Geology and Ore Deposits of the Zimapán Mining District, State of Hidalgo Mexico

By FRANK S. SIMONS *and* EDUARDO MAPES V.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 284

Prepared in cooperation with the Instituto Nacional para la Investigación de Recursos Minerales of Mexico, under the auspices of the Technical Cooperation Administration of the Department of State

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1956

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C.

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GEOLOGY AND ORE DEPOSITS OF THE ZIMAPAN MINING DISTRICT, STATE OF HIDALGO, MEXICO

By FRANK S. SIMONS and EDUARDO MAPES V.

ABSTRACT

The Zimapán lead-zinc-silver district is near the town of Zimapán, an old mining center of several thousand inhabitants on the Pan American Highway 207 kilometers north of Mexico City, in the western part of Hidalgo, southeast-central Mexico. The district has a maximum relief of about 1,500 meters from the bottom of the Río Tolimán canyon to the top of the Sierra de El Monte. The climate is warm and dry, and vegetation and landforms are typical of the semiarid central plateau of Mexico.

The rocks range in age from Late Jurassic to Recent. They include, from oldest to youngest: an unknown but great thickness of thin-bedded blackish-gray phyllitic shale and limestone intercalated by thin beds of dark limestone of Kimmeridgian(?) and Portlandian age; thin-bedded gray limestone with tabular lenses and nodules of chert, some thick beds of fossiliferous limestone, and minor calcareous and sandy shale of Neocomian(?) to Cenomanian age; thin-bedded gray limestone and buff calcareous shale of Turonian to Maestrichtian age; the poorly sorted El Morro fanglomerate, composed largely of angular fragments of Upper Cretaceous rocks, of Oligocene(?) age; the Las Espinas andesitic and basaltic lava flows with a few dacite flows and subordinate tuff and agglomerate of late Oligocene(?) to early Pliocene(?) age; the very coarse Zimapán and Daxi fanglomerate, composed almost entirely of pebbles and cobbles of limestone of Early Cretaceous age cemented by caliche, of probable Pleistocene age; and terrace deposits and alluvium of Pleistocene to Recent age. Contacts between the Mesozoic rocks seem to be conformable and, in general, gradational. A strong angular unconformity separates the Cretaceous sedimentary rocks from the overlying Tertiary rocks.

The layered rocks are intruded by dikes of rhyolite, quartz latite, latite, trachyte, dacite, andesite, vogesite, granophyric basalt, and olivine basalt. Rhyolite porphyry, rhyolite felsite, quartz-latite porphyry, hypersthene-hornblende andesite, and augite diabase occur in small irregular intrusive masses. The most significant intrusive rock, in regard to the ore deposits, is monzonite, which crops out in several areas.

The Mesozoic rocks are characterized by northwestward-trending folds which range from large open structures to isoclinal overturned or recumbent folds, both large and small. Axial planes of most folds dip southwest. The only thrust fault recognized was the Daxi thrust, which brings gently dipping overturned(?) Lower Cretaceous limestone over tightly folded Upper Cretaceous shale. Fracture cleavage was formed concomitantly with folding in parts of the Upper Cretaceous shale and limestone, and to lesser extent in cherty sections of the Lower Cretaceous limestone. The deformation of the Cretaceous rocks is believed to have occurred during a single orogenic period in latest Cretaceous and earliest Tertiary time.

The Tertiary rocks, in contrast, show only minor folding, tilting, or faulting. The most important structures formed after the Early Tertiary are high-angle normal faults. Of these, the Malacate fault is by far the largest; it has been traced with varying degrees of accuracy for about 15 kilometers diagonally across the entire area mapped. The throw is estimated to be considerably in excess of 500 meters. The Sierra de El Monte north of Zimapán owes at least a part of its height to uplift along this fault.

Dynamic metamorphism has produced some slaty cleavage in the Upper Cretaceous shale and minor recrystallization in the highly deformed Lower Cretaceous limestone. Igneous metamorphism produced irregular tactite aureoles around intrusive bodies in the Lower Cretaceous limestone. Chert has been converted to silicates in places. Dikelike sheets of tactite are common in the Carrizal mining area. A notable proportion of the sulfide ore is associated with tactite. Silicification and marmarization were noted in a few areas. Jasper is a very uncommon associate of the ores. Igneous rocks have undergone propylitization and sericitization.

Mining began at Zimapán in 1632. Total silver production appears to have been worth at least 10 million pesos (equivalent to about the same number of dollars). Lack of data precludes any estimate of total lead production, but from 1945 to 1949 the district probably yielded some 15,000 tons of lead and about the same amount of zinc. The great bulk of production in recent years has come from the Lomo de Toro and Los Balcones mines; production from the El Monte mines was significant from 1947 to 1949.

The ore deposits have a close spatial relationship to monzonitic intrusives. Two general structural types of deposits are recognized: replacement in limestone, and veins along faults in shaly limestone, fanglomerate, volcanic rocks, and monzonite. The replacements occur as "mantos" (tabular bedding replacements) and "chimneys" (elongate bodies of irregular cross section which may transect bedding). Chimneys have yielded most of the ore mined in the district; very little production has come from the veins.

Deposits of both pyrometasomatic and mesothermal types are present, although the latter predominate. Pyrometasomatic (tactite) deposits are characterized by sphalerite, pyrite, galena, arsenopyrite, pyrrhotite, chalcopyrite, jamesonite, and meneghinite in a gangue of tactite minerals. The mesothermal deposits contain sphalerite, galena, and pyrite as the only abundant sulfides; the only common gangue mineral is calcite.

Ores were emplaced after the accumulation of the Tertiary formations (El Morro fanglomerate and Las Espinas volcanic rocks), and they may thus be dated as late Miocene (?) or early Pliocene (?).

The deposits have been oxidized to depths exceeding 200 meters. The oxidized ores are unique in that the predominant valuable mineral is plumbojarosite, which occurs in enormous masses totaling many thousands of tons. Silver may occur in the mineral argentojarosite mixed with the plumbojarosite.

Excellent possibilities for discovery of new ore deposits or extensions of known deposits exist in the Carrizal group and, to a lesser extent, in the El Monte group of replacement deposits. The vein deposits offer little hope of significant production.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The Zimapán (see-mah-PAHN) mining district is in the western part of Hidalgo, in southeast-central Mexico about 153 kilometers north of Mexico City (fig. 1). Zimapán, a town of several thousand inhabitants and the center of mining activity in the district, is at approximately 20° 45′ N. lat and 99° 23′ W. long. The Pan American Highway, a paved all-weather road between Laredo, Tex., and Mexico City, passes through Zimapán at a point 207 kilometers north of Mexico City. A good all-weather road extends 15 kilometers northwestward from Zimapán to the Lomo de Toro and Los Balcones mines, and another road, rough but passable, leads in the same general direction to the San Pascual-Poder de Dios mine area. A rough truck road extends northward some 3.5 kilometers into the Sierra de El Monte, and short roads lead southward from the main highway to the settlements of Temoté and Los Remedios. In addition to the main Pan American Highway, a paved cutoff extending from San Pedro southward to a point near Los Remedios eliminates the necessity of passing directly through Zimapán. Many trails are found throughout the area; the north slope of El Monte would be virtually inaccessible without them. Transportation to and from the hinterland is almost completely dependent on burros.

A recently completed oiled-gravel airstrip about 1,000 meters long makes it possible for light aircraft to land near the town. There are no rail communications; the nearest railhead is Huichapan, 88 kilometers by road southwest of Zimapán.

Zimapán is the only town of appreciable size in the area, but there are a number of small settlements, including Las Verdosas to the north, San Pedro to the northeast, Los Remedios to the southeast, Temoté and Santiago to the south, and El Detzaní, El Dedhó, Puerto Angel, and La Ortiga to the northwest. The largest of these settlements, Las Verdosas, has only a few hundred inhabitants. In general, the area is sparsely inhabited.

TOPOGRAPHY

Zimapán lies near the center of a small mountain-rimmed valley at an altitude of 1,770 meters. The surrounding mountains rise to a maximum altitude of 2,684 meters in Cerro de San Nicolás, a high peak almost due north of town in the eastward-trending range known locally as the Sierra de El Monte, which forms the north rim of the valley (pl. 1). The east rim consists of a group of volcanic hills, in which the lowest pass is Puerto de La Estancia through which the Pan American Highway runs. These hills merge westward into the Sierra de El Monte and they continue southward beyond the area mapped. A second group of volcanic hills forms the south boundary of the valley. To the northwest these hills are succeeded by the limestone mass of Cerro de Daxi with which they form what is known as the Sierra de Daxi.

The Zimapán valley is drained by the Río Tolimán, which heads at Puerto de Xithá some 11 kilometers south of Zimapán. The river follows a general north-northwest course and finally joins the Río Moctezuma about 15 kilometers north-northwest of town. At the northwest edge of the area mapped the altitude of the river bottom is 1,160 meters, the lowest point in the area. The maximum relief within the area is thus about 1,525 meters. In its upper reaches the Río Tolimán flows in a broad valley, but farther north it has cut a tremendous gorge which begins west of Zimapán and extends to the confluence of the Río Tolimán and Río Moctezuma. This gorge reaches a maximum depth of more than 1,200 meters, and in places its walls are nearly vertical cliffs 180 to 230 meters high. In the vicinity of one of the mining areas, the gorge has been called Barranca de Tolimán and will be referred to as such in various parts of the report. Barranca de Tolimán is a truly remarkable physiographic feature, difficult to describe and virtually impossible to photograph. We believe that anyone interested in erosional features who may at one time or another pass through Zimapán will find his time well spent in a visit to the area. The road to the Lomo de Toro and Los Balcones mines leads directly to the barranca, and views from various parts of the road are magnificent.

In general, the mountainous parts of the area are extremely rugged. On Cerro de Daxi and on the north side of El Monte, slopes of 40°–45° are common and local relief approaches 750 meters. In the vicinity of Barranca de Tolimán, local relief is greater and a considerable part of the terrain is inaccessible because of cliffs. The principal topographic features are shown roughly in plate 1.

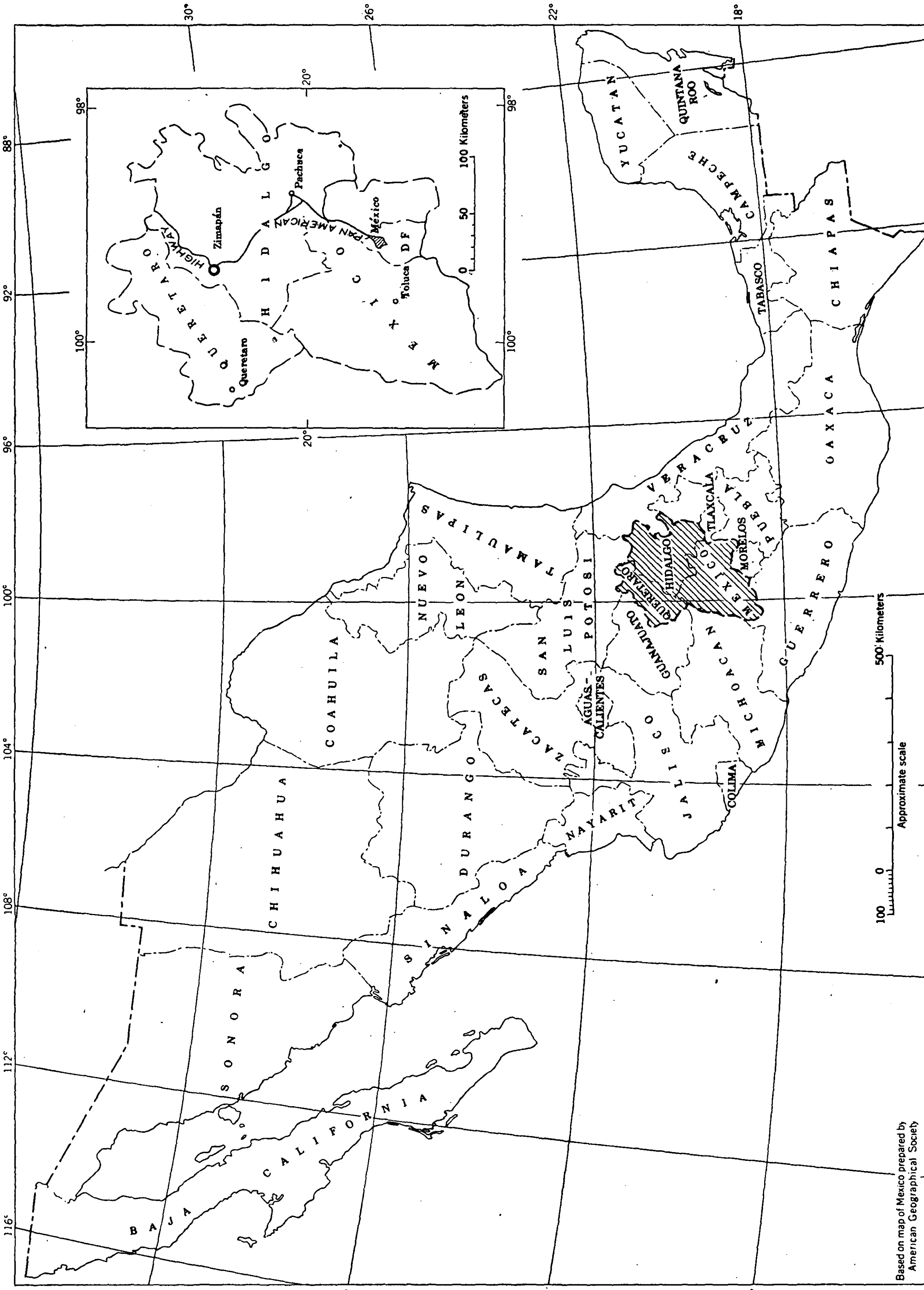

FIGURE 1.—Index map showing location of Zimapán mining district, State of Hidalgo, Mexico.

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CLIMATE AND VEGETATION

The Zimapán district is near the eastern edge of the central plateau of Mexico and has a climate similar to that of most of the plateau, which in general is warm and dry. The average annual temperature at Zimapán is 19° C, with extreme temperatures ranging from 39.2° C to −0.1° C. Summer days are generally hot, but nights are always cool.

Nearly 90 percent of the precipitation falls during the rainy season, from May until October, when severe thunderstorms are common. Rainfall on the north slope of El Monte is much greater than at Zimapán itself, although no exact figures are available. This higher rainfall is presumably caused by the interruption by the high Sierra de El Monte of moisture-bearing winds moving southwestward from the coastal plain. Snow is rare; the first snowfall in many years was recorded on Christmas Day of 1947, when 5 cm fell in Zimapán and considerably more fell in the higher areas. Frost occurs on an average of 7 days per year. Climatological data are summarized in the table below.

Climatological data for Zimapán, 1921–35

[Data from Atlas Climatológico de México, 1939]

Month	Average daily temperature		Monthly precipitation	
	°C.	°F.	Millimeters	Inches
January	16.0	60.8	9.9	0.39
February	18.2	64.6	2.2	.09
March	20.3	68.5	5.6	.22
April	21.4	70.5	9.3	.37
May	21.6	70.8	35.9	1.41
June	20.5	68.9	77.9	3.06
July	20.2	68.4	41.0	1.61
August	20.0	68.0	47.0	1.85
September	19.3	66.7	87.0	3.42
October	18.5	65.3	41.7	1.64
November	16.4	61.5	8.6	.34
December	15.5	59.9	7.0	.28
Total			373.1	14.7
Average annual temperature	19.0	66.2		
Maximum	39.2	102.6		
Minimum	−0.1	31.8		

Only one perennial stream, the Río Tolimán, flows through the district, and even it disappears locally during the last part of the dry season. The rest of the streams carry water only during and shortly after rainstorms. Zimapán derives its water supply from a well at the north edge of the town. A small spring flows at the east end of El Monte, and other springs are known near El Detzaní, Hacienda de La Estancia, and at several places on the divide between the Río Tolimán and the Río Moctezuma. Numerous small farms on terraces along the Río Tolimán are irrigated, but most of the scant agriculture in the area depends on rainfall. The chief crop of the district is maguey, a species of agave whose milky sap is fermented to produce the mildly intoxicating beverage called pulque; small amounts of corn, beans, tomatoes, bananas, sugarcane, avocados, and limes are also produced. Great numbers of goats and sheep and a few cattle are raised throughout the area.

With the exception of the north slope of El Monte, the country is relatively barren and has the same general appearance as much of the Basin and Range province of the western United States and northwestern Mexico. The Zimapán valley and its surrounding hills support a typically desert flora; among the more common plants are mesquite, pricklypear, barrel cactus, organpipe cactus, ocotillo, narrow-leafed maguey (agave striata), pricklepoppy, and California-poppy. Locally, dense growths of "uña de gato" (catclaw) interfere considerably with fieldwork. Along the crest of El Monte are numerous pines of at least two species, and madrone, basswood, wild cherry, and currant are found locally. The north slope of El Monte is covered by a dense jungle growth with many vines and ferns. Wild flowers are abundant, especially in El Monte, where morning-glory, penstemon, bouvardia, salvia, and scarlet pimpernel are abundant. Many of the larger trees and shrubs in the mountain areas have been cut for use in making charcoal, the only relatively cheap fuel available in the region, and it would seem to be a matter of only a few decades until nearly all the large trees are gone. Reforestation has been attempted with some success in a few localities.

FIELDWORK AND ACKNOWLEDGMENTS

The geologic investigation that led to the present report was undertaken as a cooperative project between the United States Geological Survey, under the auspices of the Technical Cooperation Administration of the Department of State, and the Instituto Nacional para la Investigación de Recursos Minerales of the Mexican Government. Certain laboratory work and facilities were contributed also by the Instituto de Geología of the Universidad Nacional Autónoma de México. The Zimapán district was chosen with the hope that mining might be stimulated there gradually, in order to supplant an eventual decrease in mining activities in the nearby Pachuca-Real del Monte district, where a supply of skilled miners might become available as time went

on. The writers wish to acknowledge the continued support, guidance, and assistance given during field and laboratory work and the preparation of the report by Dr. Jenaro González Reyna, chief geologist of the Instituto Nacional para la Investigación de Recursos Minerales, by Sr. Ing. Ricardo Monges López, director of the Instituto de Geología, and by Carl Fries, Jr., chief of the Geological Survey office in Mexico.

The fieldwork was carried out during the 8-month period from February to September 1948. Approximately 5½ months were spent studying the areal geology, and 2½ months studying the ore deposits. Field mapping was done entirely on vertical aerial photographs taken by the Comisión Cartográfica, Ministerio de Defensa Nacional of the Mexican Government. The photographs were on a scale of approximately 1:16,500. The triangulation net for the base map was established in the field by Kenneth Segerstrom of the U. S. Geological Survey, and triangulation computations were later completed by the writers. Intermediate altitudes were determined by aneroid barometer. The writers compiled the base map from the aerial photographs by means of the radial-line method. The junior author spent several weeks in August 1953 in a review of new mine developments and brought up to date the maps of the Lomo de Toro and Los Balcones mines.

We acknowledge with pleasure the many kindnesses and helpful cooperation of the people of the district. Our thanks are especially due to Sr. Adolfo Lángenscheidt for maps of part of the Lomo de Toro mine, reports, and many other kindnesses; to Sr. Arturo Ramsden, superintendent of the Lomo de Toro mine, for unfailing cooperation at all times; to Sr. Jorge Preisser for maps of the Los Balcones mine workings; to Sr. Ing. Jesús Becerril, of the Compañía Minera La Llave, for several reports and maps; and to Sr. Ing. Aldo Cicognani for several reports and maps of the La Paz mine. We are also indebted to the Compañía Minera Fresnillo of Fresnillo, Zacatecas, for permission to use certain maps of the El Monte mining area and for information on ore deposits being explored. Richard Tighe and Charles Rabling of the Compañía Minera Fresnillo were most helpful during our work at El Monte. Other acknowledgments for specific aid are made elsewhere in this report.

SCOPE OF THE STUDY

Although the study of the Zimapán district was undertaken primarily to evaluate the lead-zinc-silver deposits, a considerable amount of time was devoted to deciphering the structure of the district as a whole and to a petrographic study of the rocks of the area. About 200 square kilometers were mapped geologically. Nearly all accessible workings, whether in operation or not, were entered and most of the workings were mapped roughly. All the producing mines were mapped in some detail. We hope that these general studies of a district on which published information has heretofore been virtually nonexistent will be of some aid in more detailed work in the future.

PREVIOUS GEOLOGIC WORK

All published papers mentioning the Zimapán mining district are listed in the bibliography, and some are followed by brief annotations. Literature on the district is very scarce and most of the papers are too generalized or sketchy to be of much value to people interested in mining the ore deposits.

With the exception of many private mine examinations whose results are not available to the public, the only published field studies of the Zimapán district are of a short reconnaissance of the mining areas carried out in 1919 by a commission of the Instituto de Geología of Mexico under the direction of Teodoro Flores (1924), and of a contact deposit by Lindgren and Whitehead (1914).

GENERAL GEOLOGY

The rocks of the Zimapán district range in age from Kimmeridgian(?) or late Jurassic to Recent (see pl. 2.). Fossils were found only in the Mesozoic strata, and the ages of the overlying formations have been inferred indirectly.

The layered rocks mapped consist of shale, limestone, shaly limestone, and minor quantities of mudstone and sandstone of Mesozoic age (shale and limestone of Late Jurassic age, limestone of Early Cretaceous age, limestone and shale of Late Cretaceous age); fanglomerate and overlying andesitic and basaltic volcanic rocks of Tertiary age (El Morro fanglomerate and Las Espinas volcanic rocks); fanglomerate of Pleistocene age (Zimapán and Daxi fanglomerates); and terrace deposits and alluvium of Recent age (see plate 7*A*). The thicknesses of the Tertiary rocks are known within fairly narrow limits, but those of the Jurassic and Cretaceous rocks are uncertain and are estimated only roughly. A diagrammatic columnar section of the layered rocks is given in figure 2.

Igneous rocks include dikes of rhyolite, quartz latite, dacite, trachyte, latite, andesite, and several varieties of basalt; irregular small masses of rhyolite porphyry, rhyolite felsite, quartz-latite porphyry, hypersthene-hornblende andesite, and augite diabase; and a large body and several small masses of monzonitic rock. Along the contacts of the monzonitic bodies a great

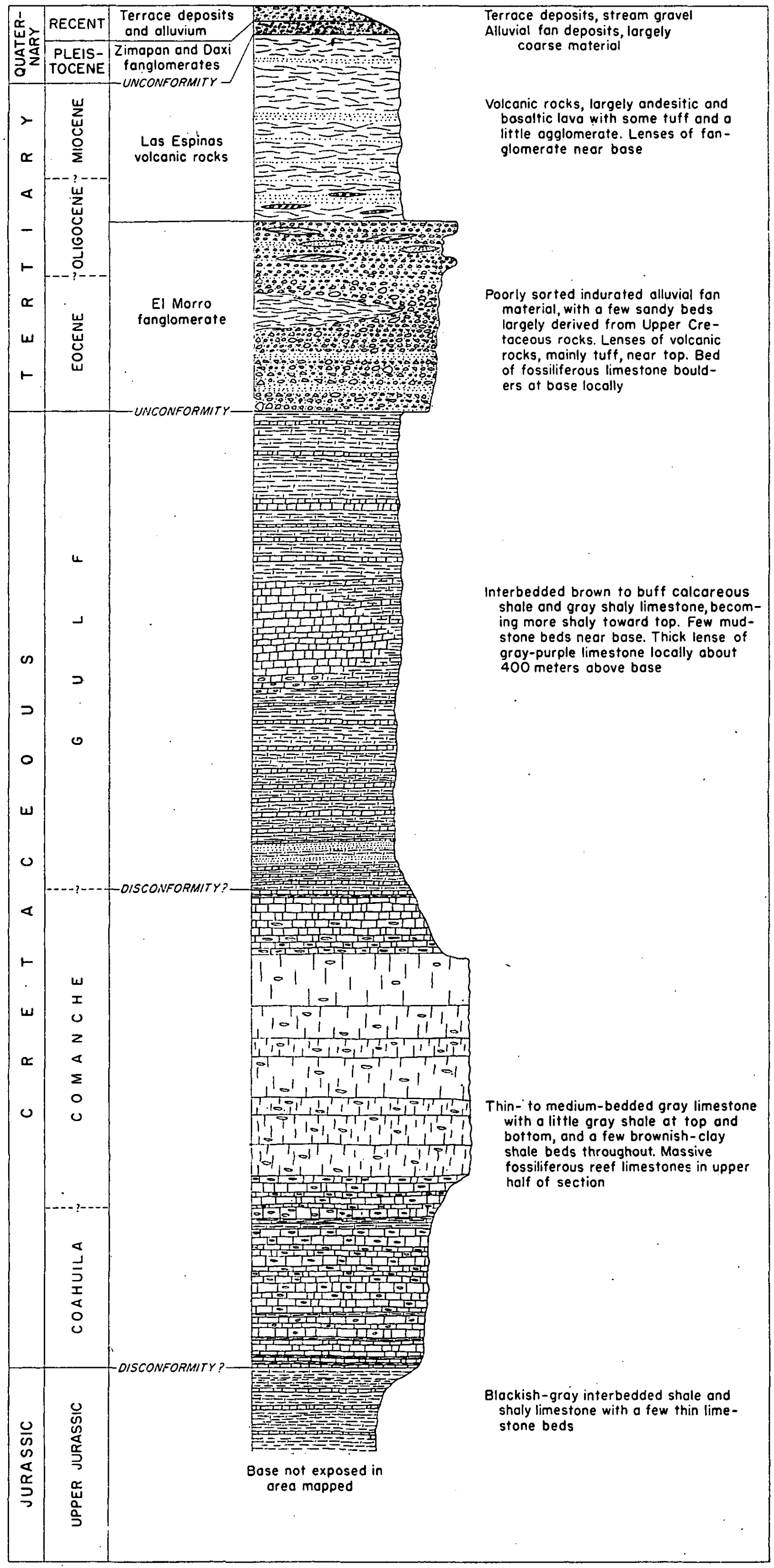

FIGURE 2.—Columnar stratigraphic section of the Zimapán district.

variety of metamorphic rocks has been formed, including several types of hornfels and tactite, as well as garnetite and diopsidite. Silicification and marmarization have been minor metamorphic processes.

SEDIMENTARY ROCKS

JURASSIC SYSTEM—UPPER JURASSIC SHALE AND LIMESTONE

The oldest rocks in the area consist of a sequence of very thin beds of blackish-gray impure phyllitic shale and limestone, intercalated by a few thin beds of relatively pure limestone. These rocks lie conformably below the Lower Cretaceous limestone. They were not studied in detail. Maximum development of the sequence is along the lower course of the Río Tolimán, beginning about 3 kilometers north of the Los Balcones mine and extending to the north edge of the area mapped. The contact is well exposed where it is crossed by the river; there it is gradational within a narrow stratigraphic range.

Very similar beds are exposed in the first 200 meters of the Chalma adit of the San Francisco mine, in the extreme northeast corner of the area mapped. Inasmuch as these and the Río Tolimán beds are rather distinctive in appearance, being completely unlike any of the younger rocks, and as they have similar stratigraphic relationships, there is little doubt that they are correlative.

A small collection of poorly preserved fossils was taken from locality 1 (see pl. 2) by Carl Fries, Jr., W. E. Humphrey, Manuel Maldonado K., and Kenneth Segerstrom. The presence of an aptychus, several uncoiled ammonites, and a lytocerid ammonite was noted by R. W. Imlay and John Reeside, who examined the collection. Imlay points out that such a combination, in the Gulf region of the southern United States, may occur in the Lower Cretaceous or in the Portlandian stage of the Upper Jurassic. Humphrey noted the presence of *Mazapilites* at the locality; this genus of ammonites is characteristic of the upper part of the Kimmeridgian stage of the Upper Jurassic (Imlay, 1952, chart 8C). The rocks are similar to the Tamán formation of Kimmeridgian and probable Portlandian age, whose type locality is about 75 kilometers northeast of the Río Tolimán locality (Heim, 1940, p. 334), and the fossil evidence seems to favor correlation of the two formations. The shale and limestone therefore seem to be mainly of Late Jurassic age.

CRETACEOUS SYSTEM

LOWER CRETACEOUS LIMESTONES

DISTRIBUTION

Lower Cretaceous limestone makes up virtually the entire Sierra de El Monte. It occupies the entire northeast half of the area mapped (about 90 square kilometers), and extends without any break from a point about halfway between San Pedro and Los Remedios northwest to beyond Cerro de Los Lirios, a distance of 17 kilometers. A small upfaulted block of this limestone about one kilometer southwest of Cerro de La Estancia, and the limestone mass of Cerro de Daxi, are the only exposures in the area mapped that are completely isolated from the main area of outcrop.

Exposures of the Lower Cretaceous limestone are good everywhere except on the north slope of the Sierra de El Monte, where heavy vegetation and deep soil obscure much of the bedrock. In the higher parts of the range the formation supports a fairly heavy pine forest; elsewhere the vegetation is dominated by agave, mesquite, scrub oak, piñón, and various cacti. The limestone is extremely resistant to erosion and erodes characteristically to steep or even cliffy slopes. Most of the higher peaks in the district are carved from Lower Cretaceous limestone; these include the highest point in the area, Cerro de San Nicolás in the Sierra de El Monte, as well as the massive crag of Cerro del Juaxidó and the imposing Cerro de Los Lirios, which rises to 2,365 meters above sea level.

THICKNESS

The complex folding of the Lower Cretaceous limestone throughout its area of outcrop, together with the apparent lack of recognizable marker beds, precludes any reliable estimate of its thickness. In the Sierra de El Monte the limestone is invariably tightly or even isoclinally folded, so that the apparent great thickness measurable in traversing the range across the regional strike, along a northeastward-trending line, may be largely illusory. The apparently rather thick vertical section exposed in the Carrizal mine area to the northwest of Zimapán is a result, in considerable part at least, of many repetitions due to widespread, nearly horizontal isoclinal folding.

A fairly reliable minimum thickness can be measured across the southwest limb of the Puerto Angel anticline southwest of Cerro del Juaxidó. At that locality about 600 meters of essentially unfolded beds are present, but the full thickness must be greater, as the base of the formation is not exposed. The southwest end of structure section *EE'* in plate 2 crosses the Carrizal area where the structure is also such that a minimum thickness can be measured. From this rather hypothetical section, the thickness appears to be about 500 meters, but again the base is not exposed. A very rough measurement of the maximum thickness was made by traversing the Río Tolimán canyon from the top of the formation, beginning at the Malacate fault (p. 32), to the base, 3½ kilometers north-northeast. The maximum thickness exposed in the canyon is about 1,170 meters, but this figure is almost surely too high for the true thickness, as the beds are repeated by isoclinal folding and many minor reversals of the predominant south-southwestward dip, factors that were not taken into consideration. The great width across the strike exposed in the Sierra de El Monte (at least 6 kilometers), however, suggests that in spite of the ubiquitous isoclinal folding, the maximum thickness as estimated from the Río Tolimán traverse is probably not much greater than the true thickness. A reasonable estimate of the true thickness, considering all the scanty and inconclusive lines of evidence, would be about 1,000 meters.

STRATIGRAPHIC RELATIONS

The Lower Cretaceous limestone includes all the thin- to thick-bedded relatively pure limestone and limestone with chert that lies between the underlying sequence of blackish-gray shale and limestone described above, and the overlying Upper Cretaceous strata. Both the upper and lower contacts are without pronounced angular unconformity, but an erosional disconformity is present at the lower contact and may be present at the upper contact. Near San Pedro the Lower Cretaceous strata are overlain unconformably by the El Morro fanglomerate of Tertiary age, and by Tertiary volcanic rocks. They are also overlain locally by small patches of Quaternary alluvium.

LITHOLOGY

The Lower Cretaceous limestone consists of beds of medium-gray to dark-gray nearly pure limestone and limestone with chert, as well as subordinate moderate-red to grayish-purple-red shaly limestone and a little grayish-red sandy limestone. Purple limestone and thin-bedded reddish shaly limestone form the low knob of Cerro del Piñón, and red to maroon platy sandy limestone crops out northwest of San Pedro. A thin bed of phyllite occurs on the hill northeast of El Detzaní. Bedding is almost invariably regular, although slightly wavy bedding is not uncommon. Limestone beds average less than 10 cm in thickness, although a few beds range from 2 to 5 meters in thickness. One of the most prominent beds, which is 2 to 3 meters thick, crops out at the portal of the San Rafael Viejo adit at the Los Balcones mine.

Prominent, although quantitatively very minor, beds within the area in which Lower Cretaceous rocks outcrop consist of brownish-gray calcareous shale, which contains a few sandy layers as much as 5 cm thick, and many purple phyllitic partings. The shale weathers a conspicuous light brown to reddish brown. The low passes of Puerto Colorado, Puerto del Atole, and Puerto del Jarro, through which the trail from Zimapán to the El Monte mining area leads, are eroded in a section of calcareous shale 150 meters thick. A few thin gray limestone beds occur in the brownish-gray lustrous calcareous shale of the pass of Puerto Angel.

Several thick fossiliferous limestone beds, in part brecciate, are conspicuous features of the Lower Cretaceous limestone. These reeflike beds crop out on the steep slope west of the Zimapán-El Monte trail between Cerro de Caravantes and Las Ventoleras, along the crest of the Puerto Angel anticline, in Barranca del Malacate just west of El Dedhó, and to a lesser extent along the canyon leading north from Puerto Angel. The full thickness of the largest reeflike bed, that of the Cerro de Caravantes-Las Ventoleras belt, cannot be estimated, for only the upper surface of the bed is exposed on a dip slope in the area of maximum development, but the bed in Barranca del Malacate is known to attain a thickness of at least 25 meters locally. In the vicinity of the thick beds, the enclosing thinner limestone layers are highly contorted, owing to adjustments to the movement of the massive beds during the period of intense folding; bedding slips and local faulting are common.

The thick reeflike beds consist of medium- to coarse-grained gray or dark-gray limestone containing limestone breccia fragments and numerous fragments of corals, pelecypods, algae, and a few gastropods. Irregular knots of black chert are abundant throughout these beds. The thinner beds above and below these thick beds invariably contain many thin tabular bodies of black chert.

Dark-gray to black chert is an abundant constituent of the Lower Cretaceous limestone, and seldom can a thickness of more than a few tens of meters be found that is free of chert. The thickest chert-free limestone section seen was on the low hill northeast of El Detzaní; there steeply dipping, isoclinally folded limestone beds crop out for nearly 1,000 meters across the surface. Chert occurs as thin persistent beds, as series of isolated thin lenses along a single limestone bed, as series of irregular lenses that may not lie within a single limestone bed but are usually restricted to a thin sequence of beds, and less commonly as highly irregular knots and nodules that are usually restricted to thick limestone beds. Most of the lenses seen in plan were elliptical; a few nearly circular lenses resembled a discus. The chert commonly weathers yellow brown, and on gentle slopes a red soil may develop on limestone with chert, as has happened near Las Ventoleras and east of the Carrizal mining area.

Excellent exposures of Lower Cretaceous chert-bearing limestone can be seen in a road-metal quarry 1.4 kilometers south of San Pedro. The beds there consist of flat-lying gray thin-bedded limestone containing perhaps 10–15 percent of chert by volume. Most of the chert occurs as lenses lying parallel to the bedding of the enclosing limestone. The lenses commonly have rounded terminations but a considerable number terminate in knife edges (fig. 3*A*). A few chert nodules of more irregular form transect the bedding through a stratigraphic range of as much as 10 cm (fig. 3*B*). In addition to lenses, chert also occurs as thin uniform layers interbedded with limestone. Some of the thin chert beds are strikingly persistent; one, averaging about 1.5 cm thick, is exposed for a length of more than 15 meters in the quarry face.

Chert is confined to certain horizons. A limestone bed that contains chert in one place contains chert throughout its exposure length, while the overlying and underlying limestone beds are completely chert-free. Moreover, the size and shape of the chert lenses along a given horizon are similar everywhere along that horizon. Figure 3*C* shows two of a remarkable series of at least 20 chert lenses along a particular horizon, all characterized by rounded terminations, slight transection of bedding, and notable upward convexity.

In a large number of chert lenses the relict limestone bedding is clearly visible. Figure 3*B* is an excellent example of the preservation of a number of limestone bedding planes in an irregular chert nodule. There seems to be little doubt that the bulk of the chert has formed by replacement of limestone. Figure 3*A* shows two thin chert lenses that have cores of black chert, a thin rind of limestone partly converted to chert, and relict bedding visible in both core and rind. Convincing evidence of the time of formation of the chert lenses with respect to the enclosing limestone was not found at Zimapán. White has described a similar occurrence of chert at Soyatal, Querétaro, and concludes, on strong evidence, that the chert there is diagenetic in origin, being formed either very shortly after the deposition of the limestone it replaces or deposited directly on the sea floor (White, 1947). The only strong suggestion of diagenetic origin seen in the field at

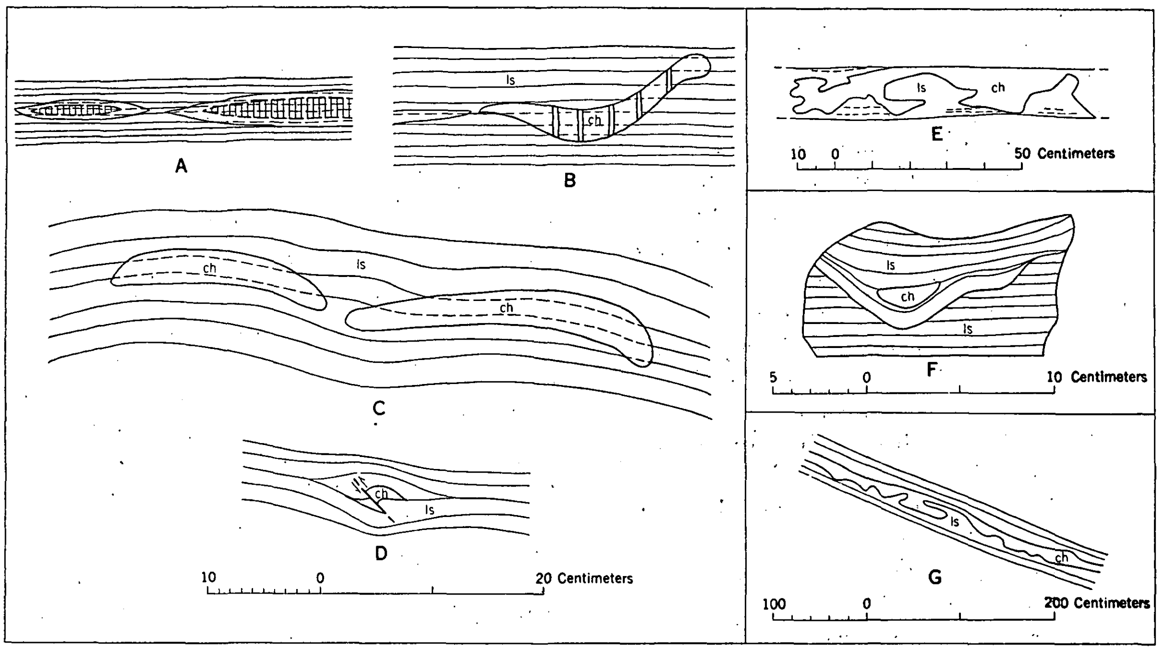

FIGURE 3.—Examples of the occurrence of chert in the Lower Cretaceous limestone. *A–D*, quarry 1.4 kilometer south of San Pedro. *A*. Black chert lenses (crosshatched) with gray transition rim of partly silicified limestone. *B*. Irregular chert nodule transected by veinlets of calcite, probably along contraction cracks. *C*. Two of a series of chert lenses along the same horizon; all lenses are characteristically concave in the same direction, probably downward in the section, although position of the beds cannot be determined. *D*. Stubby chert lens offset by small reverse fault; suggestion is that chert nodule and overlying limestone lens were deposited in a tiny syncline. Faulting probably took place soon after deposition of chert, as overlying beds are not cut by fault. If this is so, then strong drag of chert along fault indicates that chert was in somewhat plastic condition. Lack of evidence of slippage in enclosing limestone beds suggests that these too were only semiconsolidated. Limestone bedding is well preserved in chert nodules of *A*, *B*, and *C*. *E*. Highly irregular chert layer, just northeast of Zimapán airport. Bedding of limestone has been completely obliterated in the chert and locally within the limestone near the chert contact. *F*. Chert lens, probably syngenetic, deposited in channel of local unconformity in limestone. El Monte mining area. *G*. Irregular chert layer, between Lomo de Toro and Balcones mines. Here, as elsewhere, irregularities of chert layers tend to be confined to one surface of the layer; scanty evidence suggests that the bottom surface is usually the irregular one.

Zimapán is given by the occurrence illustrated in figure 3*D*. A small stubby chert lens is dislocated by a reverse fault that does not cut the underlying or overlying beds. The chert and the overlying limestone lens show considerable drag along the fault and were probably in a semiconsolidated condition when faulting took place. The failure of the fault to cut the overlying beds, the thinning of the superjacent beds over the slight hump formed by faulting, the plastic deformation of the chert, and the lack of evidence of deformation elsewhere in the quarry suggest that the chert was deposited and faulted before the overlying beds were deposited. The chert lens may have been deposited directly on the sea floor in a small wrinkle, but there is no evidence that it formed by replacement of limestone.

A small amount of chert appears to be syngenetic and was probably deposited directly on the sea floor. Figure 3 *F* shows a small thick chert lens that was deposited in a channel in limestone. Some of the thin persistent beds of chert may also have been deposited directly without replacing limestone. It would be difficult to explain the origin of an extensive continuous bed of chert 1 to 2 cm thick by replacement of limestone, especially when in the same outcrop the chert that has clearly formed by replacing limestone is seen to occur as fairly irregular discontinuous lenses that commonly transect bedding to some extent.

Many chert lenses in the Lower Cretaceous limestone are asymmetrical with regard to their equatorial planes, in that one surface may be almost smooth and the other irregular. (See figure 3 *F* and *G*.) In any given outcrop the relative position of these surfaces is remarkably constant. Scanty evidence suggests that the irregular surface is the lower one stratigraphically.

Only one specimen of unmetamorphosed Lower Cretaceous limestone was examined under the microscope. A thin section of brownish-gray calcareous shale from Puerto del Atole revealed a few tiny angular quartz grains set in a pale-brown matrix of thin irregular carbonate stringers interleaved with extremely fine grained irresolvable argillaceous material containing a few minute plates of muscovite.

Two specimens of limestone were dissolved in dilute hydrochloric acid and the residues were examined under the microscope. The first, a medium-grained dark-gray limestone from near the Todos Santos mine in the Carrizal mining area, contained 1.2 percent of insoluble material, which consisted largely of quartz and a little carbonaceous matter. A medium light-gray sample from the thick fossiliferous reeflike bed near Las Ventoleras had 0.9 percent of insoluble material, all of which appeared to be quartz.

AGE

The Lower Cretaceous limestone of the Zimapán district resembles the Cuesta del Cura limestone (upper Albian and lower Cenomanian) of northern and central Mexico, and also the upper lithologic unit of the Tamaulipas limestone (upper Aptian to lower Cenomanian) of northeastern Mexico; it resembles less strongly the lower part of the El Abra limestone (upper Albian and lower Cenomanian) of east-central Mexico. The lower part of the limestone at Zimapán is lithologically similar to the La Peña formation of northern Mexico, in that it is dark gray, thin bedded, and interbedded with black chert. (See Humphrey, 1949, p. 107–109; Imlay, 1936, p. 1125; 1944a; 1944b, p. 1093.)

Fossils were collected from 14 localities within the outcrop area of Lower Cretaceous strata, first by the writers and later by Kenneth Segerstrom and Carl Fries, Jr., of the U. S. Geological Survey. The collections were studied in part by the late F. K. G. Mullerried of the Instituto de Geología of Mexico, by Yvette Eternod of Petróleos Mexicanos, by R. W. Imlay of the U. S. Geological Survey, and by J. W. Wells of Amherst College. The thick fossiliferous limestone bed exposed in Barranca del Malacate just northwest of El Dedho (locality 2 in pl. 2) yielded *Titanosarcolites?* sp., an undescribed new genus and species of Radiolitidae, and indeterminate species of Hexacoralla, Echinoidea, Foraminifera, Caprinidae, and *Ostrea*, according to Mullerried. This assemblage was dated by Mullerried only as post-middle Albian. Undescribed new species of *Tepeyacia?*, *Titanosarcolites*, and indeterminate species of Radiolitidae and Echinoidea were identified from locality 3 (pl. 2) on the south slope of Cerro del Muí, also by Mullerried, who assigned this fauna to the upper Turonian-lower Senonian on the basis of *Titanosarcolites*. Fossils from the overthrust block of Cerro de Daxi (locality 4 in pl. 2) were identified by Mullerried as *Toucasia texana* (Roemer), *Toucasia neoleonesa*, *Caprinuloidea?* cf. *C. multitubifera*, and indeterminate species of Monopleuridae, Radiolitidae, Caprinidae, Hexacoralla, Miliolidae, *Ostrea*, and *Nerinea*, and were assigned by him to a middle Albian age.

Mullerried considers *Toucasia texana*, *Caprinuloidea?* cf. *C. multitubifera*, and the Miliolidae as index fossils of the middle Albian. In assigning a middle Albian age to *Caprinuloidea*, Mullerried follows MacGillavry (1937). Palmer (1928), however, considered *Caprinuloidea* to belong to a Cenomanian fauna principally, some forms continuing on into the Turonian, and his opinion is supported by Imlay (1944a, p. 1012). The Miliolidae are abundant in the upper part of the El Abra limestone, which was dated by Muir (1936) as lower Cenomanian on the basis of the occurrence of *Pecten* (*Neithea*) *roemeri* Hill. They are probably not usable, therefore, as indicating a middle Albian age. The use of *Toucasia texana* as a middle Albian index fossil is also beset with difficulties. It seems possible that *Toucasia texana* may have a much greater range than that assigned by Mullerried; indeed, Carl Fries, Jr., of the Geological Survey, has found *Toucasia texana* and *Toucasia patagiata* associated with *Hippurites*, considered by Mullerried to indicate a Turonian age (Imlay, 1944a, p. 1019, 1026), in limestones between Cuernavaca and Cuautla in Morelos, along the Río Chinameca in the southern part of Morelos, and at Apaxco in the northern part of the Estado de México (written communication).

The genus *Titanosarcolites* has been found in Cuba in beds of Maestrichtian age (Habana formation) by MacGillavry (1937) and in the Kemp clay of Texas associated with the Maestrichtian marker *Sphenodiscus* (Stephenson, 1938, p. 1635). Mullerried has assigned an upper Turonian to middle Senonian age to *Titanosarcolites* of Chiapas, Mexico. The occurrence of *Toucasia* and *Titanosarcolites* (if Mullerried's identification of the very poorly preserved material be correct) in the same formation at Zimapán suggests that the range of both these genera may be rather long.

Several shale partings between thin limestone beds exposed 1 kilometer north of El Detzaní (locality 5 in pl. 2), in the western one of two large arroyos, yielded microfossils. A composite sample of these partings representing about 3 meters of strata was examined by Yvette Eternod of Petróleos Mexicanos, who submitted the following report on the fauna present and its stratigraphic range.

Microfauna	*Stratigraphic range*
Globigerina planispira Tappan, 1940	Cenomanian
Oligostegina sp.?	Cenomanian to Santonian
Globotruncana havanensis? Voorwijk, 1937	Upper Cretaceous
Globotruncana sp.	Upper Cretaceous

Other micropaleontologists workings with the Cretaceous in the southern United States and northern Mexico have indicated that the *Globotruncana* extend down into the Lower Cretaceous. This then means that the best age assignment that can be made for these beds is Cenomanian, either the top part of the Lower Cretaceous or the bottom of the Upper Cretaceous.

Fossils from 10 localities in the Zimapán district (numbered 6 to 15 in pl. 2), within the area mapped as Lower Cretaceous limestone, were examined by R. W. Imlay in 1952. The report is in part as follows:

Most of the fossils cannot be identified certainly below the rank of "Class". The ammonites are barely recognizable as such. The rudistids occur mostly in coquinas, although there are a few specimens that might be identified by a specialist. One rudistid (from a limestone bed two meters thick on the east side of the Piñón anticline about 5 kilometers northeast of Zimapán, at locality 6) belongs possibly to *Eoradiolites* and, if so, is more likely to be Albian in age than Cenomanian or Turonian. The gastropods belong mainly to the family Nerineidae and some belong to the genus *Nerinea*. This again suggests that the beds are older than Cenomanian, but does not prove it.

A coral fragment from a limestone bed on a ridge 1 kilometer north-northwest of El Detzaní (locality 7 in pl. 2) was examined by J. W. Wells, who reported on it as follows:

Budaia travisensis Wells 1933. Originally described from Buda limestone (Albian), central Texas; *B. felixi* Wells from Neocomian and Aptian of Venezuela and Trinidad may be the same. If one poor specimen of one species has any significance, this suggests Lower Cretaceous age.

J. S. Williams of the U. S. Geological Survey, points out that a number of palentologists, especially those who study ammonites, consider the Buda to be of early Cenomanian age.

The lower part of the limestone has not yet yielded any recognizable fossils. It is characterized by thin beds of dark-gray limestone interbedded with thin tabular lenses of black chert. Some interbeds of gray shale are also present. This part of the limestone is similar in lithology to the La Peña formation of Aptian age in northeastern Mexico (W. E. Humphrey, written communication) and may represent rocks of that age and possibly also of Neocomian age. No unconformities were recognized within the Lower Cretaceous series.

Despite the conflicting assignments of stratigraphic range to the poorly preserved faunal remains found in the limestone unit, the correlation of the Lower Cretaceous limestone of the Zimpán district with the Cuesta del Cura limestone, the Tamaulipas limestone, and the La Peña formation is reasonably certain when these age assignments are considered in conjunction with the lithologic similarity of the formation mentioned. Strata of Neocomian to Cenomanian age may therefore well be present.

UPPER CRETACEOUS LIMESTONE AND SHALE

DISTRIBUTION

Upper Cretaceous limestone and shale overlie conformably the Lower Cretaceous limestone and are the youngest of the pre-Tertiary rocks in the Zimapán district. The beds are exposed in two northwestward-trending belts. One is a relatively narrow strip extending some 7 kilometers northwestward from El Detzaní; the Lomo de Toro-Los Balcones mine road is cut in this belt from El Detzaní to Puerto de La Pared Blanca. Another and more extensive belt extends from Cerro del Potrero, 3½ kilometers south of Zimapán, to Cerro de Santa Elena, 15 kilometers northwest, and continues to the northwest beyond the area mapped. Most of the ridge between the Río Tolimán and the Río Moctezuma is composed of Upper Cretaceous rocks. These beds are also exposed in a small area near Hacienda de La Estancia, 7 kilometers northeast of Zimapán, at the east end of the Sierra de El Monte.

Exposures of the Upper Cretaceous strata are good throughout their outcrop area, although many of the more gentle slopes are covered with caliche. Areas occupied by these strata generally have gentle slopes and rounded topography; where protected by the more resistant El Morro fanglomerate, however, extremely steep slopes are common (pl. 7 *B*).

THICKNESS

The Upper Cretaceous strata are nearly everywhere so complexly folded that even the approximate total thickness cannot be estimated with any confidence. Northeast of Cerro de La Majada Grande an essentially unfolded, although steeply tilted, partial section is exposed, beginning at the mouth of the Río Tolimán gorge and extending about 1,200 meters southwest toward the peak. The average dip of the rocks is about 55° SW., which would indicate a thickness of approximately 1,000 meters. The total thickness is unquestionably much greater, however, as the outcrops are continuous for another 1,000 meters southwestward, to the edge of the area mapped, and the base of the section is not exposed. A conservative estimate of the thickness is 1,000 meters, but the full thickness is probably considerably greater.

STRATIGRAPHIC RELATIONS

The Upper Cretaceous shale and limestone as mapped by the writers include largely shaly limestone and calcareous shale interbedded with more calcareous rocks, overlying the Lower Cretaceous limestone. The contact between the Lower Cretaceous limestone and the Upper Cretaceous strata is best seen along the southwest flank of the Puerto Angel anticline northwest of El Detzaní, where thin-bedded limestone with chert grades conformably upward into argillaceous limestone with shale partings and without chert. The Upper Cretaceous strata are overlain unconformably by diverse rocks of Tertiary and Quaternary age, including the El Morro fanglomerate, volcanic rocks, terrace deposits, and alluvium.

LITHOLOGY

The lithology of the Upper Cretaceous rocks differs from place to place, but the bulk of the formation is composed of thin-bedded dark-gray limestone interbedded with gray calcareous shale. The entire assemblage weathers to a rather uniform yellowish or greenish-brown color. At Puerto de Bofay, the lower beds contain much gray flaky mudstone and purple and maroon to olive-green mudstone in beds as much as 2 meters thick. This clastic sequence passes upward into dark-gray, greenish-brown, and brown sandy and shaly limestone with gray-green shale partings and a little purple argillite. Near the pass itself a sequence of thin beds of gray limestone and shale contains prominent thin partings of purple argillite; these partings are characteristic of the Upper Cretaceous strata from Puerto de Bofay to Puerto de La Pared Blanca. At the second locality, thin-bedded dark-gray argillaceous limestone with shale partings, resembling the Agua Nueva formation of east-central Mexico, passes upward into thin- to thick-bedded gray limestone with interbedded shale resembling the San Felipe formation of east-central Mexico.

In general, limestone predominates over shale, but locally shale is the more abundant; for instance, northeast of Cerro de El Morro, beds of greenish-brown punky shale 60–70 cm thick are interbedded with dark-gray limestone layers 20–30 cm thick, which resemble the Méndez shale of east-central Mexico. In a few of the more calcareous sections, such as southwest of the Río Tolimán, southwest of Zimapán, beds of gray chert 1 to 2 cm thick are present, but chert is relatively rare as compared with its abundance in the underlying Lower Cretaceous limestone.

The Upper Cretaceous limestone is usually either argillaceous or nearly pure, but coarse sandy limestone in beds as much as 1 meter thick crops out south of Cerro de Chametla, and a sequence of hard siliceous limestone in beds as much as 50 cm thick, with thin shale partings, appears on the ridge extending south from Cerro de Santa Elena.

In the deep arroyo east of Cerro de Daxi a thin bed of coarse grit composed of subangular to rounded fragments of gray limestone in a calcareous matrix is interbedded with shaly limestone. This grit was the only coarse clastic rock found in the Upper Cretaceous strata of the Zimapán district.

Lateral variation in lithology is common throughout the unit. A good example is the lens of relatively pure, gray to purple limestone that begins about 500 meters east of El Dedhó and extends, gradually thickening, about 3 kilometers northwestward, almost to the Río Tolimán. This lens attains a maximum thickness of about 250 meters; considerable chert in irregular knotty nodules near the base and a little purple shale are the only noncalcareous rocks within the lens.

The Upper Cretaceous rocks have undergone mild dynamic metamorphism (p. 31), which has produced slaty cleavage locally, and where the rocks have been intruded by monzonite, they have been so intensely metamorphosed that the bedding has been almost completely obliterated and silication is widespread.

Only two specimens of unmetamorphosed Upper Cretaceous limestone were examined microscopically by the writers. Both specimens were of megascopically rather impure limestone. Crushed samples of each were dissolved in dilute hydrochloric acid and the residues were examined under the microscope. A medium-grained dark-gray limestone from north of Cerro de San Pascual had 50.1 percent of insoluble matter, composed largely of carbonaceous material with a little quartz. The rocks gave off a strong fetid odor when broken. A grayish-black thin-bedded hard limestone from the ridge south of Cerro de Santa Elena proved to have 90.8 percent of insoluble material; considerable fine-grained carbonate remained undissolved, however, so that the apparent proportion of insoluble material is undoubtedly much too high. The proportion of carbonate was too small to permit liberation of discrete grains of insoluble material. A thin section of the rock revealed a few tiny grains of plagioclase feldspar (near An_{10}) and quartz set in an extremely fine grained irresolvable groundmass, apparently composed largely of quartz and carbonate.

