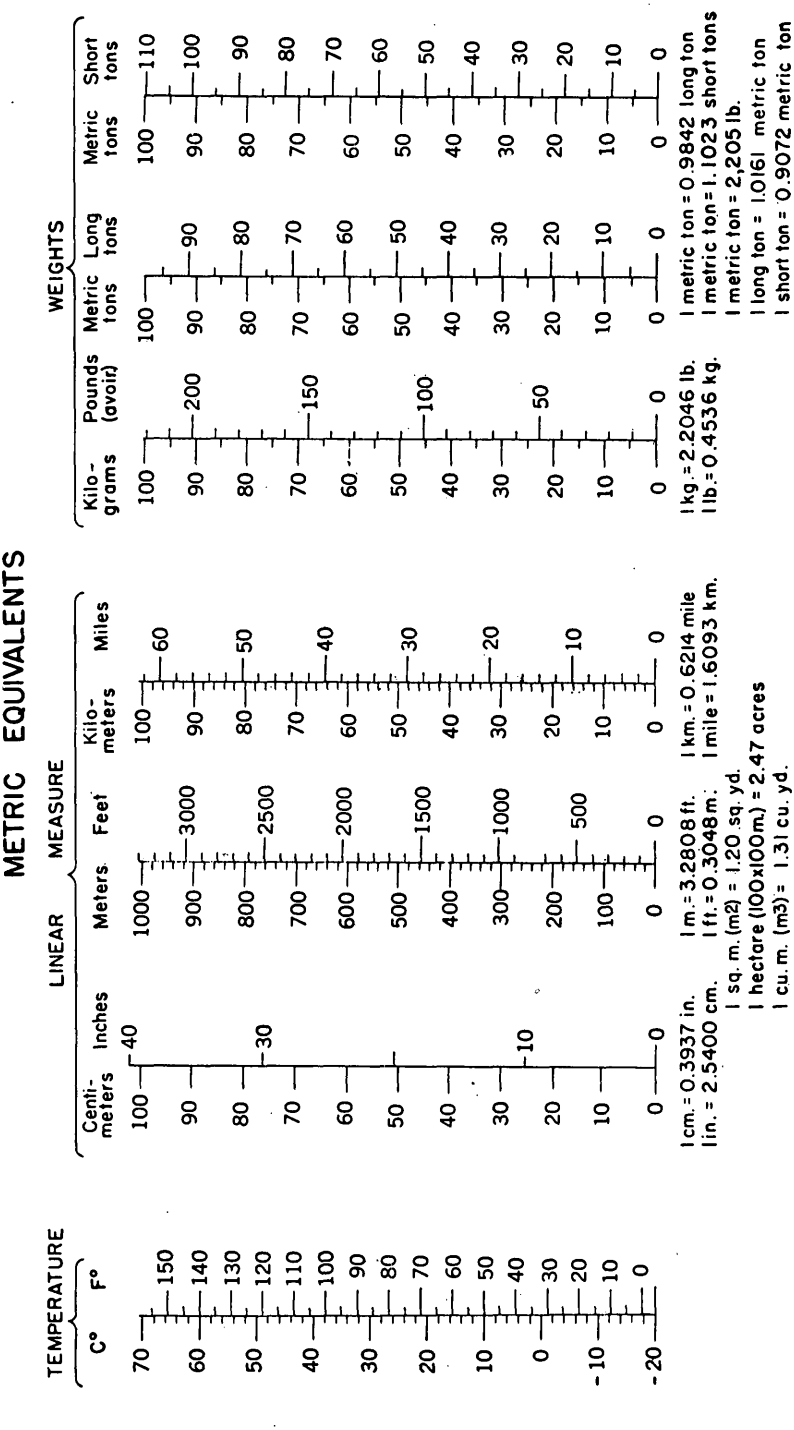
METRIC EQUIVALENTS
TEMPERATURE
C°
F°
LINEAR MEASURE
Centi-meters
Inches
Meters
Feet
Kilo-meters
Miles
1 cm. = 0.3937 in.
1 in. = 2.5400 cm.
1 m. = 3.2808 ft.
1 ft. = 0.3048 m.
1 km. = 0.6214 mile
1 mile = 1.6093 km.
1 sq. m. (m2) = 1.20 sq. yd.
1 hectare (100x100m.) = 2.47 acres
1 cu. m. (m3) = 1.31 cu. yd.
WEIGHTS
Kilo-grams
Pounds (avoir.)
Metric tons
Long tons
Metric tons
Short tons
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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