AGE

Kenneth Segerstrom and Carl Fries, Jr. found fossils in four localities (numbers 16 to 19 in pl. 2) of the Zimapán district where the Upper Cretaceous rocks outcrop. Ammonites from the schoolyard at El Dedhó (locality 16), from a gully 500 meters northwest of the schoolyard (locality 17), and from the north bank of the Barranca de Tolimán 4.5 kilometers west of Zimapán (locality 18), probably belong to the genus *Texanites*, according to R. W. Imlay. Another ammonite from the schoolyard at El Dedhó probably belongs to the genus *Nowakites*. Imlay reports that *Texanites* is common in the Austin chalk in Texas and occurs less commonly in the Taylor marl, and that these are equivalent in age to the San Felipe formation and the lower part of the Méndez shale (Coniacian, Santonian, and Campanian stages). *Nowakites* is characteristic of the part of the Texas section that is equivalent in age to the lower half of the San Felipe formation (Coniacian) of east-central Mexico.

A shale that weathers reddish purple lies from 10 to 20 meters structurally below a contact with Lower Cretaceous thick-bedded limestone believed to be overthrust, on the northeast slope of Cerro de Daxi (locality 19 in pl. 2). This shale yielded microfossils of Méndez age. A sample was examined by Yvette Eternod, who submitted the following report on the fauna present and its stratigraphic range.

Microfauna	*Stratigraphic range*
Globotruncana stuarti Lapparent	Campanian to Maestrichtian
Globotruncana cf. *G. havanensis* Voorwijk	Upper Cretaceous
Globotruncana fornicata? Plummer	Campanian
Globigerina cretacea D'Orbigny	Santonian to Paleocene
Gümbelina globulosa Ehrenberg	Senonian to Paleocene
Gümbelina ultimatumida White	Campanian to Maestrichtian

The age of this shale is probably therefore Campanian, which is well up in the Upper Cretaceous and corresponds to the lower part of the Méndez formation of eastern Mexico.

The Upper Cretaceous strata that crop out in the Zimapán district are probably equivalent to the Agua Nueva (or Xilitla) formation of Turonian age, the entire San Felipe formation of Coniacian and Santonian age, and some hundreds of meters of Méndez strata, ranging in age from Santonian up into the Maestrichtian, according to both lithologic and faunal characteristics. No attempt was made in the field to separate the Upper Cretaceous rocks into discrete units.

TERTIARY SYSTEM

EL MORRO FANGLOMERATE

DISTRIBUTION

The El Morro fanglomerate crops out in a northwestward-trending belt about 11 kilometers long extending from south of Cerro del Potrero to Cerro de San Pascual. It is named for excellent and easily accessible exposures at Cerro de El Morro on the San Pascual mine road 6 kilometers northwest of Zimapán. Although the belt is relatively narrow at its southeast end, it widens rapidly to the northwest and attains a maximum width of 3 kilometers. Southwest of Zimapán the Río Tolimán flows nearly 3 kilometers through a valley cut in the fanglomerate.

A second belt 3 kilometers long appears on the divide between the Río Tolimán and the Río Moctezuma, centered around Cerro de la Majada Grande. Other smaller outcrops occur southwest of Hacienda de La Estancia, southeast of Cerro del Muí, and along the cutoff highway between San Pedro and Los Remedios.

Outcrops of the El Morro fanglomerate are excellent throughout the district, and exposures are practically continuous in the outcrop area. The formation is thoroughly indurated and very resistant to erosion; it forms steep slopes and many cliffs. The bold escarpments on both sides of the Río Tolimán between Cerro del Arcabuz and Cerro de La Majada Grande are carved in the fanglomerate. In the vicinity of Cerro del Potrero and south of Cerro de Arcabuz the fanglomerate is covered with dense chaparral, but elsewhere it is nearly devoid of vegetation.

THICKNESS

The El Morro fanglomerate ranges in thickness from a few meters to about 400 meters; in general, changes in thickness are gradual, both along the strike and down the dip, but locally, more extreme changes are common. Nearly all the available data on thickness of the formation are assembled in figure 4, which shows diagrammatically the range of thickness in the principal area of outcrop.

STRATIGRAPHIC RELATIONS

The El Morro fanglomerate overlies unconformably the Upper Cretaceous limestone and shale in the two largest outcrop areas; elsewhere it overlies unconformably the Lower Cretaceous limestone. Excellent exposures of the contact can be seen at the base of Cerro de El Morro and from there northward along the base of the cliff below the San Pascual road (pl. 7*B*); other good exposures are in Arroyo del Potrero, 1 kilometer southwest of Temoté. Angular discordance between the El Morro fanglomerate and the underlying Cretaceous rocks is commonly near 90° (pl. 8*A*).

Nearly everywhere the fanglomerate has low dips, which average less than 20°, although in the Río Tolimán valley southwest of Zimapán, dips are slightly higher. The maximum dip observed was 60°, at a point south of Cerro del Arcabuz. This unusually high dip may have been caused in part by intrusion of monzonite and consequent doming.

Overlying the El Morro fanglomerate and interfingering with it locally is a thick sequence of andesite and basalt lavas and subordinate tuffs. Interfingering of tuff and fanglomerate is best exposed where the road to the San Pascual and Poder de Dios mines crosses Barranca Seca about 500 meters south of Cerro de El Morro. Isolated lenses of tuff in fanglomerate and of fanglomerate in volcanic rocks occur within short stratigraphic distances from the contact. Fanglomerate lenses in volcanic rocks are especially prominent in the San Pascual and Santa Gorgonia mine area; the hill above the Santa Gorgonia mine is capped by a thick fanglomerate lens.

LITHOLOGY

The El Morro fanglomerate is remarkably uniform in lithology throughout the district. It is typically a red, reddish-gray, or purplish-gray highly indurated rock consisting almost entirely of angular to subangular pebbles and cobbles of gray, or less commonly brown limestone. Most of the fragments are from 2 to 20

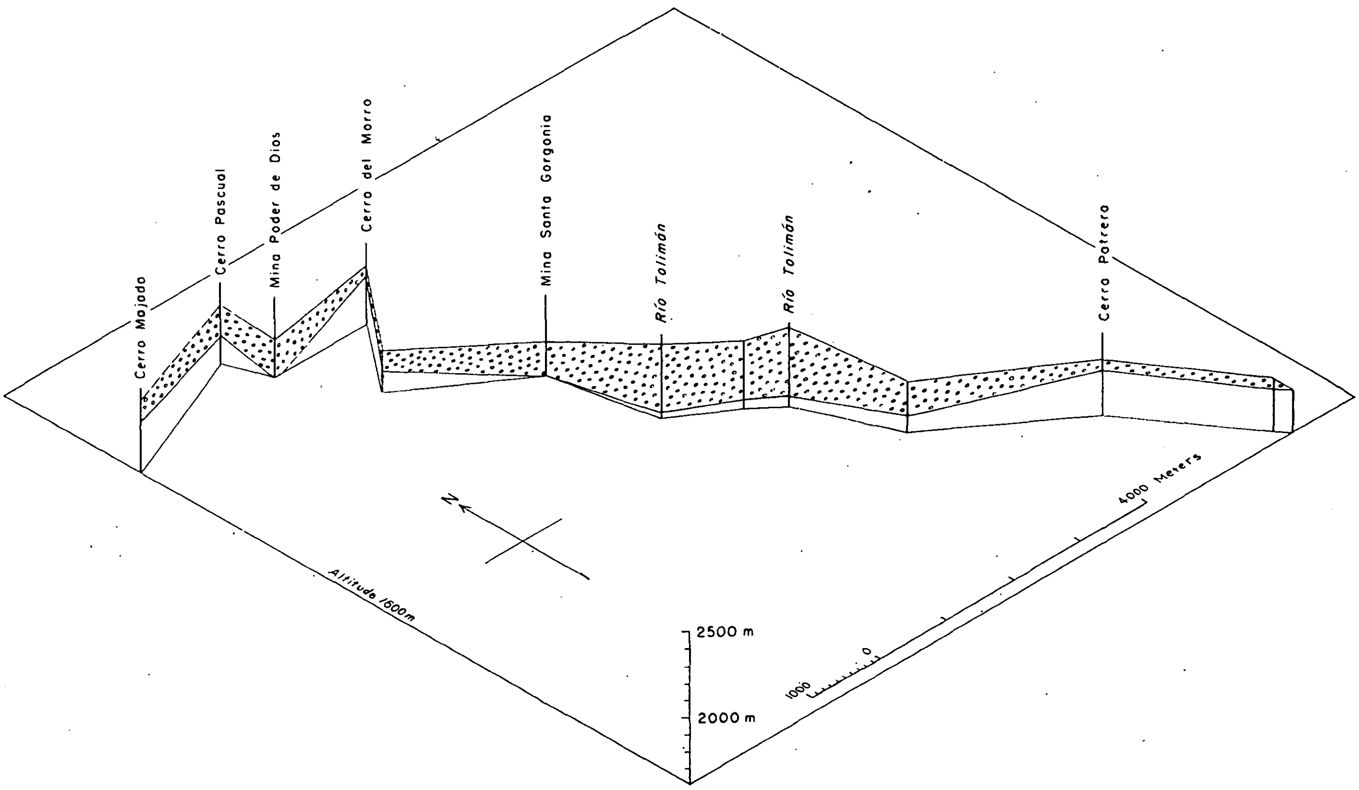

FIGURE 4.—Isometric fence diagram showing changes in the thickness of El Morro fanglomerate.

cm across; a few boulders are 45–50 cm long, and the largest boulder seen was nearly 1.5 meters across. The matrix consists largely of limestone sand, and minor quartz, feldspar, and mica grains; in places, however, it is more quartzose. Concentrations of pebbles and cobbles of volcanic rocks appear locally, and a few volcanic pebbles occur nearly everywhere, but always in small proportion. Small fragments of white and pink marble are common in the Barranca Seca area. A few fragments of limestone with chert were seen. Lithologic differences from the typical fanglomerate are few and consist usually of coarse grits containing an abundance of quartz and feldspar grains in addition to the ubiquitous limestone sand. Another difference is seen at the base of the fanglomerate in Arroyo del Potrero and elsewhere for several kilometers to the northwest; at these localities the basal few meters of the El Morro fanglomerate consist of a chaotic assemblage of cobbles and boulders of fine-grained fossiliferous gray limestone that have a maximum length of about 1.5 meters (pl. 8*B*). This accumulation of boulders appears only at the base of the fanglomerate, although scattered fragments of similar rock are present in the overlying first 5 or 6 meters of the fanglomerate.

Sorting is rather poor (pl. 8*B*), but bedding can be recognized nearly everywhere because of the many sandy layers. At places, many cobbles may be jumbled together with little interstitial material, but almost everywhere the larger fragments are embedded in a finer grained matrix. The limestone fragments are usually flattish and lie commonly parallel to the bedding; a weak tendency toward imbrication is discernible in a few places. West of Zimapán a thin flow of andesite is intercalated in the fanglomerate; fragments of this andesite are the most common noncalcareous constituent of the fanglomerate and were possibly derived, at least in part, from that flow. No fossils were found, except a few enclosed in limestone boulders.

The fanglomerate is cut by a closely spaced series of essentially vertical fractures and calcite veins trending N. 30°–45° W. These fractures show up on aerial photographs as pronounced lines of vegetation which give a false impression of stratification. In the Santa Gorgonia-San Pascual mine area, most of the ore has been produced from veins in the fanglomerate.

Intrusion of monzonite has resulted in intense metamorphism of the fanglomerate in a small area between Cerro del Arcabuz and Cerro de La Napolera (p. 37). The fanglomerate has also been intruded by many dikes.

In thin section, a specimen of fanglomerate matrix from near the mouth of Arroyo de La Chametla was seen to consist almost entirely of subrounded carbonate grains averaging about 1.5 millimeters across, set in a base of slightly recrystallized carbonate sand. A few subrounded quartz grains and small patches of secondary carbonate completed the mineral assemblage.

A thin section of grit from the El Morro fanglomerate southwest of Zimapán revealed angular to rounded grains of quartz, carbonate, and deep green-brown biotite set in a matrix of extremely fine grained very pale yellow-green material, which was probably a chlorite. A little magnetite and a few tiny fragments of igneous rock were also seen. The rock was cut by minute veinlets of carbonate.

CONDITIONS OF DEPOSITION

A pronounced angular unconformity between the El Morro fanglomerate and the underlying Mesozoic rocks indicates that intense folding and erosion affected these rocks before the deposition of the fanglomerate. The predominance of fragments similar to the limestone beds of the Upper Cretaceous rocks indicates that most of the El Morro fanglomerate was derived from those beds. Where the fanglomerate rests on Lower Cretaceous limestone, however, the evidence for its source is not so clear, but the lack of fragments of limestone with chert indicates that most of the fanglomerate was probably not derived from the chert-bearing Lower Cretaceous limestone. Lack of sorting, angularity of fragments, lack of fossils, and the reddish color suggest a terrestrial origin. The fanglomerate seems to have been little affected by disastrophism, and the dips, with the exception already noted, are thought to be largely initial. The predominance of northeastward dips in the area of main development and the presence of suitable source rocks to the southwest suggests that the fanglomerate was derived from the southwest. The angularity and relatively large size of many of the fragments suggest that the source area was one of high relief.

The El Morro fanglomerate is probably best interpreted as a piedmont fanglomerate deposited in a basin along the northeast flank of a rugged highland. Toward the end of fanglomerate deposition, volcanic activity began in the basin, and the two processes operated simultaneously for a short period before volcanism became the dominant agent of deposition.

AGE AND CORRELATION WITH OTHER "RED CONGLOMERATES" OF MEXICO

No fossils indigenous to the fanglomerate were found, although numerous boulders of fossiliferous Lower Cretaceous limestone were seen locally at the base of the fanglomerate and elsewhere, notably in a conglomerate tongue northeast of Puerto de Los Bronces. The fanglomerate was deposited after a considerable period of erosion following the Laramide orogeny in the Sierra Madre Oriental, and it was in turn buried by a great thickness of volcanic rocks. The deep canyon cut by the Río Tolimán subsequent to the deposition of the fanglomerate and volcanic rocks indicates that the fanglomerate has undergone a long period of erosion.

Similar rocks have been described from elsewhere in Mexico: at El Cuarenta, Durango, by Gallagher and Pérez Siliceo (1946, p. 158–161); at El Oro, México, and at Tlalpujahua, Michoacán, by Flores (1920, p. 22); at Zacatecas, Zacatecas, by Burckhardt and Scalia (1906, p. 20–21) and by Ordóñez (1900, p. 26–27); and at Guanajuato, Guanajuato, by Villarello, Flores, and Robles (1906, p. 15–17), by Ordóñez (1900, p. 22–23), and by Guiza (1949, unpublished report). Aguilera and Ordóñez (1896, p. 228) considered the "red conglomerate" of Cañada de Marfil in Guanajuato, of Taxco in Guerrero, and Matamoros de Izúcar, Acatlán, and Tehuacán in Puebla to be of upper Miocene or Pliocene age.

More recent studies by Edwards (1955) and by Fries, Hibbard, and Dunkle (1955) led to the discovery of fossil vertebrates in the Guanajuato red conglomerate, which indicate a late Eocene age for the lower part of the formation. In view of the similarity of the Guanajuato red conglomerate to the El Morro fanglomerate in relation to the underlying folded Mesozoic rocks and the overlying nearly flat volcanic rocks, in the color of the matrix, in the attitude of the bedding, and in the structural or tectonic history, the two formations are believed to be correlative in age. The El Morro fanglomerate is therefore very probably of late Eocene and early Oligocene age.

LAS ESPINAS VOLCANIC ROCKS

DISTRIBUTION

The Las Espinas volcanic rocks crop out in a broad strip along the east side of the area, and in the southeast corner extending from Cerro de La Estancia west-southwestward to Barranca Seca and southwestward to Cerro del Potrero. They are also exposed in the Santa Gorgonia and San Pascual mining area as an irregular isolated plate overlying the El Morro fanglomerate and extending about 2.5 kilometers southeastward from Cerro de Las Espinas, from which they take their name. About 45 square kilometers, or between one-fourth and one-fifth of the area mapped, are underlain by volcanic rocks or alluvium resting on volcanic rocks. Although the Las Espinas volcanic rocks are only partly of sedimentary origin, they are discussed here because they form an integral part of the stratigraphic sequence.

Outcrops are fairly good in the Cerro de Las Espinas area and poor elsewhere; much of the bedrock in the southeast corner of the district is hidden by alluvium and soil. In general, the volcanic rocks are easily eroded and the volcanic terrain is characterized by rolling topography; an exception is the chain of rugged volcanic hills extending about 5 kilometers south-southwestward from Cerro de La Estancia, which forms the east rim of the Zimapán basin. The major part of the cultivated land around Zimapán is underlain by volcanic rocks; in fact, with the exception of the north slope of the Sierra de El Monte, practically no soil has been developed on any rocks other than volcanic.

THICKNESS

The Las Espinas volcanic rocks range in minimum thickness from a knife edge to 250 meters on Cerro de Las Espinas, 370 meters on Cerro de La Estancia, and 375 meters on Cerro Grande, just east of the area mapped. The original maximum thickness cannot be determined, as an unknown thickness of volcanic rocks has been removed by erosion; however, it seems likely to have been much greater, perhaps several hundred meters greater, than the thickness measured on Cerro Grande, for a considerable though undetermined thickness of volcanic rocks lies below the base of the measured section on Cerro Grande.

STRATIGRAPHIC RELATIONS

The Las Espinas volcanic rocks are the youngest pre-Quaternary rocks in the area. They overlie conformably the El Morro fanglomerate in the vicinity of Cerro de Las Espinas and to the northwest, west, and southwest of Zimapán as far south as Cerro del Potrero; locally the two formations interfinger. In the northeast corner of the area the volcanic rocks rest unconformably on Upper Cretaceous limestone and shale and, at one place, on Lower Cretaceous limestone. Elsewhere the base is not exposed.

Large areas of the Las Espinas volcanic rocks in the southeastern part of the district are overlain unconformably by Quarternary alluvium and terrace deposits. In the vicinity of Zimapán, the volcanic rocks are overlain unconformably by the Zimapán fanglomerate.

The volcanic rocks are in general nearly flat lying except for local variations. Dips as high as 25°–50° were recorded southwest of Zimapán and near Cerro del Potrero, where the rocks have been tilted by normal faulting.

LITHOLOGY

The Las Espinas volcanic rocks range in composition from quartz latite through pyroxene andesite and olivine andesite to olivine basalt and olivine-hypersthene basalt, although andesites form the major part of the formation. (See p. 118 for petrographic descriptions.) Flow rocks make up the bulk of the assemblage, and subordinate tuff and agglomerate are especially abundant near the base of the volcanic section. A minor constituent of the sequence is black obsidian, whose refractive index of 1.495 corresponds to a glass with 73 percent silica, or a rock of rhyolitic composition (George, 1924, p. 365).

Most of the flows are thin, ranging from 1 to 3 or 4 meters, but a few of them such as the one capping Cerro de La Estancia, have a thickness of 10 meters or more. Many of the lavas show pronounced flow layering and some, especially those near the top of both Cerro de La Estancia and Cerro Grande, have a strong platy structure and a marked tendency to split off in thin sheets when struck with a pick.

Amygdaloidal lavas are fairly common, more so among the basalts than the andesites. Amygdules are commonly composed of chalcedony or opal and less commonly of chlorite or carbonate. They reach their maximum size in the lava flows of Cerro de Melchor, where they have a maximum diameter of 13 cm. Most of the Cerro de Melchor amygdules are composed of chalcedony, some of which show a beautiful concentric structure; a few, including the largest ones, are geodelike masses composed of quartz crystals which have a length of nearly 3 cm.

All the lava flows of the Cerro de Las Espinas area and most of the Cerro de La Estancia and Cerro Grande flows are porphyritic and have a partly crystalline groundmass. Strongly glassy rocks were seen only in a small area southeast of Cerro del Potrero. Plagioclase feldspars are usually the only phenocrysts identifiable with a hand lens; occasionally quartz, orthoclase (sanidine), pyroxene, and, very rarely, olivine may also be identified.

Sections of volcanic rocks were measured with planetable and telescopic alidade on the southwest slope of Cerro de La Estancia and on the south slope of Cerro Grande, 3 kilometers northeast of Los Remedios. The two peaks are 7.5 kilometers apart and the lava flows show a slight difference in composition; the Cerro de La Estancia lava flows are dominantly olivine andesites and basalts, whereas the principal rock type at Cerro Grande is augite or hypersthene andesite. The monotonous succession of andesite and basalt flows which makes up virtually the entire sequence on both peaks is interrupted only near the base of Cerro de La Estancia, where three prominent relatively thin layers of welded red quartz-latite tuff containing abundant lithophysae are interbedded with thicker flows of andesite, olivine andesite, and olivine basalt. These quartz-latite tuffs, which form prominent low cliffs, can be seen from the Pan American Highway just west of Puerto de La Estancia.

AGE

The Las Espinas volcanic rocks overlie conformably the El Morro fanglomerate and interfinger with it locally. Inasmuch as the youngest part of the El Morro fanglomerate is believed to be of early Oligocene age, the volcanic rocks are consequently thought to be of late Oligocene and Miocene age. On the geologic map (pl. 2) and in the columnar section (fig. 2) the two formations are thus dated.

QUATERNARY SYSTEM

PLEISTOCENE DEPOSITS

ZIMAPAN FANGLOMERATE

A caliche-covered alluvial fan occupies the center of the Zimapán valley between Zimapán and the Sierra de El Monte. Several erosional outliers of the fanglomerate are found south of Zimapán and southwest of El Detzaní. The fanglomerate consists almost entirely of angular to subangular pebbles and cobbles of Lower Cretaceous limestone and has a maximum thickness of more than 15 meters. It is well cemented by caliche throughout its entire thickness. The average slope of the fan surface from El Detzaní to Zimapán is about 3°. At the present time the fan is being dissected by intermittent streams debouching on it from the Sierra de El Monte, and gullies have been cut as deep as 15 meters. A few small springs issuing from the base of the fanglomerate are utilized for irrigation; the largest of these springs is in the northeast part of Zimapán and has an outflow of about 15 liters per minute. In general, however, the fanglomerate is completely unsuitable for farming and supports only a sparse growth of various cacti and rank grass.

DAXI AND OTHER FANGLOMERATES

An alluvial deposit similar to the Zimapán fanglomerate blankets the northeast slopes of Cerro de Daxi. It consists entirely of angular fragments of Lower Cretaceous limestone as large as 1 meter across, cemented by caliche; the maximum thickness is of the order of several meters. Initial dips are as high as 25°. The fanglomerate is dissected to a considerable extent by Recent erosion and is preserved at present only on ridges between gullies.

A few small patches of caliche-cemented alluvial deposits are found southwest, west, and northwest of

Cerro de Chametla. They are similar to the Zimapán and Daxi deposits and warrant no additional description.

RECENT DEPOSITS

TERRACE DEPOSITS

Terrace deposits have been mapped separately wherever practicable; they are most common along the upper reaches of the Río Tolimán and its tributaries. There seem to be two persistent sets of terraces, about 1 and 2 meters, respectively, above the present river level. These two groups of terraces persist until the river reaches a point about opposite Cerro de La Nopalera, where the canyon narrows and terrace formation is inhibited. A few small terraces are found along the Río Tolimán below the gorge of El Cajón; in addition to the 1- and 2-meter levels, a 6-meter level is found in a few places.

A few higher level terrace remnants occur east, south, and southwest of Zimapán; these older terraces lie 12 or 13 meters above the present valley. One similar high-level terrace and several 1-meter terraces are along Barranca Seca.

The low terraces along the Río Tolimán system are widely utilized for small-scale farming, as they are easy to irrigate. Most of the farms in the district are on these terraces, and it seems safe to say that no terrace of any appreciable size is uncultivated.

ALLUVIUM

Alluvial deposits are widespread in the Zimapán valley and along the various tributaries of the Río Tolimán. All alluvial deposits have been grouped together on the map (pl. 2).

Most of the alluvium is in the basin at the head of the Río Tolimán and its principal tributaries; a maximum thickness of 10 to 12 meters is reached locally. Alluvial deposits are being dissected everywhere at the present time; Arroyo del Potrero near its mouth is a vertical-walled valley cut 6 to 9 meters deep in its former alluvial deposits, and dissection of a similar magnitude is evident in Barranca Seca. Many of the principal gullies draining the south slope of the Sierra de El Monte were formerly alluviated to depths of several meters. Remnants of alluvium are now perched along the gully walls, and most of the gullies are floored by bed rock. In the arroyo east of Cerro del Piñón a small natural bridge has been cut in alluvium.

IGNEOUS ROCKS

RHYOLITE DIKES

Rhyolite dikes crop out throughout the district, but nowhere are they quantitatively important. They are best developed in the Cerro del Potrero and Cerro de Daxi area, where they are associated with rhyolitic plugs. Other rhyolite dikes were seen at Puerto de Los Bronces, in the Santa Gorgonia and San Pascual mining area; at the head of Barranca Colorada, northeast of the Los Balcones mine; and in the El Monte mining area above the Dolores mine. The rhyolite dikes are from 3 to 8 meters thick; the largest, near Cerro del Potrero, was traced 1 kilometer.

The rhyolite ranges from brown to gray, is everywhere porphyritic, and is usually considerably altered. Quartz is ordinarily the only mineral identifiable megascopically. Feldspar phenocrysts are usually completely altered to a dull whitish aggregate. Ferromagnesian minerals are absent.

The rhyolite of the Cerro del Potrero area is a moderate yellowish-brown rock with rounded and embayed phenocrysts of quartz as much as 4 mm in diameter and a few potash feldspar grains ranging from 1 to 3 mm in length, set in an aphanitic groundmass. Under the microscope the rock appears highly altered, the only original minerals remaining being quartz and apatite. Feldspar is completely altered to kaolin and the originally trachytic groundmass has been replaced by carbonate. A little sericite and apatite are present in the altered groundmass.

The rhyolite dike from the Dolores mine is a light greenish-gray (5*G*8/1) rock characterized by an abundance of slightly rounded greenish feldspar phenocrysts attaining a length of 8 mm. Rounded quartz grains as much as 4 mm across are common. Microscopically the feldspar phenocrysts are nearly completely altered to sericite, kaolin, and carbonate; faint zoning of the alteration minerals and a few less-altered grains showing albite twinning indicate that most, if not all, of the feldspar phenocrysts are plagioclase. The very fine grained groundmass consists almost entirely of orthoclase and quartz; abundant apatite and a little sphene, zircon, and epidote are accessory minerals. Quartz phenocrysts are deeply embayed.

A rhyolite dike at Puerto de Los Bronces consists of thoroughly sericitized phenocrysts of orthoclase and oligoclase 1 to 3 mm in length, abundant grains of quartz 1 to 2 mm in length, considerable rusty pyrite, and numerous tiny rods and radial aggregates of blue-gray tourmaline, all set in a fine-grained dusty irresolvable groundmass. Tourmaline and pyrite were probably introduced during the mineralization that produced the nearby Puerto de Los Bronces pyrite deposit. The rock is cut by thin veinlets of quartz containing fine-grained aggregates of sphene (?).

A rhyolite from near the mouth of Barranca de La Cueva deserves special mention because of its unusual mineralogy and texture. It occurs as very thin irregular dikelets cutting a contact between monzonite and metamorphosed Upper Cretaceous rocks. In hand specimen the rhyolite is a light brownish-gray fresh-appearing coarse-grained rock consisting almost entirely of quartz and pale-violet feldspar. A few irregular grains of a pale-green mineral are also visible. In thin section the rock is holocrystalline and allotriomorphic. It is composed of about 75 percent anorthoclase in crystals ranging from 0.5 to 5 mm in length, and 25 percent quartz which is interstitial in anorthoclase and replaces it locally. A few grains of pale-green hornblende as much as 0.4 mm in length are enclosed in and partly replaced by anorthoclase; the hornblende is usually somewhat altered to pale-yellow epidote. Tiny euhedral wedges of sphene are common; they are enclosed in anorthoclase and quartz. The sphene is faintly pleochroic in red and green. Anorthoclase is very dusty and cloudy from alteration to kaolin. A few crystals are twinned according to the Carlsbad law. Extinction angle $Z \wedge 010$ in 001 is about 85°; the (−) optic angle is small. Boundaries between anorthoclase grains are sinuous and in places show evidence of one grain having grown at the expense of another. A number of anorthoclase crystals have microscopic irregular patches and lamellae of albite which extinguish simultaneously in a single crystal; the texture apparently represents an intermediate stage in the development of microperthite.

QUARTZ LATITE DIKES

Quartz latite dikes were recognized only in the vicinity of the San Pascual mine, at the Nevada and San Ignacio mines, and southwest of Cerro de La Majada Grande. The dike at the portal of the Mercedes mine may be quartz latite, but it is too thoroughly altered for positive identification. The dikes range from 1 to 4 meters in thickness and have been traced as much as 750 meters along the strike. The orthoclase of all the quartz latites seems to be confined to the groundmass, for all the determinable feldspar phenocrysts are plagioclase.

The quartz latite of the San Pascual mine area is a dense, very light gray aphanitic rock with inconspicuous tiny phenocrysts of feldspar and much pyrite. Quartz is visible in hand specimen only from the dike at the portal of the San Pascual mine. Under the microscope, phenocrysts of feldspar 0.5 to 2 mm in length are set in a trachytic groundmass of tiny albite (An_5) laths, averaging 0.15 mm in length, with much interstitial orthoclase and a little quartz. No ferromagnesian minerals are present. Apatite in needles as much as 0.3 mm in length is an abundant accessory; sphene, slightly altered to leucoxene, is present but scarce. Most of the feldspar phenocrysts are plagioclase, often with a rim of orthoclase; they are thoroughly kaolinized and undeterminable. A few phenocrysts may be orthoclase. A quartz grain 1 mm in length (xenocryst?) with a rim of orthoclase was seen in one thin section. Subhedral ragged grains of late-formed pyrite are scattered through the rock. The quartz latite of the San Pascual mine carries considerable accessory zircon.

The quartz latite of the Nevada mine is a brown to brownish-gray porphyritic rock with abundant phenocrysts of milky oligoclase (An_{10-15}) 1 to 3 mm in length and a few corroded quartz grains set in a very dusty groundmass of quartz and orthoclase. Apatite is the only accessory mineral. A few grains of what was probably brown hornblende are altered to chlorite and iron oxide.

LATITE DIKES

A few fine-grained dikes in the Santa Georgonia-San Pascual mining area were classified in the field as latite. They are pale reddish brown to moderate red and average about 1 meter in thickness. The distinctive color seems to have invited prospecting, for many pits and short adits are found along all the latite dikes; none of the prospecting appears to have been productive.

The latite dike of the Arizona or El Transval claim was examined in thin section, but it proved to be too badly altered for identification. Microphenocrysts of both soda-lime and potash feldspars were recognized, however, and therefore the name latite seems reasonable.

ANDESITE DIKES

Andesite dikes occur throughout the area and are especially well formed in a belt along the Río Tolimán extending from Cerro de La Chametla north-northwest to the Carrizal mining area. The dikes of this belt strike northwest to north-northwest, parallel to the regional strike of the enclosing rocks. Andesite dikes were seen also in the El Monte mining area and at the San Francisco mine. The dikes intrude all the pre-Quaternary formations, including monzonite, but they are most abundant in the Upper Cretaceous strata in the vicinity of Cerro de La Majada Grande, Cerro del Mesquite, and Cerro de La Chametla. They are generally less than a meter thick and are discontinuous, although a few have been traced for a kilometer or more. Locally dikes occur in unmappable swarms composing as much as 15 or 20 percent of the exposed rock. The largest andesite dike mapped has a thickness of 150 meters and a length of 1,300 meters.

The andesite dikes are light-gray to dark-gray rocks, either porphyritic or aphanitic in texture. If porphyritic, they may have phenocysts of both feldspar and ferromagnesian minerals or, more commonly, only ferromagnesian minerals. Pyrite is a common accessory mineral. The andesite weathers rather easily, so that fresh specimens are not readily available; the trace of an andesite dike is often marked by a shallow trench eroded in the more resistant wall rocks.

Dikes were classified as andesite in the field on the basis of a medium-gray color and absence of megascopic quartz, potash feldspar, and olivine. Thin sections of a few dikes mapped as andesite revealed plagioclase as calcic as An_{65}.

Two groups of andesite were reported by Spurr (1907, unpublished report) and mapped at the Pamplona mine by Garrey (1924, map facing p. 112). The "earlier andesite" of Spurr and Garrey is the monzonite of this report; their "later andesite" is the rock described in this section.

A typical andesite which intrudes monzonite in Barranca de La Cruz is a dark greenish-gray (5*GY*4/1) aphanitic rock with a few needles of amphibole 1 to 2 mm in length. The microscope reveals a few euhedral phenocrysts of labradorite (An_{60-65}) 0.5 to 1 mm in length and scarce grains of amphibole 1 mm long in a trachytic groundmass of labradorite (An_{60}) laths averaging 0.15 mm long, augite granules, and dusty devitrified glass of low refractive index. A little quartz is present in the groundmass. The amphibole seems to be a hornblende near barkevikite; it is pleochroic in pale brownish green and dark yellowish brown with extinction angle $Z \wedge c$ of 16°. A small proportion of carbonate is secondary.

The andesite dike that occupies part of the San Jorge vein in the Santa Gorgonia-San Pascual mining area is a medium bluish-gray rock with abundant pyroxene phenocrysts 1 to 2 mm in length and a few grains of plagioclase feldspar 1 to 3 mm in length set in a dense aphanitic groundmass. Microscopically the rock consists of phenocrysts of labradorite (An_{53-55}), augite, and a little hornblende imbedded in an intersertal base of minute oligoclase laths, augite granules, and interstitial dusty, slightly devitrified glass. Plagioclase is partly altered to sericite; it shows both albite and Carlsbad twinning and is slightly zoned. Augite occurs in colorless subhedral grains, in part with lamellar twinning on 100. Hornblende is a greenish-brown variety near barkevikite. A few highly resorbed quartz grains may be xenocrysts. Secondary minerals include penninite, quartz, and a little carbonate.

GRANOPHYRIC BASALT DIKES

A medium bluish-gray porphyritic rock occurs as an irregular dike extending about 1,300 meters south-southeast from Cerro de La Chametla. The core of the dike is a coarse porphyry with altered phenocrysts of feldspar as long as 1 cm and numerous plates of biotite 1 mm in length, set in an aphanitic groundmass. The coarse part of the dike is bordered by a fine-grained chilled selvage containing considerable pyrite. Under the microscope the chilled margin consists largely of euhedral phenocrysts of labradorite (An_{60-65}) 1 to 3 mm in length and pale reddish-brown biotite grains 0.5 mm in length with interstitial orthoclase and quartz. Plagioclase shows both albite and Carlsbad twinning and normal oscillatory zoning; it is slightly altered to carbonate. Biotite is altered to penninite, iron oxide, and sphene; the sphene is slightly altered to leucoxene. Numerous ferromagnesian grains (pyroxene?) 1 to 2 mm in length are completely altered to pale-green penninite, iron oxide, and a little carbonate. Apatite is an abundant accessory; iron ore and zircon are minor constituents. A little secondary carbonate is present. Much of the quartz-orthoclase groundmass shows a fine-grained granophyric intergrowth, which locally replaces plagioclase to some extent.

The rather high proportion of ferromagnesian minerals and the calcic nature of the phenocrystic plagioclase suggest that the rock belongs in the basalt group. In view of the groundmass composition and texture, the best name for the rock seems to be granophyric basalt.

OLIVINE BASALT DIKES

A few dikes of olivine basalt were seen in the district; they are confined, with one exception, to the area south and southwest of Cerro del Potrero. In general, the dikes are much fresher than the olivine basalt flows of the Las Espinas volcanic rocks; fresh glassy olivine and pyroxene are visible in all hand specimens.

The largest olivine basalt dike intrudes the Las Espinas volcanic rocks 1 kilometer south of Temoté. The dike ranges from 1 to 4 meters in thickness and was traced about 300 meters along the strike. It is a grayish-black rock with prominant phenocrysts of olivine, pyroxene, and plagioclase feldspar. In thin section, subhedral crystals of olivine from 0.5 to 1 mm across, subhedral to anhedral augite grains of similar size, and euhedral plagioclase prisms averaging 1 mm in length are set in a groundmass of intersertal andesine-labradorite microlites, augite granules, iron ore, and pale-brown interstitial glass. Olivine and augite are in roughly equal proportions and compose about 10 percent of the rock. The olivine is colorless chrysolite with (+) optic sign and angle near 90°. It is slightly serpentinized along fractures. Augite is a pale-brown nonpleochroic variety with extinction angle $Z \wedge c$ in unzoned crystals about 48°. It tends to form phenocrystic aggregates with plagioclase and olivine. Rarely augite shows lamellar twinning on 100. Multiple zoning is common; extinction angles Z∧c in 010 range from 48° in the cores to 52° in the rims. Plagioclase of the phenocrysts is labradorite (An_{65-67}). Many grains are normally and continuously zoned within a narrow range from about An_{65} in the center to about An_{45} at the edges; one grain was zoned from An_{67} to An_{30}.

OTHER INTRUSIVE ROCKS

MONZONITE

Monzonite crops out in a north-northwest-trending belt along the Río Tolimán, extending from Cerro de La Chametla to a point in the river west of Cerro de San Pascual. It is also found at two places in the Carrizal mining area, 2.5 kilometers farther north. A similar rock occurs in the El Monte mining area. In addition to the main body of monzonite, numerous small intrusions and dikes are found on the ridge west of the Río Tolimán and along the southwest side of the Santa Gorgonia and San Pascual mining area. Approximately 3 square kilometers of surface are underlain by monzonite.

The main mass of the monzonite has the general shape of a thick, very irregular dike which is oriented parallel to the regional strike of the enclosing stratified rocks. The dike averages 300–350 meters in width and has a maximum width of 1,000 meters. It forms a continuous outcrop 6 kilometers long and, including the isolated outcrops in the Carrizal mining area, is known to have a total linear extent of about 9 kilometers. All the Cretaceous and Tertiary formations in the district are intruded by the monzonite, but the bulk of the principal intrusive body is enclosed in Upper Cretaceous rocks.

The monzonite is fairly resistant to erosion; some of the most rugged sections of the Río Tolimán canyon are carved in it. Outcrops are poor, however, except in the deeper gullies and canyons, and contacts are usually covered by talus and slope wash. The exact shape of the intrusive body west of Cerro de San Pascual could not be mapped accurately because of inaccessible terrain, and detailed mapping northwest of Cerro de La Chametla was prevented by heavy brush. Elsewhere, the contacts mapped are believed to be reasonably accurate, although precise location of contacts was almost nowhere possible.

All the metalliferous deposits of the district have a rather close spatial relationship to the monzonite or similar rocks, and there seems to be little doubt that there is also a genetic relationship. The relation between monzonite and ore deposits will be discussed in a later section.

The monzonite differs greatly from place to place in color, grain size, proportion of phenocrysts, and degree of alteration. The fresh rock is commonly light brownish gray to brownish gray; usually, however, it has been altered to a greenish-gray color. Varieties ranging from a greenish-gray (5*G*6/1 to 5*GY*6/1) syenitic facies, through a greenish-gray to light brownish-gray quartz-monzonitic or granodioritic facies, to a dark grayish-green dioritic facies crop out in a small area southwest of Cerro del Arcabuz. The monzonite invariably has a hiatal porphyritic texture. Phenocrysts of plagioclase feldspar are present everywhere, and pyroxene and amphibole phenocrysts are common. Quartz is not an abundant phenocrystic mineral but is usually present in the groundmass. Potash feldspar is largely confined to the groundmass; in phenocrysts it is so badly altered as to be unrecognizable in hand specimen. Apatite and sphene are generally present as accessory minerals. Carbonate and quartz are uncommon secondary minerals, and barite in veinlets and irregular patches was noted in a thin section of monzonite from Cerro del Venado.

Phenocrysts ordinarily comprise 15–25 percent of the rock; rarely, as in the dioritic facies west of Cerro de San Pascual, they comprise as much as 50 percent.

The monzonite is usually altered; indeed, none of the 11 thin sections examined revealed a wholly unaltered rock. Feldspars are commonly altered to kaolinite, sericite, or epidote. The greenish plagioclase in the monzonite of Barranca de La Cruz contains 20–25 percent epidote, and the large feldspar phenocrysts in the intrusive below the Los Balcones mine are completely altered to sericite. Chlorite, serpentine, epidote, and iron ore were noted as products of the alteration of ferromagnesian minerals. Pyrite is found in nearly every outcrop and is very abundant locally; it coats fracture surfaces and is disseminated through the rock. Most outcrops of monzonite are stained by iron oxide resulting from oxidation of pyrite. Deep bluish-black tourmaline in prisms 1 to 3 mm in length and irregular aggregates occurs in the monzonite of the Barranca de La Cruz and Barranca de Santa Inés area and is sparingly present in a few other places, such as near the La Luz mine.

Typical quartz mononite from the hill southeast of the La Cruz mine is a medium-grained greenish-gray (5*GY*6/1) porphyritic rock in which phenocrysts of potash and soda-lime feldspar 1 to 2 mm in length, quartz, and a little pyrite are the only minerals identifiable in hand specimen. Microscopically, weakly zoned antiperthitic plagioclase, probably near oligoclase in composition, is highly sericitized and orthoclase is nearly completely altered to sericite and kaolinite. Quartz grains are corroded. The groundmass consists of pale-brownish-green hornblende, yellowish chlorite, altered plagioclase laths, and a little pyrite, all flooded and partly replaced by orthoclase, giving the rock a moth-eaten appearance when the slide is slightly below focus. The groundmass texture is similar to that of the quartz monzonite of the Carrizal and El Monte mining areas in that there is much late-formed magmatic orthoclase (pl. 9*A*). A little secondary quartz is present in veinlets and irregular patches.

A dark dioritic phase of the monzonite crops out about 550 meters from the mouth of Barranca de La Cruz, southwest of Cerro del Arcabuz. The rock is a dark grayish-green porphyry with prominent phenocrysts of pyroxene and plagioclase feldspar reaching 4 mm in length. Microscopically the rock consists of poikilitic augite prisms, andesine crystals, and abundant ragged grains of dark reddish-brown biotite, 0.2 mm long imbedded in a cloudy groundmass of highly altered plagioclase laths, augite granules, biotite rods, apatite, and iron ore. The augite phenocrysts are crowded with inclusions of plagioclase, biotite, apatite, and iron ore and appear to have crystallized late. Some of the plagioclase phenocrysts are normally zoned from An_{60} in the cores to An_{45} in the edges and are rimmed by fine-grained alteration products, probably kaolinitic. A little orthoclase may be present in the groundmass. Small grains of what was perhaps early-crystallized augite are completely altered to an aggregate of penninite, epidote, and very rarely, deep greenish-black tourmaline.

Another variation of the monzonite is found in an isolated outcrop in Barranca de La Cruz just northwest of Cerro del Arcabuz. The monzonite here intrudes El Morro fanglomerate. The hand specimen is a greenish-gray (5*G*6/1) porphyry consisting of prominent phenocrysts of quartz, greenish plagioclase, and a few small grains of pyroxene set in an aphanitic groundmass. Under the microscope, poikilitic augite prisms, cloudy epidotized euhedral grains of faintly zoned oligoclase 3 to 4 mm in length, and rounded embayed quartz phenocrysts as much as 3 mm across are imbedded in a fine-grained groundmass of tiny dusty oligoclase laths, augite granules, abundant minute sphene grains, iron-ore dust, and a little yellow-brown hornblende. Considerable orthoclase and penninite are interstitial to the groundmass minerals. Augite contains inclusions of hornblende and apatite. Brown-green hornblende occurs sparingly as phenocrysts as much as 0.4 mm in length. The abundance of quartz and the scarcity of potash feldspar, unless some is occult in the groundmass, indicate that the rock is a granodioritic phase of the monzonite.

A tourmaline-bearing monzonitic facies of the monzonite crops out between Barranca de La Cruz and Barranca de Santa Inés. This facies ranges in color from light brownish gray to greenish gray and is characterized by prisms of pale-green amphibole 2 to 8 mm in length, phenocrysts of plagioclase feldspar 1 to 6 mm in length, numerous tiny prisms and knots of blue-black tourmaline, and locally much pyrite and epidote. A thin section of the greenish-gray monzonite reveals subhedral labradorite (An_{60}) crystals and ragged skeletal amphibole grains in a groundmass mosaic of albite-oligoclase grains and interstitial orthoclase. Plagioclase is slightly sericitized and faintly zoned within a narrow range from An_{60} to An_{55}. The amphibole is probably uralitic and has the following optical characters: $(-)$ $2V$, large; refractive index, $\gamma=1.644$; extinction angle, $Z \wedge c=18°$; pleochroism, X=pale yellow green, Y=yellow green, Z=pale green; and absorption, $Z>Y>X$. It has numerous inclusions of sphene and may be pseudomorphic after titaniferous augite. Late-formed minerals include pyrite, tourmaline, sphene, and epidote. Pyrite is very abundant and much of it has irregular rims of sphene. Tourmaline occurs in prisms and irregular aggregates 0.1–0.6 mm. long and strongly pleochroic, with O=deep bluish gray to deep azure blue, and E=pale yellow.

The monzonite of the El Monte mining area forms a northwestward-trending lenticular dike about 350 meters in outcrop length and 70 meters in maximum width. The rock is a light bluish-gray to light-gray porphyry with rounded phenocrysts of quartz as much as 1.5 cm across and crystals of feldspar 0.5–1 cm long, set in a fine-grained matrix. Mafic minerals are scarce. Under the microscope, highly sericitized and slightly resorbed andesine prisms as much as 4 mm long, and deeply embayed quartz grains, are imbedded in a groundmass of scarce albite-oligoclase laths, quartz, and orthoclase. A little deep reddish-brown biotite in ragged grains as much as 2 mm across, and pale-brown hornblende needles, are minor constituents. Minute grains of apatite and sphene are abundant. The relatively small proportion of potash feldspar identified in the groundmass and the abundance of quartz phenocrysts suggest that the rock is a granodioritic facies of the monzonite.

QUARTZ LATITE PORPHYRY

An irregular body of quartz latite prophyry intrudes Lower Cretaceous limestone at the head of the west fork of Arroyo de La Chametla, 5.5 kilometers southwest of Zimapán. Poor exposures prevent accurate mapping of the limits of the intrusive, which seems to be a thick dike or elongate plug 200 meters in maximum width and about 700 meters long trending roughly northward.

In hand specimen the rock is a fresh greenish-gray (5*G*6/1) porphyry with phenocrysts of plagioclase feldspar 3 to 9 mm in length, ferromagnesian prisms 1 to 3 mm in length, and a little biotite set in an aphanitic matrix. The microscope reveals crystals of andesine, augite, hornblende, and biotite in a fine-grained granular groundmass of orthoclase and quartz. Clear euhedral plagioclase grains are slightly zoned and show both albite and Carlsbad twinning. Augite occurs as ragged skeletal crystals irregularly replacing both biotite and hornblende; a little sphene is included in the augite where biotite has been replaced. The extinction angle $Z \wedge c$ for the augite is 39°. The hornblende is a greenish-brown variety with $Z \wedge c = 17°$. A few hornblende grains were seen to have inclusions of plagioclase and to be rimmed by augite granules. Some unreplaced biotite also showed rims of minute augite grains. Several crystals of some ferromagnesian mineral, probably a pyroxene, were completely altered to pale-green antigorite and iron ore. Apatite and sphene are abundant accessories; the latter is generally somewhat altered to leucoxene. Although all the phenocrystic feldspar is andesine, the greater part of the groundmass, which constitutes about half the rock, is orthoclase and therefore the name quartz latite has been perferred to dacite.

HYPERSTHENE-HORNBLENDE ANDESITE

A plug of hypersthene-hornblende andesite about 200 meters in diameter intrudes the Lower Cretaceous limestone on the northwest side of Arroyo de Santiago at a point 1.7 kilometers south-southwest of San Pedro. Except for slight recrystallization of the limestone, no contact metamorphism is evident. In hand specimen the andesite is a dark-gray fresh-appearing fine-grained rock with prominent needles of black amphibole and less conspicuous small grains of pyroxene and feldspar. Under the microscope the rock was seen to consist of prisms and needles of hypersthene as much as 2 mm in length and slender grains of hornblende as much as 3 mm in length, set in a hyalopilitic base of andesine (An_{45}) microlites, a little glass, and very abundant iron-ore dust. A few sericitized phenocrysts of plagioclase feldspar, probably about An_{50}, were also noted. Hypersthene is strongly pleochroic, with X=brownish red and Z=pale green. The hornblende is a variety near barkevikite, with the following optical properties:

(−)2*V* large
dispersion $r > v$ strong
extinction $Z \wedge c = 13°$
index $\gamma = 1.700$
pleochroism X=pale yellow green
Y=yellow brown
Z=dark brownish green

The hornblende crystals are altered to an opaque aggregate around their borders. A little quartz and apatite, and scattered patches of a fibrous radiating zeolite with positive elongation and slightly inclined extinction, probably epistilbite, occur in the groundmass.

AUGITE DIABASE

Three small bodies of augite diabase intrude the El Morro fanglomerate in a tributary of Barranca Seca about 700 meters east of the Santa Gorgonia mine. The largest of the bodies is only about 50 meters long, but it is probably an offshoot of a considerably larger intrusive, as the normally red fanglomerate has been bleached nearly white for distances as much as 100 meters from the intrusive contacts. The diabase is a grayish-black coarse-grained fresh rock with prominent ophitic texture visible in the hand specimen. In thin section the rock consists of a mesh of euhedral andesine-labradorite (An_{50}) laths from 1 to 3 mm in length which form an ophitic intergrowth with pale reddish-violet pleochroic titaniferous augite (pl. 9*B*). Abundant apatite, a little andesine, orthoclase, quartz, and minor iron ore occur interstitially to the plagioclase. The feldspar is usually perfectly clear and twinned according to the albite law; a few grains are slightly cloudy. A little apatite occurs as inclusions in plagioclase. Locally, augite appears to replace plagioclase. A strongly birefringent mineral, pleochroic in dark and light yellowish brown, probably iddingsite, replaces augite here and there, and dark-green chlorite also appears sparingly as an alteration product of augite.

A small plug of greenish-black diabase intrudes the Las Espinas volcanic rocks 700 meters south of Temoté. The rock was not examined in thin section.

POTRERO RHYOLITE PORPHYRY

A very coarse grained porphyry is exposed at several places in the vicinity of Cerro del Potrero, 3 kilometers south of Zimapán. It forms the peak of Cerro del Potrero, an irregular plug about 600 meters in diameter, and crops out over a large area at the head of Arroyo del Ortigal south of Cerro del Potrero, as well as on the high ridge between Arroyo del Potrero and Arroyo del Ortigal and at the head of the deep canyon east of Cerro de Daxi. The porphyry is intrusive into Upper Cretaceous strata, the El Morro fanglomerate, and the Las Espinas volcanic rocks; just south of Cerro del Potrero it cuts completely through the El Morro, thus forming the only break in the fanglomerate belt between Cerro de Pascual and the south edge of the area mapped, a distance of nearly 12 kilometers.

The porphyry varies greatly in appearance from place to place, but it is commonly a grayish-red to grayish-red-purple rock with subhedral to euhedral phenocrysts of whitish feldspar and rounded quartz grains set in a very fine grained matrix. Two size groups of feldspar phenocrysts are evident, one group of crystals ranging from 2 to 10 mm in length, the other from 2 to 6 cm in length. The smaller phenocrysts are completely altered to a dull claylike aggregate, and the larger crystals commonly have small unaltered remnants in a matrix of whitish alteration products. Some of the large phenocrysts are dusky red and exhibit a prominent, almost metallic luster, or schiller.

Under the microscope the groundmass appears as an extremely fine grained aggregate of quartz, potash feldspar, devitrified glass, and iron oxide. Quartz phenocrysts are deeply embayed by the groundmass. The smaller feldspar phenocrysts are generally euhedral and are completely altered to an unidentifiable fine-grained aggregate containing a little sericite and quartz. The large feldspar crystals are clear sanidine with a very small negative optic angle; they are subhedral and severely corroded by groundmass. A few grains 1 mm in length of what was apparently brown hornblende are altered to a nearly opaque dusty aggregate with an opaque rim of iron oxide.

A light-brown variation of the Potrero rhyolite porphyry, apparently intruded slightly earlier than the larger masses, has, in addition to the minerals mentioned above, large rounded phenocrysts of quartz as much as 1 mm across, with a rim of limonitic material and abundant stubby euhedral crystals of biotite 1 to 3 mm in length, pleochroic in yellow green and deep red brown. The biotite is altered to iron oxide along cleavage cracks and around borders; cleavage lamellae are partly bent or broken. Sanidine crystals as much as 1 cm in length are embayed by a groundmass composed of a little quartz, orthoclase, sericite, clay, iron-ore dust, and devitrified glass. The light-brown porphyry has baked the adjoining Upper Cretaceous shale with the production of much sideritic carbonate and the introduction of considerable quartz and chalcedony.

The complete alteration of the smaller feldspar phenocrysts, in contrast to the freshness of the large sanidine crystals, is difficult to explain unless the smaller phenocrysts were originally plagioclase; that they may have been is suggested by the almost imperceptible zoning formed in the alteration products of a few phenocrysts. The alteration seems to have been largely due to weathering, as there is no evidence of magmatic alteration of the small crystals; sandine seems clearly more resistant to weathering than plagioclase under the conditions obtaining at Zimapán.

RHYOLITE FELSITE

GENERAL FEATURES

A number of rhyolite felsite intrusives are found south and southwest of Temoté, 3.5 kilometers south of Zimapán. An irregular plug of rhyolite felsite 1.5 kilometers long and 800 meters wide forms the summits of the group of high jagged peaks 2.5 kilometers southwest of Temoté, and an elongate plug or thick dike 1.5 kilometers long and 500 meters in maximum width crops out on the summit of Cerro de Daxi. The large dike that forms the prominent ridge between Arroyo del Ortigal and the Río Tolimán is also composed of rhyolite felsite. Finally, three small plugs and a dike of similar rock occur 700 meters southwest of Temoté.

The felsite is the youngest intrusive rock recognized in the Cerro del Potrero-Temoté area. It intrudes, in several places, Lower Cretaceous limestone, Upper Cretaceous strata, El Morro fanglomerate, Las Espinas volcanics, and Potrero rhyolite porphyry. The felsite is highly resistant to erosion and forms conspicuous cliffs where softer wall rocks, primarily Lower Cretaceous strata, have been eroded away.

Flow layering is well formed in most of the felsite bodies. In the largest plug, southwest of Temoté, flow layers are parallel to contacts, usually stand at high angles from 70° to 90° and, wherever observed, dip inward. Dips as low as 20° were recorded where the flow layering is strongly swirled. Flow layering in the large dike between Arroyo del Ortigal and the Río Tolimán parallels the strike of the dike, about N. 70° W.; dips are consistently southwest and, although occasionally as low as 20°, are commonly between 40° and 70°.

A small plug of what was classified in the field as devitrified obsidian intrudes the Las Espinas volcanic rocks 600 meters southwest of Temoté. The outcrop is a nearly semicircular arc, open to the southwest and with a radius of 50–60 meters. Flow layering is vertical and the rock is thoroughly silicified at the contact with the volcanic rocks. Isolated patches of similar rock within the rim indicate that the plug was originally nearly circular in plan. Apparently the silicification accounts for the preservation of the northeast rim; the remainder of the rim and the core have completely decomposed and the area within the arcuate rim is utilized for farming.

LITHOLOGY

The felsite of the large irregular plug is a white to cream porcelainlike rock, usually without phenocrysts. It is commonly banded, thin layers of pale-purplish material alternating with the predominant light-colored bands. Minute grains of whitish feldspar are visible at places in the purplish bands. The rock emits a strong clay odor when moistened. Under the microscope the rock appears to consist almost entirely of kaolinized feldspar and subordinate quartz in irregular grains averaging 0.03 to 0.04 mm in diameter, with a little interstitial glass. A few completely kaolinized, euhedral, and slightly resorbed feldspar phenocrysts, having a maximum length of 2 mm, were seen in the one slide examined. In addition to feldspar and quartz there are many dark spherulitic aggregates as large as 0.2 mm in diameter; the minerals of the spherulites are too fine grained for identification. Flow layering is noticeable but not prominent in thin section.

The felsite dike between Arroyo del Ortigal and the Río Tolimán differs markedly both megascopically and microscopically from the felsite described above. In hand specimen the fresh rock is light gray, but nearly everywhere it has weathered to a grayish orange. It carries many tiny but conspicuous phenocrysts of quartz and a few less-conspicuous dull feldspar grains. Flow layering gives the rock a streaked appearance. In thin section subangular phenocrysts of quartz as much as 2 mm in diameter and a few subhedral feldspar grains are set in a very fine grained groundmass of rounded quartz granules averaging about 0.05 mm in diameter, a little oligoclase, and an irresolvable dusty matrix containing much slightly devitrified glass and iron-ore dust and apparently a little chlorite. The groundmass has an average refractive index a little higher than balsam. Both quartz and feldspar phenocrysts are embayed by the groundmass. All the feldspar crystals are completely kaolinized. Although no potash feldspar was identified with certainty, the high proportion of both megascopic and microscopic quartz suggests that the rock probably belongs to the rhyolites.

The felsite of Cerro de Daxi is so thoroughly silicified that its identification is uncertain. It is grouped with the rhyolites on the basis of the presence of abundant phenocrystic quartz and general similarity of appearance to the rhyolites of the immediate vicinity.

MODE OF EMPLACEMENT

The felsite bodies are all characterized by four features that partly indicate their mode of emplacement. The first is that the lithology of a given felsite mass is uniform everywhere within the mass, there being no noticeable megascopic variation from the center of the mass to the periphery, except for increased development of flow layering near the walls. Another feature is a nearly complete lack of wall-rock inclusions in the felsites at the level of observation, the only inclusion definitely identified as such being a block of andesite in the north-central part of the largest felsite body. A further indication is that the contacts with the wall rocks, best shown where the felsite cuts the Upper Cretaceous strata or the Potrero rhyolite porphyry, are cleanly crosscutting and there is no marginal schistosity or notable deformation developed in the wall rocks, even where these are soft shaly Upper Cretaceous strata (where the felsite intrudes the Las Espinas volcanic rocks, the contacts are poorly exposed and afford little evidence as to the mode of emplacement). Field relations in a few places also indicate clearly that a considerable volume of country rock has disappeared, as at a point 1.2 kilometers southwest of Cerro del Potrero, where a plate of El Morro fanglomerate and overlying Las Espinas volcanic rocks resting on Upper Cretaceous rocks has been cut off by felsite, and a block of the two formations of unknown but surely rather large volume has completely disappeared.

The general characteristics described above indicate that forceful spreading of wall rocks, laccolithic or lopolithic emplacement, or assimilation or replacement of wall rocks were not active during emplacement of the felsite bodies. Stoping may have been important, but if so, any conclusive evidence lies at depths not yet revealed by erosion. The only adequate mechanism apparent to us is the upward pushing of a plug to the surface. It seems likely, considering the great relief of the felsite masses (about 400 meters maximum) in conjunction with the amount of erosion that has taken place in the surrounding terrain since their emplacement, that the felsite, at least locally, did reach the surface; the plug of rock that would have been pushed to the surface by such a process has since been eroded away. The evidence of the wall rocks with regard to such a mode of emplacement is negative; no drag of wall rocks at the felsite contact was observed and indeed at one place Upper Cretaceous shaly limestone and shale dip toward the felsite. If the felsite was emplaced by upward "punching," it was probably bounded by a system of irregular fractures that developed early in the stage of emplacement and permitted upward movement without perceptible deformation of the walls.

IGNEOUS ROCKS OF THE CARRIZAL MINING AREA

Small dikes are a notable feature of the Carrizal mining area and are especially prominent in the vicinity of the Los Balcones mine. Two trends of major dikes are apparent: one group of dikes strikes N. 60°–80° E., the other N. 60°–80° W. A single exception is the dike southwest of the head of the aerial tram to the Las Estacas mine, which strikes about N. 25° W. All the dikes have steep dips, ranging from 70° to 90°. Figure 5 is a plot showing the strikes of 69 dikes in the vicinity

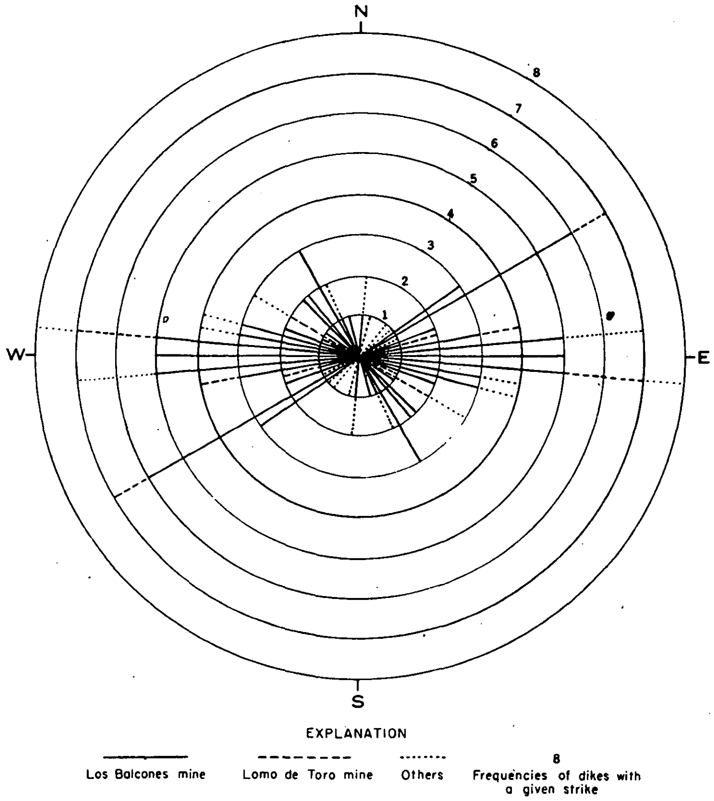

FIGURE 5.—Radial plot of the strikes of 69 dikes in the vicinity of the Lomo de Toro and Los Balcones mines.

of the Los Balcones and Lomo de Toro mines. The dike trends of the area as a whole tend to lie within 30° of east, although the trends are not as marked as those of the Los Balcones area considered separately.

The relative ages of the main dike sets are not known, as none of the intersections are exposed, either at the surface or in the mine workings. No lithologic distinctions can be made between the two dike groups; all rock types represented, except rhyolite, are found in each group. A close spatial relationship is evident between quartz monzonite and the dikes centered around the Los Balcones mine, and two dikes are clearly seen to be offshoots from the quartz-monzonite body.

Most of the dikes have been intruded along joints, but a few are along normal faults of small displacement. Figure 6 is a field sketch of two thin dikes exposed in El Cajón; they apparently have intruded a fractured zone parallel to the axial planes of two small asymmetrical folds in Lower Cretaceous limestone. A rhyolite dike just north of Puerto de La Pared Blanca has a thin breccia zone along the hanging wall; angular fragments of Lower Cretaceous limestone as much as several centimeters across are enclosed in dike rock. A few of the fragments are very slightly rounded, but little assimilation appears to have taken place. The

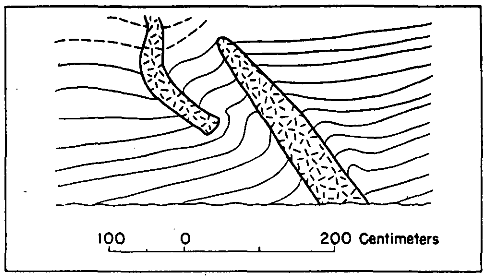

FIGURE 6.—Latite dikes intruded along axial planes of minor overturned folds of the Lower Cretaceous limestone, at El Cajón, Barranca de Tolimán.

lithologic types of rocks represented will be described in the approximate order of decreasing silica content.

RHYOLITE DIKES

The only important rhyolite dike of the area is the Santa Luisa dike, which forms the northeast wall of the Santa Luisa ore body in the Lomo de Toro mine. It strikes about N. 60° W. and ranges in dip from 75° SW to 85° NE. The dike has been traced for about 550 meters along the strike and maintains a nearly constant thickness of 4 meters throughout its length. A hand specimen from the Santa Luisa stope is a medium light-gray porphyry showing prominent rounded phenocrysts of quartz and potash feldspar, the latter somewhat whitish from alteration, set in an aphanitic groundmass carrying considerable pyrite. Under the microscope, slightly embayed phenocrysts of quartz as much as 4 mm across, and highly sericitized subhedral sanidine crystals as much as 5 mm long, seem to be imbedded in a fine-grained groundmass of quartz and orthoclase. Sanidine has been slightly replaced by carbonate. Apatite is an abundant accessory mineral; sphene is present but is not abundant.

A similar rhyolite dike appears in the lower adit of the Las Ventanas mine, several hundred meters northwest of the Los Balcones mine and on the west side of the Río Tolimán; it may be a continuation of the Santa Luisa dike, but exposures are inadequate to establish its continuity. The Las Ventanas dike carries a large proportion of pyrite, but it is otherwise identical with the Santa Luisa dike.

QUARTZ LATITE DIKES

Quartz latite dikes are not common in the area. The best example is a dike 7 meters wide that crosses the Lomo de Toro and Los Balcones road just below the ore bin of the Las Animas mine. It appears to be an offshoot of the quartz monzonite. In hand specimen the rock is a light bluish-gray porphyry with prominent phenocrysts of quartz and plagioclase and a few whitish grains of what appears to be altered potash feldspar. Irregular knots of epidote, a few tiny grains of pyroxene, and many small rusty crystals of what was probably pyrite are also visible. In thin section the rock is seen to consist of slightly embayed quartz grains as much as 3 mm across, highly sericitized euhedral oligoclase crystals as long as 4 mm, and poikilitic augite prisms as long as 2 mm, imbedded in a granular groundmass of quartz and orthoclase. Apatite and sphene are accessory minerals. Epidote replaces plagioclase locally and forms pseudomorphs after augite. A few ragged grains of tremolite and a little quartz appear to be secondary minerals.

Another quartz latite dike crops out 80 meters south of the portal of the San Guillermo adit of the Lomo de Toro mine. It is a dark greenish-gray rock in which large phenocrysts of plagioclase and pyroxene and a little quartz can be seen in the hand specimen. Under the microscope the rock is seen to be similar to the quartz latite described above; a little oligoclase and a few tiny grains of zircon are present in the groundmass, as well as some secondary carbonate and chlorite (penninite).

The quartz latite dike above the Las Estacas mine is identical lithologically to the quartz monzonite described in one of the following sections.

TRACHYTE DIKES

Trachyte dikes are found only along the north edge of the Los Balcones mine area. The most prominent is a dike 3 meters thick that crops out at the portal of the San Rafael Viejo adit and is cut underground near the portal of the La V adit. In hand specimen it is a very light gray porphyritic rock with prominent phenocrysts of potash feldspar and very pale pyroxene set in an aphanitic groundmass dotted with specks of pyrite. Microscopically the rock is composed of ragged augite phenocrysts as much as 0.5 mm in length, and sericitized and kaolinized sanidine crystals as much as 3 mm in length, with a fine-grained granular matrix of orthoclase and tiny pyroxene granules. Some of the sanidine shows baveno twinning. Sphene and apatite are abundant accessory minerals. Considerable secondary calcite replaces augite and sanidine and locally floods the groundmass. There is a little secondary epidote.

LATITE DIKES

More than half the dikes in the area have the mineralogical composition of latite. The typical latite is a light-gray to white rock with an extremely fine grained groundmass. Plagioclase feldspar is commonly the only mineral identifiable with a hand lens; pyrite and epidote are common secondary minerals and tiny aggregates of blue-black tourmaline were noted in one of the dikes of the San Miguel adit of the Los Balcones mine.

A specimen of a latite dike that crosses the San Damián and Los Balcones trail 200 meters northwest of the San Damián adit was examined in thin section. The rock is porphyritic with phenocrysts of plagioclase, epidote apparently pseudomorphic after pyroxene, and amphibole in a matrix of albite-oligoclase laths and minute amphibole rods, all imbedded in a base of orthoclase. The plagioclase grains attain a length of 4 mm; they are highly altered to sericite with a little epidote and carbonate and have the composition of nearly pure albite. All the amphibole is a colorless tremolitic variety with extinction angle $Z \wedge c$ about 17°. Apatite and sphene are common accessory minerals. Secondary minerals include carbonate in veinlets, and clusters composed of pyrite, epidote, and a little pale-green chlorite.

PYROXENE-AMPHIBOLE VOGESITE DIKES

Four dikes have been classified as vogesite; both amphibole- and pyroxene-bearing vogesites were noted. Typically the rock is grayish green to greenish gray and very fine grained; the only minerals distinguishable in hand specimen are pale needles of amphibole or pyroxene, pyrite, and rarely, plagioclase feldspar. Under the microscope, the vogesite dike from the La V adit of the Los Balcones mine consists of colorless amphibole prisms as much as 2 mm in length imbedded in a matrix of orthoclase dotted with very abundant tiny grains of sphene. Locally the groundmass texture is ophitic. The amphibole is optically $(-)$ with $\gamma = 1.640$ and extinction angle $Z \wedge c = 17°$, corresponding to a tremolite with about 16 percent of the ferrotremolite molecule, according to Winchell's table (1933, p. 246). Epidote and carbonate replace amphibole extensively.

The two large dikes that bound the La Palmita Alta ore chimney are composed of a cream-colored rock which has also been classified as vogesite for want of a better name. Except for the presence of pyroxene instead of amphibole, and a little secondary quartz, the rock is similar microscopically to the amphibole-bearing variety. It is not, however, a lamprophyre, and perhaps should be called bostonite instead of vogesite.

DACITE DIKES

Dacite dikes are found only in the vicinty of the Santa Clara mine. The rock is classified as dacite on the basis of its apparent low orthoclase content, but considerable orthoclase may be occult in the groundmass and the rock might possibly belong to the quartz-latite group. The dikes are dark greenish gray in hand specimen; plagioclase feldspar and pyrite are the only identifiable minerals. Microscopically the rock is seen to be composed of scattered phenocrysts of weakly zoned plagioclase (An_{50}) as much as 3 mm in length and poikilitic augite grains as much as 1 mm long, in a felted groundmass of labradorite (An_{55}) rods with considerable interstitial quartz and orthoclase. Sphene is a very common accessory mineral; some of it appears to be introduced along with pyrite. Apatite is also abundant. Several quartz xenocrysts with well-formed reaction rims of pyroxene granules were seen.

Locally the quartz-orthoclase portion of the groundmass, and to some extent the plagioclase also, is replaced by an aggregate of carbonate, pale-green actinolite, and a little pyrite and sphene.

ANDESITE DIKE

Only one andesite dike is known in the area; it crops out near the head of the main gully south of the El Claro patio of the Lomo de Toro mine. In hand specimen the rock is a dark greenish-gray porphyry with prominent phenocrysts of plagioclase, less prominent amphibole needles, and a scattering of pyrite and calcite, set in an aphanitic base. In thin section the rock is seen to consist of sericitized oligoclase phenocrysts as much as 3 mm long and slender pale-green amphibole prisms as much as 1 mm long, in a very fine grained groundmass of oligoclase and amphibole. Sphene is an abundant accessory mineral; it is commonly altered somewhat to leucoxene. Apatite is present but not common. The amphibole seems to be an actinolitic variety, with extinction angle $Z \wedge c$ about 15°. Secondary minerals include quartz and pyrite in veinlets, epidote and zoisite replacing plagioclase, and carbonate in irregular patches.

IRREGULAR INTRUSIVE BODIES

The large quartz monzonite body along the Río Tolimán below the Los Balcones mine is believed to be part of the much larger mass of monzonite to the south, but the rock is so thoroughly altered that its identification is uncertain. In plan the body appears to be a thick, very irregular dike striking about N. 45° E. It has been mapped for about a kilometer along the strike and attains a maximum width of perhaps 400 meters. The contact with the Lower Cretaceous limestone is everywhere covered by talus and gravel, except where the northwest contact crosses the Río Tolimán. At that place, contact metamorphism of the limestone has been slight. Near the southwest end of the intrusive, however, enormous masses of garnet have been formed in the limestone near the contact; these are discussed in the section on igneous metamorphism.

In hand specimen the rock is a light bluish-gray to yellowish-gray porphyry with prominent phenocrysts of dull feldspar and quartz and commonly some pyrite. The porphyry differs greatly in appearance from place to place, depending largely on the degree of alteration and pyritization; in the lowest exposures, along the river, it is so heavily impregnated with pyrite as to be almost unrecognizable as a porphyry. In thin section, a specimen of the porphyry from near the foot of the trail from the Los Balcones mine to the Río Tolimán was seen to be composed of phenocrysts of feldspar 3 to 4 mm in length and slightly smaller rounded quartz grains in a groundmass of quartz and sericite. The feldspar is completely altered to sericite. Tiny grains of sphene are abundant, and zircon is also sparingly present; apatite is absent.

A small mass of relatively fresh quartz monzonite crops out at the sharp bend in the river about 120 meters below the Las Estacas mine. In thin section the rock was seen to consist of augite prisms 1 mm in length and phenocrysts of andesine (?) as much as 3 mm long, together with a few deeply embayed quartz crystals, in a groundmass of quartz and orthoclase. Augite is a late-formed mineral; it occurs as poikilitic grains and also interstitially. Andesine is partly altered to zoisite, epidote, and sericite and is locally albitic. Many of the andesine grains are rimmed by orthoclase. Sphene is abundant; it occurs in irregular grains as long as 0.3 mm and is strongly pleochroic in pale yellow and brownish red. Apatite is common. Secondary minerals include epidote, which replaces andesine and augite and is scattered through the groundmass, and a little carbonate. The orthoclase of the groundmass appears to be largely late-formed magmatic; it has flooded the groundmass and produced a peculiar moth-eaten texture strikingly shown in thin section when the slide is slightly below focus (pl. 9, *A*).

STRUCTURE

The accompanying geologic map (pl. 2) shows that all the structural features within the Cretaceous rocks and most of the features involving Tertiary rocks have a prevailing northwestward to north-northwestward trend, A single noteworthy exception is the San Pedro fault, which trends north to northeast.

STRUCTURAL FEATURES OF THE CRETACEOUS ROCKS

The structures of the Cretaceous rocks are characterized by small and large folds, ranging from open folds to recumbent isoclinal folds. In general, folds are asymmetrical or overturned; axial planes usually dip southwest. Chevron or zigzag folds are more common than folds with U-shaped crests or troughs. Other features include fracture cleavage and a peculiar cleavage perhaps related to boudinage. Thrust faulting appears to have been of minor importance; the only thrust fault recognized in the district was at Cerro de

Daxi where Lower Cretaceous limestone is over Upper Cretaceous rocks. The widespread occurrence of overturned folds with axial planes of low dip suggests that additional thrust faulting may be present although unrecognized. No large normal faults of Cretaceous age are known. Only one period of deformation before deposition of the El Morro fanglomerate has been recognized, and we believe that all observed structural features can be related to that period.

It must be emphasized that structures of the Cretaceous rocks were difficult to map with any certainty because of the lack of established key horizons and the apparent uniform character of most of the rocks in the Cretaceous rock units mapped. Major features, if present, are thoroughly masked by intense isoclinal folding on a small scale. In addition, we were unable to establish any satisfactory criteria for distinguishing tops of beds from bottoms; in a section composed largely of relatively pure limestone with smaller percentages of fine-grained clastic rocks, the difficulty of determining positions of strata is readily apparent. The only reliable criterion observed was the oscillation ripple mark; it was so rare, however, as to give little evidence of the areal structure.

FOLDS

The Cretaceous rocks are nearly everywhere tightly folded, often isoclinally, and in many places the folds are overturned and even recumbent. Only two major folds proved to be mappable; elsewhere folding has been so intense and intricate as to defy mapping on any reasonable scale. The two folds mapped are the Puerto Angel and Piñón anticlines.

The Puerto Angel anticline forms the high ridge northeast of El Detzaní and El Dedhó and has been traced for nearly 5 kilometers northwest from a point about 1 kilometer northeast of El Detzaní. At its southeastern end the anticline is asymmetric, the northeast limb being essentially vertical and the southwest limb dipping steeply southwest. Plate 8*C* is a view looking southeast along the axis of the anticline from a point about 1 kilometer northwest of Cerro del Juaxidó. Two kilometers northwest of Cerro del Juaxidó the fold passes into an isoclinal overturn and cannot be recognized farther northwest. Between El Detzaní and Cerro del Juaxidó a massive bed of fossiliferous limestone occupies the anticlinal crest. The fold plunges southeast at a low angle and disappears near El Detzaní.

The axis of the Piñón anticline lies just east of Puerto del Piñón, 5 kilometers north-northeast of Zimapán. The fold has been traced for about 4 kilometers in a north-northwesterly direction from Arroyo del Muí. Both limbs dip about 60° away from the vertical axial plane; the crest is very sharp, reversal of dip for a given bed taking place in a few meters normal to the axis. Such **V**-shaped folds are typical in the Lower Cretaceous limestone and there are almost no **U**-shaped folds (pls. 10*A* and *B*, 11*A* and *B*).

The structure of the Lower Cretaceous limestone in the Carrizal mine area is extremely complex. It is shown diagrammatically near the southwest end of section *E–E′* in plate 2. The principal structure is thought to be an overturned isoclinal anticline whose axial plane dips southwestward at angles ranging from a few degrees to nearly 90°. Axial planes of drag folds dip gently southwestward at the bottom of Barranca de Tolimán and low dips are prevalent in the cliffs below the San Guillermo adit of the Lomo de Toro mine. Above the adit, dips of axial planes become increasingly steeper and at the San Damián adit the average dip is perhaps 60°. Above and northeast of the San Damián portal, dips of both Lower and Upper Cretaceous strata approach 90°.

Flat isoclinal folds are wonderfully exposed at many places in the Carrizal area. Some of the best exposures are in Barranca de La Manzanita a few hundred meters south-southeast of the San Guillermo adit, in the cliffs immediately below the same adit, and in the gorge of El Cajón (The Box, or, freely, Box Canyon). Figure 7*A* is a field sketch of folds at the bend in El Cajón; 11 repetitions of a single bed are clearly visible in a vertical interval of about 20 meters, and undoubtedly additional repetitions could be found if the cliff above were accessible. Figure 7*B* shows another group of folds just above the bend of El Cajón. Plate 10*A* is a photograph showing a chert bed broken along a small thrust fault, also in El Cajón. Flat folds are common only in the lower 200–250 meters of Barranca de Tolimán; at higher levels axial planes have steeper dips. Figure 7*C* is a field sketch of folds along the Lomo de Toro and Los Balcones mine road at an altitude of 385 meters above the bottom of the barranca; axial planes dip 35°–55° southwestward. Plate 11*B* shows folds at the portal of the El Claro stope of the Lomo de Toro mine 330 meters above the barranca bottom; dips of axial planes are 30°–40° southwestward. Figure 7D is a field sketch of folds exposed along the mine road 280 meters above the river; here axial planes dip 40° southwestward.

A recumbent fold of much larger size is exposed in the great cliff above the La Paz mine. Plate 12 is a view of the fold looking westward from a point about 1 kilometer north of the Lomo de Toro mine. The La Paz mine lies at an altitude of 1,470 meters, about 220 meters above the Río Tolimán; the vertical distance

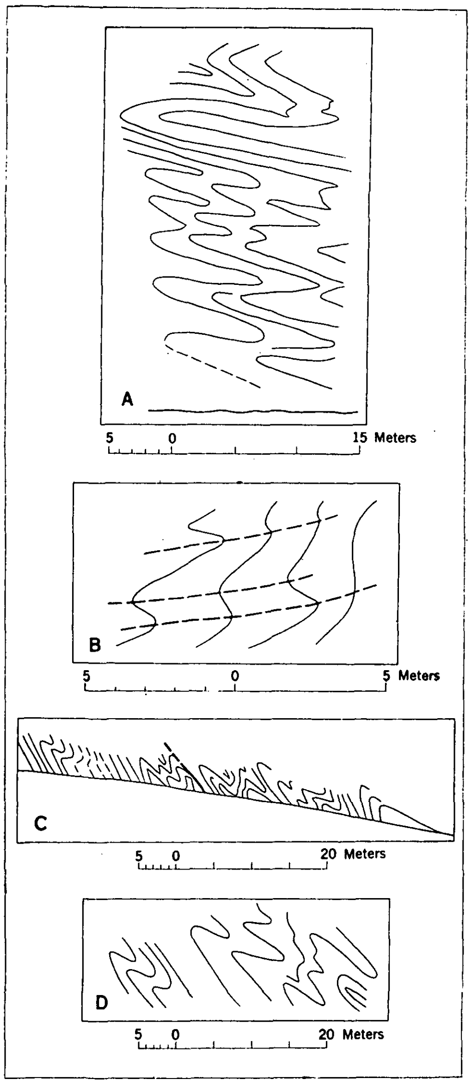

FIGURE 7.—Sketches of folds in Lower Cretaceous limestone. *A.* Southeast wall of El Cajón at bend, looking southeastward. Axial planes of recumbent folds in limestone dip approximately 10° SW. Bed at lower and center left is repeated 11 times in a vertical interval of about 20 meters. *B.* Northwest wall of El Cajón just above bend, looking northwestward. Steeply dipping folded limestone; axial planes of folds dip gently southwestward. *C.* Folded limestone along Lomo de Toro-Balcones mine road 385 meters above El Cajón, looking south-southwestward. Axial planes dip 35°–55° SW. *D.* Folds in limestone 280 meters above El Cajón; view is looking southward. Axial planes dip approximately 40° SW.; fold axes are horizontal and strike N. 50° W.

from the La Paz mine to the Todos Santos mine is 420 meters. Another large recumbent fold is illustrated in figure 8; it is clearly exposed on the north side of Cerro del Malacate and can be seen from the Lomo de Toro and Los Balcones mine road. The fold is overturned to the east; only the upper and inverted limbs are visible.

A few kilometers down the Río Tolimán from the Carrizal area the Lower Cretaceous limestone is thrown into folds of considerable magnitude. Figure 9 is a

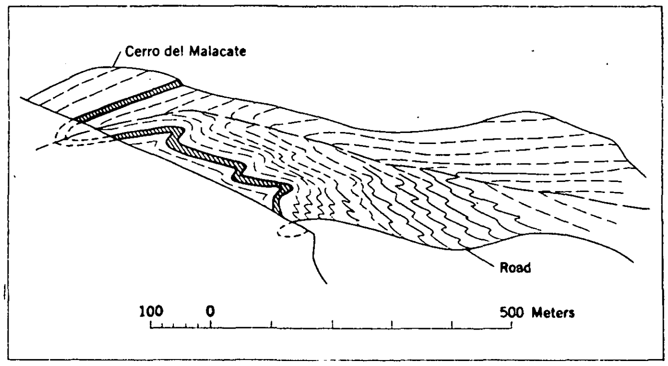

FIGURE 8.—Large recumbent fold, north side of Cerro del Malacate, seen from Lomo de Toro-Los Balcones mine road just southeast of upper hairpin curve, looking southward. Rocks are cherty limestone; ruled bed at left is reef limestone. Beds above fold axial plane (heavy dashed line) are right side up; those below are isoclinally folded and overturned. Isoclinal folding accounts for apparent increase in thickness of section along inverted limb of fold.

field sketch of an overturned anticline at the La Amistad no. 3 prospect. The beds are clearly exposed in a cliff more than 60 meters high. Crumpling in the core of the anticline is more complex than the sketch shows; axial planes of all the minor crumplings dip southward. The shape of the fold and the abrupt transition from horizontal to steeply dipping beds suggest that this fold originated through a "décollement" such as described by Buxtorf (Billings, 1947, p. 55) from the Jura mountains of France. A short distance downstream is another similar anticline; figure 10 is a sketch of this fold, showing its shape and the thickening and thinning of various beds due to flowage of limestone under compression.

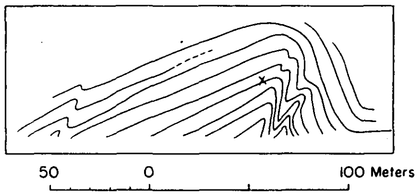

FIGURE 9.—Anticline in Lower Cretaceous limestone in Barranca de Tolimán, 1.5 kilometers north-northwest of Lomo de Toro mine; view looking west. Note abrupt flattening of bedding at base of north limb, and crumpling of beds in core. Axial planes of overturned folds dip about 65° S. *X* is portal of La Amistad No. 3 prospect adit.

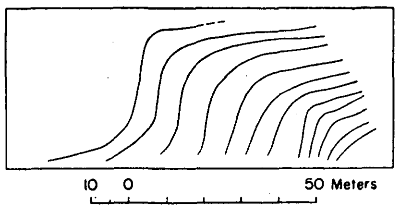

FIGURE 10.—Asymmetrical anticline in Lower Cretaceous limestone about 500 meters north of fold of Plate 9, *A* looking eastward. Axial plane dips about 25° S.

THRUST FAULT

The only thrust fault recognized in the district is in Cerro de Daxi in the southwestern corner of the area mapped. Cerro de Daxi consists of gently dipping overturned (?) Lower Cretaceous limestone resting on contorted Upper Cretaceous strata. Evidence for the thrust fault is largely paleontologic, as the outcrop is everywhere concealed by fanglomerate or caliche; the fault appears to dip southwestward at a low angle. A small klippe lies just northwest of the main mass of Cerro de Daxi.

The quartz-latite body near the headwaters of Arroyo de La Chametla was intruded after thrust faulting took place, for it cuts across the thrust plane and intrudes both Upper and Lower Cretaceous rocks. Thrust faulting was probably contemporaneous with the major deformation of the Cretaceous rocks, as there is no evidence of any important deformation of post-Cretaceous age in the Tertiary rocks.

FRACTURE CLEAVAGE

Fracture cleavage occurs widely in the Upper Cretaceous strata; it is seen occasionally in the more shaly sections of the Lower Cretaceous limestone and rarely in the limestone itself (fig. 11). It is everywhere closely related to folding and appears to have formed during folding. Where axial planes of folds have low dips, fracture cleavage has similar low dips; in areas of folds with axial planes of high dips, fracture cleavage also has high dips. Fracture cleavage and axial planes in general have northwesterly strikes and southwesterly dips, but the amount and direction of dip show no clear regional pattern; such a random orientation of fracture cleavage, at least as regards the dip, suggests that the cleavage has developed in response to local as well as regional stress. In practice, fracture cleavage was found to be of little value in determining the structure of the district.

Locally, fracture cleavage maintains a nearly constant angle with the bedding throughout a fold. Consequently the dip and, if the fold is plunging, also the strike change markedly within small distances, but in general the cleavage is approximately parallel to axial planes of folds. Plate 11*C* shows fracture cleavage cutting across bedding in an overturned fold in Upper Cretaceous limy shale; cleavage strikes northwestward and dips 20° SW. In the more calcareous sections of the Upper Cretaceous rocks, fracture cleavage is confined to shale beds interbedded with limestone. One example of fracture cleavage in a sequence of limy shale and chert is shown in figure 12. Cleavage in the chert is inclined about 10° more steeply to the bedding than in the shale, a clear illustration of the different reaction to stress of a brittle competent rock (chert) and a relatively incompetent rock (shale). The shale has presumably fractured along one of two conjugate shears; the chert has broken more nearly normal to the bedding, the angle at which minimum resistance to rupture is offered.

A peculiar type of cleavage (the word "cleavage" is used for want of a better name) formed in the chert of the Lower Cretaceous limestone warrants separate description. Plate 11*D* shows a chert bed 5 cm thick that is broken along a closely spaced series of fractures developed at a rather constant angle of 60°–70° to the bedding; the resulting blocks have been rotated as much as 25° from their original position. The blocks have been separated slightly and the open spaces filled with white calcite. No corresponding fractures are visible in the limestone; all deformation has been absorbed plastically. Although rotation and separation of individual segments have been rather small, the total lengthening of the chert layer must have been considerable.

Figure 13 is a sketch of similar cleavage exposed in Barranca del Malacate. Here a chert bed 2 cm thick

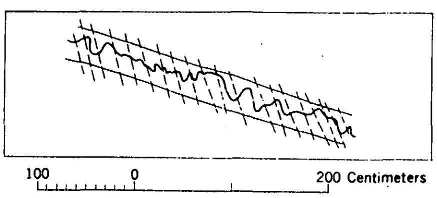

FIGURE 11.—Field sketch of contorted chert bed (heavy line) in limestone. Shortening of chert bed has been about 40 percent. Adjacent limestone is slightly wrinkled but in general has absorbed the shortening by plastic flow and minor slippage along fracture cleavage planes (dashed lines) without notable disturbance of the original bedding. Looking southeastward; both bedding and fracture cleavage dip southwestward. Approximate parallelism of axial planes of folds in chert and fracture cleavage suggest contemporaneity; fracture cleavage probably formed later but due to same stress.

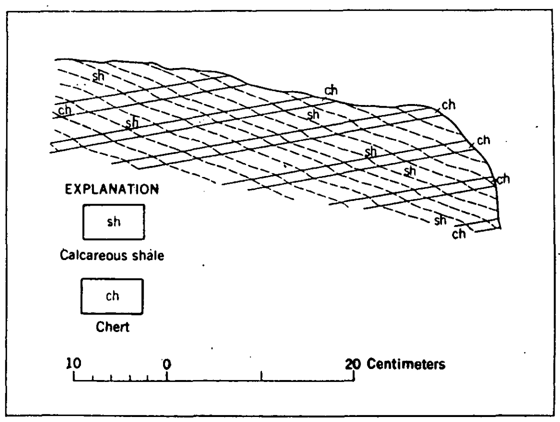

FIGURE 12.—Fracture cleavage in interbedded calcareous shale (*sh*) and chert (*ch*) of Late Cretaceous age, Arroyo de Chametla. Looking S. 20° W. along strike of beds dipping 10° SE. Fracture cleavage (dashed lines) dip 20° NW. in shale, 30° NW. in chert.

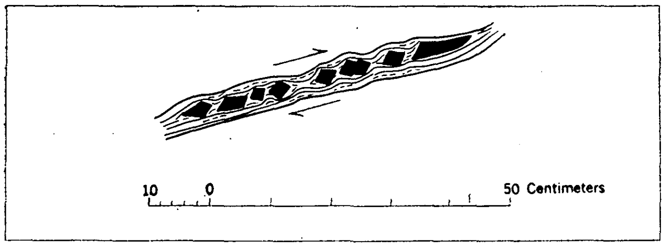

FIGURE 13.—Fractured and rotated blocks of chert in Barranca del Malacate, looking N. 40° W. along strike of beds dipping 25° SW. Chert bed (black) has been fractured and fractured blocks separated and rotated as much as 45° clockwise. Note flowage of limestone into areas between chert blocks. Fractures in chert are inclined about 80° to the bedding.

has been broken along fractures that are inclined to the bedding at about 80°, and the chert blocks have been rotated clockwise a maximum of 45°. Separation and rotation of the blocks are greater here than in plate 11*D*; lengthening of the chert bed amounts to about 20 percent. The fractures are filled with limestone that flowed plastically; no new calcite was formed. Only the thinner chert layers are fractured; the more massive chert beds at the same locality are merely stretched into ellipses or ovals without fracturing or rotation.

Although best developed and exposed in El Cajón and Barranca del Malacate, chert cleavage is seen in many places along the lower Río Tolimán. The cleavage seems to have been formed by differential movement along contiguous limestone beds during folding. Apparently the cleavage formed in the competent beds of a sequence of incompetent and competent layers.

The chert cleavage resembles in some ways the boudinage described by Cloos (1946, p. 16–17) and may be considered as a combination of the two types figured by him; the result has been a lineation parallel to the fold axes due to secondary flowage down the limbs of the folds, plus rotation around axes parallel to the fold axes. The structure does not, however, resemble boudinage as described by Quirk (1923) from the classic localities near Bastogne, Belgium.

STRUCTURAL FEATURES INVOLVING POST-CRETACEOUS ROCKS

Structural features involving post-Cretaceous as well as Cretaceous rocks include minor folding, tilting, and faulting. The post-Cretaceous rocks are nowhere folded to any appreciable extent and are tilted only slightly in several localities. Faults are the most prominent feature of post-Cretaceous structure. The dominant northwestward trend of the Cretaceous features has been inherited to some extent by the Tertiary rocks, and most features of Tertiary or later age have a northwestward trend.

FOLDS

The El Morro fanglomerate and the overlying volcanic rocks are essentially unfolded and flat lying, and have been tilted only locally. A small syncline in the El Morro fanglomerate southwest of Cerro del Potrero was the only fold recognized. Along the Río Tolimán southwest of Zimapán the fanglomerate appears to have been tilted slightly northeastward, but in general the dips are thought to be initial. South of Cerro del Arcabuz, dips of 50°–60° NE. were recorded in the fanglomerate. These steeper dips may be due to an abnormally high initial dip augmented by intrusion of monzonite; there is no suggestion that the high dips are due to drag along a fault, and the prevalence of low dips in the Tertiary rocks throughout the rest of the district indicates that compressive forces have not been active regionally since deposition of the Tertiary rocks.

Dips as high as 45° in the vicinity of Cerro del Potrero are clearly the result of tilting due to faulting. Southwest of the Lomo de Toro and Los Balcones mine road northwest of El Detzaní, the El Morro fanglomerate dips 25°–30° SW.; these dips, in the opposite direction to the regional dip of the fanglomerate, are due to drag along the Malacate fault.

FAULTS

The most prominent faults of the area are the Malacate, San Pedro, Estancia, and Muí faults. Evidence for the Malacate fault is almost entirely indirect. Its existence was first postulated in order to explain the relationship between Lower Cretaceous limestone and the El Morro fanglomerate, composed almost entirely of fragments of Upper Cretaceous limestone, along the southwest base of the Puerto Angel ridge between El Detzaní and Puerto de Bofay, and also to account for the steep lower slope of the south flank of the Sierra de El Monte. The fault is believed to extend northwestward from El Detzaní for about 6.5 kilometers along the strike and has been tentatively traced for another 2 kilometers westward. In addition, it is almost certainly present for another 7 kilometers east-southeastward from El Detzaní. It is named for Barranca del Malacate, where it can be most accurately traced; the anomalous course of the barranca is controlled in part by the fault. At El Detzaní the strike is northwestward; farther northwest, toward Barranca del Malacate, the strike changes to west-northwest, and where the fault is crossed by the Río Tolimán at the upper end of El Cajón the strike is nearly west. The fault is normal and dips 65°–70° SW. throughout most of its length; where it is crossed by the Río Tolimán it dips 45° S.

Northwest of the Río Tolimán the fault cannot be accurately located because there are no outcrops, the terrain is inaccessible, and Upper Cretaceous strata are present on both sides of the fault, but its position on the ridge south of Cerro de Santa Elena is believed to be marked by a zone of highly disturbed, folded, and shattered rocks. In the western (lower) part of Barranca del Malacate, metamorphosed Upper Cretaceous rocks are faulted against Lower Cretaceous limestone with chert which forms Cerro del Malacate; farther east a massive bed of fossiliferous Lower Cretaceous limestone is faulted against shaly Upper Cretaceous beds. The fault surface, dipping 70° SW., is exposed in several prospect pits southwest of El Dedhó. South of El Dedhó the fault again has Upper Cretaceous strata in both walls and is more difficult to trace. Just southeast of El Dedhó the fault is believed to be crossed three times by the segment of the Lomo de Toro-Los Balcones mine road leading from the mines; its possible position is marked by a series of of normal faults rather than a single break. Between El Dedhó and Puerto de Bofay the fault cannot be accurately located because there are no outcrops; it probably lies along the upper course of Barranca del Malacate. At the head of Barranca del Malacate the mine road again crosses the fault and its possible position is marked by a breccia zone several meters wide.

Northwest of El Detzaní, the El Morro fanglomerate is found in the hanging wall in contact with Upper Cretaceous rocks. The fanglomerate has been dragged up along the fault and dips 25°–30° SW. At El Detzaní the fault disappears beneath the Zimapán fanglomerate and cannot be traced with certainty farther southeast. It seems almost certain, however, that it passes southwest of Cerro del Muí and that this eminence, along with the entire Sierra de El Monte, owes part of its height to uplift along the fault. Farther southeast, a westward-striking fault with Lower Cretaceous limestone on the north side and volcanic rocks on the south side is very likely a continuation of the Malacate fault. The total probable length of the fault in the district is, then, about 15.5 kilometers.

The amount of displacement along the fault is not known, as the only formation that would give a reliable clue to the displacement, the El Morro fanglomerate, is absent along the northeast side of the fault throughout all the area from the Río Tolimán to El Detzaní. Minimum throw, measured from the bottom of the Río Tolimán canyon to the top of Cerro del Malacate, is about 540 meters; this figure is in rough agreement with the throw as estimated northwest of El Detzaní on the assumption that the El Morro fanglomerate once extended farther northeast over the site of what is now the high ridge leading to Puerto Angel. To the southeast the throw appears to decrease, as a few remnants of the El Morro fanglomerate are preserved on the upthrown side of the fault in contact with volcanic rocks, but not even a rough estimate of the displacement can be made, for the thickness of volcanic rocks on the downthrown side is not known.

It is possible that the course of the Río Tolimán through El Cajón is antecedent and that the deep gorge of El Cajón was cut by the river through a mass of Lower Cretaceous limestone that was rising on the north side of the Malacate fault. This possibility will be discussed at greater length in the section on physiography but is suggested here because it may partly indicate the age of the fault. All that is known with certainty is that the fault is younger than the El Morro fanglomerate and older than the Zimapán fanglomerate. If the Zimapán fanglomerate is Pleistocene, as seems likely, the fault is surely Pliocene or early Pleistocene in age, as the Zimapán fanglomerate was derived from the Sierra de El Monte which owes its height, at least in part, to uplift along the Malacate fault.

The San Pedro fault has been traced from a point 2.5 kilometers south of San Pedro for about 4.5 kilometers northward. From its southernmost exposure the San Pedro fault trends slightly west of north; at San Pedro it is offset about 500 meters west by a branch fault of its northern extension and then continues along a northeasterly course for 1.5 kilometers. North of San Pedro it is a reverse fault dipping 70° NW., with Lower Cretaceous limestone in the hanging wall and volcanic rocks in the footwall; south of San Pedro the dip is not known, but it is steep. Minimum throw north of San Pedro is of the order of 100 meters; the displacement decreases southward, for near the southern end small patches of El Morro fanglomerate are found on both sides of the fault at nearly the same altitude. At its southernmost exposure, minimum throw is about 30 meters. As it cuts El Morro fanglomerate and the overlying volcanic rocks the fault is younger than either. As in the case of the Malacate fault, there is no evidence of recent movement.

The Estancia fault lies 1 kilometer southwest of Cerro de La Estancia and has been traced for about 1 kilometer. It strikes N. 30° W. and is vertical, the northeast side being downthrown. Tertiary volcanic rocks are faulted down against Upper Cretaceous rocks; the minimum throw, which is very nearly the total throw, is about 90 meters. The throw of the Estancia fault is known within very narrow limits, as the base of the volcanic rocks is exposed on both sides of the fault; the exact amount of throw is uncertain as the base of the volcanic rocks is not exposed at the lowest point on the downthrown side. A small area of Lower Cretaceous limestone is exposed on the downthrown side of the Estancia fault, forming an embayment in the volcanic rocks. The volcanic rocks rest directly on this limestone in some places and are faulted down against it along small faults in others. The limestone, in turn, is faulted down against the Upper Cretaceous strata. Whether the position of the limestone above the Upper Cretaceous rocks, prior to the latest movement along the Estancia fault, was due to folding or to older and opposite movement along the fault is not known; the more probable answer seems to be faulting, and, if so, the Estancia fault is the only known normal fault of appreciable size in the district along which movement took place prior to the deposition of the Tertiary volcanic rocks.

The Muí fault is a north-northwestward-trending fracture along the west side of Cerro del Muí. Evidence for the fault is largely physiographic, as its possible exposures are limited to a small area on the west side of Cerro del Muí. Here Tertiary volcanic rocks appear to have been faulted against Lower Cretaceous limestone and dragged upward along a normal fault dipping steeply westward but the relationships are not clear. The fault probably continues northward along an arroyo that extends southward from near Cerro del Piñón, as there is no evidence of faulting in either wall of the arroyo; to the south the fault is buried by gravel and alluvium. Direction of movement along the Muí fault is not known, but the lack of topographic expression to the south suggests that the movement was predominantly horizontal, the east side moving southward relative to the west side; drag of the volcanic rocks west of Cerro del Muí indicates some vertical movement as well. The Malacate fault is offset 1,200–1,300 meters by the Muí fault.

A number of minor faults were mapped southwest and south of Cerro del Potrero. Most of them cut El Morro fanglomerate and range in throw from a few meters to slightly more than 100 meters. The larger faults have a northwestward trend; they are cut by a subsequent group of northeasterly trending minor faults.

PHYSIOGRAPHY

A relatively short time was spent on study of the physiography of the district, and insufficient observations have been made to outline completely the development of the topography. Moreover, the area studied is rather small and any thorough study of the physiography would have to consider a much larger area, extending at least to the Río Tula valley south of Zimapán, as far east as Encarnación, and west to the headwaters of the Río Moctezuma near San Juan del Río in the State of Querétaro. Physiographic studies to the north would also be desirable, but access to the terrain is extremely difficult. We are unable to outline the ancestral drainage basin of the Río Tolimán following cessation of volcanism in the district merely on the basis of observations in the limited area mapped geologically, and have therefore assumed that the major drainage pattern has remained essentially unchanged since that time.

Landforms in the Zimapán district are determined largely by the resistance of the rocks to erosion; only in the drainage system of the Sierra de El Monte, where most of the principal valleys have been eroded along the strike of the Lower Cretaceous limestone, is topography controlled by the folded structures. Areas underlain by Lower Cretaceous limestone, the most resistant rock of the region, are characterized by extremely rugged topography; examples of such terrain are the Barranca de Tolimán area and the north slope of the Sierra de El Monte, where slopes of 40°–45° or more are the rule. Some of the highest peaks in the area are along the northward-trending divide between the Río Moctezuma and Río Tolimán; the divide is a ridge underlain largely by siliceous Upper Cretaceous limestones. This divide culminates at its north end in Cerro de Los Lirios, a peak of Lower Cretaceous limestone 2,365 meters above sea level; the northeast face of Cerro de Los Lirios drops precipitously more than 1,200 meters to the Río Tolimán.

Areas underlain by the El Morro fanglomerate and volcanic rocks show characteristically a more rounded and subdued topography, but locally, as along the Río Tolimán west of Cerro de La Nopalera and east of Cerro de La Majada Grande, the fanglomerate forms cliffs. Most of the volcanic hills east and southeast of Zimapán are rounded and have gentle slopes; Cerro de La Estancia is an exception in that its east and west faces are steep. Prominent cliff-forming rocks are rhyolite felsite dikes, which form the jagged white and buff peaks south-southeast of Zimapán; cliffs nearly 100 meters high have been formed by erosion of the softer Upper Cretaceous wall rocks.

Other than fluvial erosion, the only important agent in the production of landforms in the district has been the Malacate fault, along which the Sierra de El Monte and its southern salient, Cerro del Muí, have been uplifted.

The canyon of the Río Tolimán is the most prominent physiographic feature of the region, and an acceptable theory of its origin will go far in explaining many of the other principal topographic features. The canyon begins southwest of Zimapán and continues northwestward and northward to the north edge of the area mapped, although the headwaters of the river are at Puerto de Xithá, 11 kilometers south of Zimapán. In the vicinity of the Lomo de Toro and Los Balcones mines the Río Tolimán flows through a three-storied canyon (the Barranca de Tolimán) at an altitude of 1,250–1,300 meters (pl. 13). An inner gorge 200–250 meters deep (in part called El Cajón) is succeeded upward by a more open canyon 250–300 meters deep, and this canyon in turn by a relatively rolling upland at an average altitude of perhaps 1,800–1,900 meters. The upland surface is well developed only along the east side of the barranca; the west wall is steep to the divide between the Río Tolimán and Río Moctezuma, although a small patch of rolling surface is preserved in the vicinity of La Ortiga at an altiude of 2,000–2,100 meters. South of El Cajón the inner gorge begins to merge with the middle canyon, although it is still recognizable for several kilometers southward. West of Cerro del Arcabuz, only the upper and lower canyons are recognizable.

Quite certainly the El Morro fanglomerate once extended over the present river canyon, at least from between Cerro del Arcabuz and Cerro del Mesquite as far northward as 1 kilometer or so north of Cerro de La Majada Grande. The original distribution of the Tertiary volcanic rocks along the Río Tolimán is not known, as there are no volcanic rocks overlying the fanglomerate west of the river, but perhaps a thin cover of volcanic rocks was also present. At any rate, the present course of the river was determined largely during the time when the river was flowing on the now-eroded Tertiary rocks; deeply incised meanders and complete lack of adjustment to the structure of the underlying Cretaceous rocks attest to such a superposition of drainage.

Uplift of the north side of the Malacate fault probably took place early in the development of the course of the Río Tolimán, as there is no clear evidence of dislocation of even the oldest erosion surface preserved, the surface lying at 1,800–2,100 meters above sea level. However, there is so little evidence of the presence of this surface southwest of the fault that no definite conclusion can be reached, but almost certainly there is no dislocation that could account for more than a part of the estimated displacement along the Malacate fault. The uppermost surface, then, seems to have developed after some of the movement along the Malacate fault. Inasmuch as uplift of the north side of the fault is estimated to have been at least 540 meters, and at least some of the movement is known to have been after the deposition of the El Morro fanglomerate, the river must have maintained its course northward by a concurrent downcutting through the rising block north of the fault. In other words, it seems likely that the course of the river from the south end of El Cajón, where the river crosses the fault, for an unknown distance north is antecedent; if the El Morro fanglomerate and the volcanic rocks once extended north of the fault, then the present river course is both superposed and antecedent. The pronounced bend near the middle of El Cajón is at the confluence of the Río Tolimán and Barranca del Malacate and would be difficult to explain on grounds other than superposition of a preestablished drainage system; it seems probable, therefore, that either a cover of El Morro fanglomerate and (or) volcanic rocks, or the relatively flat surface on which they were deposited, once extended north of the Malacate fault.

Barranca de Tolimán, then, formed during three cycles of erosion. The earliest stage is poorly defined and is represented by only a few small areas of rolling terrain at high altitudes. After the formation of an open valley, uplift of the entire area allowed the river to erode vigorously and carve out the second story of the valley. The second valley, in the vicinity of El Cajón, had walls with slopes as steep as 45° at its maximum size. Erosion of the second valley was followed quickly by renewed uplift, and the gorge of El Cajón 200 to 250 meters deep was carved in Lower Cretaceous limestone. This uplift north of El Cajón was probably due in part to renewed movement along the Malacate fault, and the age of formation of the gorge of El Cajón can perhaps be correlated with the scarp along the south face of El Monte. The third stage is clearly recognizable as far south as the confluence of the Río Tolimán and Arroyo de Santiago.

Depth of erosion in the northern part of the area along the Río Tolimán has been much greater than in the southern part, and the difference cannot be wholly accounted for by the gradient of the river, as the land is higher on the average toward the north. The higher average altitude of the terrain north of El Cajón is due, in part at least, to uplift along the Malacate fault plus, perhaps, greater regional uplift toward the north.

The Sierra de El Monte is thought to be a fault-block mountain uplifted along the northeast side of the Malacate fault. North of Zimapán the range trends nearly eastward, rising abruptly from the Zimapán valley. The south slope is very steep for about 300 meters above the valley, above which altitude the slope decreases abruptly. From its steep front northward the range rises gently for about 4 kilometers to the summit; this gently sloping surface may have been formed during the time of deposition of the El Morro fanglomerate and the volcanic rocks, but it is more likely to be correlated with the 1,800- to 2,100-meter surfaces above Barranca de Tolimán. The height of the steep south front is believed to correspond approximately to the throw of the latest movement along the Malacate fault. West of Cerro del Muí the fault is offset by the Muí fault, thus accounting for the prominent southward-jutting salient formed by Cerro del Muí. The Zimapán fanglomerate was deposited as an alluvial fan at the base of the newly risen Sierra de El Monte. Probably contemporaneously, the Daxi fanglomerate was deposited along the northeast base of Cerro de Daxi.

The high (12 to 13 meters) terrace deposits along the Río Tolimán southwest, south, and east of Zimapán were probably formed about the same time as the Zimapán and Daxi fanglomerates and have undergone a roughly equivalent amount of dissection during the present erosion cycle.

During a period of extreme aridity, the Zimapán and Daxi fanglomerates were cemented by caliche and at the same time most of the stream valleys leading south from El Monte and all the valleys at the head of the Río Tolimán were alluviated to depths of several meters. At the present time, a period of greater rainfall, the caliche is being dissolved and alluvial deposits along all streams are being dissected. Two prominent terrace levels, at about 1 and 2 meters, respectively, above the river level, have been formed along the headwaters of the Río Tolimán system.

The Río Tolimán is eroding actively only during the rainy season and then only during and immediately after heavy rains; at other times the river is clear and carries little water. The narrow gorge of El Cajón acts as a very effective barrier against the transport of material coarser than fine sand, and there is little evidence of transport of gravel through El Cajón even during high water. However, the ability of the river to transport very coarse material during floods was clearly demonstrated at the beginning of the rainy season in June 1948, when a massive dam composed entirely of angular blocks of mine waste from the Lomo de Toro mine, some more than a meter across, was completely destroyed and its components scattered for several hundred meters downstream. The dam was at the north end of El Cajón and received the full impact of the water of a deep, narrow, and fast-flowing stream.

METAMORPHISM

Metamorphism, or the textural and mineralogical changes exclusive of weathering that have affected the rocks of the Zimapán district subsequent to their cementation, emplacement, or consolidation, has been of two types, dynamic and igneous. Dynamic metamorphism comprises changes due to the influence of stress accompanied by few or no thermal effects; it has produced slaty cleavage in certain areas of Upper Cretaceous rocks and minor recrystallization of Lower Cretaceous limestone. Igneous metamorphism comprises changes effected in the rocks by igneous intrusions and associated fluids; the term includes both internal alteration of the igneous rocks themselves and alteration of the intruded rocks. To igneous metamorphism are ascribed principally the alterations of the country rock at the contacts of igneous intrusions and, more important, the majority of the ore deposits of the district.

DYNAMIC METAMORPHISM

Dynamic metamorphism has been rare and unimportant in the Zimapán area. Aside from the slaty cleavage formed locally in the Upper Cretaceous rocks and mentioned briefly in the discussion on structure, the only effect of dynamic metamorphism has been local slight recrystallization of the Lower Cretaceous limestone in areas of intense deformation. It seems likely that some dynamic metamorphism, at least recrystallization, accompanied the severe deformation shown by the Lower Cretaceous limestone in the Barranca de Tolimán area, but its effects, if any, have been thoroughly masked by later igneous metamorphism. Medium-grained light-gray to white marble has been formed in the Lower Cretaceous limestone of the Cerro de Daxi thrust plate, but the marble has a rather poorly defined spatial relationship to a quartz-latite intrusive and may be a product of igneous rather than dynamic metamorphism. None of the other rocks of the area show any evidence of having undergone dynamic metamorphism.

IGNEOUS METAMORPHISM

The term "igneous metamorphism" as used herein comprises all the compositional and textural changes produced in rocks by an igneous intrusion and its associated fluids. It includes both endomorphism, or internal alteration of the intrusive rock itself, and exomorphism, or alteration of the enclosing wall rocks at or near the intrusive contact. Under exomorphism are included both "normal" contact metamorphism, involving little or no transfer of material from igneous rock to wall rock, and contact metasomatism (hydrothermal or pneumatolytic) involving transfer of material from magma to wall rock. By far the more important of the two exomorphic processes has been metasomatism; it has produced the silicated rocks variously known as contact-metamorphic rocks, contact-pyrometasomatic rocks, tactite, or, in certain cases, skarn, and many of the ore deposits of the district. The writers admit a preference for "tactite" (Hess, 1919) as a general term for pyrometasomatized rock, as it lacks the ambiguity of contact-metamorphic rock, the relatively restricted meaning of skarn, and the bulkiness of contact-pyrometasomatic rock. Hess defined tactite as

> a rock of more or less complex mineralogy formed by the contact metamorphism of limestone, dolomite, or other soluble rocks into which foreign matter from the intruding magma has been introduced by hot solutions or gases. It does not include the inclosing zone of tremolite, wollastonite, and calcite.

The term "tactite" will be used in this report for all rock of pyrometasomatic mineralogy, even where a direct contact relationship to an igneous body, although most probable on geologic evidence, cannot be absolutely demonstrated. This is the usage proposed by Schmitt (1949, p. 135). The fine-grained tough products of "normal" contact metamorphism so widely developed in the Upper Cretaceous rocks will be referred to as hornfels.

In general, endomorphic alterations have not been prominent in any of the intrusive rocks, but locally the monzonite of the Río Tolimán area and the El Monte mining area has been intensely endomorphosed. The widespread alteration of igneous rocks, principally dikes, associated with the replacement deposits of the Carrizal mining area and the vein deposits in the Santa Gorgonia and San Pascual mining area, is believed to be related to mineralizing fluids introduced later and is therefore not strictly endomorphic. For convenience, however, all alteration of igneous rocks will be discussed in the same section.

In a number of places, especially in the El Monte mining area and parts of the Carrizal mining area, the formation of tactite and ore are so closely related as to be inseparable, and those occurrences will be described in this section rather than in the section on ore deposits.

EL MORRO FANGLOMERATE

Metamorphism of the El Morro fanglomerate is almost entirely restricted to a small area along the northeast side of the Río Tolimán between Cerro de La Nopalera and Cerro del Arcabuz, where the fanglomerate is intruded by the main mass of monzonite. Metamorphic effects include bleaching from red to gray or yellowish gray, recrystallization of the calcareous matrix to impure marble, formation of numerous minute grains of pale yellow-green garnet in the fragments of relatively pure gray limestone, and production of hornfels from fragments of siliceous or argillaceous limestone. A garnetized limestone boulder was found to contain 16.1 percent by weight of acid-insoluble material, largely garnet. Although the clastic texture of the fanglomerate has nowhere been destroyed by metamorphism, the outlines of many fragments, especially the smaller ones, have become blurred and indistinct. Minute quantities of sulfides, principally pyrite and a little sphalerite, have been introduced. A thin section of fine-grained metafanglomerate from just south of Cerro del Arcabuz contained fragments of what was probably siliceous limestone altered to a mosaic of quartz and calcite poikiloblastically enclosing innumerable tiny rounded grains of colorless garnet. The matrix has been recrystallized to a siliceous marble containing much garnet and a little fine-grained pyrite.

Northeast of the Santa Gorgonia mine a fine-grained siliceous marl bed in the fanglomerate has been intruded by a basalt dike 1.5 meters wide. At a distance of 1 meter or so from the contact the marl has been bleached from brownish gray to light olive gray, recrystallized, and pyritized. The dike itself, a dark-gray augite-biotite basalt with numerous quartz xenocrysts, has been propylitized and carries considerable pyrite in ragged poikilitic grains as much as 5 mm across.

Pronounced bleaching of the fanglomerate by small augite-diabase intrusions in Barranca de Los Bronces near the San Pablo mine has been mentioned in the section on other intrusive rocks.

UPPER CRETACEOUS ROCKS

Igneous metamorphism has affected the Upper Cretaceous rocks principally in the area along the Río Tolimán where they have been intruded by the largest body of monzonite in the district. Metamorphism is ordinarily restricted to a narrow aureole, commonly a few tens of meters wide, around the intrusive; rarely the metamorphosed zone may attain a width of several hundred meters, but it seems likely that the greater than usual width may be attributed to the presence of igneous rock a short distance below the surface. There seems to be no consistent difference in the width of the contact aureole whether it is measured across the strike or along the strike of the altered rocks. The typical metamorphic product is hornfels.

Upper Cretaceous rocks that have been metamorphosed to hornfels are well exposed in Barranca de La Cruz. Thin-bedded shaly limestone and shale have been converted into a yellowish-gray to greenish-gray fine-grained dense banded rock, locally impregnated with pyrite and stained by iron oxide resulting from oxidation of pyrite. The hornfels near the mouth of Barranca de La Cruz is a yellowish-gray rock with thin layers of greenish-gray dense porcellaneous rock. Under the microscope the lighter colored bands are seen to be composed almost entirely of a mosaic of ragged albite grains averaging about 0.2–0.3 mm across. Albite is kaolinized almost everywhere, and to a lesser extent sericitized; a number of grains show vague albite twinning. The mineral is so thoroughly altered that accurate determination of composition was not possible, but it seems to be nearly pure albite. Darker bands are composed of a quartz or quartz-albite mosaic. Albitic bands are highly pyritic and weather to a rusty yellow, which contrasts strongly with the less pyritized quartz-rich bands. Irregular small grains of tourmaline pleochroic in bluish black and pale violet are common along some narrow bands; identical tourmaline is found in the adjoining monzonite. Tiny grains of strongly pleochroic epidote are scattered through the rock.

A much more widespread type of hornfels crops out just east of Barranca de La Cruz. The rock is colorfully banded in yellow, yellowish gray, greenish gray, and very dusky purple; bands range from 2 to 15 mm in thickness. The microscope reveals alternating layers of very fine grained calcite-garnet-quartz rock (yellow in hand specimen), fine-grained garnetite (very dusky purple), quartz-andalusite hornfels (yellowish gray), and extremely fine grained quartz (greenish gray). Identification of the andalusite is uncertain, as the mineral occurs as shadowy poikiloblasts with poorly defined crystal outlines, not at all typical of the mineral, but the optical and crystallographic characters determined—probable negative sign, (−) elongation, extinction parallel to a good cleavage, and low birefringence—suggest andalusite. The different mineral assemblages probably reflect to a considerable extent the original composition of the various beds; thus the quartz-andalusite rock may have formed from shaly beds, the calcite-garnet-quartz layers from siliceous limestone, and the quartz-rich bands from chert or other highly siliceous material; thin layers of solid garnet represent an introduction of material, probably into a relatively pure limestone.

A similar hornfels is exposed about 600 meters from the mouth of Barranca de La Cruz. In addition to calcite-garnet-quartz bands, the rock contains layers composed of epidote, garnet, and calcite. Two varieties of garnet are seen in thin section: a colorless birefringent type, probably grossularite, and an isotropic brown to green variety, possibly andradite, which occurs as rims around the colorless garnet. Epidote and calcite are formed later than either garnet.

Fine-grained tactite has been formed at the contact of monzonite with Upper Cretaceous strata near the mouth of Barranca de La Cueva. The tactite is restricted to a few thin limestone beds in a dominantly shaly sequence. It is a light-gray rock prominently spotted with epidote and rusty pyrite. The microscope reveals a large variety of minerals. Bright-green diposide, probably a variety rich in hedenbergite, in tiny granules and kaolinized albite are most abundant. Albite forms the granulitic matrix of the rock, occurring in grains averaging about 0.1 mm across. Most of the albite grains are slightly altered to epidote. Strongly pleochroic epidote (pistacite) and actinolite occur together with calcite and a little quartz in clumps 1–2 mm across. Actinolite is pleochroic with X=pale yellow, Y=yellow green, and Z=pale blue green; the extinction angle $Z \wedge c$ is 16°. Epidote also occurs in tiny late-formed veinlets. Euhedral prisms of dark greenish-black tourmaline, many irregular grains of apatite, and tiny euhedral wedges of pleochroic sphene are minor constituents. Abundant tiny grains of zircon are probably residual. Pyrite, actinolite, diopside, and sphene are early-formed minerals; they are followed by tourmaline, epidote, albite, quartz, carbonate, and late-formed epidote.

For a distance of nearly 2 kilometers north from the La Luz mine, in the Río Tolimán canyon, the Upper Cretaceous strata are so intimately intruded by monzonite and monzonite dikes that the two rocks can be mapped separately only in a very general way. In the absence of relict bedding, it is often difficult or impossible to distinguish metamorphosed limestone from monzonite in the field, and in many places the contact appears to be completely gradational. The bulk of the altered limestone is a light-gray coarse-grained igneous-like rock with prominent greenish-gray bands ranging in thickness from a millimeter to several centimeters. In thin section the rock shows an interlocking mosaic of albite and oligoclase with a little orthoclase, all slightly sericitized. Some of the plagioclase shows albite twinning, but it is usually untwinned. Grain size averages about 0.15–0.20 mm. Apatite in euhedral prisms as much as 0.3 mm in length is abundant. Ragged grains of sphene as much as 0.5 mm across are common. Many of the sphene crystals have a core of rutile, which was evidently being replaced by sphene. Diopside is uncommon in the light-colored rock; it is rimmed and replaced to some extent by carbonate. The greenish-gray bands are composed entirely of granular diopside. Rutile is probably residual, but undoubtedly most of the sphene as well as the apatite has been introduced.

The only occurrences, known to the writers, of sulfides other than pyrite replacing Upper Cretaceous rocks are at a point a few hundred meters north of Cerro de San Pascual; the few unimportant ore deposits that have thus far been found in these rocks are veins. A thin, poorly exposed andesite dike has metamorphosed a limestone bed to a coarse-grained tactite composed of isotropic colorless garnet, wollastonite, and calcite. Garnet was the earliest new mineral to form. It occurs as inclusions in stubby euhedral wollastonite prisms, which in turn are enveloped in large grains of calcite. A little pyrite and reddish sphalerite occur as spongy grains replacing silicates and calcite formed earlier. The sulfides were probably introduced simultaneously, as pyrite occurs both in rims around sphalerite and in inclusions in this mineral.

Just east of the dike mentioned above is a thick bed of limestone that has been weakly mineralized. The limestone has been altered to a fine-grained mosaic of kaolinized orthoclase and a little quartz and purple fluorite. Fluorite is the earliest mineral formed and is almost entirely replaced by orthoclase. A few carbonate patches remain unreplaced. Arsenopyrite and sphalerite with a little galena, chalcopyrite, and pyrite are late-formed minerals. Arsenopyrite occurs as well-formed splendent needlelike prisms. Paragenesis of the sulfides could not be fully determined, but arsenopyrite, chalcopyrite, and pyrite are formed earlier than sphalerite and galena. The large introduction of potash represented by the nearly complete alteration of limestone to orthoclase and the presence of fluorite as a gangue mineral are common features of mineralization at Zimapán and will be discussed elsewhere in the report.

Banded hornfels has formed at the contact of a dike of granophyric basalt south of Cerro de La Chametla. Dense, extremely fine grained greenish-gray beds alternate with coarse-grained bands of dark-gray or greenish-black material; the beds weather pale yellowish orange and moderate yellowish brown, respectively. Under the microscope the greenish-gray bands appear so fine grained as to preclude mineral determination; they seem to be largely quartz. The darker bands consist of diopside, a little garnet, and numerous minute needles of what is probably tremolite. The contact-metamorphic effects of the granophyric basalt are more widespread than would ordinarily be expected from an igneous mass of such size; as far as 500 meters from the outcrop the Upper Cretaceous rocks are recrystallized, garnetized, and pyritized. The occurrence of a swarm of andesite and basalt dikes in the vicinity suggests that the area is underlain by a considerably larger body of igneous rock.

Small dikes in general have produced little or no alteration of the Upper Cretaceous rocks. The only megascopic effects are slight recrystallization of the purer limestone beds near the contact and, almost invariably regardless of the composition of the dike, introduction of some pyrite.

LOWER CRETACEOUS LIMESTONE

SILICIFICATION

Silicification of Lower Cretaceous limestone has been rare and was observed in only four places. It was not studied in detail.

Forty meters north of the San Rafael Viejo adit of the Los Balcones mine a narrow jasper zone trending N. 75° W. and about 25 meters long formed one wall of a small body of oxidized lead-silver ore long since mined out. This jasper zone, a jasper layer 10 cm thick in the footwall of a calcite vein in the El Chacuaco Viejo adit of the El Monte mining area, and a little bedded jasper in the lower ore body of the El Espíritu mine, are the only occurrences of jasper associated with ore deposits in the Zimapán district, so far as we know.

A small patch of jasper crops out 650 meters west of Cerro del Juaxidó. The jasper permeates limestone in a network of veinlets and replaces limestone irregularly along the bedding. A similar area is found on the crest of the Sierra de El Monte north of Cerro del Piñón.

MARMARIZATION

The Lower Cretaceous limestone in the Cerro de Daxi thrust plate at the head of Arroyo de La Chametla in the southwestern part of the area has been bleached and recrystallized to a light-gray to white pure-calcite marble. Although recrystallization may be due in part to dynamic metamorphism connected with thrust faulting, the spatial relationship of the marmarized area to an intrusive body of quartz latite porphyry suggests that recrystallization is possibly a contact-metamorphic effect. The marble crops out in a roughly U-shaped aureole around the south end of the quartz-latite intrusive. The carbonate of the marble is pure calcite with refractive index $\omega = 1.66$. Grain size ranges from 0.5 to 1 mm in the white marble and from 1 to 3 mm in the gray marble.

A number of small bodies of marble occur elsewhere along contacts of intrusive igneous rocks, but the process of marmarization has, in general, been unimportant.

METAMORPHISM OF CHERTY LIMESTONE

Cherty facies of the Lower Cretaceous limestone ordinarily consist of medium-gray to dark-gray thin-bedded limestone containing irregular beds and pods of dark-gray to black chert. Between the Lomo de Toro and Los Balcones mines, hydrothermal metamorphism related, in part at least, to latite dikes has bleached the chert to pale blue or light gray and converted some thin chert beds to a rock composed of light-green garnet and brown vesuvianite. Thicker chert beds have been recrystallized, usually with the formation of a thin selvage of plumose wollastonite along the contacts with the enclosing limestone. All stages in the bleaching of the chert can be seen. Bleaching begins with the formation of a network of fine light-colored veinlike streaks which gradually widen and coalesce until the entire chert body has been bleached. The rather spectacular "zebra rock" resulting from the bleaching process is well exposed along the road between the Lomo de Toro and Los Balcones mines, 200–400 meters northwest of the San Guillermo adit (pl. 10*C*), and in the cliffs below the road.

Although wollastonite is the most common mineral formed along contacts of chert and limestone, tremolite was also noted. A thin section across a gradational contact between chert and limestone showed a nearly continuous variation from slightly recrystallized chert through calcitic chert and calcite-tremolite-chert rock to a pale-green calcite-tremolite aggregate containing a maximum of perhaps 20 percent tremolite and finally to pure recrystallized limestone. Diopside is a minor constituent of the contact zones. It occurs as discrete grains and in veinlets.

A number of thin chert beds ranging from 1 to 3 cm in thickness have been almost completely silicated. In thin section a light-olive chert bed 1 cm thick showed a core of rock 5 mm thick containing calcite, garnet, vesuvianite, wollastonite, diopside, and pyrite, flanked on both sides by a layer of fine-grained granular wollastonite 1.5 to 2 mm thick with minor quantities of garnet and vesuvianite, and bordered by a selvage of garnet and vesuvianite 0.5 mm thick. Along the contacts, about 2 mm of the enclosing dark-gray limestone is bleached white; locally, some feathery wollastonite and a little vesuvianite have developed in the white limestone. The contacts between silicated chert, bleached limestone, and dark-gray limestone are very sharp and the rock is prominently banded both in hand specimen and thin section. Plate 10*D* shows irregular pods of bleached recrystallized chert and thin beds of silicated chert with bleached limestone selvages.

Light-gray bleached and silicated chert also crops out near the north end of El Cajón. Wollastonite, calcite, diopside, and arsenopyrite have developed in the chert. Wollastonite also occurs in veinlets 1 to 3 mm thick parallel to the bedding of the chert. The feathery wollastonite crystals, averaging about 1 mm in length, are oriented perpendicularly to the vein walls and have grown from both walls. A few minute clumps of diopside are associated with the vein wollastonite. The wollastonite veinlets are clearly formed later than the deformation of the El Monte limestone; they occupy minute fissures that presumably opened after relaxation of the forces that caused the deformation of the limestone.

TACTITE NOT RELATED TO ORE DEPOSITS

A small body of quartz monzonite that intrudes Lower Cretaceous limestone just north of the mouth of El Cajón has converted the limestone into several varieties of tactite. At the contact the limestone is almost completely altered to garnet-diopside rock. Scattered ragged diopside grains as much as 1 mm long are replaced by yellow-green slightly birefringent garnet in grains 2–3 mm across. A few unreplaced remnants of carbonate and tiny late-formed carbonate veinlets are the only other constituents. Refractive index γ of the diopside is 1.695, indicating pure $CaMgSi_2O_6$ according to Winchell's chart (1933, p. 226). The garnet is rich in the andradite molecule, the refractive index being much higher than 1.78. A detail of the intrusive contact is shown in figure 14, and a photomicrograph of garnet replacing diopside is given in plate 14*A*.

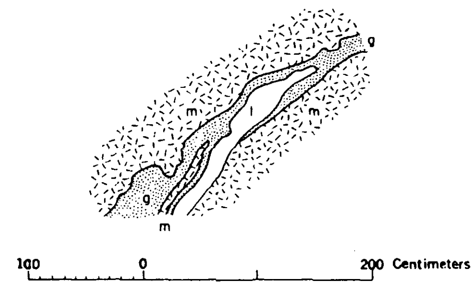

FIGURE 14.—Detail of contact between monzonite and Lower Cretaceous limestone, in Barranca de Tolimán near El Cajón. Intertonguing of limestone and monzonite is a common feature of the intrusive contact at this locality. *m*, monzonite; *g*, garnet-diopside rock; *l*, unreplaced limestone.

A short distance downstream, many thin beds have been altered to olive-green vesuvianite; discrete anhedral grains of vesuvianite are scattered through the interbedded recrystallized limestone. The vesuvianite has a refractive index $\omega=1.725$. Other beds are converted entirely to fine-grained silky wollastonite.

Highly selective replacement of other beds both upstream and downstream from the quartz monzonite has resulted in a glassy fine-grained tactite composed of green diopside, dark-brown vesuvianite, and pale yellow-green garnet. The garnet is formed later than and replaces both diopside and vesuvianite. There are many such metamorphosed beds and they strongly resemble sills.

A narrow tactite zone at the contact of a quartz latite dike in the Cinco de Mayo adit consists of a little early-formed sphene which was followed by diopside, garnet, calcite, and quartz, in that order. Paragenetic sequence is well shown in this tactite and agrees closely with the paragenesis of tactite minerals in other occurrences.

A tactite similar to that at the quartz monzonite contact occurs at the contact of a quartz latite intrusive near the head of Arroyo de La Chametla. Early-formed diopside prisms as long as 4 mm are irregularly replaced by very pale green andraditic garnet. The rock is cut by late-formed quartz-carbonate veinlets.

TACTITE BODIES RESEMBLING DIKES

Tabular bodies of contact-metasomatic mineralogy occur widely in the Carrizal mining area. Commonly they closely resemble dikes or slightly transgressive sills. A few are irregular in cross section, although they nevertheless simulate small igneous intrusions. At least six tactite bodies crop out in the Los Balcones mine area. The largest, 1.5 meters thick, is crossed by the mine track at a point 25 meters southwest of the Los Balcones adit. Another mass was cut underground in the San Rafael Nuevo adit. In addition, similar dikelike masses were seen in the San Cayetano Intermedio, San Guillermo, and Las Ventanas mines on the west side of Barranca de Tolimán and in the barranca near El Cajón. All the bodies cut Lower Cretaceous limestone.

The tactite bodies are characterized by clean sharp walls, the crosscutting of limestone bedding, and, in general, simple mineral composition. They range from grayish green to greenish gray and are commonly spotted with local concentrations of various minerals. Examination of eight thin sections revealed a rather uniform composition. Pale garnet, diopside, and calcite composed more than 90 percent of seven slides; wollastonite and vesuvianite were found in four slides. Late-formed veinlets of carbonate and quartz occurred in most thin sections. One of the masses from the San Rafael Nuevo adit has a more complex mineral composition. It is an aggregate of diopside, actinolite, and epidote with minor fluorite, zeolite, and chlorite. A little quartz and pale-yellow sphalerite were noted in one section, and sphene is prominent in one of the masses of the San Guillermo mine.

The garnet is a birefringent variety, probably rich in the andradite molecule, and is often complexly twinned. The vesuvianite is deep reddish brown to dark brown; it shows strong ultra blues and browns under crossed nicols. Paragenesis of the minerals is not identical in all slides, but diopside is everywhere formed early and is followed by vesuvianite, garnet, and wollastonite, in that order; sphene and actinolite are also early-formed minerals. Sphalerite, quartz, fluorite, and zeolites are formed late.

Figure 15 is a sketch of an irregular tactite mass exposed in Barranca de Tolimán just north of El Cajón. The tactite and silicated chert have a similar mineral content. Vague traces of what may be residual bedding are shown by dashed lines within the body of the mass.

A tactite body at the Las Ventanas mines is unusual in that it is composed largely of granular axinite, together with considerable sphene and calcite, a little apatite, and minor interstitial sericite and orthoclase (?). It forms one wall of the Las Ventanas ore chimney.

Another dikelike body of unusual mineral composition crops out on the road between the Lomo de Toro and Los Balcones mines. It is a granular light-gray glassy rock consisting of millimeter-sized grains of monticellite ($CaMgSiO_4$) and spurrite ($2Ca_2SiO_4 \cdot CaCO_3$) with abundant interstitial calcite. Accessory minerals are vesuvianite and tiny yellow-brown octahedrons of spinel. The spurrite-monticellite rock grades outward through garnetized limestone to bleached slightly recrystallized limestone and finally to unaltered gray limestone. The total thickness of

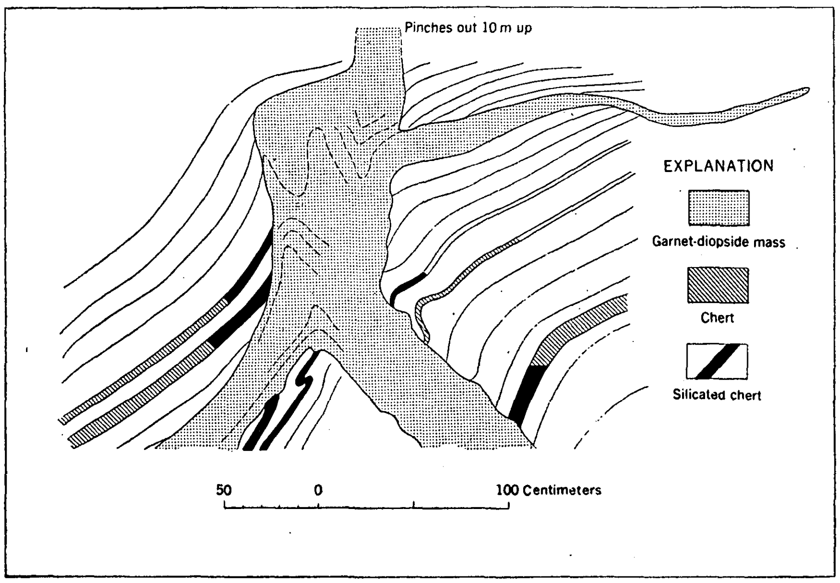

FIGURE 15.—Tactite mass in Lower Cretaceous limestone, Barranca de Tolimán near El Cajón. Dashed lines within body represent what may be residual bedding.

silicate rock is about 1.5 meters. Monticellite and spurrite are ordinarily considered to be products of thermal metamorphism of siliceous dolomitic limestone at relatively high temperatures. The temperature-pressure relations have been discussed by Bowen (1940). However, the occurrence of spurrite and monticellite in a tabular body at Zimapán suggests that perhaps the high temperatures of formation usually associated with these minerals may not have been reached and that easy escape of CO_2 into a fissure facilitated their formation at lower temperatures. Inasmuch as the Lower Cretaceous limestone is not noticeably siliceous or dolomitic, the formation of monticellite and spurrite, as well as spinel and vesuvianite, indicates that circulating fluids were active. Bowen has emphasized that the presence of solutions may induce formation of the "high temperature" minerals at lower temperatures (Bowen, 1940, p. 261–263).

Axinite, spurrite, and monticellite were identified by R. L. Smith of the U. S. Geological Survey.

TACTITE RELATED TO ORE DEPOSITS

Ore-bearing tactites of the Carrizal mining area are mineralogically similar to the nonmetallized tactites. Garnet, diopside, vesuvianite, wollastonite, epidote, and quartz are the common minerals; tremolite is rare.

The sulfide ore body of the Las Estacas mine was enclosed in a sheath of tactite composed principally of diopside, garnet, and vesuvianite with a little quartz, epidote, tremolite, and residual calcite. Diopside is the earliest tactite mineral formed. Its index of refraction γ is 1.700, which corresponds to a diopside containing about 10 percent of the hedenbergite molecule (Winchell, 1933, p. 226). The vesuvianite is a dark-brown variety of poikiloblastic habit, with inclusions of diopside. Its index of refraction ω is about 1.73. Colorless garnet encloses both diopside and vesuvianite and also occurs as veins in vesuvianite. Sulfides are clearly formed later than silicates. The age relations among the sulfides are uncertain, but pyrite and galena were probably deposited nearly simultaneously and both are formed earlier than sphalerite. A little quartz interstitial to sphalerite, and carbonate in minute veinlets are the latest minerals formed. Garnet in contact with pyrite or galena is commonly slightly altered to chlorite. Paragenesis of the minerals is well shown except in the case of tremolite, which is formed earlier than the sulfides, but its age relations to the other silicates are not clear. The paragenesis of the tactite-sulfide minerals is shown in figure 16.

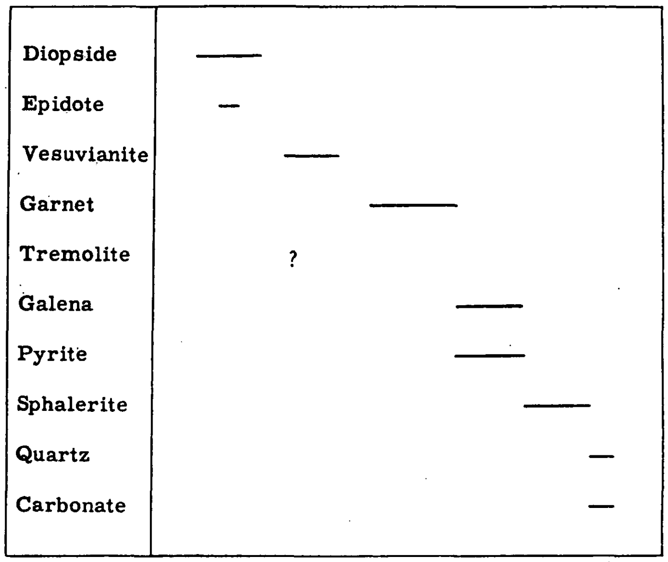

FIGURE 16.—Paragenetic relationships in metallized tactites, Las Estacas mine.

Metasomatized limestone in the San Guillermo mine is characterized by pronounced mineral banding parallel to the walls of the small sulfide bodies and the predominance of wollastonite among the silicates. Wollastonite forms an irregular selvage between limestone and ore. It occurs in a fine-grained porcellaneous form at the limestone contact and in beautiful pale-gray bladed crystals as long as 4 cm at the sulfide contact. The blades of wollastonite are oriented roughly perpendicularly to the sulfide walls. A little garnet and granular calcite commonly intervene between wollastonite and sulfides. The sulfides are zoned, showing a narrow band of galena and a little pyrite in contact with silicated wall rock, and massive sphalerite toward the center of the ore bodies. A small mass of weakly pyritized limestone along the contact of the large tactite body in the San Guillermo adit is noteworthy in that sericite and a little sphene occur as gangue minerals. Sericite forms ragged poikiloblasts as much as 1 mm long and also makes up a fine-grained aggregate. Calcite is the only other gangue mineral and pyrite is the only sulfide. This occurrence of sericitized limestone is the only one recognized in the district. The introduction of potash implicit in the formation of sericite in limestone is probably related to the endomorphic alteration of the quartz monzonite, during which much magmatic orthoclase was formed.

A small prospect located 45 meters above the Cinco de Mayo adit shows paragenetic relationships unusually well. A zone of pale-green garnetized limestone 15–20 meters wide has been developed along one wall of a latite dike. The contact of garnetized rock with limestone is very sharp and straight and was probably a pregarnetization fracture. Veinlets, pods, and irregular stringers of sulfides, principally sphalerite and pyrite with a little galena and chalcopyrite, cut the garnetized rock and extend in a few places into unaltered limestone. Sphalerite is in part deposited earlier than galena, but most of the sulfides seem to have been deposited simultaneously. A few pods of sphalerite and pyrite are rimmed by green garnet, but the bulk of the garnet is formed earlier than the sulfides. Locally the outcrop of garnet rock is coated by tiny crystals of sideritic carbonate with index of refraction ω greater than 1.78.

A specimen of wall rock found on the dump of the San Rafael Nuevo adit of the Los Balcones mine consisted of limestone and massive sulfide separated by a layer of a dusky-yellowish-green prismatic mineral 2 cm thick which replaces limestone and is replaced by sulfides. Blades of the mineral are oriented perpendicularly to the walls of the layer. The green mineral has the following optical properties: positive sign, index of refraction $\gamma=1.725$, extinction angle $Z\wedge c$ 51°–53°, dispersion $r>v$ strong, pleochroism weak. Possibly it is a hedenbergite-rich diopside, but the large extinction angle cannot be related to the index of refraction γ. The discrepancy may be due to a small content of the acmite molecule.

Tactites are associated with nearly all the ore deposits of the El Monte mining area. They occur widely in the Chiquihuites, Miguel Hidalgo, and Concordia workings and are found also at the El Chacuaco Viejo, El Camino, and El Afloramiento deposits. The El Monte tactites differ from those of the Carrizal mining area in containing fluorite, sometimes in large quantities.

Two types of tactite are found in the Chiquihuites mine. In the highly altered limestone in winze no. 1 at the northwest end of the mine the tactite consists of hedenbergite, garnet, and fluorite. Hedenbergite seems to be the earliest silicate formed. It has an index of refraction β of about 1.732 and extinction angle $Z\wedge c$ of 45°–50°, corresponding to hedenbergite with about 16 percent of the diopside molecule (Winchell, 1933, p. 226). Some of the garnet is isotropic, but most of it is birefringent and complexly twinned. Colorless fluorite replaces both hedenbergite and garnet. Sulfides, principally arsenopyrite and sphalerite with a little pyrite, occur as veins in the silicates; they are accompanied by a little quartz. Brownish carbonate in veinlets is the latest mineral formed. Another specimen of tactite from just north of winze no. 2 consists of residual carbonate, abundant fluorite, and a little birefringent garnet. Arsenopyrite, sphalerite, and galena replace fluorite and, to a lesser extent, garnet. Plate 14*B* shows the paragenetic relationships between fluorite, sphalerite, and galena.

The limestone in the inclined workings north of the Chiquihuites dike has undergone a very different type of alteration. Early-formed fluorite, orthoclase, and a little sphene and chlorite are partly replaced by quartz in a fine-grained mosaic. Veinlets and irregular patches of sulfides, mainly arsenopyrite and sphalerite accompanied by a little pyrite and jamesonite, followed introduction of quartz. Sphalerite is the latest sulfide formed. A brown carbonate forms tiny late-deposited veinlets.

The mineralized limestone of the El Camino incline consists of sphalerite, galena, and later formed pyrite in a calcite gangue. Orthoclase is the only silicate recognized. It is a late addition and replaces both calcite and sulfides. Tactite from the winze of the El Chacuaco Viejo working is composed largely of fluorite with a little pale-green birefringent garnet and rare diopside. Tactite minerals were followed by arsenopyrite, sphalerite, galena, and a small amount of quartz, which is interstitial to the sulfides.

The metallized limestone of the El Afloramiento deposit is similar to that at El Chacuaco Viejo. Early-formed fluorite is replaced by an aggregate of quartz, arsenopyrite, pyrrhotite, sphalerite, galena, jamesonite, and a little pyrite. Late-formed veinlets of carbonate cut sulfides and gangue.

The most intense contact metasomatism seen in the El Monte mining area was in the lower Concordia adit. Limestone has been altered at the quartz monzonite contact to a rock virtually indistinguishable from the quartz monzonite. The immediate contact zone is succeeded on the limestone side by tactite containing a little scheelite. Sulfides, which include arsenopyrite, pyrite, chalcopyrite, sphalerite, galena, meneghinite, and a little pyrrhotite, occur as veins and irregular replacement pockets in both tactite and quartz monzonite. Galena and sphalerite are largely restricted to altered limestone; the other sulfides occur in both wall rocks. Metallization has not been prominent in the accessible part of the mine, and none of the metallized rock seen constitutes ore. Similar contact alteration and metallization were seen in the intermediate working of the Concordia mine.

The small sulfide ore pockets in the northwest drifts of the Miguel Hidalgo adit are almost completely enclosed in a sheath of banded tactite. Development of tactite can be clearly traced from fine-grained almost-pure limestone to coarse-grained tactite and finally to essentially solid sulfide. Quartz monzonite is exposed in the main northwest drift 105 meters northwest of the adit and in a short crosscut off the northwest drift 75 meters from the adit. The tactites to be described are nowhere in contact with quartz monzonite but are concentrated to the southeast along the projected strike of the quartz monzonite body, which is roughly parallel to the strike of the enclosing limestones. Unaltered limestone near the portal of the adit is a dark-gray fine-grained rock with a few tiny detrital grains of quartz. Fifty meters along the adit toward the tactite area the limestone is slightly recrystallized and carries a few needlelike poikiloblasts of tremolite. At the entrance to the main northwest and southeast drifts, 110 meters from the portal, the limestone has been converted to a medium light-gray fine-grained marble with abundant well-formed metacrysts of tremolite as much as 0.3 mm in length. At a point in the southeast drift 45 meters from the main adit, limestone has been altered to a fine-grained tactite of pale-green birefringent garnet, diopside, and wollastonite. The contact between limestone and tactite is gradational. Tactite minerals appear first in thin bands which widen gradually and coalesce until the rock is composed entirely of silicates. Wollastonite is the dominant silicate of the nonsulfide-bearing tactites, which are much lighter in color than the metallized garnetiferous tactites.

Weakly metallized tactites consist of early-formed diopside and garnet which were followed by fluorite, sulfides, quartz, and tremolite. Alteration concluded with formation of veinlets of quartz, epidote, and carbonate. Diopside and garnet clearly preceded the sulfides in the sequence of alteration; sulfides replaced and occurred as veins in both, and in one thin section chlorite pseudomorphs after garnet occur in contact with sulfides. Diopside appears to be the earliest silicate formed, as inclusions of diopside are found in garnet. The diopside is a variety rich in hedenbergite with index of refraction γ about 1.745. Both isotropic and birefringent garnet are found. The second is far more common and is invariably complexly twinned. Fluorite formed slightly earlier than sulfides, but it is abundant only where sulfides are abundant. The position of quartz in the alteration sequence is not clear. It was found to be formed clearly earlier than sulfides in one specimen, and appears to be simultaneous with sulfides in a few thin sections, but the bulk of it seems to be formed later than sulfides. Quartz and fluorite everywhere have close spatial relationship to sulfides. Tremolite is formed later than sulfides and the other silicates. Finely fibrous tremolite replaces diopside, garnet, and quartz and forms rosettes around sulfides. Carbonate in veinlets is the mineral formed latest in all the thin sections examined.

The paragenesis of the tactite minerals in the Miguel Hidalgo adit, as deduced from a study of 10 thin sections, is shown in figure 17. Inasmuch as the complete sequence is not shown in any one slide and relations of

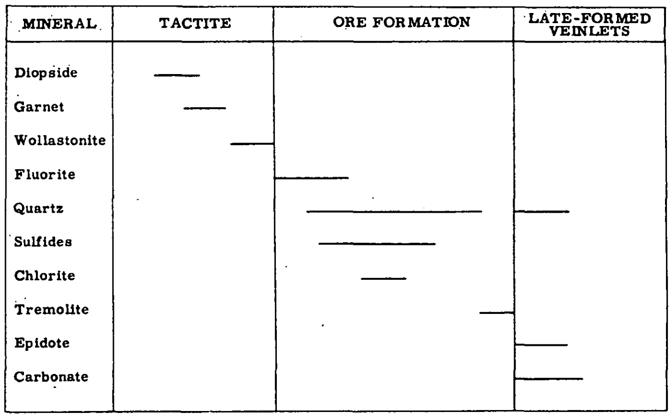

FIGURE 17.—Paragenetic relationships in metallized tactites, Miguel Hidalgo adit.

several minerals, such as the garnet-diopside-wollastonite and the quartz-sulfide groups, are not well defined, the paragenetic succession is only approximate, but the general relations shown are thought to be correct.

Mineral banding in the tactite is common. Layers of nearly pure wollastonite alternate with bands rich in calcite, garnet, and diopside in the nonmetallized tactites, and sulfides alternate with silicates in the ore-bearing tactites. Sulfide layers are also banded within themselves. A specimen from the ore body near the entrance to the main northwest drift shows a band rich in sphalerite in contact with tactite, succeeded toward the center of the sulfide mass by a layer rich in pyrrhotite and then by a mixed layer of sphalerite, pyrrhotite, jamesonite, chalcopyrite, and pyrite. Occasionally thin bands of solid sulfide are found isolated in tactite, but commonly the sulfides are concentrated toward the center of a given tactite body.

GARNETITE AND DIOPSIDITE

A large mass of garnet rock about 700 meters long and 400 meters wide has been formed at the southwest end of the thick quartz monzonite dike that crops out in Barranca de Tolimán below the Los Balcones mine. In addition to the main mass, a tongue of garnet rock extends some 500 meters south. Its south end is in Upper Cretaceous rocks. The garnet is an olive-green andradite-rich variety with refractive index far above 1.78. Both massive garnet and poorly developed dodecahedral crystals have formed. The southeastern part of the main garnet mass is impregnated with pyrite and interlaced with thin pyrite-sphalerite-calcite veinlets.

At the contacts of two monzonite dikes that are completely enclosed in garnetized limestone, irregular masses of granular diopside have developed. The diopside grains average less than 1 mm across. Refractive index γ of the diopside is 1.702, indicating about 12 percent of the $CaFeSi_2O_6$ molecule, according to Winchell (1933, p. 226).

IGNEOUS ROCKS

The principal types of alteration affecting the igneous rocks of the area have been propylitization and sericitization; additional minor processes have been introduction of orthoclase and, to a lesser extent, of tourmaline. Rock alteration has been mentioned briefly in the petrographic description of a number of the rocks and will not be repeated here.

Propylitization involves the alteration of feldspar to sericite, epidote, and carbonate, or occasionally, in the case of the soda-lime feldspar, to albite; the alteration of ferromagnesian minerals to chlorite, carbonate, and epidote; and the introduction of pyrite, sometimes accompanied by tourmaline. Propylitization is widespread and has affected nearly all the dike rocks associated with mineralization. The process has been especially active in the Santa Gorgonia and San Pascual mining area. A porphyritic quartz latite (?) dike intersected by the Santa Gorgonia vein shows typical propylitic alteration. Feldspars are almost completely replaced by carbonate and sericite; a few unreplaced remnants are albitic. Mafic minerals are completely altered to carbonate, chlorite, and iron oxide. The groundmass is composed of fresh quartz, sericitized plagioclase laths, pyrite, carbonate, iron oxide, and abundant pale-green chlorite, probably penninite.

A latite dike that forms one wall of an old stope west of Cerro de Las Espinas contains highly sericitized andesine phenocrysts and mafic minerals completely altered to chlorite, epidote, and iron oxide. Andesine is also altered sporadically to a pale-brown cryptocrystalline or amorphous mineral of low refractive index, probably opal. The groundmass consists of fine-grained granular quartz and orthoclase. Orthoclase is probably a late-formed mineral. Introduced minerals include epidote, sphene, quartz, abundant pyritohedral pyrite, and a little blue-gray tourmaline which invariably replaces feldspar.

Propylitic alteration of monzonite has been discussed briefly in the petrographic description of that rock. The process has affected the monzonite throughout virtually its entire outcrop area. The most widespread effect has been the introduction of pyrite, and almost everywhere outcrops of monzonite are stained by iron oxide resulting from the weathering of pyrite. Propylitized monzonite is typically a grayish-green or greenish-gray rock with milky feldspar phenocrysts and pale-green mafic minerals. In one thin section of weakly propylitized monzonite from Barranca de La Cruz, veinlets and irregular patches of barite were noted. The barite is a late-formed mineral and is probably not related to the propylitic alteration.

Sericitization, which involves principally the alteration of feldspar to the fine-grained scaly or fibrous variety of muscovite known as sericite, has been common throughout the mineralized areas. Most noticeable sericitization has been that affecting the large monzonite dike of the Carrizal mining area (p. 28). A thoroughly sericitized dike forms the north wall of the main stope in the San Miguel de Los Palacios adit of the Los Balcones mine. The original trachytic texture of the dike has been perfectly preserved, although all feldspar phenocrysts and the plagioclase laths of the groundmass are completely altered to sericite.

The fine-grained rhyolite or quartz latite dike of the Puerto de Los Bronces mine in the Santa Gorgonia and San Pascual mining area is thoroughly sericitized. Most of the feldspar phenocrysts are largely converted to sericite and an isotropic mineral of low refractive index, possibly allophane, and the groundmass is completely sericitized. Scattered through the rock are innumerable tiny grains of pyrite.

Dikes exposed underground in the San Francisco mine, east-northeast of the El Monte mining area, show sericitization in the area of mineralization and some propylitization elsewhere. The andesite dikes near the portal of the Chalma adit contain pyroxene altered to calcite, zoisite, and epidote; nearly fresh feldspar and a little pale-brown hornblende; and abundant secondary carbonate and pyrite. A diabase(?) dike that forms one wall of the Guadalupe crosscut near the mineralized area is composed of completely sericitized feldspar phenocrysts in a matrix of sericitized albite laths, needles of zoisite, and interstitial pale bluish-green chlorite. Pyrite is abundant, as are quartz-pyrite veinlets. A mineralized diabase(?) dike was cut underground in the northern part of the mine after the writers' examination. This dike crops out immediately west of the mine area. Although no sulfides were seen at the outcrop, the dike shows alteration similar to that of the dike in the Guadalupe crosscut. Plagioclase is altered to sericite and albite, mafic minerals to an opaque aggregate, and groundmass feldspars to sericite. A little interstitial albite and possibly orthoclase are present in the groundmass.

The quartz monzonite facies of the monzonite in the La Luz mine shows a type of alteration that combines sericitization with introduction of orthoclase. Although the La Luz vein is unique in the district in that its principal metal is copper, the wall-rock alteration is similar to that elsewhere. Alteration becomes progressively more thorough as the vein is approached. Relatively fresh quartz monzonite is medium light gray with abundant fresh-appearing phenocrysts of plagioclase and green amphibole, and much pyrite. Under the microscope, sodic andesine with oscillatory zoning is highly sericitized and partly replaced by epidote; amphibole is a nearly colorless variety, apparently a bleached hornblende. Abundant accessory apatite and sphene are unaltered. The groundmass is composed of small irregular patches of quartz imbedded in granular orthoclase which is clearly formed late and replaces all minerals formed earlier. Similar late-formed magmatic orthoclase has been mentioned in the section on igneous rocks as a prominent feature of the monzonite of both the Carrizal and El Monte mining areas. In the more intensely altered rock nearer the vein, both feldspar and amphibole are milky white. In thin sections, amphibole has been replaced by carbonate, sericitization of feldspar phenocrysts is nearly complete, sphene is almost entirely altered to leucoxene, and apatite is partly replaced by the fine-grained groundmass of orthoclase and quartz. Finally, in the quartz monzonite of the vein walls, all feldspar of both phenocrysts and groundmass is completely altered to sericite and the rock is impregnated with pyrite accompanied by a little tourmaline. The introduction of orthoclase appears to be a strictly endomorphic change and has no clear relation to mineralization. The sericitization, which followed, seems to be related to mineralization of the La Luz vein.

Introduction of orthoclase as a late-formed magmatic mineral has been mentioned in a number of places above and will not be discussed at length here. The results of large-scale introduction of potash are well shown in thin sections of monzonite from the Carrizal and El Monte mining areas and of quartz monzonite from the La Luz mine. Photomicrographs of orthoclasized quartz monzonite from the Carrizal and El Monte mining areas are shown in plates 9*A* and 14*C* and *D*. Orthoclasization was also noted in the latite(?) dike of the San Vicente mine in the Carrizal mining area. The groundmass of the dike is entirely granular orthoclase, enclosing epidotized plagioclase feldspar, carbonatized amphibole, and a few patches of garnet-calcite rock.

Highly altered quartz monzonite from the lower adit of the Concordia mine shows a rather complicated and poorly defined sequence of alteration. The rock has been almost completely reconstituted; the only original mineral components are sericitized feldspar phenocrysts and a little apatite and zircon. Apparently the first stage of alteration following sericitization was introduction of fluorite, sulfides (mainly sphalerite and pyrite), and quartz. This stage was followed by wholesale introduction of orthoclase, which replaces all the minerals formed earlier except sericitized feldspar. A photomicrograph of the resulting texture is shown in plate 14, *C* and *D*.

In the table below is presented a partial analysis of the El Monte monzonite (a quartz-monzonite or granodiorite facies of the monzonite) and, for comparison, the compositions of Daly's average quartz diorite, quartz monzonite, and granodiorite (1933). Although the sums of the oxides given, other than silica, are roughly equal for each rock, the El Monte rock shows an overwhelming preponderance of potash over soda and lime combined, and a much higher absolute percentage of potash than would be expected in a nonfeldspathoidal rock.

Comparison of partial analyses: El Monte quartz monzonite with average quartz diorite, quartz monzonite, and granodiorite.

Oxide	1 (percent)	2 (percent)	3 (percent)	4 (percent)
SiO_2	62. 52	61. 59	66. 64	65. 01
CaO	1. 33	5. 38	3. 50	4. 42
Na_2O	. 49	3. 37	3. 41	3. 70
K_2O	8. 64	2. 10	3. 72	2. 75

1. Orthoclasized quartz monzonite, El Monte mining area. A. Obregon P., analyst.
2. Average quartz diorite. Daly, 1933, p. 15.
3. Average quartz monzonite. Daly, 1933, p. 15.
4. Average granodiorite. Daly, 1933, p. 15.

The orthoclase-rich dike of the Santa Teresa adit in the El Monte mining area is a light-gray fine-grained rock whose original composition is unknown but was perhaps andesitic. The primary minerals are altered to a finely crystalline aggregate of albite and zoisite and are widely replaced by orthoclase accompanied by flourite and a little garnet. Introduction of orthoclase was followed by dissemination of sphalerite and pyrite. A similar alteration has affected the medium bluish-gray latite(?) dike of the Tecomates mine. Plagioclase laths are altered to albite and zoisite, and abundant sericite occurs as pseudomorphs, possibly after orthoclase, and is scattered through the groundmass. Late-formed orthoclase and pyrite, apparently introduced simultaneously, form irregular patches and veinlets.

Introduction of large quantities of tourmaline as a process of igneous rock alteration was noted only in a monzonite dike exposed in the Río Tolimán canyon just south of the mouth of Barranca de Santa Rita. The dike is a light-gray fresh-appearing porphyry speckled with prominent crystals and aggregates of black tourmaline and fresh pyrite. The microscope reveals completely sericitized feldspar phenocrysts as much as 1 mm across, in a base of oligoclase-andesine laths as much as 0.3 mm long, abundant sphene and apatite, a little augite, and interstitial orthoclase. Pyrite, accompanied by a little apatite and quartz, was the earliest mineral to be introduced. It was followed by tremolite in ragged poikiloblastic grains, some of which enclose pyrite. Tremolite was followed by tourmaline, which forms subhedral crystals as large as 3 mm across. The tourmaline is pleochroic with O=prussian blue, very dark blue gray, or black, and E=pale yellow brown. Refractive index ω is 1.665, which corresponds to a composition of schorlite $_{65}$-dravite $_{35}$, or schorlite $_{75}$-elbaite $_{25}$, according to Winchell (1933, p. 303). The schorlite-dravite composition seems the more probable one. Following tourmaline is a little epidote; a second generation of tremolite; quartz, sphene, and apatite in small knots; and lastly calcite, which floods some of the altered areas and also occurs as veinlets.

WALL-ROCK ALTERATION

Alteration of wall rocks in the Zimapán ore deposits has been of two general types. Limestone has been converted to tactite in some of the limestone replacement deposits, and volcanic rocks have been propylitized, and changed to potash-rich rocks in the vein deposits. Alteration of the wall rocks of the veins was not studied in detail as these deposits have not, in general, been very productive. Two examples of alteration believed to be typical are discussed briefly.

ALTERATION IN THE LIMESTONE REPLACEMENT DEPOSITS

Alteration of the wall rocks in the replacement deposits in limestone, as typified by the ore bodies of the Los Balcones mine and the El Monte mining area, has been entirely tactitic. Intensity of alteration is naturally closely related to distance from the presumed source of the tactite-forming fluids, namely the monzonite or quartz monzonite that underlies both the Carrizal and El Monte mining areas, although it is dependent in part on the availability of suitable channels of circulation. Thus, tactitic alteration in the Los Balcones mine is most prominent in the lowest working, the La V2 adit, which lies about 73 meters below the highest outcrop of quartz monzonite; the alteration becomes less intense in the Los Balcones adit, 207 meters above the La V2 adit, and the San Rafael Nuevo adit, 234 meters above that same adit; and it is not present in the higher workings of San Rafael Viejo, La Palmita, and San Miguel de Los Palacios. Even in the Los Balcones and San Rafael Nuevo adits, tactite minerals are present only in some dikelike tactite bodies which form walls of ore chimneys. Sulfides are clearly formed later than the silicates and have a simple carbonate gangue. No wall-rock alteration of any kind was noted in any of the workings of the Lomo de Toro mine, which is about 110 meters higher than, and more than 450 meters southeast of, the nearest outcrop of quartz monzonite.

A similar relation of intensity of alteration to distance from quartz monzonite is evident in the small ore deposits on the west side of Barranca de Tolimán. Tactite is prominent in the Cinco de Mayo and lower Santa Clara adits, which lie just above the quartz monzonite, it is sparingly present in the upper Santa Clara mine workings and in the San Guillermo adit, 30–40 meters above the quartz monzonite, and it is absent in the Las Animas mine, 248 meters above the Cinco de Mayo working.

Lack of recognizable wall-rock alteration, exemplified by the La Palmita-Los Balcones sulfide ore body and all the oxidized ore bodies of the Lomo de Toro mine, is, insofar as the writers have been able to ascertain, rather common in the lead-silver-zinc limestone replacement deposits in Mexico. Abrupt changes from solid or nearly solid sulfides to unaltered limestone are the rule at Zimapán. Perhaps the best example is the downward continuation of the La Palmita chimney, which was discovered in the Los Balcones adit in 1948. After cutting the ore body with a diamond drill, the owners drove a crosscut to intersect the ore. According to the mine operator, there was no suggestion of nearness to the sulfides until they were discovered during the drilling of a round. Walls of the crosscut were examined carefully by the writers, but no rock alteration, either recrystallization, silicification, or silication, could be detected. The ore body at the Los Balcones level is essentially solid sulfide, largely pyrite and sphalerite with a scant gangue of calcite. Similar lack of wall-rock alteration is strikingly shown by the inclined pipe of sulfides in the San Rafael Nuevo adit in the same mine. Here the unaltered limestone walls are separated from essentially solid sulfide by a selvage of calcite 1 to 5 cm thick. In a number of small deposits a zone of disseminated sulfides lies between limestone and ore, but even in such cases the only gangue mineral in the zone of disseminated sulfide is calcite. A good example is the upper deposit of the Dos Amigos mine, across Barranca de Tolimán from the Los Balcones mine, where 15–18 cm of rock consisting of bands of pyrite, galena-calcite, and sphalerite-calcite lies between unaltered limestone and massive sphalerite-pyrite ore.

ALTERATION IN THE VEIN DEPOSITS

Vein deposits in the Zimapán district are largely restricted to the El Morro fanglomerate, the Las Espinas volcanic rocks, and the monzonite. The only productive veins of any importance are entirely in the El Morro, although a small production has come from veins in the volcanic rocks. Wall-rock alteration in the fanglomerate has been negligible as far as could be detected in the field. The walls of the Santa Gorgonia vein, which has been explored to a depth of more than 200 meters, appear fresh and unaltered from the surface to the deepest accessible level 180 meters below. Similarly, the fanglomerate walls of the San José Maravillas-Poder de Dios vein are fresh wherever seen underground. However, where the vein intersects the lens of volcanic rock along which the San José Maravillas adit has been driven, wall rocks have been considerably altered. The orginal composition of the volcanic rock is unknown, but it was probably latitic or andesitic. The rock has been altered to a fine-grained aggregate of orthoclase, pale yellow-green chlorite, sericite, and a little quartz, and has been impregnated with pyrite. Original feldspar phenocrysts are completely altered to extremely fine grained orthoclase. Epidote and tremolite have formed in small amounts. Abundant tiny grains of apatite and a little sphene and zircon are residual minerals. Average grain size is less than 0.02 mm. With slightly more intense alteration, chlorite becomes less abundant and the altered rock consists largely of orthoclase, sericite, quartz, and pyrite.

The explored part of the Santo Tomás vein lies entirely in the Las Espinas volcanic rocks, principally greenish-gray to dark greenish-gray porphyritic dacite lavas. Alteration of the vein walls is dominantly propylitic. Mafic minerals are altered to chlorite, carbonate, and some sphene, or, rarely, to carbonate only. Feldspars are altered to kaolinite and sericite and are irregularly albitized, and abundant chlorite has formed in the groundmass. Large quantities of carbonate have been introduced, which replaces the groundmass and also forms replacement rims around embayed quartz phenocrysts. Wall rock adjacent to the vein is bleached to a light greenish gray and has undergone wholesale replacement by carbonate. A few remnants of feldspar phenocrysts and patches of groundmass are the only survivors of the carbonatization.

GEOLOGIC HISTORY

Although the sequence of many of the events that outline the geologic history of the Zimapán district is fairly well established, an accurate dating of all the events has not been feasible. Upper Jurassic and Lower and Upper Cretaceous rocks have been dated on paleontologic evidence, but the chronology of later Cretaceous and post-Cretaceous rocks depend on inference, based largely on the scant information available concerning early Tertiary red conglomerates and later Tertiary volcanism on the central plateau of Mexico, and on local physiographic evidence. There are many gaps or uncertainties in the sequence of events. For example, the succession of the various intrusive rocks is only imperfectly known.

The recognizable geologic history of the district begins in Late Jurassic time with the deposition of shale and limestone, succeeded upward conformably by the Lower Cretaceous limestone and limestone reefs and by the Upper Cretaceous limestone and calcareous shale. The surface on which the Upper Jurassic rocks were deposited is not exposed in the area mapped.

At some time near the end of the Cretaceous period, the area was elevated above sea level and the rocks were folded in response to compressive forces that acted in a southwest-northeast direction. Open folds were formed locally, but more commonly the rocks were folded isoclinally, with the formation of overturned and even recumbent folds. Thrust faulting appears to have been unimportant, as only one thrust, which brings gently dipping, overturned (?) limestone of Early Cretaceous age over tightly folded Upper Cretaceous rocks on Cerro de Daxi, was recognized. Many minor thrusts, however, may not have been recognized during the field work. The many overturned and recumbent folds suggest that thrust faulting may have been more important than it appears. Concurrently with folding, fracture cleavage formed locally in the Upper Cretaceous rocks and to a lesser extent in chert layers in the Lower Cretaceous limestone.

The intense folding of the Cretaceous rocks was followed by prolonged erosion, which uncovered Lower Cretaceous rocks in the anticlinal cores. Probably beginning in late Eocene or early Oligocene time, the El Morro fanglomerate was deposited over lowlands or in basins formed by erosion or tectonic movements. The source of the fanglomerate was probably a highland to the southwest underlain by Upper Cretaceous rocks; the prevailing climate was probably humid in the uplands and somewhat drier in the lowlands, as suggested by the red color of the fanglomerate.

Late in the period of fanglomerate deposition, perhaps during Oligocene time, volcanism began in the area. For a short time fanglomerate and volcanic rocks were laid down contemporaneously, after which time volcanism became the dominant agent in supplying materials for deposition. The great bulk of the Las Espinas volcanic rocks consists of andesitic and basaltic lavas, with a few dacite flows; tuff and agglomerate are subordinate. Some of the dikes in the area may have been contemporaneous with the effusive rocks, but no evidence was found.

Either during the last stages of volcanism or after volcanism had ceased (perhaps in late Miocene or early Pliocene time), several bodies of monzonite (including facies of syenite, quartz monzonite, monzonite, granodiorite, and diorite) intruded the earlier rocks. Intrusion of many dikes, predominantly andesite but ranging in composition from rhyolite to basalt, was probably nearly contemporaneous with emplacement of the monzonitic rocks. In a few places the monzonite is cut by lamprophyre dikes.

Where the monzonite intruded the Lower Cretaceous limestone, emanations from either the monzonite bodies themselves or from a deeper mass of cooling magma permeated the wall rocks and formed an aureole of tactite as well as many dikelike bodies of similar composition. Wall rocks of Late Cretaceous age or El Morro fanglomerate were converted to hornfels. The latest stage in the intrusion of monzonite was the formation of the sulfide ore deposits of the district. No postmineralization igneous activity of any kind has been recognized. Ore deposits were formed by replacement of limestone, replacement of tactite, and fissure filling.

The position in the intrusive sequence of the rhyolite porphyry and rhyolite felsite of the southern part of the area is not clear, inasmuch as neither was found in contact with monzonite. They may have been nearly contemporaneous with the monzonite or may have been formed later.

After establishing itself on the postvolcanism surface, the Río Tolimán began to downcut vigorously. Probably at about the same time, uplift along the northeast side of the Malacate fault initiated the rise of the Sierra de El Monte. Continued downcutting by the river resulted in its superposition on the underlying Cretaceous rocks, in removal of great quantities of El Morro fanglomerate and Las Espinas volcanic rocks from the area, and finally in the carving of Barranca de Tolimán. The cross section of the barranca indicates that three stages of canyon cutting were involved.

Following uplift of the Sierra de El Monte, the Zimapán fanglomerate was deposited along its south base, probably during the Pleistocene. At about the same time, the Daxi fanglomerate was deposited along the northeast base of Cerro de Daxi. Age of deposition of fanglomerate is probably to be correlated with profound canyon cutting by the Río Tolimán.

After fanglomerate deposition, and probably during a period of extreme aridity, stream valleys were alluviated to considerable depths (exceeding 12 meters locally) and much caliche was formed in fanglomerate areas. Renewed stream erosion in very recent time, perhaps as a result of increased rainfall, has resulted in the dissection of older alluvium and solution of caliche, both processes being active at present.

Oxidation of the ore deposits probably began soon after Barranca de Tolimán began to develop and has continued to the present day. The geologic history of the Zimapán district is summarized as follows:

Jurassic:
- Deposition of limestone and shale.

Cretaceous:
- Deposition of limestone and limestone reefs.
- Deposition of shale and limestone.

Tertiary:
- Folding: overturned or recumbent isoclinical folds, some opén folds, minor thrust faulting from southwest.
- Prolonged erosion, reduction of postfolding surface to low relief.
- Deposition of El Morro fanglomerate. Source was highland to southwest, underlain by Upper Cretaceous rocks.
- Deposition of Las Espinas volcanic rocks: andesitic and basaltic lavas, a few quartz latite and dacite flows, minor tuff and agglomerate.
- Intrusion of monzonitic rocks and associated dikes.
- Metamorphism of Lower Cretaceous limestone to tactite, of Upper Cretaceous rocks and El Morro fanglomerate to hornfels.
- Ore deposition by replacement and fissure filling.
- Canyon cutting by Río Tolimán, superposition on Cretaceous rocks, uplift along northeast side of Malacate fault.
- Oxidation of ore deposits begins?

Quaternary:
- Deposition of Zimapán and Daxi fanglomerate.
- Alluviation, formation of caliche.
- Dissection of alluvium, solution of caliche.

ORE DEPOSITS

HISTORY OF MINING AND PRODUCTION

Any attempt to outline a history of mining at Zimapán is immediately beset by many difficulties, not the least of which are lack of basic information and extreme sketchiness of available data. Lack of data may be attributed to two principal causes; scarcity of published statistics during the epoch of Spanish domination of Mexico (1519–1810) and destruction or nonpublication of data during the long period of the War of Independence (1810–21) and the succeeding internal disturbances culminating in the Reform (approximately 1855–67). No records whatsoever of total production, either from the district as a whole or from any given mine, are available. Production records for a few widely separated periods and for a few of the bonanzas are scattered through the meager literature, but gaps in the record are far longer than the periods covered. The résumé of mining history and production to follow has been compiled from a number of widely differing sources, including a British consular report, descriptions by early travelers in Mexico, sketchy and unreliable earlier compilations, private reports of various mining engineers and geologists, a bulletin of the Geological Institute of Mexico, and conversations with present mine operators. The Lomo de Toro mine has probably always been the most important mine in the district and is mentioned in nearly all the sources; the history of the district is practically a history of that mine, although a number of smaller mines are mentioned occasionally.

According to Humboldt (1808, p. 495) and Dahlgren (1883, p. 215–218), the discovery of the Lomo de Toro mine by Lorenzo del Sabra in 1632 initiated mining at Zimapán. Silver and lead were the principal metals sought. No records of production, either in tonnage or value, are available from the date of discovery to 1785. Dahlgren states that the Lomo de Toro mine was worked without interruption from 1632 to 1810, when the War of Independence interrupted mining and brought about the wholesale exodus of Spanish mine operators from Zimapán, but work must have been on a relatively small scale as the combined volume of the largest stopes of that era (El Claro, La Piedad, San Vicente, and Ave María) is not consistent with uninterrupted large-scale mining over a period of 178 years. According to Falletite (1868, unpublished report), at the time the war began, approximately 40 furnaces were operating in and around Zimapán and another 12 or so were in the El Monte area. A few production figures for the period 1785–93 are given by Dahlgren and Falletite: from 1785 to 1788, smelted metal worth 247,000 silver marks or 1,976,000 pesos, and metal from the old patio amalgagation process worth 9,720 pesos, were produced. The silver mark was worth eight pesos. The peso, in turn, was worth eight Spanish reales and was known in many parts of the world as the piece of eight or Spanish dollar. Inasmuch as the coin was adopted as the standard monetary unit, or dollar, by the American colonies after the War of Independence, the peso value of metal produced in the 18th and early 19th centuries is the same as the dollar value. Some of the lead from Zimapán was used for pipe in Mexico city. In 1793, a bonanza struck in the Lomo de Toro mine yielded 5,700 tons of lead for a certain Don Angel de Bustamante, Marqués de Batopilas. From 1791 to 1793 the same owner extracted more than 100,000 pesos worth of ore yearly from the Santa Rita mine (Ward, 1828, p. 441).

Although Dahlgren says that the mines were not worked during most of the 19th century, Flores (1924, p. 23) mentions an annual production of more than 200 barras of silver for the years 1830–40. The barra of silver was worth approximately 1,085 pesos, so the yearly production of silver alone must have been about 200,000 pesos and total production for the period roughly 2 million pesos. Ward (1828, p. 405) says that the old Compañía Minera Real del Monte y Pachuca worked the Lomo de Toro mine from 1825 to 1828, and a Compañía Anglomexicana operated the La Cruz, San Fernando, and Guadalupe mines.

In 1840 a Sr. Juárez extracted lead and silver worth more than 40,000 pesos from a bonanza in the El Monte mining area (Falletite, 1868, unpublished report). The mine or mines worked are unknown, but among them were probably the Dolores, Chiquihuites, and Rosario.

For the period from 1840 to about 1878 there are no data. Apparently the production was slowed because of the upset political conditions in Mexico at that time. According to Dahlgren, four smelters and four small furnaces were operating in 1878, smelting ore worth from 35 to 64 pesos per ton.

Interest in the Lomo de Toro mine was revived from 1890 to 1901, during which time the San Damián and San Guillermo adits were driven and the Los Bronces and San Agustín winzes were sunk from the Ave María stope. During the same time the La Luz mine was developed. From 1901 to 1910 a small amount of ore was produced from the San Antonio, La Bota, and San Damián workings. The revolution of 1910 put an end to mining at Lomo de Toro and work was not resumed until 1929.

Small operations at the Concordia mine and perhaps other mines in the El Monte mining area were carried on by the Hidalgo Copper Mining and Smelting Co. for a number of years beginning about 1913; in that year, 1,742 tons of ore, averaging 21 percent lead, and 806 grams of silver was smelted.

At the time of Flores' study (1921), three companies were operating in the district. The Compañía Fundidora y Minera de Zimapán operated the Rosario, Santa Gorgonia, La Candelaria, San Gerónimo, Poder de Dios, and Las Animas mines; the Hidalgo Copper Mining and Smelting Co. operated mines in the El Monte mining area, and also the Nevada and Purísima mines; and the Preisser family operated the San Francisco and Los Balcones mines. The lack of activity in the district was attributed by Flores to shortage of capital and high freight costs (13 pesos per ton from some mines to the Zimapán smelters).

In 1929, several other companies were mining in the district. The Compañía Minera Mexicana was operating the San Pascual and La Cruz mines and the Negociación Minera La Aurora worked the Preciosa Sangre and San José Maravillas deposits. The Lomo de Toro mine also came into production again with reopening of the San Antonio, La Bota, and San Damián workings. Ore was smelted locally until 1939, when shipments to the American Smelting and Refining Co. at San Luis Potosí were begun. The large oxidized ore bodies of the present Lomo de Toro mine were discovered in 1945, and construction of an all-weather road into the Carrizal mining area in 1946–47 provided stimulus for greatly increased production, mainly from the Lomo de Toro and Los Balcones mines. From 1929 until mid-

1948, the Lomo de Toro mine produced about 35,000 tons of high-grade lead-silver ore.

In 1948 the Compañía Minera Fresnillo began exploratory work in the El Monte mining area. Although no large ore bodies had been found by 1949, a significant production came from El Monte during 1948–49.

In 1949 very little ore was being smelted at Zimapán. The only smelter operating was a small one of the Compañía Minera La Llave. Oxidized ores from Lomo de Toro were shipped to the American Smelting and Refining Co. smelter at San Luis Potosí; sulfide ores from the Los Balcones and other smaller mines were sent to the same company's custom mill at Charcas, San Luis Potosí, for beneficiation. Ore from the El Monte operation of the Compañía Minera Fresnillo was shipped directly to the parent establishment at Fresnillo, Zacatecas. Ores were shipped by truck from Zimapán to the railhead at Huichapan, 88 kilometers distant, and thence by railroad to smelter or mill. From the Carrizal mining area, ore was transported by truck to Zimapán, but El Monte ores had to be carried by burro for a distance of 10.5 kilometers to Zimapán.

MINERALOGY

MINERALS OF THE ZIMAPAN MINING DISTRICT

All the minerals found during this survey or reported elsewhere from the Zimapán mining district are listed alphabetically below. Brief descriptions of the ore and gangue minerals of the ore deposits are given. A distinction is made between the hypogene minerals, or the original minerals deposited by fluids derived from igneous sources, and supergene minerals, or those formed as a result of weathering processes acting on the original minerals. The ore minerals are further grouped under the principal metal contained. In the list, minerals marked with an asterisk have been reported from the district but were not found during this survey.

Actinolite	$Ca_2(Mg, Fe)_5(Si_4O_{11})(OH)_2$
Adamite	$Zn_2(AsO_4)(OH)$
*Alamosite	$PbSiO_3$
Albite	$NaAlSi_3O_8$
Analcite	$NaAlSi_2O_6 \cdot H_2O$
Anglesite	$PbSO_4$
Apatite	$(Ca(F,Cl))Ca_4(PO_4)_3$
*Argentite	Ag_2S
Arsenopyrite	FeAsS
Augite	Aluminous pyroxene
Aurichalcite	$2(Zn, Cu)CO_3 \cdot 3(Zn,Cu)(OH)_2$
Axinite	$H(Fe,Mn)Ca_2Al_2BSi_4O_{16}$
Azurite	$2CuCO_3 \cdot Cu(OH)_2$
Barite	$BaSO_4$
Biotite	$H_2K(Mg,Fe)_3Al(SiO_4)_3$
Bornite	Cu_5FeS_4
Calcite	$CaCO_3$
Cerussite	$PbCO_3$
Chalcanthite	$CuSO_4 \cdot 5H_2O$
*Chalcocite	Cu_2S
Chalcopyrite	$CuFeS_2$
Chlorite	Hydrous silicate of Fe, Mg, Al
Chrysocolla	$CuSiO_3 \cdot 2H_2O$
*Cinnabar	HgS
Clinozoisite	$HCa_2(Al,Fe)_3Si_3O_{13})$
Copper	Cu
*Danburite	$CaB_2(SiO_4)_2$
Diopside	$Ca(Mg,Fe)(SiO_3)_2$
Dolomite	$(Ca,Mg)CO_3$
Epidote	$HCa_2(Al,Fe)_3Si_3O_{13}$
Fluorite	CaF_2
Galena	PbS
Garnet (andradite)	$3CaO \cdot Fe_2O_3 \cdot SiO_2$
Gypsum	$CaSO_4 \cdot 2H_2O$
Hematite	Fe_2O_3
Hornblende	Aluminous amphibole
Hypersthene	$(Mg,Fe)SiO_3$
Iddingsite	$MgO \cdot Fe_2O_3 \cdot 3SiO_2 \cdot 4H_2O$
Jamesonite	$4PbS \cdot FeS \cdot 3Sb_2S_3$
*Löllingite	$FeAs_2$
Malachite	$CuCO_3 \cdot Cu(OH)_2$
*Manganese oxides	
*Massicot	PbO
Melanterite	$FeSO_4 \cdot 7H_2O$
Meneghinite	$Pb_{13}Sb_7S_{23}$
*Mimetite	$PbClPb_4(AsO_4)_3$
*Molybdenite	MoS_2
*Molybdite	$Fe_2O_3 \cdot 3MoO_3 \cdot 8H_2O$
Monticellite	$CaMgSiO_4$
Muscovite	$H_2KAl_3(SiO_4)_3$
Olivenite	$Cu_2(AsO_4)(OH)$
Olivine	$(Mg, Fe)_2SiO_4$
Opal	$SiO_2 \cdot nH_2O$
*Orpiment	As_2S_3
Orthoclase	$KAlSi_3O_8$
Plagioclase feldspars	$(NaAlSi_3O_8)$, $(CaAl_2Si_2O_8)$
Plumbojarosite	$PbO \cdot 3Fe_2O_3 \cdot 4(SO_3) \cdot 6H_2O$
*Pyrargyrite	$3Ag_2S \cdot Sb_2S_3$
Pyrite	FeS_2
*Pyromorphite	$PbClPb_4(PO_4)_3$
Pyrrhotite	Fe_7S_8
Quartz	SiO_2
*Realgar	AsS
Rutile	TiO_2
Sanidine	$KAlSi_3O_8$
*Scapolite	$(CaCO_3 \cdot 3CaAl_2Si_2O_8)$, $(NaCl \cdot 3NaAlSi_3O_8)$
Scorodite	$FeAsO_4 \cdot 2H_2O$
Serpentine	Hydrous magnesium silicate
Siderite	$FeCO_3$
*Silver	Ag
Smithsonite	$ZnCO_3$
Sphalerite	ZnS
Sphene	$CaTiSiO_5$
Spinel	$MgAl_2O_4$
Spurrite	$2CaSiO_4 \cdot CaCO_3$
*Stibnite	Sb_2S_3
Sulfur	S
*Tennantite	$3Cu_2S \cdot As_2S_3$
*Tetrahedrite	$3Cu_2S \cdot Sb_2S_3$
Tourmaline	Complex borosilicate of Na, Mg, Fe, Li, Al, Mn, Ca.

Tremolite	$Ca_2Mg_5(OH_2)(Si_4O_{11})_2$
*Vanadinite	$PbClPb_4(VO_4)_3$
Vesuvianite	$Ca_6(Al(OH,F))Al_2(SiO_4)_5$
Wollastonite	$CaSiO_3$
*Wulfenite	$PbMoO_4$
Zeolite	Hydrous silicates of Al, Ca, Na.
*Zinkenite	$PbS{\cdot}Sb_2S_3$
Zircon	$ZrSiO_4$
Zoisite	$HCa_2Al_3Si_3O_{13}$

HYPOGENE ORE MINERALS

SILVER

Argentite.—Argentite has been reported from the Nuestra Señora mine west of Cerro de La Nopalera in the La Luz and La Cruz mining area, and from the Santo Niño mine, whose location is unknown. It was also reported by Bárcena (1811) from a smelter in Zimapán. No hypogene silver minerals were recognized during this survey.

Pyrargyrite.—Pyrargyrite, ruby silver, was reported by Flores (1924) from the Santa Gorgonia mine.

LEAD

Alamosite.—The rare lead silicate, alamosite, was recorded in an unpublished report by R. Cepeda (1928), from the San Pascual mine. There is no confirmation of the occurrence, and the mineral may possibly have been confused with wollastonite.

Galena.—Galena is the only important hypogene lead mineral in the district. It was found in nearly every sulfide ore. Both coarse-grained galena, as much as 4 cm across a cleavage face, and the very fine-grained variety, which looks like steel, are found. Beautiful crystals of galena more than a centimeter across were found in vugs in the Los Balcones mine. Most, if not all, of the silver in hypogene ores appears to be contained in galena. Coarse-grained galena from the Miguel Hidalgo mine contained 2,794 grams of silver per ton, and the fine-grained galena from the Santa Gorgonia mine is said to contain 2.5 to 4 kilograms of silver per ton. A number of lead and silver assays of sulfide ores from the Chiquihuites and Miguel Hidalgo mines are plotted in figures 18 and 19, respectively; the percentage of lead is plotted against grams of silver per ton. Although for most ore bodies a considerable scattering is evident, analyses of both the Chiquihuites ores, and sulfides from ore bodies 1 and 3 of the Miguel Hidalgo mine, show a rough linear plot. The analyses

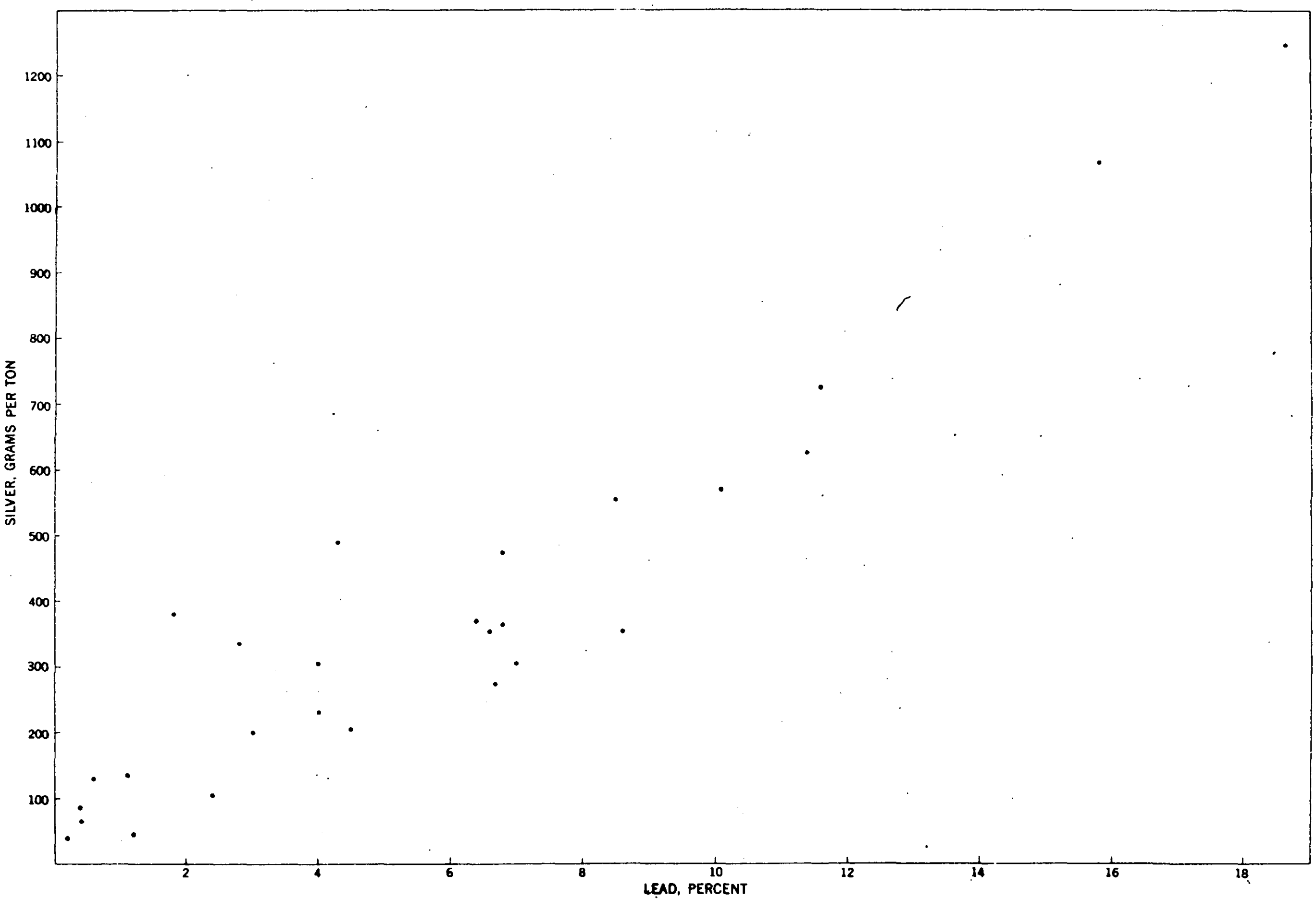

FIGURE 18.—Graph showing relation of lead to silver in sulfide ores at the Chiquihuites mine, El Monte mining area.

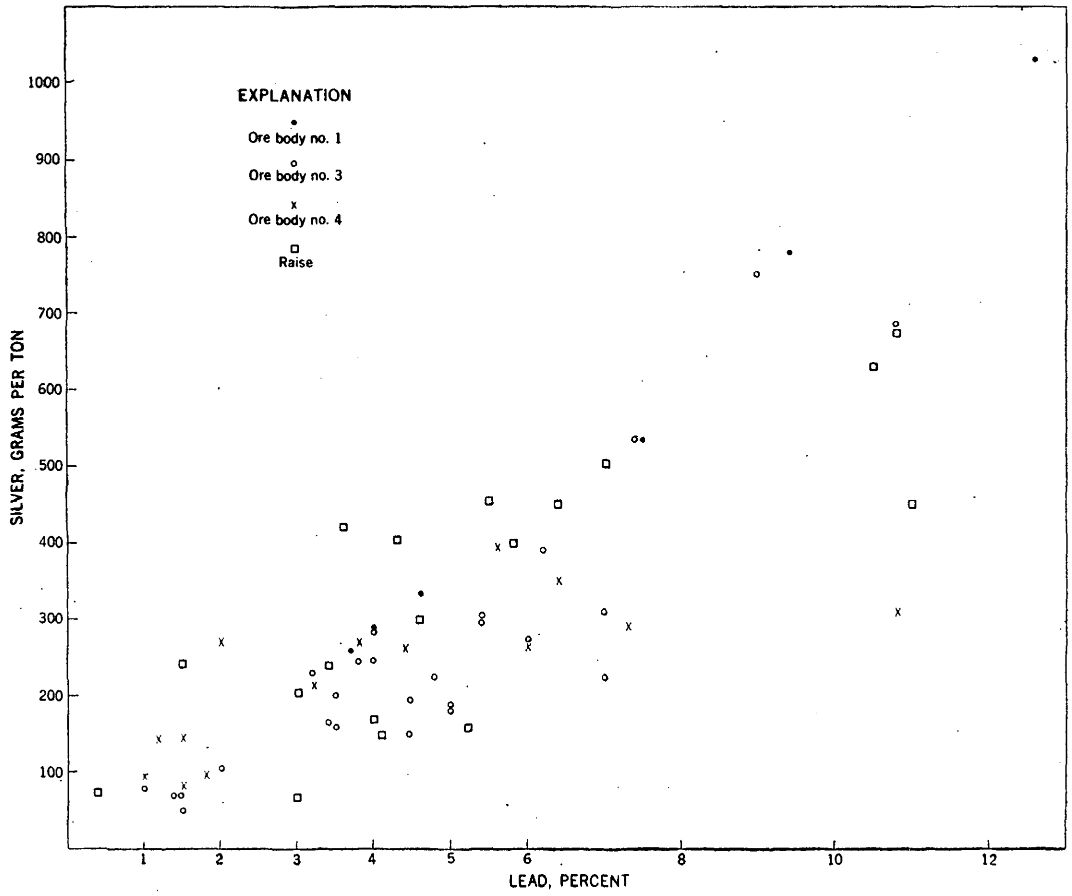

FIGURE 19.—Graph showing relation of lead to silver in sulfide ores of the Miguel Hidalgo adit, El Monte mining area.

of Miguel Hidalgo ore body 1 lie very close to a straight line. On the other hand, a similar graph of assays of ore from the Concordia mine shows a total lack of linear pattern. Apparently silver is not contained in galena at that mine. In an unpublished report on the San Pascual mine, Bonillas (1929) says that concentration tests on galena raised the grade of lead ore about 200 percent but had no comparable effect on the silver content, and he concludes that silver is present as a separate sulfide.

Galena is almost invariably associated with sphalerite and commonly with both sphalerite and pyrite. In the calcite vein of the Buenavista mine, galena is the only sulfide. Less common associates are pyrrhotite (Los Balcones and San Guillermo mines and many localities in the El Monte mining area), jamesonite (El Monte area and San Vicente mine in the Carrizal mining area), chalcopyrite, and, very rarely, arsenopyrite.

Meneghinite.—Small grains of a dark-gray splendent mineral in tactite from the lower level of the Concordia mine proved to be the lead-antimony sulfide meneghinite. The mineral was identified by X-ray methods by J. M. Axelrod of the U. S. Geological Survey.

Jamesonite.—Silver-gray to lead-gray jamesonite in beautifully formed small divergent fibrous masses is a minor constituent of ores from the Miguel Hidalgo, El Afloramiento, Chiquihuites, and Tecomates mines in the El Monte mining area. It was also noted in very small quantity at the San Vicente mine in the Carrizal mining area, and was described by Lindgren from the La Sirena prospect northwest of the Carrizal mining area. Jamesonite seems to be a late-formed mineral, associated with sphalerite, pyrite, and pyrrhotite, and less commonly with galena and chalcopyrite. Microchemical tests on jamesonite from the El Monte area gave positive reactions for lead, antimony, and iron, and negative reactions for copper, arsenic, and silver.

Zinkenite.—The lead-antimony sulfide zinkenite was reported from the San Francisco mine (Salazar Salinas, 1923b).

ZINC

Sphalerite.—Sphalerite is the only hypogene zinc mineral recognized in the district and is probably the most abundant sulfide in the Zimapan ore deposits. It ranges in composition from a very pale yellow, nearly pure zinc sulfide (Las Estacas mine, La Salvadora prospect) to very dark brown iron-bearing marmatite (Los Balcones mine). The most common sphalerite is brown to deep red. Sphalerite from the Los Balcones mine is said to contain a small amount of cadmium. Large masses of nearly solid sphalerite occur in the Los Balcones mines, where cleavage faces as much as 6 cm across are common in parts of the mine. Sphalerite is always associated with pyrite and usually with galena. The average sulfide ore of the Carrizal mining area contains considerably more sphalerite than galena. Commonly sphalerite contains tiny blebs of chalcopyrite.

COPPER

Bornite.—A specimen of massive bornite from the La Luz mine was shown to us by the mine owner. The parts of the mine where it might be seen in place were flooded at the time of our study.

Chalcopyrite.—Chalcopyrite was the only hypogene copper sulfide found during this investigation. Although widespread, it is not abundant except in the Concordia mine. It occurs both as late-formed veinlets cutting other sulfides and as inclusions in sphalerite. Chalcopyrite is commonly found in the pyrometasomatic deposits, associated with arsenopyrite, pyrrhotite, and sphalerite. It is less abundant in the deposits of sphalerite, pyrite, and galena of mesothermal origin. It was also seen in the veins of the Santa Gorgonia, San Pablo, and San José Maravillas and Poder de Dios mines, but in minute quantities.

Tennantite.—The copper arsenic sulfide tennantite was reported by Flores (1924). It is said to be very rare.

Tetrahedrite.—The copper-antimony sulfide tetrahedrite has been reported by various workers from the Santa Gorgonia, Dolores, La Luz, and Los Balcones mines; it was doubtfully identified by Spurr (1907, unpublished report) at the Concordia and Purísima mines. It apparently never occurred in large quantities and was not found by us.

IRON

Arsenopyrite.—See arsenic minerals.

Löllingite.—See arsenic minerals.

Pyrite.—Pyrite is the commonest iron sulfide in the district and is next to sphalerite in abundance. It was found in every ore deposit. In one deposit, north of Cerro de La Majada Grande, massive pyrite was the only sulfide. Pyrite is usually massive, without well-formed crystal faces. Where there are crystals, the common form is the cube, but pyritohedral pyrite was seen in a few places. Perfect cubic molds after pyrite were seen in a mass of gray opal at the Amistad no. 3 prospect. Pyrite apparently was deposited throughout the sequence of mineralization, occurring as both an early-formed and a late-formed mineral in the same ore deposits.

Pyrrhotite.—Pyrrhotite, or magnetic pyrite, is abundant in the El Monte mining area and was seen also at the San Rafael and La V workings of the Los Balcones mine and at the San Guillermo mine. It is a characteristic mineral of the pyrometasomatic deposits, such as Concordia, Miguel Hidalgo, El Afloramiento, Chiquihuites, and El Chacuaco Viejo in the El Monte mining area, but it occurs also at the Tecomates mine in a presumably lower temperature environment. It is associated with sphalerite, arsenopyrite, pyrite, and chalcopyrite, and in the main San Rafael chimney it occurs with galena.

ARSENIC

Arsenopyrite.—Arsenopyrite, or mispickel, is abundant in most of the sulfide deposits of the El Monte mining area. It was also seen in the La V adit of the Los Balcones mine, in the Santo Tomás vein of the Santa Gorgonia-San Pascual mining area, and at the San Francisco mine. Together with pyrrhotite, it is a typical mineral of the pyrometasomatic deposits. Arsenopyrite is invariably an early-formed mineral and occurs commonly as euhedral prisms imbedded in gangue or later formed sulfides.

Löllingite.—The iron diarsenide löllingite is reported from the Santa Rita mine (Salazar Salinas, 1923b).

Tennantite.—See copper minerals.

ANTIMONY

Jamesonite.—See lead minerals.

Meneghinite.—See lead minerals.

Pyrargyrite.—See silver minerals.

Stibnite.—Stibnite has been reported by Salazar Salinas (1923b) and Brinsmade (1921) from a mine near La Ortiga; it was not found during this survey.

Tetrahedrite.—See copper minerals.

Zinkenite.—See lead minerals.

SUPERGENE ORE MINERALS

GOLD

Although no gold of hypogene origin has been recognized in the Zimapán district, some of the sulfide ores carry a little gold which is liberated on oxidation. The oxidized ores of the Lomo de Toro mine contain small quantities of gold, commonly 1 or 2 grams per ton.

SILVER

Argentojarosite.—Although argentojarosite was not identified positively, it may be abundant in the oxidized ores of the Lomo de Toro, Miguel Hidalgo, and Las Animas mines. The silver content of megascopically homogeneous plumbojarosite ores range from about 300 to about 1,700 grams per ton, and probably much of the silver is in the mineral argentojarosite.

Native silver.—Native silver has been reported from the Nuestra Señora mine.

LEAD

Anglesite.—Anglesite is not abundant in the Zimapán district; it was seen in quantity only in parts of the Lomo de Toro mine, where it occurs both as dull-gray masses with vugs containing gypsum and plumbojarosite, and as thin shells around galena masses. It was also seen at the Preciosa Sangre mine and was reported by Cepeda (1928, unpublished report) from the San Pascual mine.

Cerussite.—Cerussite, ordinarily the second oxidation product of galena, is a common mineral in all the mining areas but is abundant only in the Lomo de Toro mine, where it occurs as loosely packed granular material known as "sand carbonate," as an alteration product of anglesite in thin rims around galena-anglesite masses, and as perfectly formed tiny 4- and 6-rayed stellate twinned crystals in vugs. It is abundant at the Preciosa Sangre mine and was seen at the Todos Santos, Dolores, Concepción, and Miguel Hidalgo mines. At the latter mine it occurs as needles in vugs and as veinlets flanked by thin walls of plumbojarosite.

Massicot.—The rare lead monoxide massicot was reported (Salazar Salinas, 1923b) from the Guadalupe mine. It is probable that the mineral identified as massicot was the ubiquitous plumbojarosite, which is not mentioned in the bulletin.

Plumbojarosite.—Plumbojarosite is the most abundant of the lead oxide minerals and was found in every oxidized lead-bearing ore deposit. Identification of the mineral was checked by the Division of Geochemistry and Petrology of the Geological Survey and by the Bureau of Mines experimental station at Boulder City, Nev. Plumbojarosite is commonly a moderate-yellow to grayish-yellow extremely fine grained mineral with silky luster. It is greasy or unctuous when damp, powdery when dry.

Plumbojarosite is the last mineral to form in the oxidation of galena, which followed the usual sequence of galena-anglesite-cerussite-plumbojarosite. Specimens showing all four minerals in roughly concentric layers are abundant in the Lomo de Toro mine, especially in the deeper parts of the mine. They are known locally as "eyes of St. Peter." The mineral occurs in enormous masses in the Lomo de Toro mine. The Santa Luisa ore body, which was largely plumbojarosite, was 35 meters long and about 10 meters wide, and has been mined to a depth of more than 35 meters. At one stage a face of apparently solid plumbojarosite about 15 meters wide and 8 meters high was exposed in the stope. The great ore chimney of El Claro, which was 65 meters long, 35 meters wide, and 105 meters high, was probably plumbojarosite, as all the ore remnants seen in the stope are plumbojarosite. Other large bodies of plumbojarosite have been exploited in the Las Animas, El Espíritu, El Rosario, Chiquihuites, and Miguel Hidalgo mines. Plumbojarosite at Miguel Hidalgo occurs both as massive material and as perfect, although spongy, pseudomorphs after cerussite. An analysis of the plumbojarosite from Miguel Hidalgo gave 17.8 percent lead, 2.7 percent zinc, and 1,695 grams of silver per ton. The silver is probably present as argentojarosite.

Mimetite and Pyromorphite.—The lead arsenate and lead chloride mimetite and the lead phosphate and lead chloride pyromorphite were reported from the Guadalupe mine (Salazar Salinas, 1923b). They were not found during this survey, although minute stubby greenish crystals, possibly pyromorphite, were seen in oxidized ore from the Dolores mine.

Vanadinite.—The lead vanadate and lead chloride vanadinite was first reported from Zimapán, according to Ford (Dana, 1932). According to local residents, the mineral was found in the San Damián deposit of the Lomo de Toro mine. The walls of the San Damián stope are at present thickly coated with mud as a result of flooding in 1943 and any possible occurrences of the mineral are effectively concealed. The mineral was not noted at any locality during this study.

Wulfenite.—The lead molybdate wulfenite was reported by Cepeda (1928, unpublished report) from the San Pascual mine, which is now almost entirely inaccessible.

ZINC

Adamite.—The basic zinc arsenate adamite was found in tiny veinlets in oxidized ore from the Miguel Hidalgo mine. The mineral was pale yellowish green. Optical characters determined by the writers agreed closely with those measured by Mrose (1948, p. 452) on adamite from the Ojuela mine at Mapimí, Durango, Mexico, except that all the refractive indices were slightly higher.

Aurichalcite.—Aurichalcite, the basic zinc-copper carbonate, was seen only in the walls of the Santa Luisa stope of the Lomo de Toro mine, where it occurs as pale blue-green pearly blades and tufts associated with malachite.

Smithsonite.—Smithsonite is very rare in the Zimapán district. It was found in the Lomo de Toro mine, where it occurs as beautiful yellow-green botryoidal masses along the northeast wall of the Santa Luisa dike; in the La V adit of the Los Balcones mine, as a dull-brown bedded material intimately mixed with hematite; and as thin veins in oxide-ore debris from the Dolores and Peñalejos mines.

COPPER

Aurichalcite.—See zinc minerals.

Azurite.—The blue basic copper carbonate azurite is very rare in the district. It was seen only at the San Pablo and Lomo de Toro mines, associated with malachite.

Chalcanthite.—Beautiful curved spongy prisms of chalcanthite, hydrous copper sulfate or blue vitriol, as much as 50 mm long and 5 mm thick were seen in a small stope above the Los Bronces winze of the Lomo de Toro mine. A small pocket of the mineral was seen in the Cinco de Mayo adit, and streaks of chalcanthite appear locally in the fault zone of the San José Maravillas and Poder de Dios mine. A little chalcanthite was seen in the La Mora and El Barreno workings of the Lomo de Toro mine.

Chalcocite.—Chalcocite was reported by Salazar Salinas (1923b) from the Guadalupe mine. No chalcocite is visible in the accessible parts of that mine, and none was seen elsewhere in the district.

Chrysocolla.—The hydrous copper silicate chrysocolla was found coating parts of the walls of the stope in the La Paz mine. The chrysocolla ranges in color from pale sky blue through olive green to dark liver brown and has a refractive index of about 1.585. Calcite is the only associated mineral.

Copper (native).—Native copper in thin sheets and small irregular masses is common in the oxidized ore of the La Luz mine.

Malachite.—The green basic copper carbonate malachite occurs in small quantities in a number of mines, but mainly in the La Luz and Lomo de Toro mines. It was seen also at the San Pablo and Dolores mines. It is neither a widespread nor an abundant mineral.

Olivenite.—Thin crusts of a dark olive-green mineral believed to be olivenite, copper arsenate, were seen at the Dolores and Miguel Hidalgo mines in the El Monte mining area. The mineral is associated with scorodite and is probably an oxidation product of arsenopyrite and chalcopyrite, or possibly of tennantite.

IRON

Hematite.—Hard reddish-brown hematite occurs mixed with smithsonite in the La V working of the Los Balcones mine. It was also identified during an examination of oxidized ore from the Lomo de Toro mine by the Bureau of Mines experimental station, Boulder City, Nev., and by R. L. Smith of the U. S. Geological Survey.

Limonite.—Limonitic iron oxides are common constituents of the oxidized ores in every mine in the district. In the Lomo de Toro mine the bodies of oxidized ore are overlain by a thin layer of limonite lying between the ore and the shrinkage above the ore body. Less commonly, limonite is concentrated at the base of the ore bodies. It is also found in vugs in the oxidized ore. The Bureau of Mines reports a considerable concentration of zinc in the limonite from the Lomo de Toro mine.

Melanterite.—Silky efflorescences of melanterite, hydrous ferrous sulfate, were seen in a few places in the Lomo de Toro mine.

Molybdite.—See molybdenum minerals.

Scorodite.—See arsenic minerals.

ARSENIC

Adamite.—See zinc minerals.

Arsenic sulfides.—The arsenic sulfides realgar and orpiment were reported from the Zimapán district by Salazar Salinas (1923b).

Mimetite.—See lead minerals.

Olivenite.—See copper minerals.

Scorodite.—Dark liver-brown scorodite, the common oxidation product of arsenopyrite, is abundant at the Miguel Hidalgo mine in oxidized ore from the winze. It was also doubtfully identified in a thin section of ore from the Mercedes mine.

MINERALS OF OTHER METALS

Manganese.—The manganese oxides hausmannite (Fe_3O_4) and wad (earthy manganese oxides) are reported (Salazar Salinas, 1923b) from somewhere in the Zimapán district. No manganese minerals of any kind were recognized in this study.

Mercury.—Cinnabar is mentioned by Salazar Salinas (1923b), but was probably not found in the area covered by this report.

Molybdenum.—The molybdenum sulfide molybdenite is reported (Salazar Salinas, 1923b) and was doubtfully identified at the Concordia mine by Spurr in his unpublished report (1907). According to Salazar Salinas (1923b), it was found in Cretaceous limestones. Possibly the mineral was graphite, which is common in some of the limestones of both the Upper and Lower Cretaceous formations. The hydrous ferric molybdate molybdite is reported (Salazar Salinas, 1923b). For wulfenite, see lead minerals.

Tungsten.—The calcium tungstate scheelite is present in extremely small quantities in the contact zone of the Concordia mine, where it occurs in tiny square prisms and is visible only in fluorescent light.

Vanadium.—For vanadinite, see lead minerals.

GANGUE MINERALS

Many of the gangue minerals are described in the section on metamorphism, and for these minerals only a brief recapitulation will be given here.

Apatite.—Apatite was seen only in a thin section of ore from the Chiquihuites mine, where it occurs in tiny veinlets.

Barite.—Barite was identified by Spurr (1907, unpublished report) from the vein of the Pamplona mine, which is now inaccessible.

Calcite.—Calcite is the most abundant gangue mineral in the district and has been seen in nearly every deposit of sulfide ore. It is common in the limestone replacement deposits but is much more conspicuous in the vein deposits. Calcite ranges in color from white through cream and smoky gray to brown. All the carbonate checked proved, with two exceptions, to be essentially pure calcium carbonate with index of refraction $\omega=1.660$ or slightly less. It is usually fine grained, but in the Santa Gorgonia mine cleavage faces 5 cm across are common. Calcite occurs both as unreplaced residual material and in late-formed veinlets with quartz and epidote.

Chlorite.—In this report no effort has been made to distinguish between the several varieties of chlorite. The mineral is uncommon in the ore deposits. It occurs as an alteration product of garnet in the Las Estacas mine, and in perfect pseudomorphs after garnet in the Miguel Hidalgo mine. In both cases the alteration was apparently contemporaneous with introduction of sulfides into tactite. Chlorite is a minor gangue mineral in the sulfide ore bodies of the Chiquihuites and San Damián deposits.

Danburite.—The calcium borosilicate danburite was recognized by Lindgren (1933) in tactite of the La Sirena deposit northwest of the Carrizal mining area. This deposit was not studied during our survey.

Diopside.—Minerals of the diopside-hedenbergite group are very common in the pyrometasomatic deposits. They range in composition from essentially pure calcium-magnesium metasilicate (diopside) to a mineral containing about 80 percent of the hedenbergite molecule. Diopside from the San Rafael workings of the Los Balcones mine contains probably about 15 percent of the acmite molecule. Diopside is commonly the earliest formed silicate of the metallized tactites.

Dolomite.—Small cream-colored plates of dolomite were seen perched on galena and calcite in a vug in the sulfide ore body at the south end of the Los Balcones adit. The refractive index ω of 1.685 corresponds to a dolomite with a small proportion of the ferrodolomite molecule. White dolomite with refractive index $\omega=1.707$ is a minor gangue mineral in the sulfide ore of the El Barreno adit of the Lomo de Toro mine. No dolomite was recognized elsewhere.

Epidote.—Epidote is a minor gangue mineral in the pyrometasomatic deposits. It occurs generally in late-formed veinlets with carbonate, but is probably contemporaneous with diopside in the tactite of the Las Estacas mine. Epidote is usually the strongly pleochroic iron-rich variety pistacite.

Fluorite.—Fluorite is a widespread gangue mineral in the sulfide deposits of the El Monte mining area and is also prominent in the Santa Clara mine and in the San Rafael chimney of the Los Balcones mine. It is commonly colorless, but purple fluorite was seen at the Chiquihuites mine and at a prospect near the bend in El Cajón, and light-green fluorite is conspicuous in the Santa Clara sulfide ore. A very beautiful malachite-green fluorite was seen on the dump of a caved prospect south of Cerro de La Nopalera. The color is due to the presence of very thin layers of malachite along cleavage planes. Fluorite is a typical gangue mineral of the pyrometasomatic deposits and is intimately associated with sulfides; it seems to be in part formed earlier than, and in part contemporaneously with, sulfides.

Garnet.—Brown to green garnet is an abundant gangue mineral in the pyrometasomatic deposits of both the Carrizal and El Monte mining areas. It is an andradite-rich variety with index of refraction much higher than 1.78. Both isotropic and birefringent garnet are found, sometimes in the same deposit. The birefringent garnet is usually complexly twinned. Garnet is commonly the second most abundant mineral to be formed in the tactites, following diopside. Most of the garnet is formed earlier than sulfides, but tactite from the Cinco de Mayo adit and from a nearby prospect contains garnet which is formed later than sulfides.

Gypsum.—Gypsum is a widespread but not abundant constituent of oxidized ores throughout the district. It is especially abundant in the San Damián stope of the Lomo de Toro mine and in the lower La Palmita working of the Los Balcones mine, where it occurs as white needles.

Jasper.—Jasper is a very minor gangue mineral. It was seen only at the El Chacuaco Viejo mine along the footwall of a thin calcite vein and at the El Espíritu mine, where it occurs interbedded with a little plumbojarosite in the lower manto.

Opal.—Dark-brown to gray opal is abundant at the Amistad no. 3 prospect north of the Carrizal mining area, where it is peppered with cubic pyrite molds. Opal also fills vugs in ore from the Preciosa Sangre vein. It is an uncommon gangue mineral.

Orthoclase.—Orthoclase is a minor gangue mineral in the Chiquihuites and El Camino deposits in the El

Monte mining area. In the Chiquihuites mine it is associated with fluorite and is formed earlier than sulfides. At the El Camino deposit it is formed late and replaces sulfides.

Quartz.—Quartz occurs both as the principal gangue mineral in a few veins (Preciosa Sangre, Mercedes) and as a minor gangue mineral in many of the limestone replacement deposits. It is fairly widespread but not abundant. Quartz usually occurs in late-formed veinlets with carbonate and epidote cutting sulfides or, as in the Cinco de Mayo and Las Estacas deposits, occurs interstitial to sulfides, but occasionally, as in the Chiquihuites, El Afloramiento, Miguel Hidalgo, and San Francisco mines, it is formed slightly earlier than or contemporaneous with sulfides. A few irregular prisms of quartz as large as 10 cm long by 2 cm thick were found lying in the Ave María stope of the Lomo de Toro mine. The source of these crystals is unknown.

Siderite.—A little reddish-brown sideritic carbonate occurs coating garnet in a small ore deposit above the Cinco de Mayo adit. Its index of refraction ω is much greater than 1.78.

Sphene.—Sphene was noted as a gangue mineral in a thin section of metallized limestone from the incline north of the main dike in the Chiquihuites mine and in weakly pyritized limestone in the San Guillermo adit. It is not abundant and was not noted elsewhere.

Sulfur.—Pale yellow-gray native sulfur occurs as a thin stringer along the footwall of a small dike that forms one wall of a small ore body at the lowest level of the Lomo de Toro mine.

Tremolite.—Tremolite is a minor gangue mineral in the Las Estacas and Miguel Hidalgo mines. It is formed earlier than sulfides at the Las Estacas deposit and later than sulfides at Miguel Hidalgo.

Vesuvianite.—Dark-brown vesuvianite is an abundant gangue mineral only at the Las Estacas mine. It is formed earlier than garnet among the silicates and also formed earlier than sulfides. In thin section it displays strong ultrablue and ultrabrown interference colors between crossed nicols. Vesuvianite was also noted as a minor gangue mineral in the San Cayetano mine. It seems to be lacking in the El Monte mining area, although it might be expected to occur somewhere in the tactites so well developed at El Monte.

Wollastonite.—Wollastonite is a prominent gangue mineral in the pyrometasomatic deposits of the Miguel Hidalgo mine in the El Monte mining area and was also noted at the San Guillermo mine in the Carrizal mining area. In each place wollastonite is a late-formed silicate but is formed earlier than sulfides. The index of refraction β of wollastonite from both mines is 1.630, corresponding to essentially pure calcium metasilicate. At the San Guillermo mine wollastonite occurs between limestone and sulfide as a selvage of beautiful prismatic crystals as long as 4 cm. Wollastonite of the Miguel Hidalgo mine forms a dense mat of tiny acicular prisms.

Zoisite.—Zoisite was doubtfully identified in the quartz-rich gangue of pyritized limestone from the San Francisco mine, where it occurs as minute needles. It was also seen in a thin section of the mineralized dike of the El Arenal mine.

DISTRIBUTION

The very large number of mines and prospects mapped in the Zimapán district has indicated a close spatial relationship between ore deposits and intrusive bodies of monzonite or quartz monzonite. Only at the San Francisco mine is there no nearby outcrop of monzonitic rock, but the abundance of dikes in the mine area indicates the presence of an igneous mass at depth. All the other known ore deposits are found within 2 kilometers of monzonitic masses and every important deposit lies less than 1 kilometer from a monzonite contact. A few deposits, such as the La Luz and Pamplona, have been found within the intrusive bodies themselves, but the overwhelming majority of the ore deposits occur in the enclosing stratified rocks. Ore deposits of the Carrizal mining area are clustered around a large quartz monzonite dike. The El Monte deposits are grouped around a lenticular dike of quartz monzonite. Metalliferous deposits of the Santa Gorgonia-San Pascual and La Luz-La Cruz mining areas lie within or northeast of the largest mass of monzonite in the district. A few small deposits have been found in this area as far as 2 kilometers from the monzonite contact, but all the major mines (San Pascual, Poder de Dios, San José Maravillas, and Santa Gorgonia) are less than 1 kilometer from the monzonite.

CLASSIFICATION

For convenience in discussion, the Zimapán ore deposits my be grouped into two general structural types; replacement deposits in limestone and shaly limestone, and vein deposits in shaly limestone, fanglomerate, and volcanic rocks or intrusive igneous rocks.

REPLACEMENT DEPOSITS IN LIMESTONE

The bulk of the metal production has come from replacement deposits in Lower Cretaceous limestone, in which are included all the ore bodies of the Carrizal and El Monte mining areas.

Deposits of pyrometasomatic, hypothermal, and mesothermal types are represented, although only mesothermal deposits have yielded large production. The difficulty in classifying a given deposit as pyrometasomatic or hypothermal is a formidable one, as a large group of minerals, including both silicates and sulfides, is common to both types of deposits. Moreover, at Zimapán the stage of exploitation of most of the mines is such that in only two or three places can metallized limestone be seen in direct contact with intrusive igneous rock. If demonstrable contact with an intrusive body is a necessary criterion for classifying a deposit as pyrometasomatic, then only two ore deposits seen at Zimapán by the writers can be so classified. On the other hand, if hypothermal deposits are considered to be localized by fissures and (or) have a veinlike or tabular form, then there are no demonstrable hypothermal deposits among the limestone replacement ore bodies. The highly restricted meaning of pyrometasomatic is not the generally accepted usage and such a restriction would seriously vitiate the usefulness of the term. Deposits have been considered as pyrometasomatic on the basis of mineralogy and geometry where there is no clear relation to an igneous contact and even where no intrusive rock is known to exist. The copper deposits of Ducktown, Tenn. are perhaps the best known examples in the United States. In this report, the classification of pyrometasomatism will include all the deposits of pyrometasomatic mineralogy. All such deposits at Zimapán have a very close spatial relationship to intrusive igneous rock.

In the Carrizal mining area the pyrometasomatic deposits grade, with increasing distance above and away from intrusive bodies, into lower temperature deposits which were classified by Lindgren (1933, p. 598–599) as mesothermal. Very rapid gradation from pyrometasomatic to mesothermal metallization is shown in the Chiquihuites mine in the El Monte mining area. Gradation from pyrometasomatic to mesothermal temperatures of deposition would seem to imply an interval of deposition at intermediate or hypothermal temperatures. However, at Zimapán the change from pyrometasomatic to mesothermal deposition takes place within a very narrow range, so that the hypothermal stage is not well defined and cannot be distinguished except on a purely arbitrary basis. It seems unnecessary to establish any hypothermal zone of deposition. At least, pyrometasomatic deposits grade imperceptibly into mesothermal deposits with distance from the igneous contacts, and the gradation is characterized by change from silicate to carbonate gangue and by decrease in amounts of arsenopyrite, pyrrhotite, and chalcopyrite among the metallic minerals. The inference is strong that pyrometasomatic metallization and hypothermal metallization in limestone replacement deposits are the same.

PYROMETASOMATIC DEPOSITS

Ore deposits of pyrometasomatic origin are abundant in both the Carrizal and El Monte mining areas, but they have not yielded large tonnages of ore. In the Carrizal area the Las Estacas, Santa Clara (in part), Cinco de Mayo, and San Guillermo deposits, and the La V and San Rafael deposits of the Los Balcones mine (in part) may be cited as typical examples. The El Monte area has the Concordia, Miguel Hidalgo (in part), Chiquihuites (in part), El Chacuaco Viejo, and El Camino deposits as a few examples. Mineralogy of the deposits has been described in the sections on metamorphism and will only be summarized here. Gangue minerals are dominantly silicates. Diopside-hedenbergite, garnet, vesuvianite, and wollastonite are common, and tremolite and epidote are abundant locally. Principal nonsilicate gangue minerals are carbonate (pure calcite in every checked occurrence), quartz, and fluorite. Sulfides include sphalerite, pyrite, galena, arsenopyrite, pyrrhotite, chalcopyrite, jamesonite (only in the El Monte area and the La Sirena deposit), and meneghinite. Tetrahedrite and molybdenite were tentatively identified by Spurr (1907, unpublished report) at the Concordia mine but were not seen during the present investigation. Sulfides are usually formed later than silicates, but at least one example of later formed tremolite is known. In general, however, the sequence of deposition established by various workers and summarized by Knopf (1933) is well displayed at Zimapán. A diagrammatic comparison of the paragenetic relationships at three localities is given in figure 20. The sequences given for localities 2 and 3 is synthesized, as all stages of mineral formation are not shown at any one place.

Pyrometasomatic sulfides are commonly fine to medium grained and show either poorly developed mineral

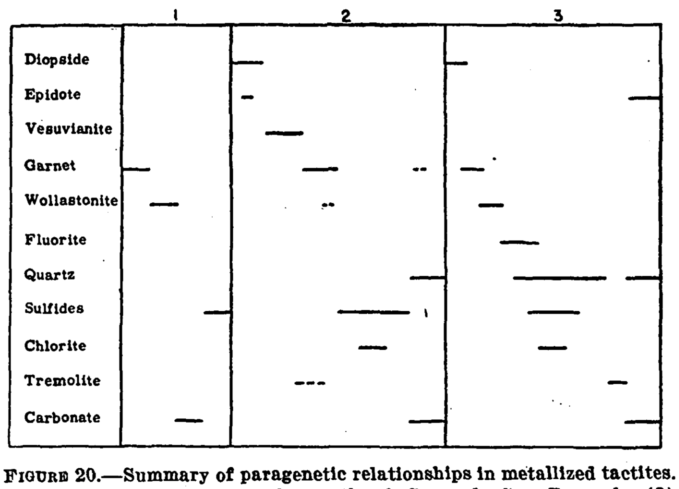

FIGURE 20.—Summary of paragenetic relationships in metallized tactites. (1) Upper Cretaceous rocks north of Cerro de San Pascual; (2) Carrizal mining area; (3) El Monte mining area.

banding or, more commonly, a heterogeneous mixture of minerals. In most deposits, sulfides are in contact with unaltered limestone. In the San Rafael Nuevo and San Guillermo workings, several ore bodies have a dike or dikelike tactite body as one wall and a thin layer of tactite lying between ore and limestone elsewhere.

MESOTHERMAL DEPOSITS

The mesothermal limestone replacement deposits are estimated to have yielded more than 90 percent of metal production at Zimapán. The small, but often rich, sulfide ore bodies of the Los Balcones mine and the large oxidized ore bodies of the Lomo de Toro and Las Animas mines are mesothermal. Other deposits classified as mesothermal include the Santa Clara (in part), El Vaquero, La Cuña, La Chiripa, and a host of smaller ore bodies in the Carrizal mining area, as well as the Chiquihuites (in part), Miguel Hidalgo (in part), San Vicente, El Arenal, Dolores, and a large number of unimportant ore bodies in the El Monte mining area. The mesothermal deposits are characterized by very slight or no alteration of wall rocks, calcite gangue or nearly total lack of gangue, and predominance of sphalerite, pyrite, and galena among the sulfide minerals. Silicates are lacking among gangue and wall-rock minerals, but fluorite is abundant locally as a gangue mineral and dolomite occurs in two places. Arsenopyrite, chalcopyrite, and pyrrhotite are scarce or lacking, and jamesonite is known only from the Tecomates deposit in the El Monte mining area. Deposits that are probably to be considered as intermediate between pyrometasomatic and mesothermal occur in the Los Balcones, El Camino, El Afloramiento, and Tecomates mines; they are characterized by abundance of pyrrhotite and arsenopyrite and lack of silicates other than orthoclase.

The sulfides of the mesothermal deposits are medium to coarse grained and usually show a layering parallel to the walls of the ore body. Beautiful mineral banding is showed by the massive sulfide ore of the La V, San Rafael Nuevo, and Tecomates deposits. Where replacement of limestone has been incomplete, sulfides are concentrated almost everywhere in irregular layers with intervening layers of sparsely disseminated sulfide in calcite gangue. Good examples of banded sulfide-calcite ore were seen in the La Palmita, Santa Clara, and San Vicente mines. Occasionally the sulfide ore is very coarse grained; sphalerite cleavage faces 6 cm across were seen in the ore body at the south end of the Los Balcones adit, and galena cleavage faces 3–4 cm across are common in the massive sulfides of the Miguel Hidalgo adit. Coarse crystalline galena with cleavage faces 1–2 cm across is abundant in the San Rafael Nuevo, La Palmita, and Los Balcones workings of the Los Balcones mine and in the Santa Clara mine. Galena crystals 0.5–1 cm across were noted in the Las Ventanas, Los Tres Alcangiles, and Lomo de Toro mines.

Calcite is usually the only gangue mineral. It is commonly fine to medium grained, but occasionally, as in the Santa Clara and La Palmita deposits, it appears in crystals 1 cm or more in size. Some vugs seen in the Santa Clara and Los Balcones deposits contained calcite crystals measuring more than 2 cm across a rhombohedral face. Fluorite is an abundant gangue mineral only in the San Rafael chimney of the Los Balcones mine and in the Santa Clara mine, where it occurs as a fine-grained colorless mineral and also in vugs in beautiful light-green crystals as much as 2 cm across. Dolomite was noted in only two places. In the ore body at the south end of the Los Balcones adit, dolomite coats crystals of galena and calcite in a vug. The dolomite occurs in tiny cream-colored thin tabular crystals with an index of refraction ω of about 1.685. In the sulfide manto of the El Barreno working of the Lomo de Toro mine, white dolomite with refractive index $\omega = 1.707$ is a minor gangue mineral.

VEIN DEPOSITS

The vein deposits of the Zimapán district are confined mainly to the Santa Gorgonia-San Pascual and La Luz-La Cruz mining areas, which have a combined area of about 12 square kilometers; two vein deposits are known at El Monte. The main area includes the largest mass of monzonite in the district. Only the vein deposits in the El Morro fanglomerate appear to have yielded any appreciable output of ore, but there are a large number of small mines and prospects in veins, dikes, and fractures in both the Upper Cretaceous rocks and the Las Espinas volcanic rocks. More than 130 mines and prospects were seen in the area; 72 prospects were in the El Morro fanglomerate, 38 in the Las Espinas volcanic rocks, and 20 in the older rocks. The most important vein mines in the El Morro fanglomerate have been the Santa Gorgonia, San Pascual, and San José Maravillas-Poder de Dios mines. The only mines yielding (1948) from veins in the Las Espinas volcanic rocks were the Preciosa Sangre and Santo Tomás, both of which were very small producers. The La Luz, Pamplona, Guanajuato, La Cruz, San Fernando, and a number of other small mines and prospects are located in veins, dikes, or fractures in monzonite or quartz monzonite, but only the La Luz and San Fernando mines were accessible in 1949 and only the La Luz appears to have yielded any appreciable amount of ore.

Two types of productive veins, characterized either by calcite or quartz gangue, occur in the district. Of the more than 130 prospects or mines examined, 29 were on calcite veins and 9 on quartz veins; the others, along fractures or dikes, apparently did not intersect ore.

VEINS WITH QUARTZ GANGUE

Quartz-sulfide veins are uncommon and have yielded only a very small amount of ore. The only examples seen were the Preciosa Sangre and Mercedes veins. Both are composed largely of granular quartz with an average grain size of 1–2 mm. Quartz of both veins shows undulatory extinction and concentric structures suggesting growth in open spaces. In addition to quartz, the Preciosa Sangre vein has considerable quantities of chalcedony in vugs and abundant tiny needles of pale-blue tourmaline. The only sulfides recognized were galena, pyrite, and arsenopyrite. Galena occurs in veinlets and small irregular pods replacing quartz in the Preciosa Sangre vein, and pyrite and galena are disseminated in the quartz of the Mercedes vein.

A few apparently barren quartz veins on the ridge leading from the Río Tolimán to Cerro del Arcabuz, in the area southeast of the Santa Gorgonia mine, and to the east of the San Pablo mine have been explored superficially. These veins range from 3 to 15 cm in width and are composed of vuggy quartz stained by iron oxide. All the quartz veins were formed at shallow depth (p. 66) in the epithermal zone.

VEINS WITH CALCITE GANGUE

Calcite-sulfide veins are very abundant in the Santa Gorgonia-San Pascual mining area, but only a few have contributed much to ore production. Most of the mines on calcite veins are now inaccessible; the only mines we were able to enter were the Santa Gorgonia, San José Maravillas-Poder de Dios, Santo Tomás, San Pablo, San Pascual, Buenavista, and Guadalupe mines. The last three were closed and the others were being worked on a very small scale by buscones (buscones or gambusinos are miners who work, usually part time, on contract or for their own account, either in mines that are not suitable for large-scale operations or in parts of a mine that have been abandoned by a mine operator). The Buenavista and Santo Tomás mines are in the Las Espinas volcanic rocks; the others are in the El Morro fanglomerate. Accessible portions of the San Pascual, Santo Tomás, and Buenavista mines offer practically no information on the nature of the vein or the ore extracted, and only very limited data are available in the other mines. Most of the observations on which the following description is based were made in the Santa Gorgonia mine and in a small part of the San José Maravillas mine.

The principal veins are localized along faults of small displacement and are characterized by clean walls, highly erratic metal content, and very simple mineral composition. Although the vein structure may be very strong over considerable distances (the Santa Gorgonia vein has been mined for more than 470 meters along the strike and as much as 220 meters in depth), the veins themselves are erratic in both thickness and content. The Santa Gorgonia vein structure, for instance, consists of two nearly vertical parallel fractures from 10 to 150 cm apart; the vein itself is usually confined to a narrow zone 1–80 cm wide along either the hanging wall or the footwall of the main vein structure, but often two or three veins are present, and rarely the vein fills the entire structure. The average vein thickness in the pillars now left in the mine is perhaps 10 cm; presumably it was greater in the stopes. In nearly every place in the mine, country rock (El Morro fanglomerate) composes more than half the fracture zone and in places fills the zone to the total exclusion of vein material. The fanglomerate in many places is slightly brecciated and cemented with vein calcite.

The vein structures of the San José Maravillas-Poder de Dios and San Pascual mines are similar except that in a number of places only one wall is a strong fracture surface.

The mineral composition of the veins is simple. Galena and sphalerite are the only abundant sulfides; pyrite is scarce, and chalcopyrite and arsenopyrite are very rare. Tetrahedrite, pyrargyrite, and arsenopyrite have been reported from the Santa Gorgonia mine, and arsenopyrite from the San Pascual mine, but none of these minerals was found in those mines during the present study. Calcite is the only gangue mineral except for a little white quartz in vugs in the San José Maravillas mine. Smoky-gray to cream-colored or white calcite forms the gangue in the Santa Gorgonia, Buenavista, and San Pablo mines. In many of the smaller mines and prospects calcite is yellow to brown. Calcite cleavage faces 5 cm across are common in the Santa Gorgonia mine, but the mineral is usually fine grained. All the calcite checked by the oil-immersion method proved, regardless of color, to be pure calcium carbonate with index of refraction ω about 1.660. Galena is commonly the fine-grained variety that looks like steel, which in the Santa Gorgonia mine is said to assay 2.5–4 kilograms of silver per ton. Rarely, as in the deeper parts of the San José Maravillas mine, galena may form crystals as much as 1 cm across. Sphalerite and galena seem to have been deposited simultaneously; pyrite is usually formed late.

The veins show characteristics of both epithermal and mesothermal deposition. Although the banded ores and crustiform or colloidal structures common to epithermal deposits are not abundant, evidence of deposition in open spaces is not entirely lacking. Banded calcite veins are common; good examples were seen near the San Pablo mine and to the south of Cerro de El Morro. Moreover, the depth of formation of the veins must have been very shallow, probably less than 500 meters. In the deeper parts of the San José Maravillas mine the vein shows prominent replacement features. El Morro fanglomerate lying between parallel fractures is replaced in a highly selective manner by galena and sphalerite, which occasionally form perfect pseudomorphs after fragments of limestone in the fanglomerate. Inasmuch as the upper levels of the mine are either inaccessible or have no visible vein material, it is not known whether the replacement ore found at depth was also the type of ore mined at higher levels. It seems possible, however, that the vein of the upper levels was a calcite-sulfide mixture similar to that of Santa Gorgonia. The San José Maravillas mine, although at nearly the same altitude as the Santa Gorgonia mine, is much nearer the monzonite considered to be the source of the mineralizing fluids and might therefore be expected to show features of deposition at higher temperatures. At any rate, the occurrence in this mine of a replacement vein instead of a fissure vein at depth indicates that open spaces were not available for ore deposition and that depositional environment was more closely related to the mesothermal than the epithermal zone.

VEINS IN MONZONITE OR QUARTZ MONZONITE

The only true vein ore deposit in intrusive igneous rock seen by the writers was in the La Luz mine, where a strong, nearly northward-trending vein has been mined above the water level. Unfortunately, the only workings in which the nature of the vein filling might have been seen were flooded. Copper was the principal valuable metal in the vein; lead and silver were also present. Bornite was the most abundant valuable sulfide, and native copper in thin sheets was common. The country rock, quartz monzonite with pendants or inclusions of Upper Cretaceous rocks, is heavily pyritized and carries a little tourmaline.

STRUCTURAL FEATURES OF ORE BODIES

REPLACEMENT DEPOSITS IN LIMESTONE

Various workers in describing the ordinarily very irregular limestone replacement ore bodies of Mexico have used such terms as "manto," "chimney," "pipe," "flat," "run," "blanket," and other terms, in referring to the shape or position of an ore body, but there seems to be no general agreement as to the meaning of several of the terms. Chimney would seem to carry a clear implication of vertical or nearly vertical position, but Prescott (1926, p. 247), for instance, states as part of his fifth basic principle underlying the occurrences of limestone replacement deposits in Mexico:

> The orebodies are essentially chimneys or pipes, whether standing vertically and obviously fulfilling the accepted idea of a chimney or pipe, whether inclined at any angle, or even lying horizontal.

Manto is a Spanish mining term ordinarily considered to be nearly equivalent to blanket and, strictly speaking, would imply a flat lying or nearly flat lying ore body with its two horizontal dimensions much greater than its vertical thickness, but Prescott (1926, p. 248) mentions mantos at Santa Eulalia, Chihuahua, "30 or 40 feet in width by the same in depth," and "inclined mantos" are mentioned or figured by most writers on the subject. Manto in its most general usage carries no implication of the relation of the ore body to the bedding of the enclosing rocks, but in fact, practically all mantos known to us are confined rather closely to one bed or series of beds; they are, in other words, bedding replacement ore deposits. The distinction between manto and chimney in an area of flat-lying rocks in not difficult because the mantos, being bedding replacement deposits, are practically horizontal. However, at Zimapán and many other camps in Mexico, such as Pinal de Amoles, Querétaro, Ojuela, Durango, and Avalos, Zacatecas, limestone is highly folded and bedding replacement ore bodies may have a very steep dip or even be vertical. Prescott calls the vertical bedded deposits at Avalos chimneys, but no figure is given showing the shape of the ore bodies in the plane of the bedding.

The various terms mentioned above are defined for use in this report as follows: manto will refer to a tabular ore body with two dimensions much greater than the third, which dips at any angle and lies approximately parallel to the bedding of the enclosing limestone; pipe will refer to ore bodies with one dimension much greater than the other two and with a plunge of less than 45°; and chimney will refer to ore bodies with a roughly equidimensional horizontal cross section and a dip or plunge of more than 45°. Tabular ore bodies that cut across the bedding will also be referred to as chimneys. Most of the chimneys at Zimapán are essentially vertical and have the shape of vertical pipes. Although these definitions are somewhat arbitrary, they are in general accordance with well-established usage in Mexico.

CHIMNEYS

Chimneys have been the principal source of ore in the Carrizal mining area and have yielded an appreciable production in the El Monte mining area. Most of the great ore bodies of the Lomo de Toro mine (El Claro, La Piedad, San Pedro, Santa Luisa, and San Damián) and all the important deposits of the Los Balcones mine have been nearly vertical chimneys. Chimneys at both the Santa Clara and La Paz mines have produced a substantial but unknown tonnage. The largest chimney found so far was the El Claro ore body of the Lomo de Toro mine, which measured 65 meters in length by 35 meters in width and was worked from the outcrop to a depth of 105 meters.

Structural controls of chimneys include dikes, fractures, beds favorable to replacement, and to a probably lesser extent, disturbed beds. Chimneys of the Lomo de Toro mine are controlled in large part by a combination of beds standing at high angles and a series of north-northwestward-trending steep fractures roughly parallel to the strike of the beds. The influence of contorted bedding is difficult to evaluate, but the highly folded and fractured beds seen in the walls of the El Claro, Santa Luisa, and San Pedro stopes probably aided in localization of ore by providing easy channels of circulation for the ore-forming fluids.

Premineralization dikes are an important control of the chimney in the Santa Luisa ore body of the Lomo de Toro mine and in all the chimneys of the Los Balcones mine. The Santa Luisa chimney is bounded on the northeast side by a nearly vertical dike; ore is confined, at least in the immediate vicinity of the stope, to the southwest side of the dike, with the exception of a thin vein of galena within the dike itself and a small pocket of smithsonite on the northeast wall of the dike. The Santa Luisa chimney, then, was localized by a combination of favorable beds, strong north-northwestward-trending fractures, a dike that truncates both bedding and fractures and, probably, to some extent, by the folded and fractured state of the limestone. The San Damián chimney of the Lomo de Toro mine is controlled by a thin vertical dike that trends about east-northeastward. At the San Damián level the chimney is about 35 meters long by 1–5 meters wide. There are no recognizable controlling fractures in the limestone, which strikes at nearly right angles to the dike. A small chimney near the portal of the La Mora working of the Lomo de Toro mine was formed at the acute intersection of a dike and a fault, which dip in opposite directions.

Structural controls of the Los Balcones chimneys are, with one exception, less well defined. The La Palmita chimney, a triangular ore body measuring about 25 by 20 meters at its base, was deposited under the gable formed by the acute intersection of two dikes, one vertical and the other dipping 50–60°. The La V–Los Balcones chimney, an elongate ore body more than 80 meters long and averaging 4–5 meters wide, was formed along the footwall of a steep-dipping, nearly eastward-trending dike. That this dike was a factor in the control is obvious, but controls within the limestone were not recognized. The north-northwestward-trending ore body of the Los Balcones adit is a bedding replacement deposit dipping steeply westward. It terminates to the south against the dike that controls the La V–Los Balcones chimney and is continuous with that chimney. The entire ore body is an example of a chimney that passes upward into a bedding replacement deposit where beds favorable to replacement were met by the ascending mineralizing fluids. The San Rafael chimney is an irregular ore body ranging in cross-sectional area from about 50 square meters on the San Rafael Nuevo level to more than 150 square meters at the San Rafael Viejo level above. It is controlled in part by a nearly vertical east-trending dike which forms its south wall, but as with the La V–Los Balcones chimney, controls within the limestone are not apparent. A chimney at the south end of the San Rafael Nuevo adit was deposited in the footwall of a thin eastward-trending dike dipping 75° S.

Premineralization faults have played a very minor role as structural controls of chimneys. The only examples seen were the two small chimneys of the Santa Clara mine, each of which occurs in the footwall of a steep-dipping premineralization fault.

The chimney of the La Paz mine, worked to a depth of more than 90 meters, is inaccessible for most of its depth, but no obvious controls, such as intersecting fractures or dikes, were seen in its upper part.

Structural controls of the small chimneys in the El Monte mining area are, for the most part, rather obscure. The highly irregular chimneys at the north end of the Chiquihuites mine seem to be controlled by intersections of steeply dipping favorable beds with a series of east-northeastward-trending fractures. Similar controls are more clearly displayed in the main northwest drift of the Miguel Hidalgo adit, where several small tactite-sulfide ore bodies confined to a narrow stratigraphic zone are seen to end abruptly against very weak northeastward-trending fractures. The veinlike chimney of the El Arenal adit lies along the footwall of a steep-dipping highly altered dike. An unusual structure is shown by the Peñalejos chimney, which is a tabular ore body roughly parallel to the axial plane of an overturned anticline striking northwestward, and which lies in the footwall of a northeastward-trending strongly sheeted zone dipping steeply southeastward. The chimney is thus localized by a tight fold and a fracture zone which intersect at nearly right angles.

MANTOS

Manto deposits at Zimapán are closely controlled everywhere by a single bed or series of beds. Local irregular transections of bedding are common, but most of the mantos are very regular in thickness and often follow faithfully the minor plications in the limestone. The nature of the controls exerted by replaceable beds is not known, but is seems likely to have been textural rather than chemical. No bedded dolomite was found in the district, either associated with the ore deposits or elsewhere. Manto ore bodies that have formed by replacement of dolomitic limestone are common in Mexico. Prescott (1926) cites the commonly dolomitized "Lower Fossil horizon" as being "remarkably prolific and favorable," but later states that considerable investigation has resulted

in the rejection of any idea [on localization of ore bodies] founded on chemical differences between this bed and the others of the [Lower Crĕtaceous] column * * *.

He also mentions the San Carlos manto ore bodies at the Ojuela mine at Mapimí, Durango, as having replaced dolomitic limestone in part. Fletcher (1929, p. 511) cites Sierra Mojada, Coahuila, as another example; manto beds there have a MgO content of from 13 to 20 percent. Hayward and Triplett (1931) give as further examples of lead-zinc deposits in the dolomitic limestones of northern Mexico the deposits of Minas Viejas, Nuevo León; Higueras, Coahuila; and El Diente, Nuevo León. Unless chemical control not detectable by simple field tests has been operative at Zimapán, one must conclude that textural differences have permitted certain beds to be more easily replaced than others. Limestone of unreplaced blocks in several ore bodies was noticeably coarser grained than elsewhere. Although the coarseness of grain might conceivably be due to recrystallization during mineralization, the complete lack of recrystallization in the limestone walls of many sulfide ore bodies suggests that it is probably an original feature and is perhaps the principal control over the highly selective replacement of the mineralized beds. Fletcher (1929, p. 511–512) believes that even replacement of dolomitic beds is controlled more by texture than by composition—that the textural differences that permitted dolomitization of certain beds also permitted mineralization by replacement.

There are very many manto deposits, but only a few have been large producers. The Ave María and San Vicente mantos of the Lomo de Toro mine were the largest in the district; the Ave María stope is 75 meters long, at least 40 meters wide, and has a thickness of perhaps 15 meters. Other smaller manto deposits at Lomo de Toro include the La Victoria, Pepito, La Bota, San Antonio, El Barreno, and La Mora (in part). The La Victoria has yielded a considerable tonnage; Pepito is a smaller but higher grade deposit. Mantos have not yielded large amounts of ore in the Los Balcones mine. The thin mantos associated with the La Palmita chimney, the lower La Palmita-Los Balcones manto, and the San Miguel de Los Palacios mantos are the only ones of importance. Other mantos in the Carrizal mining area are those of the Santa Clara, La Paz, and Las Animas mines. At the Las Animas mine, five separate mantos, some connected by small chimneys, occur at different levels in an area approximately 150 meters long by 70 meters wide. Thin but rather extensive mantos were exploited in both the Rosario and Espíritu mines, 4 kilometers north of the Carrizal mining area. At each mine there were two parallel mantos 10–15 meters apart, connected by small chimneys.

In the El Monte mining area, mantos are uncommon and have not been highly productive. The largest was the Chiquihuites manto, an ore body that replaced a thin bed in the trough and along both limbs of a V-shaped syncline. Apparently, mineralizing fluids rose along the fractured beds at the trough of the syncline and spread laterally up both limbs along a bed favorable to replacement. The Tecomates and San Vicente mantos are very small; only the Tecomates has produced any appreciable amount of ore.

PIPE

The only pipe in the district, except for many small offshoots from chimney and manto ore bodies, is in the San Rafael Nuevo adit of the Los Balcones mine. It is nearly circular, averages 3–4 meters in diameter, and plunges about 40° NW. The pipe has been mined both above and below the San Rafael Nuevo level for more than 45 meters along its axis. Ore minerals are banded parallel to the walls; 1–5 cm of white coarsely crystalline calcite at the walls is succeeded inward by 2–3 cm of galena, 2–3 cm of sphalerite, and finally by the core of the pipe, which is essentially sphalerite and pyrite. No structures of any kind that might have been controlling factors in the localization of the pipe were recognized. The strike of the pipe, about northwest, is roughly that of the bedding in the mine and of many fractures, but the formation of such a pipe rather than a chimney is puzzling.

RELATIONS OF CHIMNEYS AND MANTOS

Mantos are found above, below, or as offshoots from chimneys in a number of mines. In the Lomo de Toro mine, the San Antonio and La Bota mantos are upward continuations of the San Damián chimney, which is in turn the upward continuation of a thin manto. The Ave María manto is an upward continuation of what is probably a chimney in the inaccessible Los Bronces workings. The La Victoria manto is a long tonguelike upward extension of a small chimney connected below with the San Vicente manto. Finally, the manto of the La Mora working is connected directly with a chimney in the same working.

In the Los Balcones mine, the thin but extensive manto of the upper La Palmita working is a gently dipping offshoot of the great La Palmita chimney. The chimney passes downward into a manto that probably connects through another chimney with the manto at the south end of the Los Balcones adit. The San Miguel de Los Palacios manto is very likely connected genetically with the chimney at the southeast end of the San Rafael Nuevo adit below, although slight exploration has failed to find the connection. Other examples of mantos lying above and connected with chimneys are found in the Santa Clara, Las Animas, and La Paz mines. The last is perhaps the finest example in the district; there a well-defined vertical chimney averaging perhaps 8 meters in diameter terminates upward in a nearly horizontal manto about 60 meters long and 35 meters wide.

In the El Monte mining area, the poorly defined chimneys at the north end of the Chiquihuites mine pass upward into a thin manto.

The interconnecting relationships between mantos and chimneys is mentioned in nearly every publication dealing with Mexican limestone replacement deposits and will not be discussed at length here. Fletcher (1929, pp. 510, 512–513) has proposed a general sequence in limestone replacement deposits: his idealized sequence begins with a complex sulfide ore in fractures in the igneous source rock, succeeded upward by a contact phase (tactite-sulfide), a chimney or vein phase, and a manto phase. At Zimapán the igneous phase has not been found as yet, and the remainder of the sequence is not displayed in its entirety in any one mine, but the transitions between the contact and chimney phases and between the chimney and manto phases can be seen in a number of places. The southwestern workings of the Los Balcones mine show all three phases: contact in the La V working (tactite-sulfide), chimney in the Los Balcones working above, and manto in the Los Balcones and La Palmita workings, but only the contact-chimney and chimney-manto connections are known to date. It seems quite likely, however, that future development will reveal the entire sequence. The upward sequence is not invariable. A chimney may connect two mantos (as in the Las Animas mine, the San Damián-San Antonio-La Bota workings of the Lomo de Toro mine, and the El Rosario and El Espíritu mines north of the Carrizal mining area), or less commonly a manto may lead both upward and downward into a chimney (as possibly between the La Palmita chimney and a chimney connecting with the Los Balcones manto below).

The contact and chimney phases can form under a variety of structural controls or apparently, in many cases, without any recognizable controls; the manto phase ordinarily can occur only where a bed favorable to replacement is met by the mineralizing fluid. Fletcher (1929, p. 509) proposes as a general formula:

> A lead-silver orebody in its manto and precedent phases always follows the course of least resistance from its igneous source to the surface.

Such a formula would imply that a manto phase might be lacking because mineralizing fluids rising along a chimney failed to find a favorable bed, and indeed in several districts (Fletcher cites three) the chimney or contact phase is the highest one found.

The geometry of the Zimapán deposits, then, is typical of the lead-zinc-silver limestone replacement deposits in Mexico. Structural controls are apparent in some places, are obscure in others, and seem to be lacking in others. Such a variety of structural features is characteristic of the Mexican deposits and has been summarized admirably by both Prescott and Fletcher. That these two leading students of Mexican ore deposits, differ in the importance they assign to the several structural controls is easily understandable after study of the Zimapán district. There the control by fractures emphasized by Fletcher, and the apparent lack of any control that could be designated as "structural" described by Prescott from many localities, are both in evidence.

VEIN DEPOSITS

Most of the structural features of the vein deposits have already been described. A great many veins have been explored in the Santa Gorgonia-San Pascual and La Luz-La Cruz mining areas. An early visitor (Falletite, 1868, unpublished report) to the area wrote (freely translated):

> There, more than 400 veins crop out, cutting up the terrain in every direction, forming an incomprehensible fabric of veins crossing at every angle and, like serpentine cast to the wind, like furrows and serpents, come and go on every side.

Actually, only a small proportion of the so-called veins are really veins. Innumerable prospect pits, shafts, and adits have been driven on dikes and fractures. The reddish latite(?) dikes have been very attractive, although apparently not remunerative, to prospectors. In places veins have a dike as one wall (Guadalupe, Buenavista), but no such veins have proved to be very productive. Outcrops of veins are not prominent, as the dominant calcite gangue is about as resistant to erosion as the country rock, and the lack of abundant sulfides has inhibited formation of a prominent gossan.

The veins, dikes, and fractures in the Santa Gorgonia area have strikes trending northwestward to north-northwestward and dips ranging from 60° to about 90°. In the vicinity of the San Pascual and San José Maravillas-Poder de Dios mines, veins strike from northward to west-northwestward. The general northwesterly trend of the veins in both areas is roughly parallel to the regional strike of all the layered rocks of the district, to the well-developed fracture system in the El Morro fanglomerate, and to a majority of the dikes. A few of the veins are along normal faults (San Pablo and several unnamed prospects), and others are along reverse faults (Santa Gorgonia, Guadalupe), but direction of movement along most of the mineralized faults could not be determined because of similarity of rocks on both sides of the faults. The faults are, without exception, of small displacement.

A casual inspection of the longitudinal projections of stopes in the Santa Gorgonia-Providencia mine (pl. 3) and in the San Gerónimo workings of the Poder de Dios mine (fig. 21) shows that well-defined ore shoots within the veins are virtually nonexistent. Although both the projections are compilations from old maps, and probably do not show all the stopes, the lack of ore shoots is nonetheless very marked. Metallization within the veins was obviously very erratic and followed no clearly defined trends. The main ore body of the San Pascual mine was at the intersection of the main northward-trending San Pascual vein structure and a nearly eastward-trending vein. The largest ore shoot, according to Cepeda's unpublished report (1928), was 160 meters long, 60 meters high, and 3.5–10 meters wide; the stope has been called El Salón Grande de los Carbonatos (the large room of the carbonates) and is shown in vertical projection in figure 22. No information is available on the size or shape of stopes and ore shoots in the other vein mines, for most of them are completely inaccessible, and no maps of the workings are known to exist.

AGE OF MINERALIZATION

Mineralization in every area took place after the major deformation of the Cretaceous rocks, as ore bodies show no evidence of deformation. Many ore bodies lie along steep-dipping premineralization dikes that cut directly across highly folded beds and are entirely undeformed. In the Santa Gorgonia-San Pascual mining area, mineralization occurred after both the El Morro fanglomerate and the Las Espinas volcanic rocks were formed, for veins are found in each formation. In several places (Santa Gorgonia, Guadalupe) single veins cut both formations. There is no direct evidence that mineralization was contemporaneous or at least penecontemporaneous in all the mining areas, but the close spatial and, we believe, genetic relationship of ore deposits in every area to bodies of similar intrusive igneous rock makes the assumption of practically contemporaneous mineralization the most tenable one. Inasmuch as the age of the El Morro fanglomerate is probably late Eocene or early Oligocene and that of the Las Espinas volcanics is perhaps late Oligocene and Miocene, the time of mineralization is most probably late Miocene or possibly early Pliocene.

DEPTH OF FORMATION OF ORE DEPOSITS

The depth of formation of the Zimapán ore deposits is not known exactly because of the prolonged, or at least severe, erosion subsequent to their formation. However, some ranges of depth of deposition can be given that are believed correct.

The thickness of volcanic rocks removed by erosion is not known for any part of the district, but the impressive postvolcanic erosional features suggest that it may have been several hundred meters. An assumption of 300 meters of postvolcanic lowering of the original volcanic surface appears to be a generous one; perhaps a smaller thickness of rocks has been removed, but almost certainly the figure is a maximum. In the Santa Gorgonia-San Pascual mining area a maximum of approximately 250 meters of Las Espinas volcanic rocks overlies the El Morro fanglomerate. Vein deposits are known to occur within a few meters of the highest volcanic rocks in the area (Cerro de Las Espinas). The Mercedes quartz-galena vein in the Las Espinas volcanic rocks crops out about 90 meters below the summit of Cerro de Las Espinas, and a few small unnamed veins have been explored at higher levels. Vein deposits, then, were formed within 400 meters of the original surface. The Santa Gorgonia vein crops out 220 meters below Cerro de Las Espinas, or 520 meters below the original surface; the San Pascual and San José Maravillas adits lie 230 meters below Cerro de Las Espinas, or 530 meters below the old surface. In the Santa Gorgonia mine the deepest workings are 220 meters below the present surface, or 740 meters below the original premineralization surface. The known range of depth of deposition of veins, then, on the assumption of 300 meters of postvolcanic and postmineralization erosion, is from about 400 to 740 meters below the surface; the actual range may be considerably greater, as the Santa Gorgonia vein is still strong at the lowest explored level.

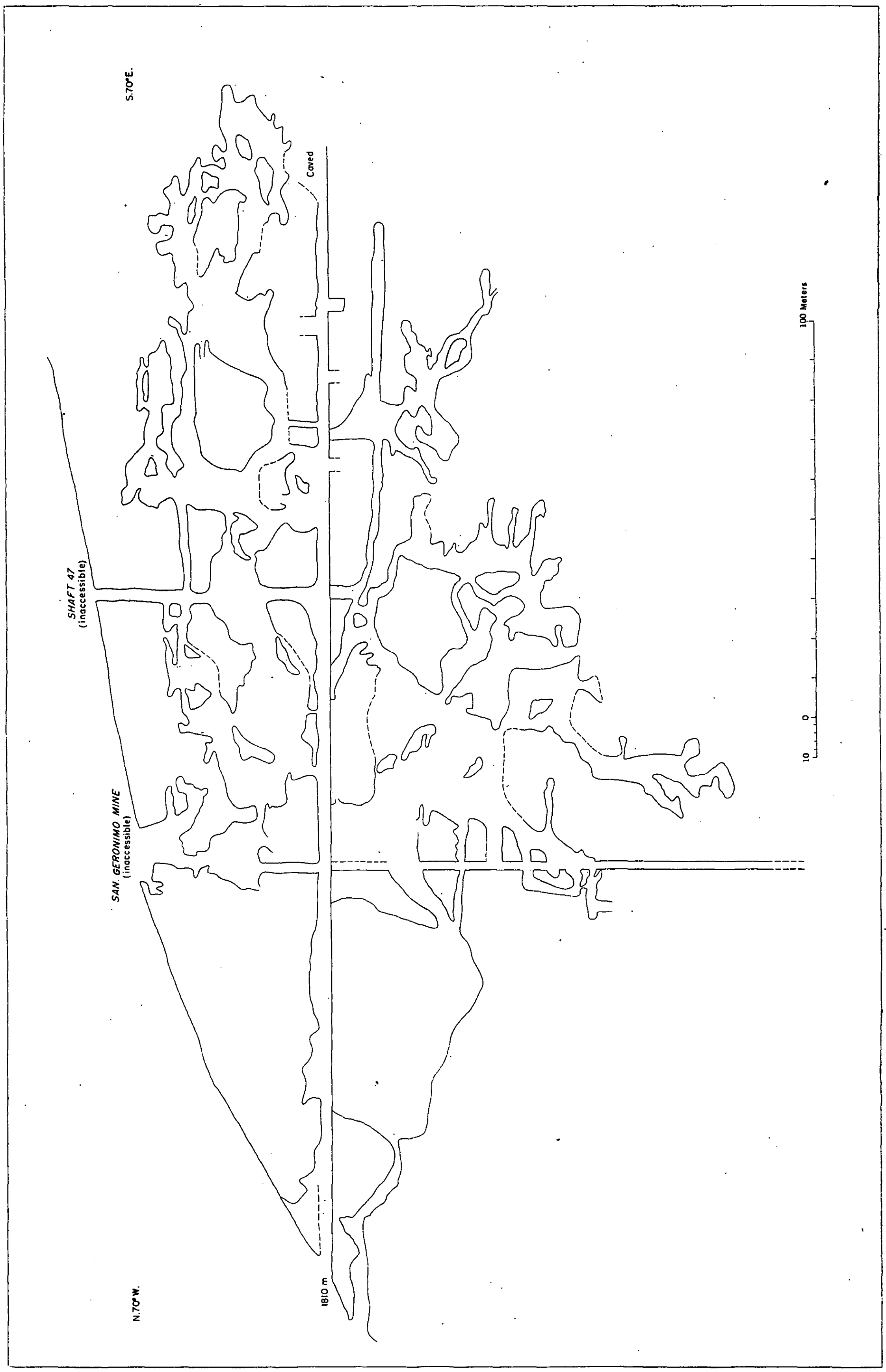

FIGURE 21.—Longitudinal projection of stopes, San Gerónimo workings of the Poder de Dios mine.

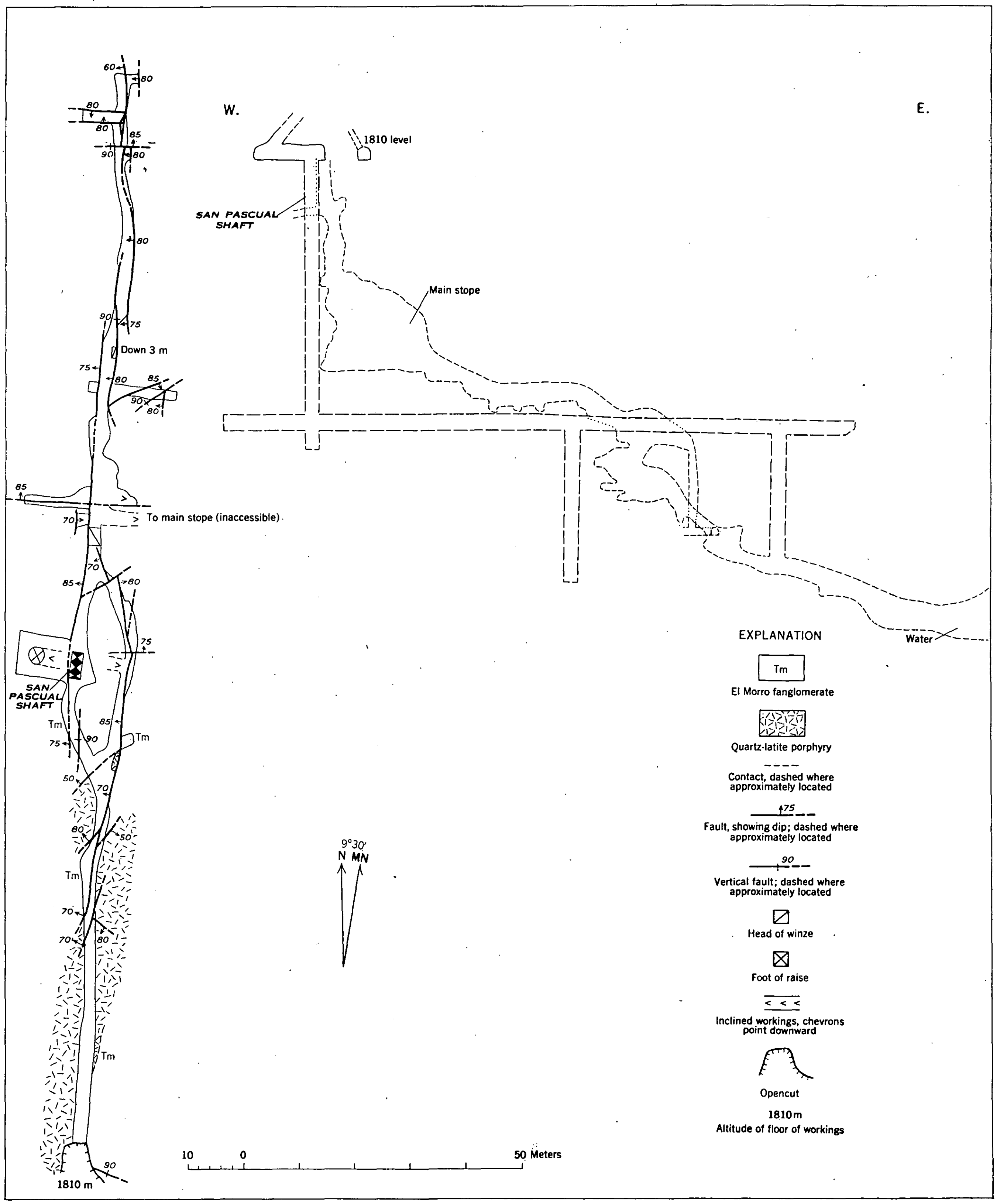

FIGURE 22.—Map of the main level and projection of shaft and main stope, San Pascual mine.

Depth of deposition of the limestone replacement deposits in the Carrizal and El Monte mining areas is more difficult to estimate. There are no remnants of either El Morro fanglomerate (maximum thickness about 400 meters) or Las Espinas volcanic rocks (maximum thickness more than 375 meters) in either mining area, but, as explained in the section on physiography, it seems likely that either the fanglomerate or the volcanic rocks, or perhaps both, once overlay at least the Carrizal mining area. The total vertical range of ore deposits in the Carrizal mining area, from the Las Estacas mine at the bottom, to the Todos Santos mine at the top, is about 620 meters; about 200 meters of limestone lies above the Todos Santos mine. Assuming postore erosion of the maximum thickness of El Morro fanglomerate (400 meters) and Las Espinas volcanic rocks (almost certainly less than 700 meters), the depth of deposition ranges from about 1,300 to 1,900 meters below the preore surface. It seems highly unlikely, however, that the maximum thickness of both El Morro fanglomerate and Las Espinas volcanic rocks was developed in the area; moreover, the assumption of 300 meters of postore erosion in the Santa Gorgonia-San Pascual area, although thought to be generous, would change to an assumption of about 1,100 meters in a nearby area. Although the Carrizal area has probably undergone more severe erosion than the Santa Gorgonia-San Pascual area because of its uplift along the Malacate fault, the difference can hardly be so large; an assumption of perhaps 500 meters of postore erosion is probably a generous one. The depth of formation of the deposits, then, would be from 700 to 1,300 meters below the original preore surface.

With almost any reasonable assumption as to postmineralization erosion, it is evident that depth of formation of even the deepest deposits as yet known anywhere in the Zimapán district was relatively shallow, and that considerable telescoping of the various temperature-pressure zones has taken place to allow formation of pyrometasomatic, hypothermal, mesothermal, and epithermal deposits within a vertical range of perhaps 700 meters.

OXIDIZED ORES

Until fairly recently, the existence of a mining industry at Zimapán has depended upon the thoroughly oxidized and easily smelted lead-silver ore bodies. As far as can be ascertained from the scanty literature, oxidized ores were the only ones utilized from the inception of mining in 1632 until late in the 19th century. Inasmuch as oxidized ores still contribute a large part of the production at Zimapán, a brief discussion of their mineralogy and occurrence seems in order.

All the great limestone replacement ore bodies exploited thus far in the Lomo de Toro mine (El Claro, La Piedad, Ave María, San Vicente, San Pedro, Santa Luisa), as well as several in the Los Balcones mine (La Palmita, San Miguel de Los Palacios, Los Balcones), were oxidized. Other large oxide ore bodies exploited in the past were Las Animas in the Carrizal mining area, and Dolores, Chiquihuites, and probably El Santísimo in the El Monte mining area. According to some old reports, oxidized ore was mined from a number of vein deposits; the largest ore body seems to have been that of the San Pascual mine. The Santa Gorgonia and Poder de Dios mines have also produced oxidized ore, but its importance in those mines is not known.

Depth of oxidation has little relation to topography. The Lomo de Toro ores have been oxidized to depths of more than 200 meters, yet in the adjacent Los Balcones mine sulfide ores occur within a few meters of the surface and outcrops of sulfide ore are common in both the Carrizal and El Monte mining areas. In the Miguel Hidalgo adit in the El Monte area, bodies of solid sulfide ore occur within a few meters of completely oxidized ore. No well-defined water table is present in the Carrizal area, as might be expected in an area of great relief and inpermeable rocks. Water is perched at various heights above the Río Tolimán, standing at about 1,450 meters, or 140 meters above the river in the Lomo de Toro mine and at other levels both higher and lower in the Los Balcones mine. Sulfide ore is found both above and below the present water level, and oxide stopes are dry. The highly erratic oxidation was obviously controlled by local conditions around each ore body, and few generalizations can be made safely. Bedding replacement ore bodies, both chimneys and mantos, are usually oxidized, at least at the higher levels of each area, whereas chimneys and pipes that sharply transect bedding are unoxidized, with the exception of the La Palmita chimney, which was, however, different from the rest of the Los Balcones chimneys in that it cropped out and was much larger. Evidently oxidation took place more readily where oxidizing solutions circulated along the bedding than where they had to cross the bedding.

The description of oxide mineralogy and stages of oxidation, to follow, is based largely on study of the Lomo de Toro mine, but oxidation in all the limestone replacement deposits has followed a similar course, with only minor differences.

The sulfide ore bodies throughout the Carrizal mining area are nearly alike in mineral content. Principal sulfides are pyrite, sphalerite, and galena, with minor pyrrhotite, arsenopyrite, and chalcopyrite. In the oxidized ores lead and silver are the only important valuable metals. Zinc has been nearly completely removed; three analyses of oxide ore from the Lomo de Toro mine gave 1.41, 1.5, and 0.4 percent zinc, respectively, and a sample from the Miguel Hidalgo adit at El Monte contained 2.6 percent zinc. The principal lead minerals in the oxidized ore are, in order of decreasing abundance, plumbojarosite, cerussite, and anglesite. Silver is probably present as argentojarosite, for a megascopically homogeneous specimen of plumbojarosite ore from the Miguel Hidalgo oxide ore body contained 1,695 grams of silver per ton. Plumbojarosite ($PbO \cdot 3Fe_2O_3 \cdot 4SO_3 \cdot 6H_20$) is by far the most abundant lead oxide mineral and is estimated to have contained more than 90 percent of the lead produced from oxidized ores. It was found in every deposit that has undergone any appreciable oxidation. Plumbojarosite ordinarily follows cerussite in the oxidation sequence of galena-anglesite-cerussite, although in one stope of the Lomo de Toro mine it appeared to have formed directly from anglesite. It was seen coating cerussite crystals in many places, and spongy pseudomorphs of plumbojarosite after cerussite were seen in the Miguel Hidalgo oxidized ore. The same oxidation sequence is shown on a large scale in the deeper workings of the Lomo de Toro mine; plumbojarosite becomes less abundant at depth, its place being taken first by cerussite and then by cerussite and anglesite.

Smelter analyses of two carload lots of oxidized ore from Lomo de Toro gave the following results.

	1	2
Pb percent	20. 75	19. 2
Zn do	1. 5	0. 4
Fe do	30. 7	31. 55
Ca do	0. 0	1. 0
Insol do	9. 9	10. 3
H_2O do	10. 0	11. 1
Ag g/ton	419	385
Au do	1. 8	1. 85

Recalculated on a water-free basis.

	1	2
Pb percent	23. 0	21. 6
Zn do	1. 66	0. 45
Fe do	34. 1	35. 5
Ca do	0. 0	1. 1
Insol do	11. 0	11. 6

Inasmuch as plumbojarosite contains 18.3 percent lead and 29.6 percent iron, these analyses may come near to representing a pure plumbojarosite ore, the additional lead being supplied by the other oxidized lead minerals and perhaps galena, and the additional iron by limonitic iron oxides.

Although many minerals have been reported from the oxidized ores of Zimapán, only a few besides the already mentioned plumbojarosite, cerussite, and anglesite were identified in the course of this investigation. Zinc minerals found include scarce smithsonite and aurichalcite, and the rare basic arsenate adamite. Copper minerals are malachite, azurite, chalcanthite, chrysocolla, aurichalcite, and a copper arsenate believed to be olivenite. Although widespread, none of these minerals is abundant. The iron arsenate scorodite is common as an oxidation product of arsenopyrite in the El Monte mining area. Limonitic iron oxides are commonly found above or below the oxidized lead-silver ore bodies in the Lomo de Toro mine. A clean separation of iron has been effected during oxidation; iron necessary for the formation of plumbojarosite was utilized, after which the excess iron was removed from the part of the ore bearing lead and silver and deposited separately as limonite. Gypsum is a very common mineral of the oxidized zone and is found in nearly every ore body, although always in small quantities. A thin stringer of native sulfur was seen in the footwall of a dike bounding a small ore body in the Lomo de Toro mine. Small vugs lined with quartz crystals are not uncommon in the plumbojarosite ore at the Lomo de Toro mine.

The nearly complete removal of certain constituents of the sulfide ore is noteworthy. Zinc, as mentioned above, is almost entirely removed, although in the typical sulfide ore of the area, sphalerite is much more abundant than galena. The carbonate gangue is also thoroughly removed; the calcium content of the Lomo de Toro oxidized ore averages 1 to 2 percent. Iron is commonly present in about the proportion needed to approximate the formula for plumbojarosite, although local concentrations of nearly pure iron oxide are common above and below oxidized ore bodies; iron content averages 25–30 percent iron. Insoluble material composes about 10 percent of the Lomo de Toro ore. It seems to be largely quartz, although such a large proportion of quartz is never evident megascopically.

ORIGIN OF ORE DEPOSITS

The origin of the different types of deposits has been touched upon before and will be briefly summarized here. All the ore deposits of the area, with the exception of the San Francisco deposits, stand in close spatial relationship to bodies of monzonite or quartz monzonite. A nearly complete sequence of mineralization processes, starting with intense endomorphism and pyritization of the intrusive igneous rocks, followed by pyrometasomatic metallization, and ending with lower temperature hypothermal(?) and mesothermal mineralization, is displayed in the Carrizal and El Monte mining areas. Zonal arrangement of the different types of deposits around the monzonitic bodies—pyrometasomatic near the intrusives, hypothermal(?) and mesothermal farther away—leaves little doubt of a genetic relationship, either to the monzonite and quartz-monzonite bodies or to deeper igneous bodies below the monzonitic rocks. The intense alteration of the monzonitic rocks in the metallized areas suggests that the source of the metallizing fluids was a deeper seated igneous mass. The spatial and genetic relationship between intrusive igneous rocks and lead-silver limestone replacement deposits in Mexico has been emphasized by Fletcher (1929, p. 513), who mentions intrusive rocks in 11 of the 17 districts described by him.

The earliest manifestations of mineralization was sericitic alteration of the monzonitic rocks. Sericitization was followed by the introduction, in many places, of fluorite, quartz, sulfides, tourmaline, and orthoclase. At or near the intrusive contacts, limestone was converted to tactite by action of emanations from the intrusive rock. Formation of tactite was followed by introduction of sulfides, which are usually formed later than tactite silicates, but in a few places the silicates both preceded and followed sulfides. Sulfides tended to be deposited at some distance from the intrusive contact, commonly on the "limestone side" of the tactite zone but also within the tactite although not at the immediate intrusive contact. Silicate minerals were formed close to the intrusive bodies, and with increasing distance from the intrusive rocks, the proportion of silicates to sulfide diminished until deposition of essentially solid sulfides took place. The sulfide bodies near the intrusive rocks are commonly vertical chimneys. If the ascending metal-bearing fluids found a bed favorable to replacement, sulfides were deposited as bedding replacement ore bodies, either chimneys or mantos. Although the entire sequence is not developed at any one mine, the various stages and transitions are all shown at different places. The transition between alteration of quartz monzonite and formation of metallized tactite is seen at the Concordia mine in the El Monte mining area. Transition from metallized tactite to nonsilicate-bearing sulfide ore is shown in several places, such as the Los Balcones and Santa Clara mines.

In common with most mining districts whose ore deposits are believed to be magmatic in origin, Zimapán does not offer unequivocal proof that its deposits had as their source the bodies of intrusive igneous rocks now exposed in the district. The weakest assumptions in the sequence from igneous intrusion to ore deposits are the relations between monzonitic rocks and tactites, and between tactites and metallized tactites. As for the first hypothesis, we are not able to say categorically either that the tactite-forming fluids were derived from the immediately adjacent igneous rock or that they were derived from some deeper seated source. Evidence at the Concordia mine suggests that both alteration of the quartz monzonite and formation of tactite may have been accomplished by fluids derived from a deeper source, as several new minerals are common to both altered intrusive rock and tactite. Elsewhere, however, the lack of tactite minerals within intrusive igneous bodies contrasts so strongly with their abundance in the wall rocks of the intrusive that reference to a deeper source for the tactite-forming solutions seems unnecessary. Dikelike tactite bodies, as far as we know, are found only within limestone. That they have not been found cutting intrusive igneous rocks is a negative sort of evidence that they are derived from the intrusive rocks in the same manner as the contact-pyrometasomatic tactites. Admittedly the abundance of calcium-bearing minerals in the tactites (diopside, garnet, vesuvianite, epidote, and others) indicates that the presence of limestone may have been necessary for their formation. The difficulty involved in the second hypothesis becomes less important with recognition of the often-noted tendency of sulfides to be deposited later than and farther from their supposed igneous source than silicates. The mineralogical similarity of metallized and nonmetallized tactites is so pronounced that a common source for both seems a most likely assumption.

The presence of many dikes cutting monzonite in the La Luz-La Cruz mining area indicates a second stage of intrusion later than the consolidation of the monzonite and shows that molten magma was present under the area after emplacement of the monzonite. Veins in the monzonite, such as the La Luz and Pamplona veins, are clearly formed later than the monzonitic rocks; mineralization of such veins must be related to deeper sources than the monzonitic rocks themselves, perhaps to the same source responsible for the dikes formed after the monzonite. Evidence that the other vein deposits of both the La Luz-La Cruz and Santa Gorgonia-San Pascual mining areas do or do not have the same relationship to the monzonite is lacking. In the Carrizal and El Monte mining areas, no dikes or veins formed after the monzonite are known within the monzonitic rocks.

A complete discussion of the relative merits of the two most likely theories—that the sequence of mineralization originated within the bodies of intrusive igneous rock now exposed in the area, or that the sequence originated in deeper seated igneous bodies not yet exposed—is not within the scope of this report. Field evidence in many places offers some support for the first theory, but evidence for the second, such as offered by the Concordia mine, is more direct and convincing. That there is some sort of genetic relationship between monzonite and quartz-monzonite bodies and ore deposits seems an inescapable conclusion, but whether the relationship is that of parent and offspring or that of common parentage was not determined during our work in the Carrizal and El Monte mining areas, although we lean strongly to the second interpretation.

FUTURE OF THE DISTRICT

VEIN DEPOSITS

Only a few vein deposits at Zimapán have yielded any appreciable production; the largest have been those of the San José Maravillas-Poder de Dios and San Pascual mines, followed by the Santa Gorgonia mine. The San Pascual mine was closed and largely inaccessible in 1949, and little can be said about its potentialities; it seems unlikely that it will become an important producer, especially since the higher prices for lead and zinc in 1949 failed to provide any stimulus toward its operation. The San José Maravillas vein is strong and well mineralized in the deepest parts of the mine and is being explored actively; a small production seems certain. The metal content of the Santa Gorgonia vein at depth is very low and the mine was almost nonproducing, although it was well developed with a good shaft and excellent manways; it will continue to yield a very small production of high-grade lead-silver ore almost indefinitely but will probably never be an important mine. Other vein mines of the Santa Gorgonia-San Pascual area have never been substantial producers, and there is little reason to expect any appreciable production from them in the future. The mining area has been so thoroughly explored that possibilities of discovering new and important ore bodies seem very remote.

The only vein mine in the La Luz-La Cruz mining area that appears to offer any possibility of future production is La Luz. The mine was being pumped in July 1949, but a large inflow of water from the Río Tolimán, coupled with the corrosive action of copper-bearing water on pump machinery, was causing the operators considerable trouble. The mine's potential value could not be estimated. Other vein mines in the same mining area were not producing and had been nonproductive for many years. Many of them were flooded and their potentialities are unknown.

LIMESTONE REPLACEMENT DEPOSITS

The future of the limestone replacement deposits is very different from that of the vein deposits, and excellent possibilities exist in one part of the district.

In the Carrizal mining area, the mines on the west side of Barranca de Tolimán have not been highly productive, with the exception of the Las Animas mine, which seems to be largely worked out, and the La Paz mine, which was inaccessible in its only potentially productive areas. All the other mines are very small. Only the Santa Clara and Las Estacas mines have yielded any appreciable production, but possibilities for continued small-scale production at the Santa Clara mine and for discovery of another ore body in the worked-out Las Estacas mine are good. The mines on the west side can continue to yield a small production for sometime, but to judge by past records, the area cannot be considered as one of great potentialities.

The Los Balcones and Lomo de Toro mines on the east side of Barranca de Tolimán have been the leading producers of the Carrizal mining area, and together they have probably yielded over 90 percent of the production from the Zimapán district. Known reserves of neither mine are large, but their potential reserves appear to be very large. Much unexplored ground remains at the Los Balcones mine, both between the San Rafael-San Miguel de Los Palacios workings and the La V-Los Balcones-La Palmita workings and at depths from the La V level downward. Quartz monzonite crops out 150 meters west of the nearest Los Balcones ore body, the La V-Los Balcones chimney, but the intrusive contact strikes about north-northeastward and seems to dip steeply northwestward, so a large block of potential ore-bearing ground remains between the quartz monzonite and the known ore bodies. The Los Balcones area is considered to have good potentialities, but the high cost of mining and the high zinc content of the ore, rather than any lack of ore, are the principal factors that will determine whether or not the mine will continue to be a major producer.

The Lomo de Toro mine has always been a producer of high-grade oxidized lead-silver ore; it seems likely that several of the old Spanish stopes (Ave María, San Vicente) were terminated in sulfide ore and abandoned. Likewise, the Los Bronces working has been abandoned for many years, although a deposit of high-grade sulfide ore is known to exist there. Recently (1949) the oxidized ores of the higher levels have given way to partly oxidized ores at the lowest level of the mine, and it seems a matter of only a short time until the main production from the mine will be sulfide ore. Potential reserves of sulfide ore are very large; excellent possibilities exist below the already mentioned Ave María and San Vicente stopes as well as below the recently exploited San Pedro and Santa Luisa ore bodies.

A block of unexplored ground perhaps 30,000–40,000 square meters in area lies between the Lomo de Toro and Los Balcones mines. The area between the Santa Luisa stope of the Lomo de Toro mine and the southernmost chimney of the San Rafael Nuevo working is especially promising, as it lies along the prominent ore trend of the San Rafael Nuevo-San Rafael Viejo-San Miguel de Los Palacios and San Guillermo (Lomo de Toro) workings. Another promising area lies along the southeast extension of the La V-Los Balcones-La Palmita ore-bearing area. The Los Balcones-Lomo de Toro area is considered by far the most promising in the district as regards reserves in extensions of known ore bodies and possibilities of discovery of new ore bodies.

The potentialities of the El Monte mining area are difficult to assess. The scanty data on former production and the size of the few accessible stopes suggest that the area has never been a large producer, but several of the reputedly largest old mines (Dolores, El Santísimo, El Chacuaco Viejo) are inaccessible and no information as to the size of their ore bodies is available. The visible sulfide ore bodies of the area are small and irregular, although some are very high in grade (Miguel Hidalgo, El Chacuaco Viejo). The conclusion arrived at by consideration of all available data is that the El Monte mining area, although capable of sustaining a small production for an extended period, probably does not have a potentially large production.

No assessment whatsoever can be made of the potentialities of the San Francisco mine, for all the old stopes are inaccessible and much of the mine is flooded. The ore was said to have been very rich in silver, but nothing is known about the production. Both mines of the Rosario-Espíritu area appear to be nearly worked out and to offer little possibility of future production. The El Rosario mine is badly caved but appears to have been thoroughly cleaned out; a few tons of high-grade plumbojarosite ore remain in the El Espíritu mine, and the possibility of finding an extension of the upper manto is fair, but the remoteness of the area from transportation makes its possibilities somewhat less attractive.

In summation, we believe that only the Carrizal mining area offers any great expectation of continued significant production and discovery of sizeable new ore bodies. Within the area, the Lomo de Toro-Los Balcones ground appears to be most favorable.

MINES AND PROSPECTS

SANTA GORGONIA-SAN PASCUAL MINING AREA

Most of the mines in the Santa Gorgonia-San Pascual mining area (see pl. 1 for location) were inaccessible and no information is available on any of them except San Pascual and El Resquicio. Ten accessible mines and two small prospects are described below.

EL ARCABUZ PROSPECT

The El Arcabuz prospect is 1 kilometer southeast of Cerro del Arcabuz on the trial between Barranca Seca and Barranca de La Cruz. An adit 85 meters long follows a series of steep-dipping northwestward-trending fractures in El Morro fanglomerate (fig. 23). The prospect is entirely barren.

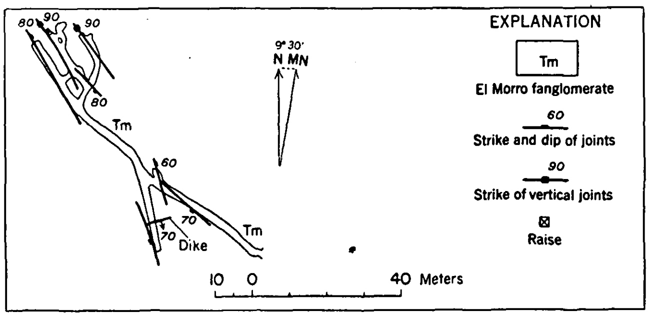

FIGURE 23.—Map of the El Arcabuz prospect.

BUENAVISTA MINE

The Buenavista mine is at the upper end of Barranca de Las Animas, 950 meters north-northeast of Cerro de La Nopalera. Mine workings consist of a northeastward-trending adit 145 meters long, with two drifts 25 and 80 meters, respectively, from the portal (fig. 24). The workings are entirely in Las Espinas volcanic rocks. A short drift and a 20-meter winze were driven on a deeply weathered dike found 25 meters from the portal; the dike strikes northwestward and is cut off in the adit by a fault along which the adit was begun. The drift 80 meters from the portal is on a vertical calcite vein 30 cm thick along a fault. The vein contains a little disseminated galena, and thin galena veinlets occur along the vein walls. The calcite vein has been stoped upward 12–15 meters. Just beyond the vein and parallel to it is a thin altered dike flanked by veinlets of calcite with a little galena. A winze was sunk at

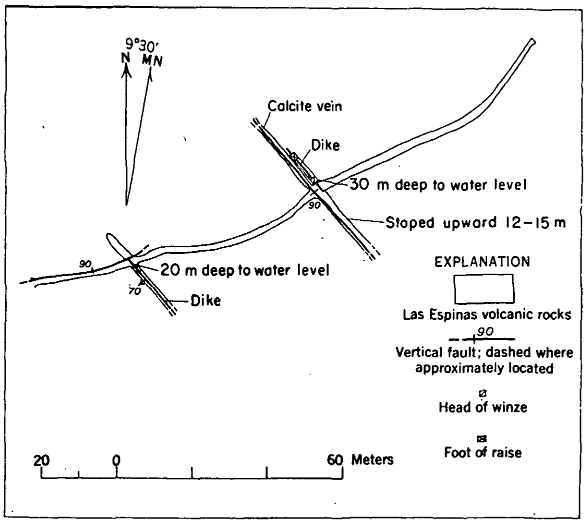

FIGURE 24.—Map of the Buenavista mine.

least 30 meters on the dike. A considerable amount of rock has been removed from stope and winze, but the few remnants of ore indicate that very little metal was produced. The mine was closed and appeared to have been so for many years.

GUADALUPE ADIT

The Guadalupe adit is in a small branch of Barranca de Las Animas 500 meters north-northwest of Cerro de La Nopalera. An adit about 180 meters long was driven in El Morro fanglomerate along a hard pyritic andesite dike striking N. 77° W. and dipping 60°–80° S. (fig. 25). The dike reaches a maximum thickness of about 40 cm. Faulting after the formation of the dike has produced as much as 70 cm of gouge along the dike and has cut off the dike 75 meters from the portal. A calcite vein 15 cm thick appears in the hanging wall of the dike 40 meters from the portal and continues to the end of the working. The vein locally carries a little disseminated pyrite, but no ore is in sight anywhere in the adit. No work was being done in the adit in 1948.

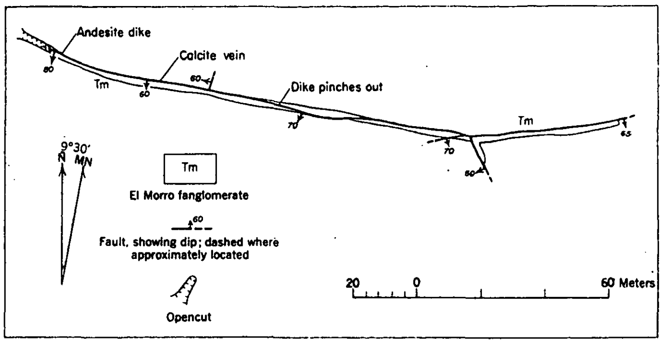

FIGURE 25.—Map of the Guadalupe adit.

MERCEDES MINE

The Mercedes mine is about 400 meters northwest of Puerto de Los Bronces. Mine workings are entirely in Las Espinas volcanic rocks and consist of a northeastward- to northwestward-trending irregular incline. The mine portal is on a latite dike 1 meter thick striking N. 25° E. and dipping 80° SE. Just inside the portal a fault along the hanging wall of the dike changes from N. 25° E. to N. 30° W. and cuts off the dike. The incline continues for about 50 meters along the fault and descends perhaps 15–20 meters. At the portal a quartz vein 15 to 25 cm thick along the fault contains a little galena. The vein appears sporadically along the fault as far as the face, where it is 25 cm wide and contains a little galena and pyrite. The vein reaches a maximum thickness of 45 cm and pinches out in several places. Nowhere does the vein contain enough galena to be mined. Production has been negligible.

PRECIOSA SANGRE MINE

The Preciosa Sangre mine is on the south slope of Cerro de Las Espinas near the upper end of the north branch of Barranca de Las Animas. The mine portal lies just above a thin lens of fanglomerate intercalated in Las Espinas volcanic rocks. Mine workings are shown in figure 26.

A quartz vein along a fault striking about N. 30° W. and dipping 70°–75° NE. is opened by a northwestward-trending adit, which for the first 145 meters from the portal lies in agglomerate composed largely of tuff fragments as much as 50 cm across. Sixty meters from the portal the fault divides into two parallel faults, which rejoin 50 meters farther on. The vein pinches and swells along the strike, pinching out at one place and widening to a maximum of 1.5 meters elsewhere. Short spur veins striking about N. 60° W. were found 95 and 115 meters, respectively, from the portal. Along most of the adit the vein has been stoped upward for several meters.

At about 145 meters from the portal, andesitic lava appears in the back of the adit, and an irregular flat stope about 30 meters long and perhaps 15 meters wide has been opened along the base of the lava. The main fault forms the northeast wall of the stope and has been followed for more than 40 meters beyond the stope at lower levels. Three splits from the main fault are found in the hanging wall in the northwest part of the mine.

The vein material is gray to reddish-brown fine-grained quartz with small pockets of galena, the only sulfide seen. Numerous vugs are lined with light-gray opal. Cerussite and plumbojarosite are also found in vugs; anglesite is rare. Most of the ore produced from the mine has been oxidized material from the northwest workings. The ore body extracted from the flat stope 145 meters from the portal was apparently localized along the base of the relatively impermeable lava. Mineralizing fluids rising along the fault spread out at the base of the lava in the highly permeable agglomerate. Recent production has come from oxidized vein material northwest of and below the earlier stope. Ore was cobbed to very small fragments and carefully sorted by hand. The most abundant lead mineral was plumbojarosite, followed by cerussite. The mine was shut down in 1949 after yielding several hundred tons of shipping ore of unknown grade.

EL RESQUICIO MINE

The El Resquicio mine is near the top of the ridge southwest of the Santa Gorgonia mine. The mine workings are inaccessible, but an old map indicates that a vertical ore body 50 meters high and 30 meters in max-

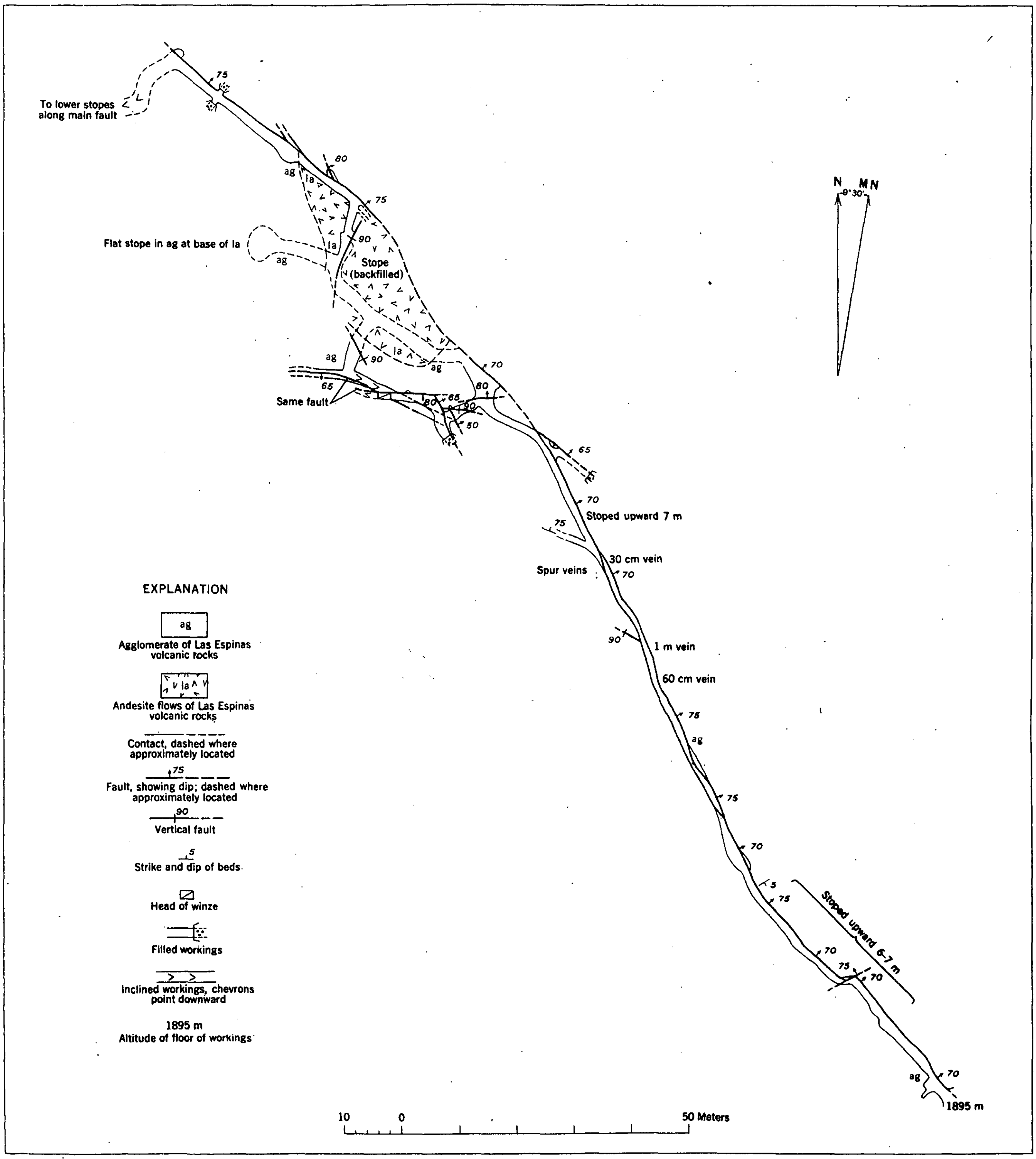

FIGURE 26.—Map of the Preciosa Sangre mine.

imum length was exploited. Nothing is known about the type, grade, or tonnage of ore produced.

LA SALVADORA PROSPECT

The La Salvadora prospect is due south of the El Arcabuz prospect on the south bank of the Río Tolimán. A silicified zone 1 meter thick in Upper Cretaceous rocks just below the base of the El Morro fanglomerate is cut by veinlets of calcite, sphalerite, galena, and pyrite which attain a maximum thickness of about 7 cm. The sphalerite has a beautiful light yellow-green color.

The prospect is remote from known productive areas and shows little promise.

SAN JOSE MARAVILLAS-PODER DE DIOS MINE

The San José Maravillas-Poder de Dios mine is in Barranca de San José, 9 kilometers by road northwest of Zimapán. The San Gerónimo portal is just above the point where the barranca begins its precipitous 400-meter descent to the Río Tolimán. Only a small part of the San Gerónimo workings of the mine is accessible, but old maps indicate that the mine is second to the Santa Gorgonia-Providencia in being the most extensive vein mine in the district. The Poder de Dios vein has been developed for 450 meters along the strike and to about 250 meters in maximum depth; approximately 5 kilometers of levels and inclines have been driven.

The San Gerónimo workings consist of an east-southeastward-trending adit 280 meters along, several short crosscuts, and many stopes, most of which are inaccessible. Formerly ore was hoisted through a 145-meter underground shaft 105 meters from the portal; the shaft was not being used in 1948–49 and the small amount of ore mined was carried in sacks. No data on past production are available, but the size of the stopes indicates that the mine must have yielded a large amount of ore (see fig. 21). Early production was from oxidized ore at the top of the vein. Flores (1924, p. 125) mentions iron oxide, cerussite, and galena as the principal minerals found. Later a small mill was installed to treat sulfide ore, but it was dismantled several years ago. Active exploration in the deepest parts of the mine was being carried on in 1949 by Sr. Jorge Preisser, operator of the Los Balcones mine, and a small yield of lead-zinc-silver ore was being maintained. In 1947, 1,214.6 tons of ore was mined, averaging 10 percent lead, 6 percent zinc, and 475 grams of silver per metric ton.

The country rock is El Morro fanglomerate. About 85 meters from the portal a lens of volcanic rock (andesite lava?) was found and the remainder of the adit lies in volcanic rocks. The thickness of the volcanic lens is unknown, but fanglomerate was seen on the surface above the adit and underground at lower levels. A large proportion of the workings is in fanglomerate. The San José Maravillas-Poder de Dios vein is along an east-southeastward-trending fault zone dipping from 90° to 75° in either direction. No single well-defined fault is present; instead, the zone consists of overlapping and bifurcating faults with numerous branches into either wall. At the underground shaft the main vein structure is offset about 10 meters to the southwest along a fault striking N. 60° E. Figure 27 is a geologic map of the adit level.

Apparently ore occurred in irregular pockets along the vein structure. The extreme irregularity of mineralization is shown in the vertical projection of the stopes (fig. 21). Faults in the unstoped areas above the adit are very tight and show very weak sulfide mineralization, largely pyritic. Vein thickness ranges

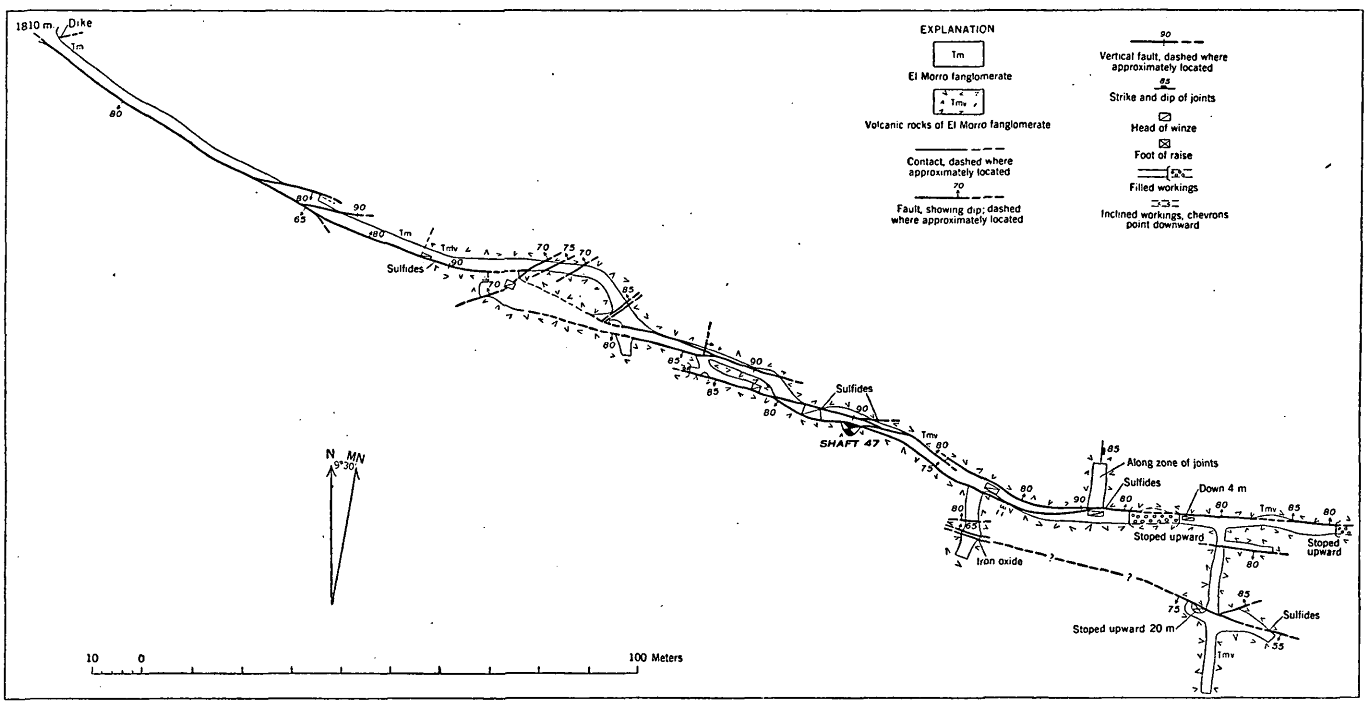

FIGURE 27.—Map of the main level, San Gerónimo workings, Poder de Dios mine.

from a knife edge in many places to about 6 meters near the shaft. The offsetting fault at the shaft is probably premineralization in age and its intersection with the main fault system may have provided a suitable place for the localization of a large ore body. No idea of the nature of the vein material at the adit level can be gained, as all presumably mineralized parts of the vein have been stoped. However, the vein at the one accessible place near the bottom of the mine gives a clue to the mineralization elsewhere. Here a vein 2 meters wide lies between clean parallel fractures in El Morro fanglomerate. The vein is a replacement vein, sulfides having selectively replaced certain fragments of fanglomerate at one place and formed solid masses of ore at others. The sulfide mineral composition is simple; sphalerite and galena are abundant, pyrite is scarce, and chalcopyrite is very rare. Dark-brown to black sphalerite was the earliest valuable sulfide formed. Fragments of fanglomerate converted to solid sphalerite are replaced along the periphery by a network of galena veinlets. Sphalerite is usually more abundant than galena, but locally galena predominates. Pyrite occurs in two generations, one formed earlier than either sphalerite or galena and one in veinlets cutting both sulfides. Gangue other than unreplaced fanglomerate is scarce. Quartz and a little calcite are interstitial to sulfides and in vugs. Although sulfide mineralization is very spotty, the common occurrence of large masses of galena and sphalerite is sufficient to insure a small production for an extended period. According to Bonillas (1929, unpublished report), a little sorting of mine-run ore gave a product containing about 14 percent lead and 500 grams of silver per ton. Most of the ore seen by us on the mine patio would run a little higher in lead and would also contain 15–20 percent of zinc.

A small chimney of oxidized ore along a steeply dipping fault was mined in the south crosscut at the end of the main adit. The working is inaccessible, but the chimney was apparently an elongate ore body several meters thick and at least 20 meters high.

SAN PABLO MINE

The San Pablo mine is in a small arroyo about 500 meters east-northeast of the Santa Gorgonia mine shaft. Mine workings lie entirely in El Morro fanglomerate and consist of a partly caved open stope, an inaccessible shaft, and a steep, very irregular incline which reaches a depth of about 40 meters. The incline extends westward along an eastward-trending fracture, which dips steeply southward at the portal and steeply northward at the bottom of the incline. Near the end of the workings the fracture is filled by a vein of white calcite 10 cm thick containing sparse disseminated galena and a little chalcopyrite, sphalerite, and pyrite. Sulfides are oxidized slightly, and flecks of plumbojarosite, malachite, and azurite appear in places.

The open stope is along a normal fault striking N. 35° W. and dipping 65°–70° NE. At the northeast end, an andesite dike 1 meter thick lies along the fault. Nothing is known about the material mined. The shaft is at the southeastern end of the stope and lies along the extension of the stope fault; it is at least 50 meters deep but has apparently never been utilized.

Production from the San Pablo mine is very small and the mineralization seen shows little promise.

SAN PASCUAL MINE

The San Pascual mine is directly west of the San José Maravillas-Poder de Dios mine across Barranca de San José and is reached by the same road. Workings along the San Pascual vein extend to the top of the ridge north of the San Pascual adit, but the only accessible one is the adit, which lies entirely in El Morro fanglomerate. Nothing is known about past production, but the great number of workings on old maps and a sketchy description of the main ore body by Cepeda (1928, unpublished report) suggest that a considerable amount of ore has been extracted from the mine. Ore was formerly hoisted through a well-constructed three-compartment underground shaft, now in disuse and inaccessible.

The San Pascual vein structure is similar to that of the San José Maravillas-Poder de Dios vein. The adit, which trends almost due north, was driven along a highly faulted quartz-latite dike. Seventy meters from the portal the dike is cut off by a northeastward-striking fault and the main northward-trending San Pascual vein structure was intersected. The vein structure is a fault zone of overlapping discontinuous faults, splits, and minor offsets (see fig. 22). All the faults exposed in the adit are tight and unmineralized.

The main ore body of the mine was found at the intersection of the main northward-trending fault zone with an eastward-trending fault zone found about 115 meters from the portal. An eastward-trending vertical projection of the stope on this ore body is shown in figure 22. According to Cepeda's unpublished report (1928) this stope, known as the Salón Grande de los Carbonatos, was 160 meters long, 60 meters high, and 4 to 5 meters wide; it was completely inaccessible in 1949, but looked into from the main level it is an imposing room. Cepeda reports cerussite as the most abundant mineral found and also mentions anglesite, wulfenite, and the rare lead silicate alamosite. According to him, oxidized ore from the "Great room of the carbonates" gave the following assay.

Pb	percent	9
SiO_2	do	40–50
Fe	do	18–20
Ag	g/ton	290
Au	do	0.3–0.4

Sulfides from the same ore body carried as much as 900 grams of silver per ton, but otherwise averaged about the same as the oxidized ore. Galena, pyrite, and a little sphalerite and arsenopyrite are mentioned as the principal sulfides.

No information on the vein structure or type of mineralization is available, as all mineralized parts of the mine are inaccessible. The mine has not been worked for many years, except for extraction by the gambusinos of remnants of oxidized ore in some of the higher workings.

SANTA GORGONIA MINE

The Santa Gorgonia mine, together with its inaccessible extension, the Providencia mine, is the largest vein mine in the district in amount of underground workings, although its total yield was probably less than that of either the San José Maravillas-Poder de Dios or San Pascual mines.

The mine is 5.2 kilometers northwest of Zimapán by road and about 600 meters north of Cerro del Arcabuz. Mine workings consist of an inclined shaft 2 meters square and 220 meters deep, levels at 85, 135, and 180 meters below the shaft collar, and many stopes, the great majority of which are inaccessible. The shaft is along the plane of the Santa Gorgonia vein and is well constructed, having two sets of steel rails and a massive headframe (the only headframe in the Zimapán district), but most of the hoisting machinery has been dismantled and the shaft has not been used for many years.

The strike of the Santa Gorgonia vein ranges from N. 20° W. to N. 65° W. and averages very close to N. 40° W.; the dip ranges from 70° to 80° SW. The Las Espinas volcanic rocks are the country rock at the shaft collar, but at 26–27 meters below the surface the El Morro fanglomerate is entered and the rest of the mine is in that formation. Displacement of the volcanic rock-fanglomerate contact indicates that the vein is along a reverse fault with a throw of about 1 meter; the same direction of displacement is shown where the vein offsets a premineralization dike on the 85-meter level.

The vein structure consists of two nearly parallel fractures from 10 cm to 1.5 meters apart; the average thickness of the structure is perhaps 90 cm. Although the fractures are faults of very small displacement, they persist throughout the mine. Fanglomerate between the fractures is slightly brecciated in places and mineralization is localized either along the main fractures themselves or along fractures in the brecciated fanglomerate. Vein material is largely calcite, which contains minor quantities of sulfides, principally sphalerite and galena with a little chalcopyrite and pyrite. The calcite veins range in thickness from a knife edge to 80 cm and average less than 20 cm in the accessible parts of the mine. The veins are along either the footwall or the hanging wall of the vein structure. Rarely a vein crosses from one wall to the other or splits into two veins, and elsewhere there may be a vein along each wall and perhaps a third vein somewhere between. Within the veins themselves, sulfides may be disseminated in calcite or, more commonly, may form thin selvages along vein walls. Rarely, stringers of solid sphalerite fill the main fractures. The sulfide selvages along vein walls may be solid sphalerite, solid galena, or sphalerite with a thin core of galena. The thickest selvage seen was 10 cm of solid galena, in the southeast end of the mine on the 157-meter level. A typical section of the Santa Gorgonia vein is shown in figure 28.

Near the northwest end of the 85-meter level a vertical premineralization rhyolite dike striking N. 60° E. forms the southeast wall of a weakly mineralized split from the main vein. Faulting along the dike has offset the main vein structure about 2 meters northeast along the northwest dike wall. The split was followed 15 meters southwest until a calcite vein 10 to 20 cm thick striking N. 20° W. was uncovered, and this vein was in turn followed northwestward for 18 meters until

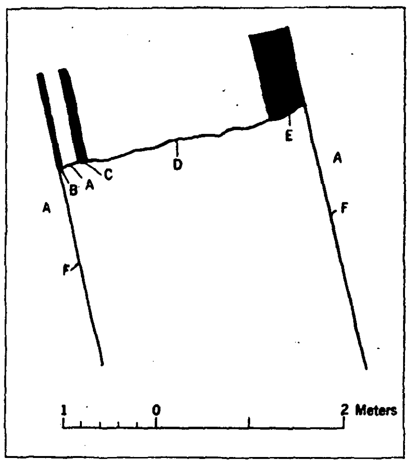

FIGURE 28.—Typical section of the Santa Gorgonia vein at northwest end of 135-meter level, looking southeastward. *A*. El Morro fanglomerate. *B*. Calcite vein with disseminated sphalerite. *C*. Calcite vein with veinlets of sphalerite and a little disseminated galena. *D*. El Morro fanglomerate cut by thin stringers of galena and sphalerite. *E*. Vein of coarse calcite, flanked by veinlets of galena and a little sphalerite. *F*. Fracture. The vein structure here is 1.35 meters thick, but vein material constitutes only about 27 cm of the thickness and sulfides less than 5 cm.

the main vein structure was again cut. Just southeast of the shaft on the 85-meter level the vein structure swings sharply to the south and then back to southeast; the maximum thickness of the vein structure occurs between the two bends.

On the 135-meter level, the vein is cut off at the northwest end by a fault striking N. 65° W. and dipping 75° SW. El Morro fanglomerate is brought into contact with a lens of volcanic rock along the fault.

On the 180-meter level the strike of the main vein structure has changed to N. 65° W. A S. 30° E. split from the main vein structure begins 10 meters northwest of the shaft. This split has a strong roll just above the level, so that the dip reverses to 80° NE. The only active mining at the time of our study was along this split vein. Mineralization consisted of thin stringers of either calcite-sphalerite or solid galena.

Water stands in the shaft at about 195 meters. At the lowest accessible point, the Santa Gorgonia vein was 10–40 cm thick but very weakly mineralized.

Most of the stopes are inaccessible, but the irregularity of minable ore shoots is shown by a vertical longitudinal projection of stopes compiled from several old maps (pl. 3). As far as can be ascertained from scanty records, the mine has never been a large producer, even though an impressive volume of stope is in evidence. The very small proportion of ore to waste in the visible parts of the vein structure is suggestive of a probable low productivity. The mine was closed in 1949, but it will probably be worked on a very small scale by gambusinos from time to time, as the galena is said to be rich in silver, which runs from 2.5 to 4 kilograms per ton of sorted ore.

SANTO TOMAS MINE

The Santo Tomás mine is at the upper end of the east branch of Barranca de Las Animas, just north of the Buenavista mine. Mine workings lie entirely in the Las Espinas volcanic rocks and consist of a north-northeastward-trending lower adit 225 meters long and an irregular series of workings along the Santo Tomás vein, which connect with the adit near its northeastward end. The map of the adit is given in figure 29.

A series of barren calcite veins was cut near the adit portal, but no ore was found until the main vein was struck. The vein is along a fracture that strikes from N. 35° W. to N. 60° W. and dips steeply northeastward. It ranges in thickness from 5 to 20 cm and is composed of calcite with disseminated pyrite, galena, and arsenopyrite. Small pockets of galena are found rarely; they are commonly oxidized slightly to plumbojarosite. In most parts of the vein the only abundant sulfide is pyrite.

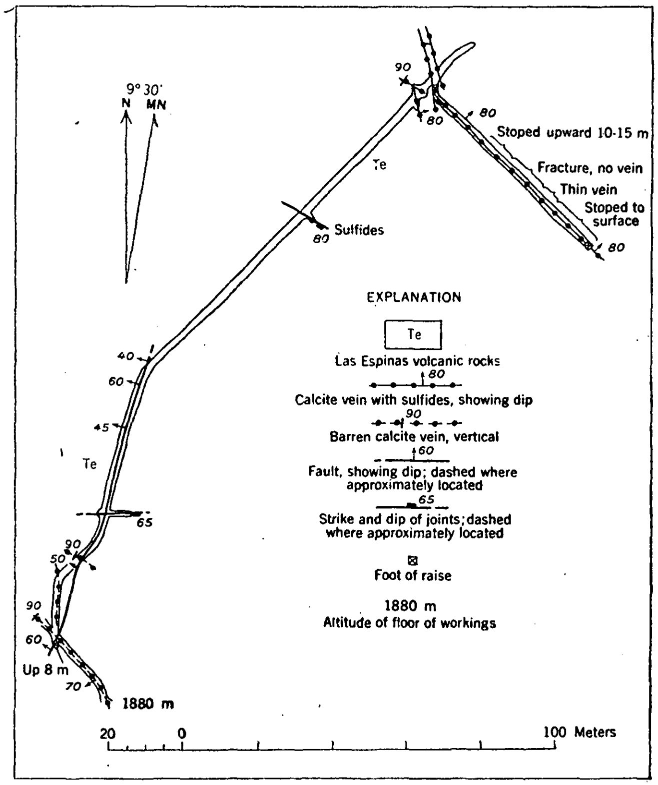

FIGURE 29.—Map of main level, Santo Tomás mine.

Past production from the Santo Tomás mine is not known, but the size of the largest stope (50–60 meters long and perhaps 40 meters high) suggests a rather considerable yield, even though the metal content of the vein is usually less than 10 percent. Production in 1948 was negligible and the operators were about to cease operations.

LA LUZ-LA CRUZ MINING AREA

Although the La Luz-La Cruz mining area (see pl. 1 for location) is literally peppered with shafts, adits, and prospect pits, only two adits were accessible in 1948, and only one mine, the La Luz, was in the process of being reopened. The rest of the old mines were closed and have been closed for many years.

LA CRUZ MINE

The La Cruz mine is in Barranca de La Cruz 300 meters from the Río Tolimán and 5 kilometers slightly north of west from Zimapán. Mine workings consist of a shaft, flooded at 60 meters below the collar, and an adit with a winze near the portal; all the workings are inaccessible. Country rock is pyritized monzonite. According to Flores (1924, p. 112), the mine was worked in 1910–11 and the La Cruz vein was also exploited in the Nuestra Señora, El Hueco, and San Fernando mines. The size and number of ruined buildings on the mine patio indicate a rather large operation. Brinsmade (1921) says that equipment included a 120-horsepower charcoal-gas producer, a gas-driven generator, electric hoist, centrifugal sinking pump, and two piston-type sinking pumps, but that inflow of water was so great that the mine had to be abandoned in 1911 at a depth of 68 meters.

Ore from the La Cruz mine is said to have been very rich in silver, containing as much as 10 kilograms per ton. Argentite and native silver as well as argentiferous galena have been reported from the Nuestra Señora mine.

LA LUZ MINE

The La Luz mine is 6.5 kilometers west-northwest of Zimapán in the Río Tolimán canyon just downstream from the mouth of Barranca de Las Animas. Mine workings consist of a west-southwestward-trending adit 225 meters long and drifts 58 meters north and 92 meters south along the La Luz vein. Country rock consists of Upper Cretaceous strata complexly intruded by quartz monzonite. The area is intricately faulted, as may be seen on the geologic map of the adit shown in figure 30. The Upper Cretaceous rocks are so intensely metamorphosed that it was difficult to distinguish them from quartz monzonite underground.

The La Luz vein is along a fault zone striking about N. 10° W.; dips range from 60° W. to 80° E. Wall rocks of the vein are either Upper Cretaceous rocks or quartz monzonite. The most productive parts of the vein appear to have been in quartz monzonite, as the largest stopes are in that rock. Little is known about the vein material, as all winzes are flooded and all the ore above the adit level has been stoped. The adit lies only a few meters above the Río Tolimán, and water in the winzes is at about the same level as the river bottom.

According to Bonillas' unpublished report (1929), mine-run ore contained about 5–6 percent copper and 1–1.5 kilograms of silver per metric ton; selected ore contained an average of 12 percent copper and 3 kilograms of silver as well as a little gold. Bornite and native copper are the only copper minerals known by us to have been mined; Busto (1880) reports tetrahedrite and "blue copper" (bornite?).

Apparently the mine was abandoned many years ago because of water rather than lack of ore at deeper levels. An attempt to pump the mine was made in 1949 by the mine owner, Sr. Adolfo Lángenscheidt of Zimapán, but the large inflow of water from the Río Tolimán and the corrosive action of copper-bearing waters on pumps proved to be major difficulties. In August 1949, metallic copper was being precipitated by pumping mine water over a series of sheet-iron baffles.

SAN FERNANDO MINE

The San Fernando mine is 100 meters west of the La Cruz mine on the northwest side of Barranca de La Cruz. An adit 70 meters long trending N. 35° W. ends in an inaccessible incline and stope to the northwest along a fault between Upper Cretaceous rocks and monzonite. The fault strikes N. 25° W. and dips 65° NE. It is sealed locally by a thin dike. The Nuestra Señora-La Cruz vein probably lies along this fault, which is not mineralized in the accessible parts of the San Fernando adit. A current of air from above indicated that the adit is connected to the inaccessible Nuestra Señora mine above. Much highly pyritized Upper Cretaceous limestone is on the dump. It must have come from inaccessible parts of the mine, as the country rock in most of the adit is monzonite.

EL MONTE MINING AREA

Twenty-one mines and prospects were examined in the El Monte mining area (see pl. 1 for location). In addition, there were probably at least as many workings that we were unable to enter. Figure 31 is a claim map of part of the area, showing claim boundaries and relative locations of a number of the mine workings. Mines and prospects are briefly described below.

EL AFLORAMIENTO PROSPECT

The El Afloramiento (The Outcrop) prospect is on a mineralized vertical bed of Lower Cretaceous limestone 2–2.5 meters thick and striking N. 25° W.; the outcrop is about 40 meters long. A series of shallow pits and what appeared to be a filled shaft were the only workings. Ore is largely pyrrhotite and arsenopyrite; sphalerite and galena are less abundant and jamesonite and pyrite are scarce. Early-formed pyrrhotite and arsenopyrite were followed by sphalerite and galena, and then by jamesonite. Pyrite occurs in two generations, one as inclusions in pyrrhotite and the other in veinlets cutting all other sulfides. Fluorite is the only abundant gangue mineral. An assay of the ore gave the following results: 8.4 percent lead, 8.3 percent zinc, and 466 grams of silver per ton. In common with many such deposits in the El Monte mining area, the presence of sulfides at the outcrop has discouraged mining because of the lack of facilities for smelting the complex ore directly.

EL ARENAL MINE

The El Arenal adit (fig. 32) is along an altered and presumably mineralized dike that strikes about S. 70° W. and dips 65°–80° S. The adit is 75 meters long and ends in an inaccessible winze. The dike has been stoped upward along some 35 meters of the adit.

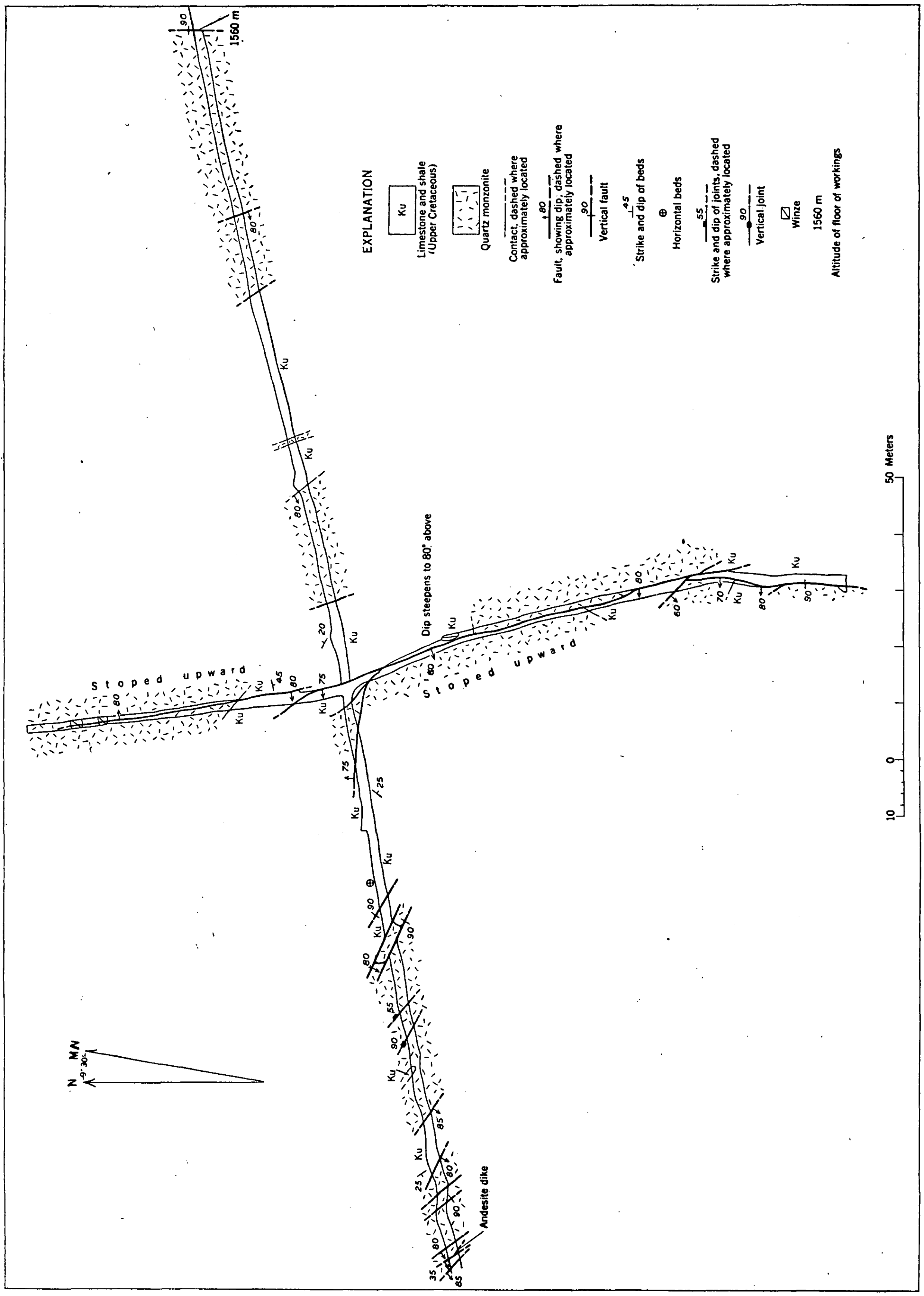

FIGURE 30.—Map of La Luz mine.

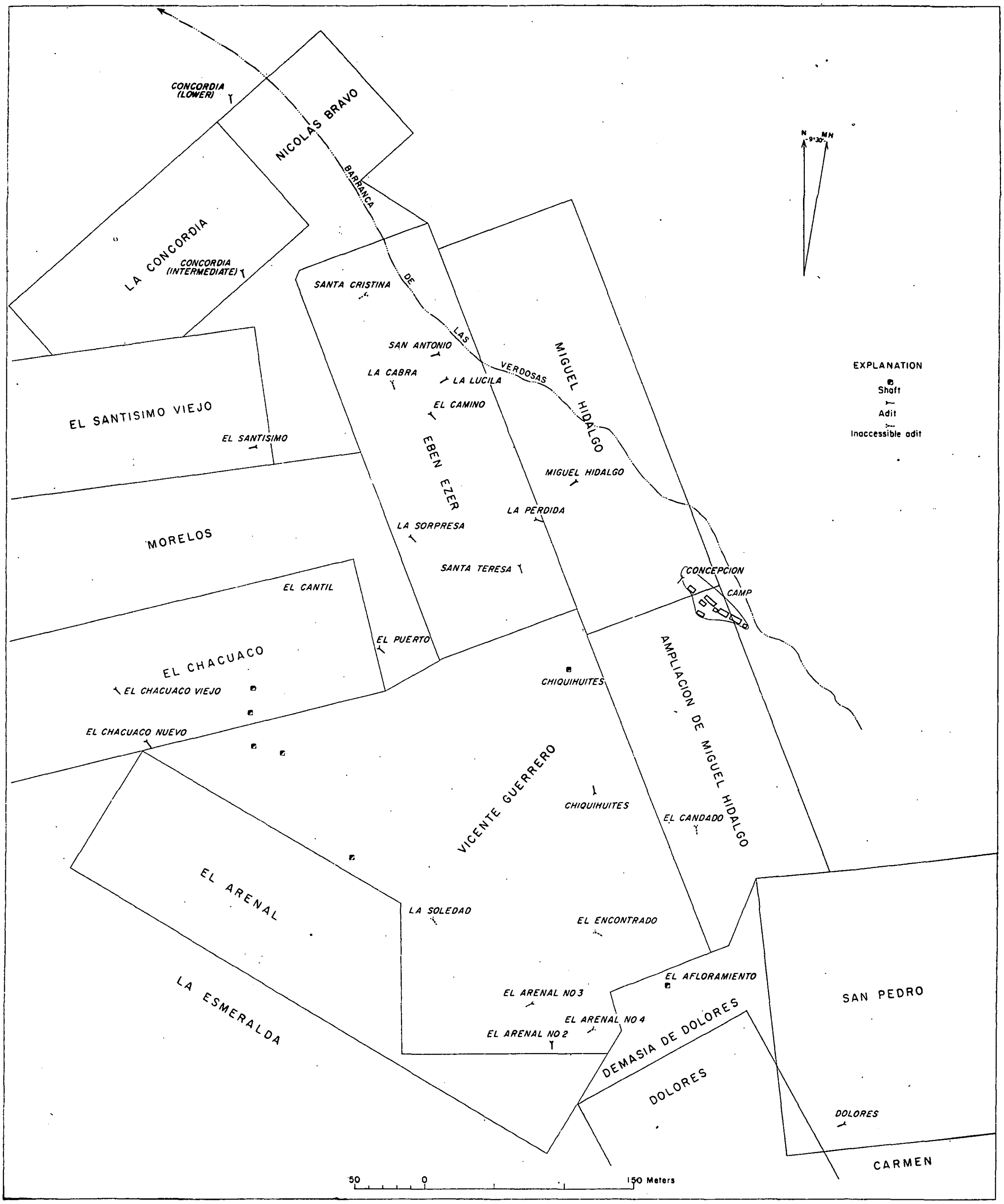

FIGURE 31.—Claim map of El Monte mining area, showing location of principal adits and shafts.

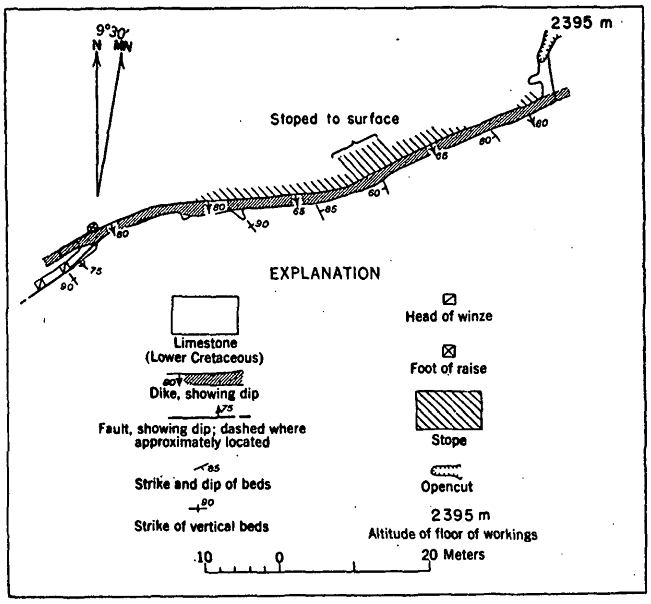

FIGURE 32.—Map of the El Arenal adit.

The country rock is isoclinally folded Lower Cretaceous limestone striking about N. 30° W. The dike was probably an andesite, which is now altered to zoisite, albite, garnet, diopside, and a little galena. Apparently the dike was mined for its very low galena content. Production of metal must have been insignificant, insofar as can be estimated from the type of ore remaining in the stope.

EL CAMINO INCLINE

The El Camino incline is along the contact of Lower Cretaceous limestone and the southernmost tip of the El Monte quartz-monzonite body. Mine workings consist of a steep incline 20 meters long with a short drift at the bottom (fig. 33). At the portal the limestone is weakly mineralized at the quartz-monzonite contact, but in the rest of the working a thin layer of unmineralized limestone lies between sulfides and quartz monzonite. Ore consists of from 20 to 70 cm of sulfides in a calcite gangue, the ore body lying parallel to the vertical intrusive contact. Coarse-grained sphalerite and pyrite appear to be the earliest sulfides formed; they were followed by a fine-grained aggregate of pyrite, galena, and sphalerite. Calcite is the only gangue mineral recognized megascopically. Late-formed orthoclase was noted in a thin section. The ore is of good grade, containing 2–9 percent lead, 12–23 percent zinc, and several hundred grams of silver per ton, but the expectable tonnage is very small.

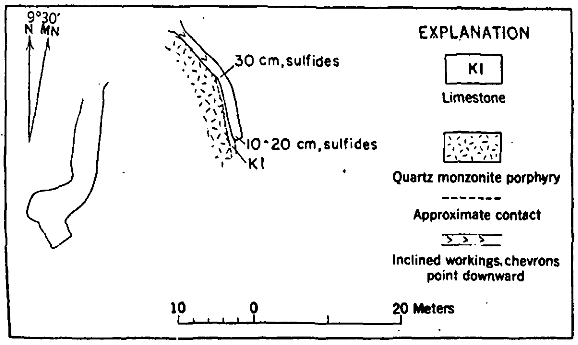

FIGURE 33.—Map and projection of the El Camino incline.

EL CANTIL ADIT

The El Cantil adit is a 58-meter incline along the bedding of Lower Cretaceous limestone, which strikes N. 25° W. and dips 60° SW. The incline ends in an inaccessible winze (fig. 34). The incline follows a rusty seam along the bedding of the limestone. A little calcite appears here and there, but no ore was seen.

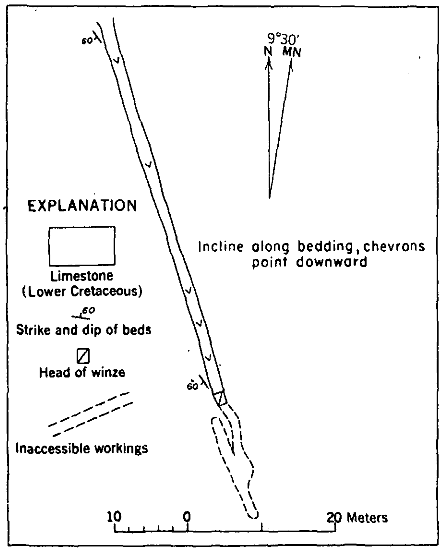

FIGURE 34.—Map of the El Cantil adit.

EL CARMEN MINE

The El Carmen mine consists of a 40-meter adit and stope along a tight eastward-trending fracture in Lower Cretaceous limestone, which strikes N. 35° W. and dips 85° NE. A little iron oxide and calcite were seen along the fracture.

EL CHACUACO NUEVO ADIT

The El Chacuaco Nuevo adit was driven southeastward in folded Lower Cretaceous limestone striking about N. 30° W. For the first 45 meters the adit lies along the crest of an anticline; it then swings southwestward, extends across the trough of an adjacent syncline, and cuts a thin calcite vein which it follows northwestward for 30 meters, ending in an inaccessible raise (fig. 35). The calcite vein is along the bedding of the limestone, which dips 45°–75° NE. and reaches a maximum thickness of 40 cm. A few thin stringers of

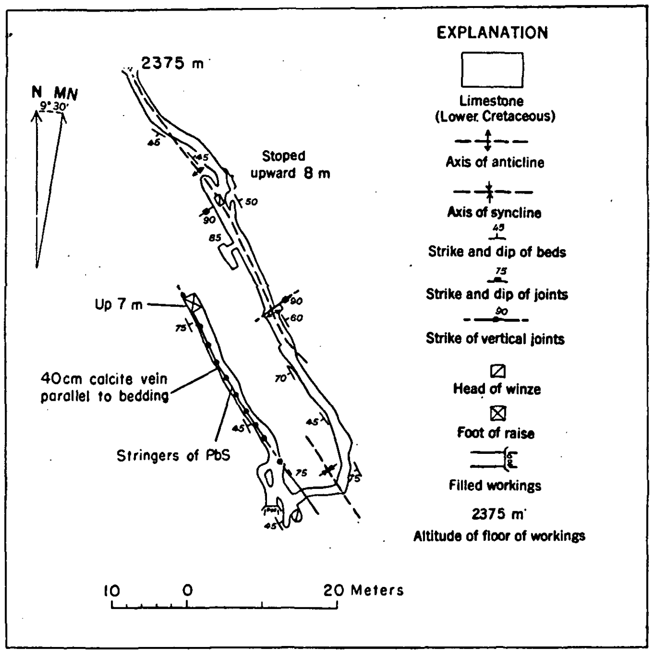

FIGURE 35.—Map of the El Chacuaco Nuevo adit.

galena cut the calcite vein parallel to the vein walls; no other mineralization was seen.

EL CHACUACO VIEJO ADITS

The El Chacuaco Viejo workings consist of two parallel adits 31 and 35 meters long, respectively (fig. 36). These adits were driven southeastward along an overturned anticline in Lower Cretaceous limestone. The lower and shorter adit is along the crest of the fold, and the upper adit is along the southwest limb of the fold. No ore was seen in the upper adit. At the end of the lower adit, 70 cm of weakly mineralized limestone appears in the back for a distance of 7 meters. Two inaccessible winzes are sunk on the mineralized zone.

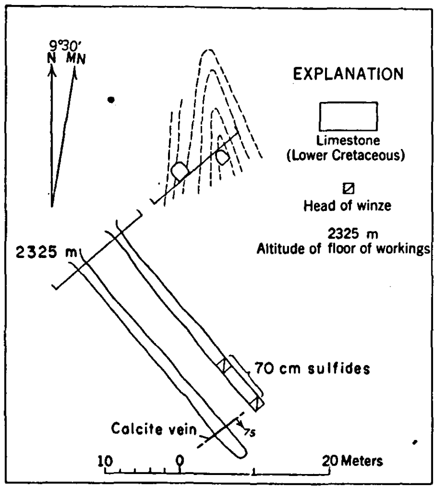

FIGURE 36.—Map of the El Chacuaco Viejo adits.

Mineralization consists of veinlets of arsenopyrite, sphalerite, galena, and a little pyrite. Veinlets show pronounced mineral banding. Arsenopyrite is the earliest sulfide formed; it occurs as a mat of tiny needles. Sphalerite and galena appear to be formed simultaneously. The only megascopic gangue minerals are fluorite and garnet; diopside and quartz were seen in thin section. According to local miners, a large vertical chimney of high-grade lead-silver ore was found in the winzes, one of which is said to be about 100 meters deep.

CHIQUIHUITES MINE

The Chiquihuites mine is the largest accessible mine in the El Monte mining area. It was worked as long as 110 years ago and has not been worked for at least 30 years. The main ore body exploited in the past was oxidized and apparently consisted largely of plumbojarosite. No oxidized ore in any appreciable amount is left in the mine workings, but several sulfide ore bodies are known, which were exploited on a very small scale.

The old mine was opened by an inclined shaft along the intersection of a steep-dipping eastward-trending rhyolite dike with a southwestward-dipping manto, and also by a north-northwestward-trending incline along the same manto ore body in steeply dipping Lower Cretaceous limestone. The only entrance to the mine was along the incline. Mine workings are shown in figure 37; they are so complicated, like many mines in limestone replacement ore bodies, that a complete description cannot be given.

For the first 45 meters the incline followed a manto ore body along the trough of a bend in steeply dipping limestone. The next 45 meters is along the same manto ore body in the trough of a tightly folded syncline, which first appears in the southwest wall of the incline. Five cross sections at various places along the incline are given in figure 37. At 90 meters from the portal, the syncline is offset 10–11 meters to the west by a fault along the Chiquihuites dike. The synclinal structure can be followed only a short distance northwest of the dike, as the beds become so tightly folded that the major structure is hidden. Workings extend nearly 50 meters northwestward from the dike. The manto ore body of the old mine gives way at depth to a poorly defined group of three or four small chimneys at the extreme northwest end of the mine workings. A northeastward-striking dike forms one wall of a chimney; the other walls are apparently minor steep-dipping fractures.

The major structure of the Chiquihuites mine, then, is a north-northwestward-trending syncline. The main

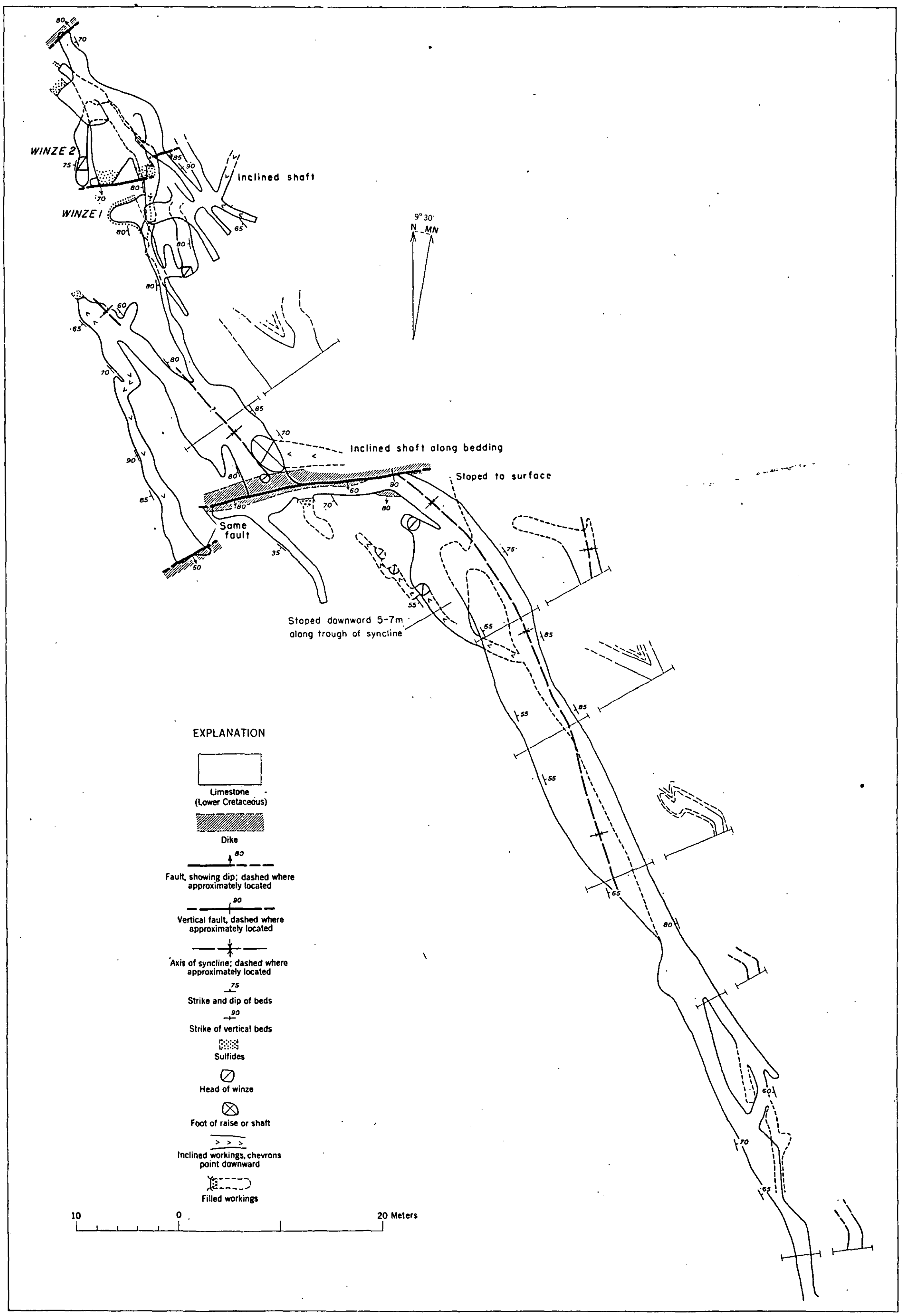

FIGURE 37.—Map of the Chiquihuites mine.

ore body was a manto which occupied both limbs of the syncline locally but was confined largely to the southwestward-dipping limb. Southeast of the Chiquihuites dike the manto was apparently fed through a fracture zone along the trough of the syncline; northwest of the dike it appears to have been an offshoot of a system of vertical chimneys. The sulfide chimneys have a complex assemblage of minerals. Early-formed arsenopyrite, pyrrhotite, and pyrite were followed by sphalerite, galena, and a little jamesonite; late-formed veinlets of pyrite and chalcopyrite cut sulfides formed earlier. Purple fluorite is the only megascopic gangue mineral, and hedenbergite, garnet, quartz, and orthoclase were seen in thin section.

Lead and silver assays of the sulfide chimneys are shown graphically in figure 18. The ore averages 5–6 percent lead, 6–7 percent zinc, and about 300 grams of silver per ton. The chimneys are all rather small, so that no large tonnage of ore can be expected from the mine. The ore is rather low grade for the Zimapán district, and this fact, coupled with the difficulties of transporting ore to Zimapán, accounts for the long period of inactivity.

CONCEPCION MINE

The Concepción mine is unique in the El Monte mining area in that it is the only mine that has yielded ore from a vein deposit. Mine workings consist of a west-southwestward-trending incline and stope along a calcite vein 2 meters thick, and a level extending south-southwestward from the bottom of the stope. Country rock is Lower Cretaceous limestone, which strikes north-northwestward and dips steeply northeastward in most of the mine. A map and projection of the workings are given in figure 38.

The few pillars left in the main stope seem to be solid calcite, with little or no sulfide content. Arsenopyrite and a little galena were seen in a thin branch vein along the bedding of the limestone. The main vein is cut off at the bottom of the stope by a fault that strikes N. 80° E. and dips 60° S. An exploratory level driven along the fault for 80 meters to the west failed to find any ore other than a small pocket of cerussite. No ore was seen in the mine, which has been abandoned for many years.

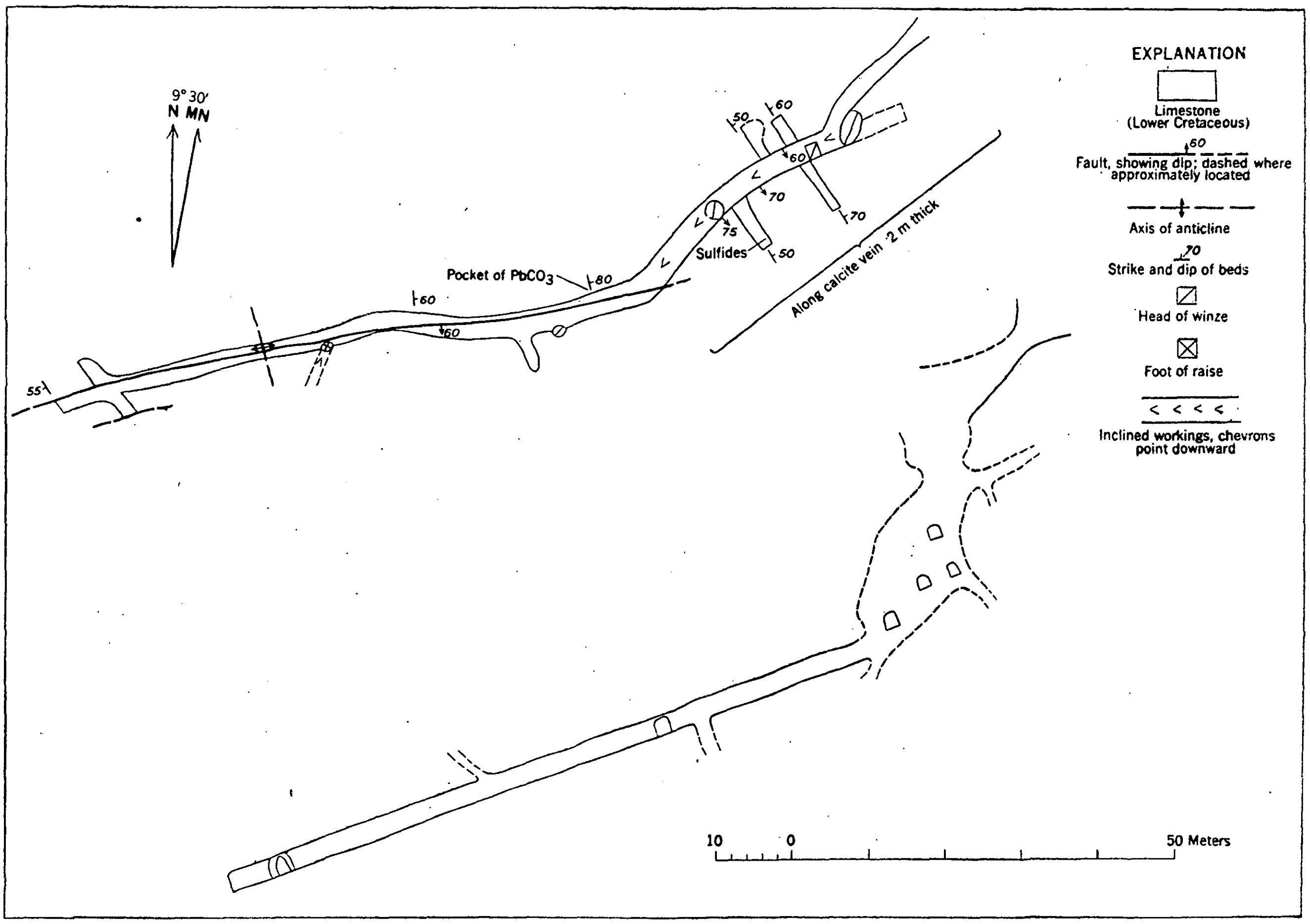

FIGURE 38.—Map and projection of the Concepción mine.

CONCORDIA MINE

The Concordia mine is the only one in the El Monte mining area whose principal production is said to have been copper and silver rather than lead and silver. Little is known about the occurrences of the copper ore, as the only productive parts of the mine are caved. The two principal workings will be described separately.

MAIN ADIT

The southward-trending main, or lower, adit follows contact between the Lower Cretaceous limestone and an El Monte quartz-monzonite dike (fig. 39). A northeastward-trending fracture zone seen 190 meters from the portal was also followed both northeastward and southwestward from the main adit. The accessible parts of the mine have not been productive, for the only mineralization, along the limestone and quartz-monzonite contact, has been very weak although present everywhere along the contact. Sphalerite, galena, pyrite, meneghinite, and chalcopyrite are found in the limestone; chalcopyrite, arsenopyrite, and pyrrhotite are found locally in the quartz monzonite. The metallized limestone contains an average of about 2.5 percent lead, 4–5 percent zinc, and perhaps 400 grams of silver to the ton. According to Spurr (1907, unpublished report), the largest ore bodies occurred along the intersections of the quartz monzonite with east-northeastward-trending vertical fractures in the limestone. Mine-run oxidized ore contained an average of 4.5 percent copper and 500 grams of silver per ton. The mine was worked to a maximum depth of about 45 meters below the adit level. According to Brinsmade (1921), the Concordia ore shoot was from 1 to 4 meters thick and as much as 100 meters long. A typical ore shipment contained 4–5 percent of lead, 1.2 percent of copper, and 800 grams of silver per ton.

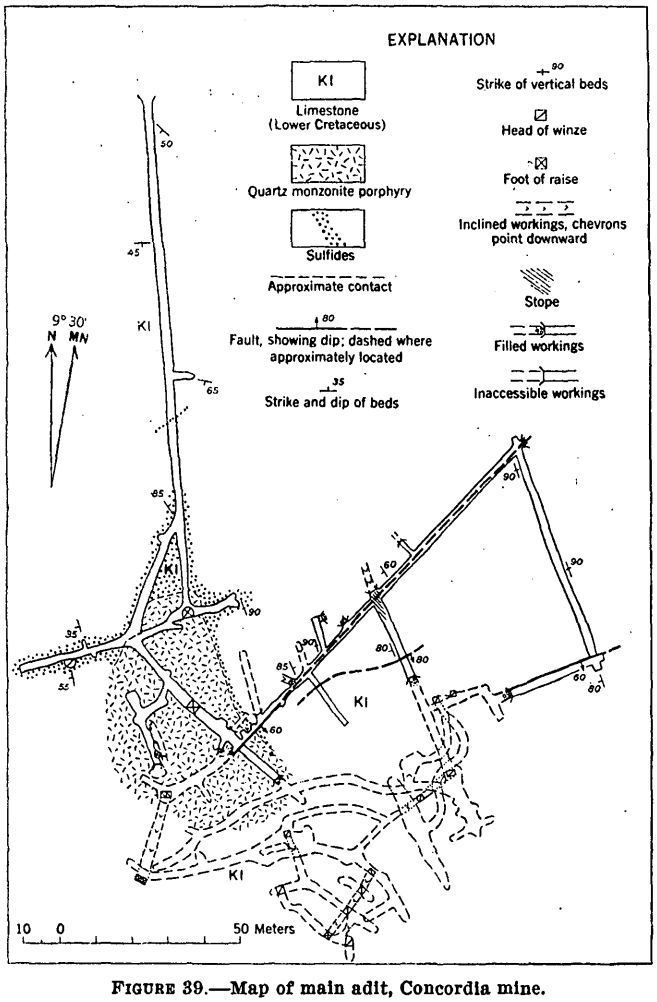

FIGURE 39.—Map of main adit, Concordia mine.

The mine has not been worked for many years and most of the workings at the south end are in bad condition. There seems little likelihood of the caved part of the mine being reopened, as local miners who formerly worked in the mine say that heavy ground caused a nearly total collapse of the old stopes.

INTERMEDIATE ADIT

The intermediate adit follows the Lower Cretaceous limestone and quartz-monzonite contact on two levels, maps of which are given in figure 40. The limestone along the contact is weakly metallized on both levels, but none of the metallized limestone constitutes ore. The same mineral assemblage is present as in the lower Concordia adit.

DOLORES MINE

The Dolores mine has probably been one of the major producers in the El Monte mining area. Most of the mine workings were either inaccessible or flooded at the time of our work in the area, but there is at least one sizeable stope of oxidized ore in limestone. According to Flores (1924, p. 125), ore was found along the contact of igneous rock and limestone; he says that galena, chalcopyrite, cerussite, and malachite were found in highly marmarized limestone, and he mentions an average grade of 10–15 percent of lead and 500–700 grams of silver per ton. Brinsmade (1921) states that the largest ore body was 40 meters long and was worked in oxidized ore to a depth of 100 meters, where sulfides were found.

Remnants of oxidized ore in the old stopes were being extracted on a very small scale by gambusinos in 1948–49. The ore was largely plumbojarosite accompanied by a little smithsonite, cerussite, galena, and a copper arsenate, perhaps olivenite.

LA LUCILA ADIT

The La Lucila adit (fig. 41) follows the contact between Lower Cretaceous limestone and deeply weathered

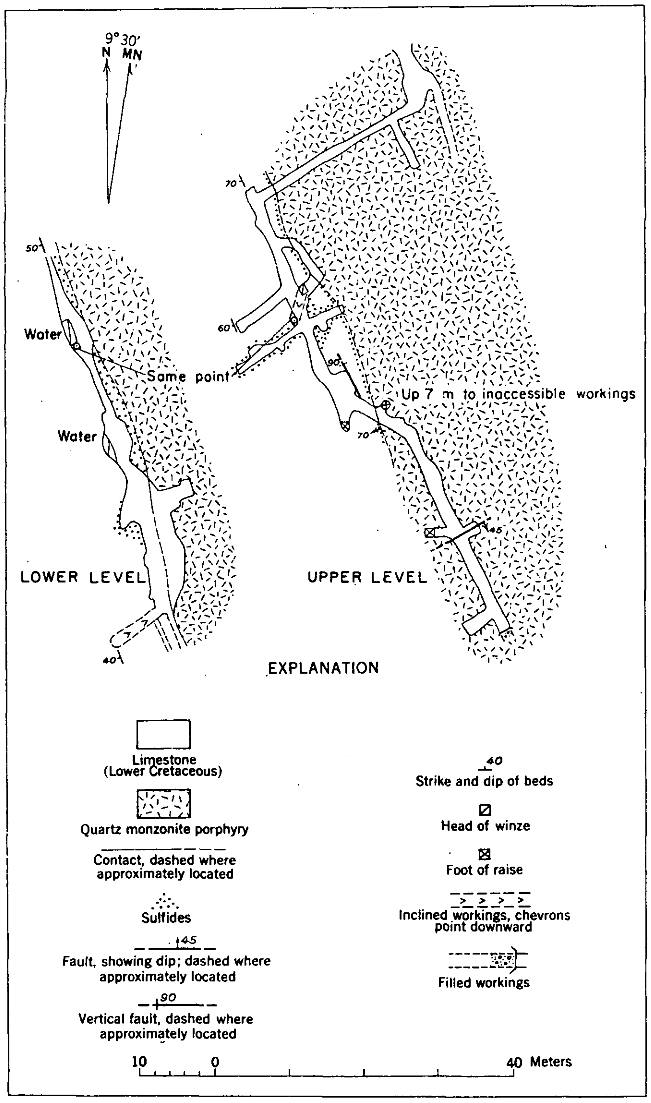

FIGURE 40.—Map of the intermediate adit, Concordia mine.

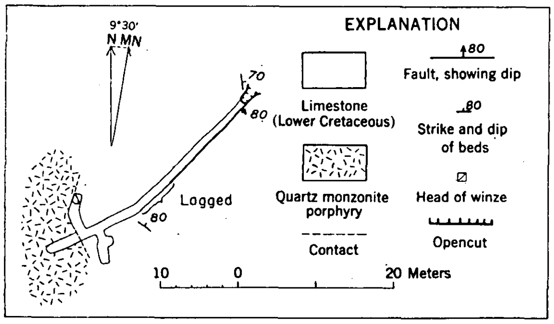

FIGURE 41.—Map of La Lucila adit.

quartz monzonite. The workings below the winze were inaccessible and no ore was seen in the adit.

MIGUEL HIDALGO MINE

The Miguel Hidalgo mine was the only one in the El Monte area that was yielding a significant amount of ore during 1948–49. It was the center of the Compañía Minera Fresnillo exploration program.

Mine workings consisted of a 220-meter southwestward-trending adit, six drifts, and many winzes and raises (fig. 42). The country rock is largely steep-dipping Lower Cretaceous limestone striking northwestward, and quartz monzonite appears near the end of the main northwest drift. A 57-meter winze 110 meters from the portal was formerly the source of a small production of oxidized ore. This winze was inaccessible because of gas infiltration in 1948. Beyond the winze a series of northwest and southeast drifts follow two mineralized zones lying approximately along the bedding of the limestone. A series of joints with a dominant northeastward trend was found in the workings southwest of the winze. The last 40 meters of the adit is along a northeastward-trending gougy fault with a strike-slip displacement of 10 meters.

Although a little oxidized ore has been found along some of the joints, mainly in the second and third northwest drifts, southeast of the winze, the only sizeable ore bodies found have been in the first northeast drift (fig. 43). Four small sulfide ore bodies, the largest of which was 32 meters long and averaged about 1 meter in thickness, were found along this drift over a distance of 90 meters. In addition, a small chimney of sulfide ore was found 40 meters from the mouth of the drift, and an oxidized chimney was cut 5 meters from the southwest wall of the drift 55 meters from the mouth. The shape of the chimney was not known at the time of our survey, but the sulfide chimney had been disclosed by a 45-meter raise inclined about 40° SE., and the oxide chimney by an irregular raise 24 meters high.

The ore bodies of the northwest drift are typical pyrometasomatic replacement deposits. Their gangue mineral content has been described in the section on metamorphism. Pyrite and arsenopyrite are the earliest sulfides formed, and they are followed by sphalerite and pyrrhotite. Galena, a little jamesonite, and chalcopyrite in veinlets are the latest sulfides formed. Lead-silver assays of the three largest ore bodies in the northwest drift are plotted in figure 19. The ore averages 4–5 percent lead and about 250 grams of silver per ton. Zinc is commonly much more abundant than lead, averaging probably 10–15 percent of the ores.

Sulfides of the sulfide chimney are similar to the others and need no further description, except that they are slightly richer in lead and silver than the sulfides of the drift. Ore from the oxide chimney is largely plumbojarosite, although a little cerussite and unoxidized galena are also present. The ore is much richer in lead and silver than any of the sulfide ore, aver-

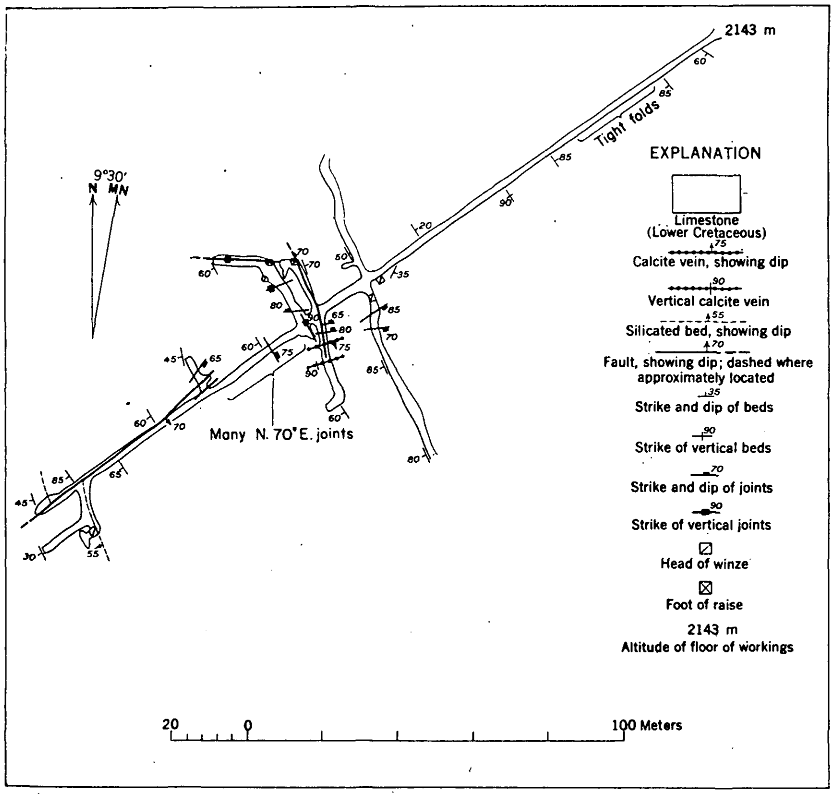

FIGURE 42.—Map of level, Miguel Hidalgo mine.

aging perhaps 18–21 percent lead and about a kilogram of silver per ton. A selected sample of what appeared to be pure plumbojarosite assayed 17.8 percent lead and 1,695 grams of silver per ton.

PEÑALEJOS MINE

The Peñalejos mine is almost completely inaccessible, although the bottom of the mine was reached by a series of ladders. The ore body exploited was a tabular chimney localized in the footwall of a steep-dipping shear zone along its intersection with a tightly folded overturned anticline. The ore consists of early-formed arsenopyrite and pyrrhotite cut by veinlets of sphalerite, galena, and a little chalcopyrite. The upper part of the ore body was oxidized. A little oxidized material on the dump carries iron oxide, gypsum, and a little plumbojarosite and smithsonite.

SAN ANTONIO ADIT

The San Antonio adit extends S. 75° W. for 50 meters along a sheared vertical dike in Lower Cretaceous limestone. The adit ends in an inaccessible winze, and no ore was seen.

SAN FRANCISCO MINE

The San Francisco mine is 2 kilometers east-northeast of the El Monte mining area but is included in this section for convenience. Although it is one of the best known and largest mines in the district, practically nothing is known of the type, grade, or amount of ore produced. All the stopes are inaccessible, and many parts of the mine are flooded. The mine is very wet and walls of workings are coated in many places with a thick crust of travertine. Accessible workings are the Chalma and San Miguel adits (see fig. 44); the San Francisco adit is caved at the portal.

The Chalma, or lower, workings consist of a west-southwestward-trending adit 470 meters long, drifts to the northwest and southeast 300 and 235 meters long, respectively, and many other drifts and crosscuts totaling about 500 meters in length. Most of the production came from stopes above the southeast drift. Country rock near the portal is shaly limestone of Upper Jurassic(?) age, and the rest of the mine is in folded Lower Cretaceous limestone, which in general strikes northwestward to north-northwestward. Three thin andesite dikes and a diabase(?) dike were cut underground. The only ore seen was a thin bed of plumbojarosite along the intersection of Lower Cretaceous limestone dipping 40° SW. with a vertical diabase dike striking eastward. According to Flores (1924, p. 125), the ore bodies formerly exploited were either bedded replacement deposits (mantos) or veins. As far as we could tell, the bedded deposits must have been the more productive, as the stopes appeared to follow bedding.

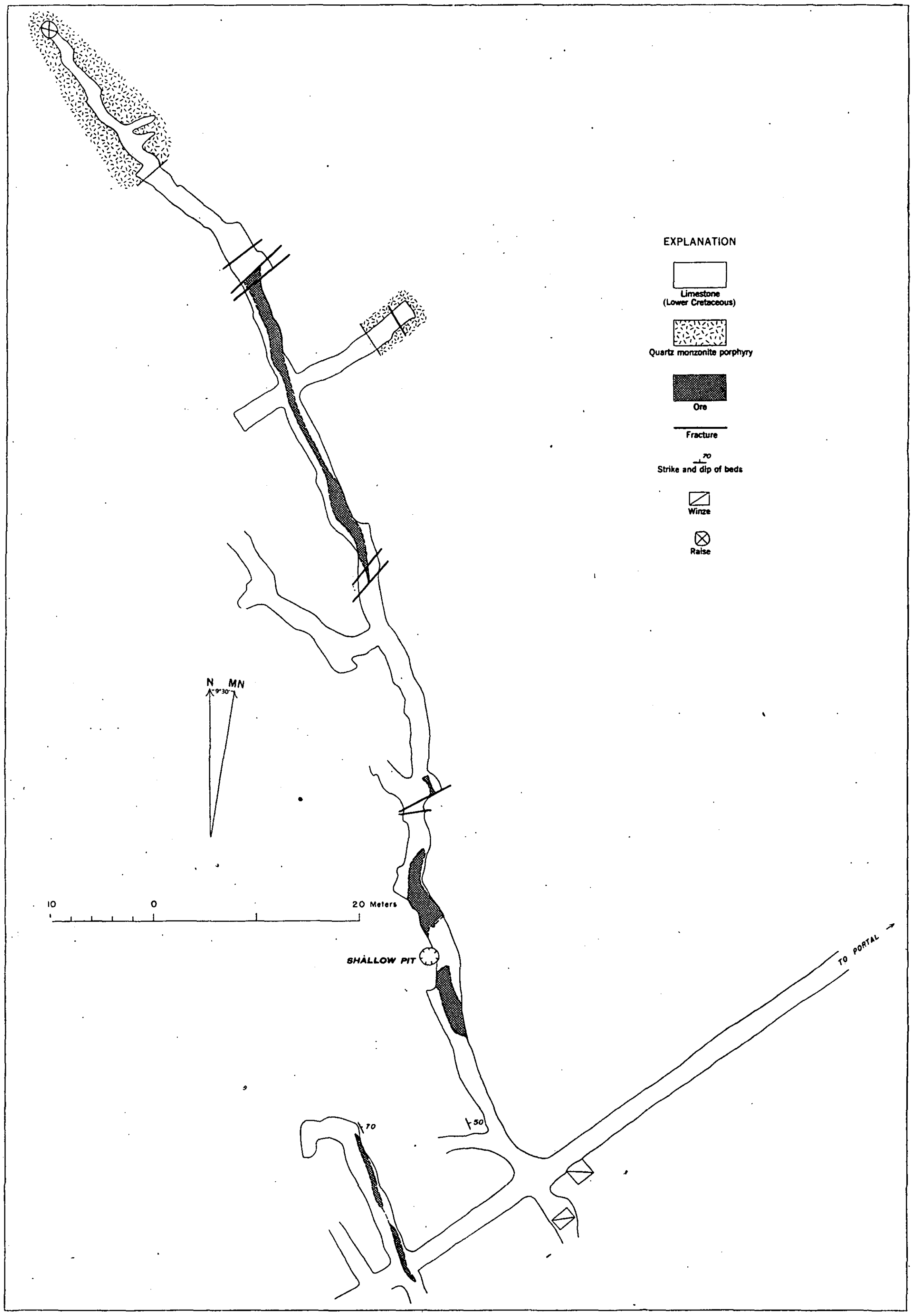

FIGURE 43.—Map of northwest drifts, Miguel Hidalgo adit.

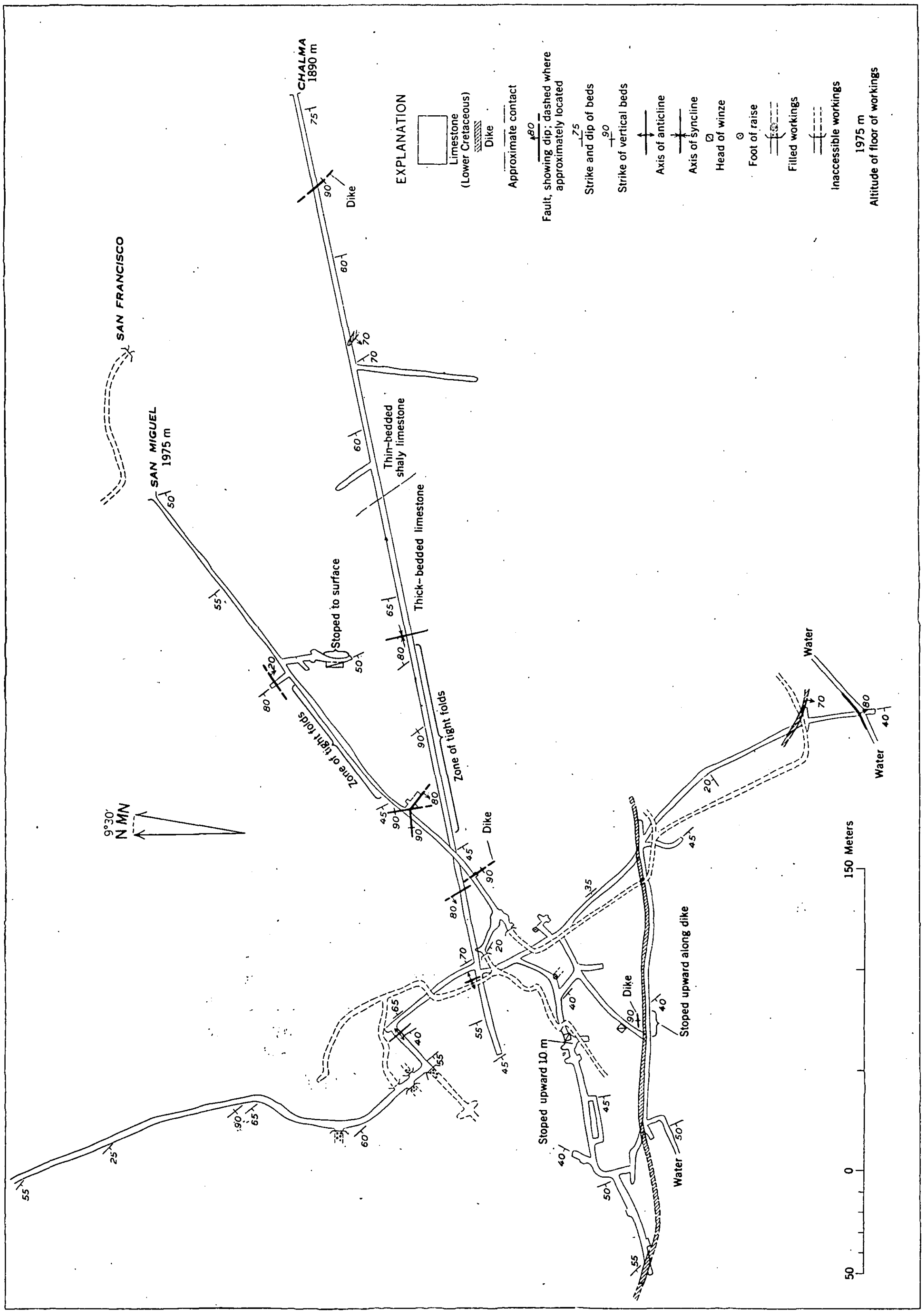

FIGURE 44.—Map of workings, San Francisco mine.

The San Miguel workings, 85 meters above the Chalma workings, consist of a southwestward-trending adit 275 meters long and several short drifts along the bedding of the limestone. The adit is caved at the southwest end, but old maps show drifts northwest and southeast along the same mineralized zone as that followed by the main drifts of the Chalma workings. A small oxidized ore body in the south drift 105 meters from the portal has been stoped to the surface. No other ore deposit or mineralization of any kind was seen in the adit.

The only information as to the type of mineralization comes from dump material. Most of the dump rock is highly pyritic quartz with a little arsenopyrite, galena, and sphalerite. Banded quartz-pyrite rock is abundant. A thin section of quartz-pyrite-arsenopyrite rock showed euhedral sulfide grains imbedded in quartz which grew in two generations. Early-formed granular quartz with many tiny vugs was followed by late-formed quartz which filled the vugs. The late-formed quartz grew in optical continuity with the early-formed crystals projecting into the vugs. Many needles of a mineral believed to be zoisite are imbedded in the quartz. In addition to quartz-pyrite rock, a little calcite with disseminated pyrite and scarce sphalerite was seen. Inasmuch as the dump material probably represents the lower grade ore that was rejected, it gives few clues as to the higher grade mineralization. According to the mine owner, Sr. Jorge Preisser, the ore was very rich in silver, some of it assaying several kilograms per ton.

In 1949, exploration was being carried out along the northwest drift of the Chalma adit, but no ore had been found, although weak sulfide mineralization appeared along a dike intersected some 325 meters from the adit.

SAN VICENTE MINE

The San Vicente mine is the northernmost mine of the El Monte mining area. Mine workings consist of an adit which leads to an incline along a rusty limestone bed, and two exploration headings at the bottom of the incline (fig. 45). Country rock is Lower Cretaceous limestone. The lower workings of the mine are the source of much of the water used at the Compañía Minera Fresnillo camp.

Apparently the only ore produced came from an oxidized ore body along the contact of a deeply weathered dike cut in a short crosscut off the main adit. The stope is about 22 meters long, 2 meters wide, and 7 meters high, but no ore of any kind was seen in it.

According to local miners, good ore was found in a flooded winze at the bottom of the incline. No ore was seen in either of the exploration workings, one of which is along a fault striking about N. 45° E. and dipping 55°–65° SE. A few small stopes have been opened along oxidized zones in faults or fractures, but none appears to have yielded ore.

SANTA TERESA ADIT

The Santa Teresa adit is short, trending south-southeastward in Lower Cretaceous limestone along the crest of a nearly symmetrical anticline striking N. 30° W. The anticlinal limbs dip at about 50°. Weak mineralization along a limestone bed produced fluorite, quartz, and a little garnet and diopside, followed by sphalerite, galena, and sparse arsenopyrite.

EL SANTISIMO MINE

The El Santísimo mine is completely caved except for a 60-meter adit along a deeply weathered dike striking S. 75° W. and dipping 70°–80° SE. Country rock is Lower Cretaceous limestone which strikes north-northwestward and dips steeply southwestward. The mine was operated at least 70 years ago. Busto (1880) mentions ore from three "veins" containing 10–12 percent lead and 20 ounces of silver per ton. The mine was also probably operated during 1913, according to local miners. Nothing is known about production, but the size of the caved area suggests that a large stope was opened.

LA SORPRESA MINE

The La Sorpresa mine consists of an incline 50 to 60 meters long and a short adit. The upper incline is along a deeply weathered bed in Lower Cretaceous limestone striking N. 30° W. and dipping from 70° NE. to 60° SW. Just beyond the portal the working becomes too steep to descend. No ore was seen.

The lower adit trends S. 20° E. along a 50-cm weathered dike which parallels the axis of a tightly folded anticline overturned to the southwest. At the portal the limestone is slightly metamorphosed for a few centimeters from the dike and carries a little sphalerite. A rusty bed on the northeast limb of the anticline has been followed by several short inclines, but no ore was found. The working ends against an eastward-trending vertical fault.

TECOMATES MINE

The Tecomates mine yielded ore from a small manto deposit enclosed in Lower Cretaceous limestone. Mine workings are a 57-meter adit trending nearly due west and a crosscut to the ore body, which was stoped to the surface (fig. 46). A deeply weathered dike of unknown composition was cut near the end of the adit. The dike strikes N. 70° E. and dips 80° SE.; it may have been a channel of circulation during the formation of the ore body but is not in contact with the ore at any point.

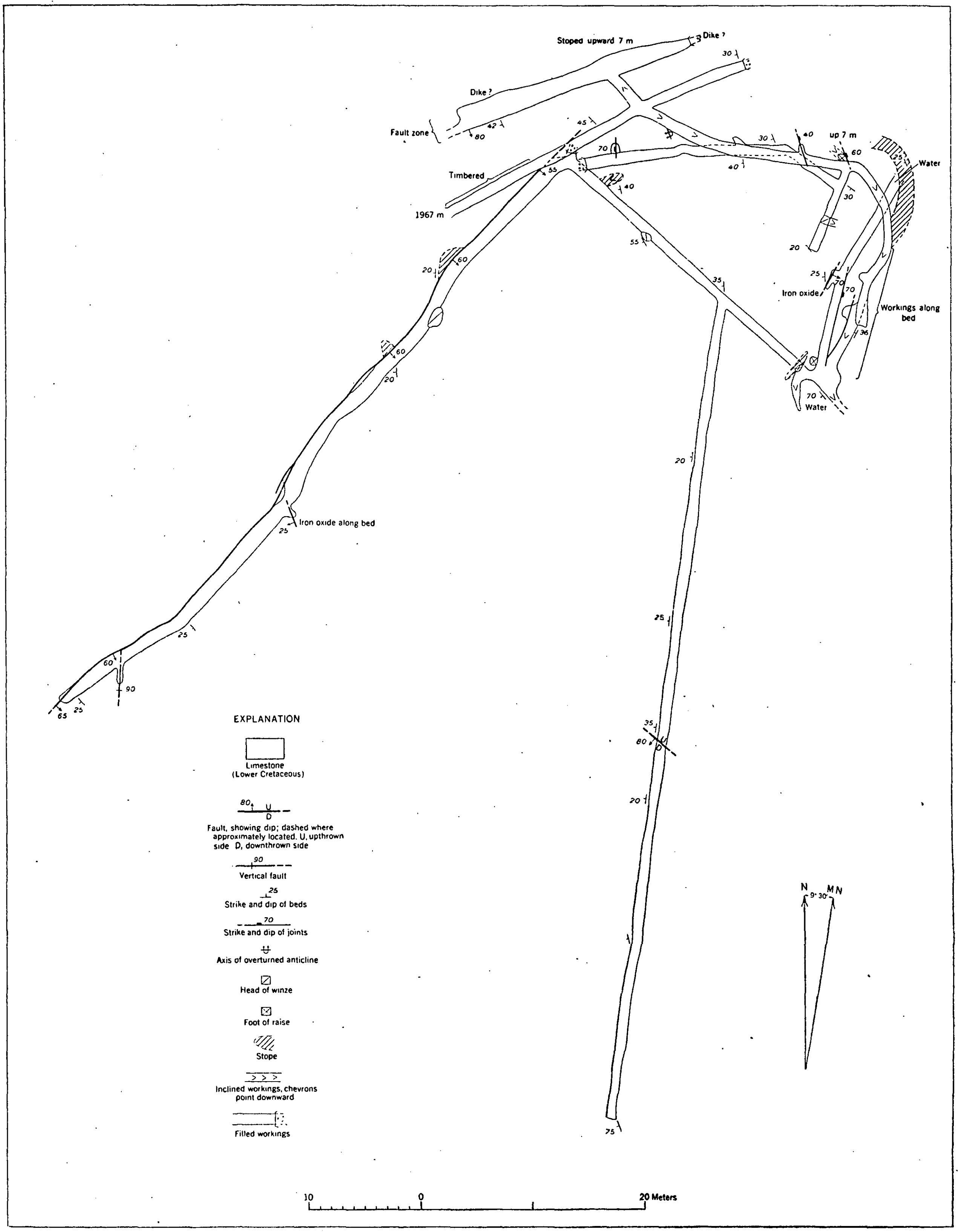

FIGURE 45.—Map of San Vicente Mine (El Monte).

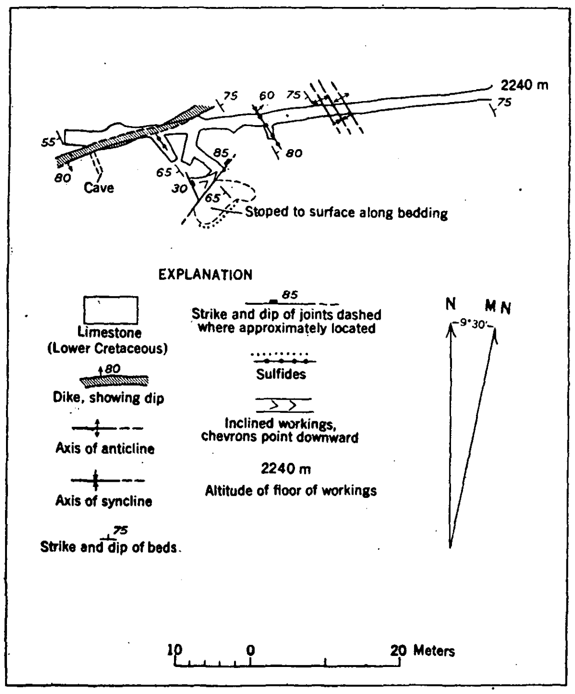

FIGURE 46.—Map of Tecomates mine.

The manto itself lies along the bedding of Lower Cretaceous limestone which strikes N. 40°–50° W. and dips 55°–65° SW. The northwest wall of the manto is a nearly vertical joint striking N. 35° E. The ore body was very small, averaging perhaps 1 meter in thickness by 5 meters in width, and it was stoped for about 25 meters. Ore minerals are the typical El Monte assemblage. Arsenopyrite and pyrite appear to be the earliest sulfides formed, followed by sphalerite, pyrrhotite, and jamesonite; galena is very scarce. Calcite and unreplaced limestone are the only gangue minerals. Most of the ore extracted was apparently not utilized, as a large pile of it was seen near the mine. Assays of mine-run ore average about 20 percent lead, 12 percent zinc, and 1 kilogram of silver per ton. Most of the lead is in jamesonite. The deposit appears to be mined out, and only a few thin sulfide stringers were seen in the workings.

CARRIZAL MINING AREA

Nineteen mines and prospects in the Carrizal mining área (see pl. 1 and fig. 47 for location) are described below. Many other mines and prospects were seen during the course of this survey, but for reasons of inaccessibility or lack of importance they are not included here. For convenience in discussion, the mines on the west side of Barranca de Tolimán will be considered separately from those on the east side. The west-side mines are all small producers.

WEST SIDE OF BARRANCA DE TOLIMAN

AMISTAD NO. 3 PROSPECT

The Amistad no. 3 prospect is about 1 kilometer north of the center of the Carrizal mining area, near the bottom of the Río Tolimán canyon. The only excavation is a short adit along a calcite vein 60 to 100 cm thick which strikes N. 20° E. and dips 65° NW. A lead-bearing segment 30 cm thick along the footwall of the vein is thoroughly oxidized to plumbojarosite. Considerable pyritic opal occurs in pockets along the vein. The prospect is not important.

LAS ANIMAS MINE

The Las Animas mine is 370 meters above the Río Tolimán. It has produced more than the other west-side mines, but recent production has been small and has consisted largely of ore rejected in earlier mining and piled in the stopes. Production will probably continue to decline, as the easily removed rejected ores were nearly mined out in 1948 and new exploration had not proved very productive. Ore was carried by a gravity-operated aerial tram to a platform near the Santa Clara mine, and from there by another aerial tram to the bottom of the barranca, whence it was hoisted by a third tram to loading bins near the Los Balcones mine. Figure 48 shows mine workings and sections.

Ore occurs along a series of nearly flat mantos bounded along the northwest side of the mine by a premineralization dike which strikes N. 45° E. and dips 65°–80° NW. A series of northwestward-trending fractures seems to have been a minor structural control. The thickest manto in the mine, 5–7 meters, was found where mantos 2 and 3 were united along a northwestward-trending, essentially vertical fracture. Mantos 2 and 4 have been most productive; manto 2 averaged about 4 meters in thickness, and manto 4 between 1.5 and 2 meters. Manto 1 was a very narrow ore body, and manto 5 is highly pyritic. Mantos 2 and 5 appear to have been connected by an irregular inclined chimney along a northwest fracture.

All the former production was probably of oxide ore, for no sulfides were seen anywhere in the old stopes. Ore being mined in 1948 was largely plumbojarosite. The only new ore body recently found was manto 5, which proved to be largely pyrite. The manto is about 1 meter thick, but nearly half of it is unreplaced limestone. The mine seemed to be practically worked out, unless, as appears very unlikely, manto 5 should improve with further exploration.

LA CHIRIPA MINE

The La Chiripa mine is on the north side of Barranca del Malacate, 1 kilometer west of El Dedhó.

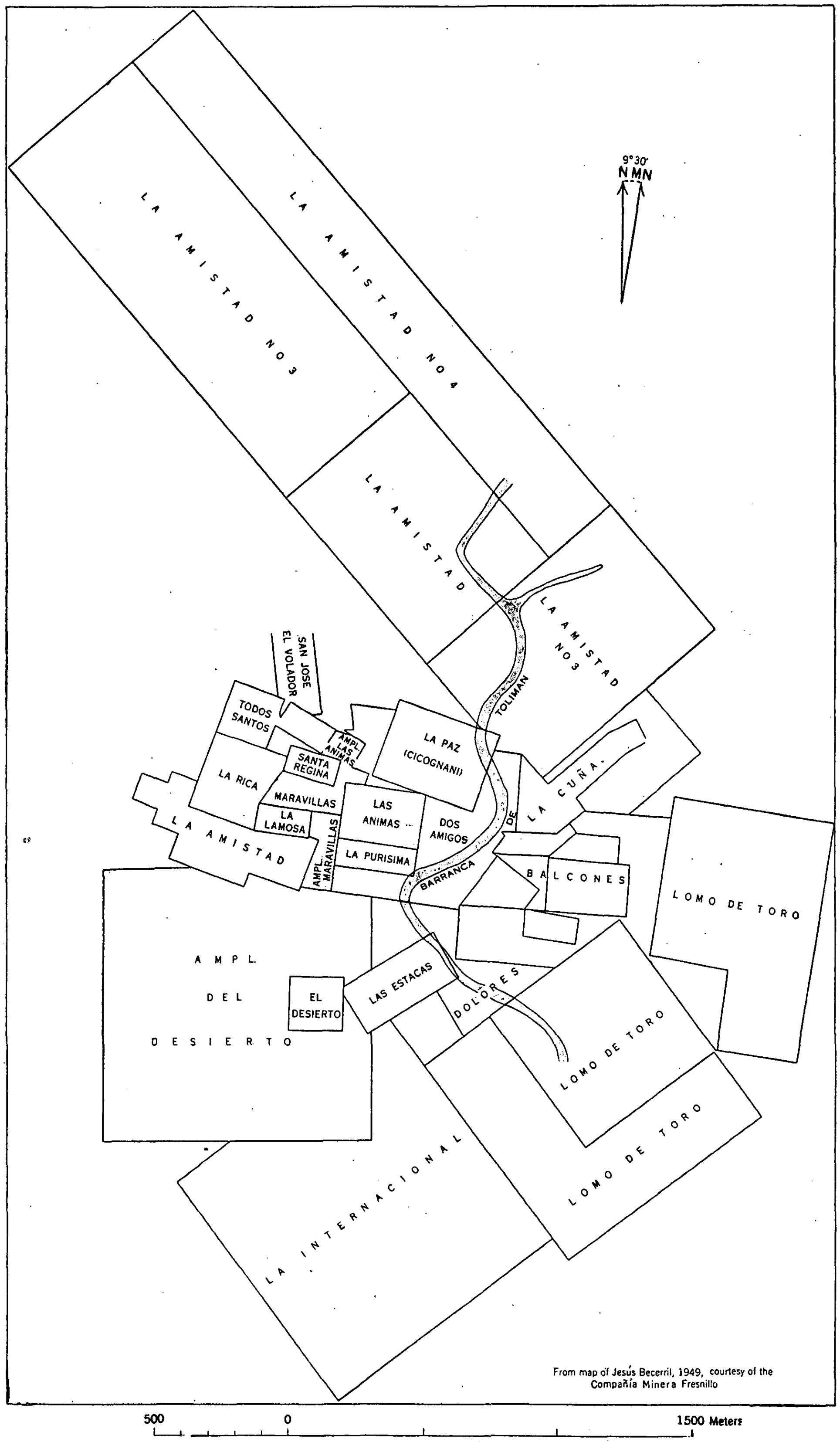

FIGURE 47.—Map of principal mining claims, Carrizal area.

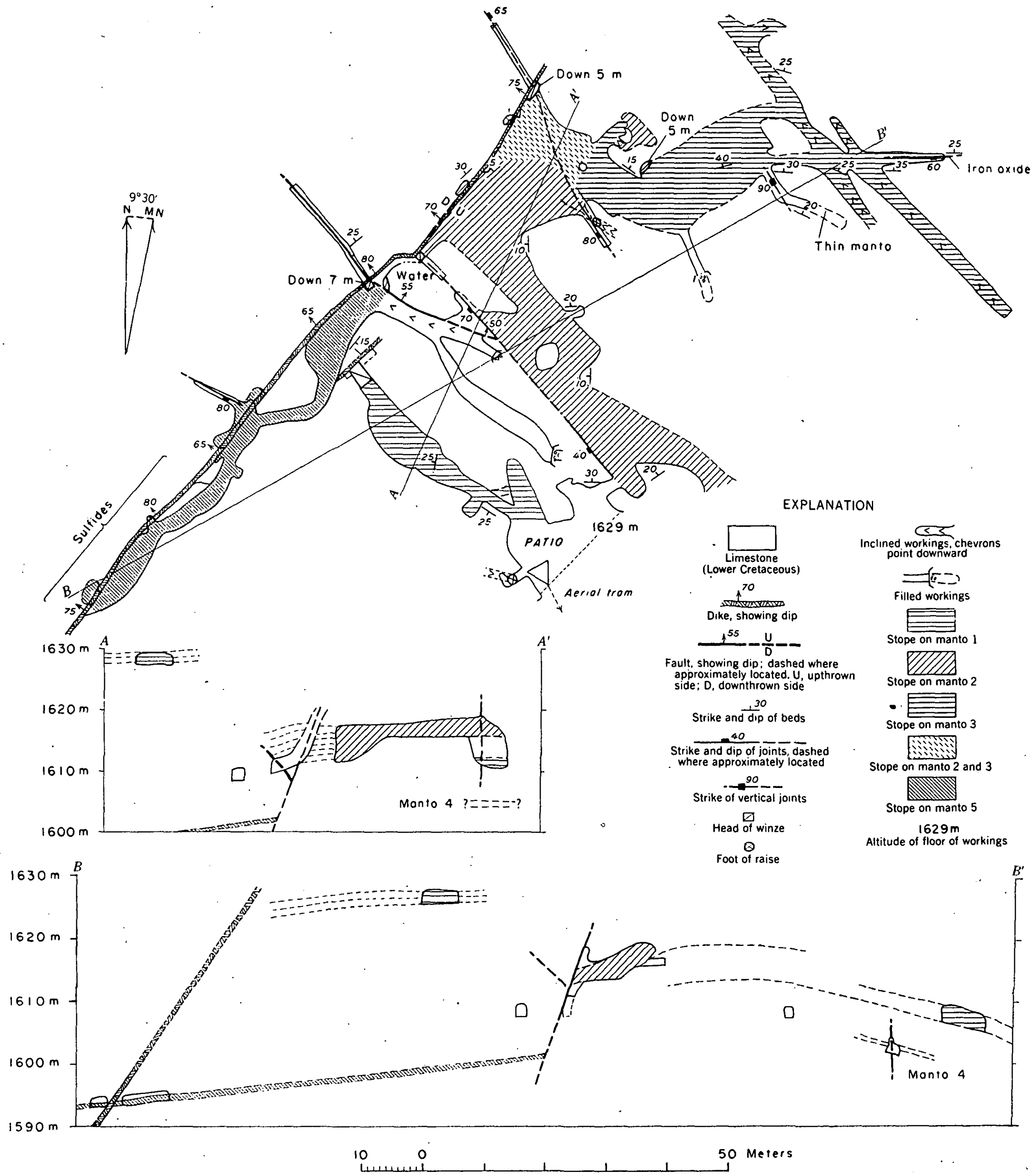

FIGURE 48.—Map and sections of workings, Las Animas mine.

Workings consist of two short adits along northwestward-striking dikes about 50 meters apart. Both adits cut the same thin manto striking N. 75° W. and dipping 45° SW. The lower workings on the manto are below the level of Barranca del Malacate and are flooded. No ore was seen in place, but a little galena was seen on the dump. The only gangue mineral was brown carbonate. The mine has been closed for many years and will probably continue to be so because of water seepage.

CINCO DE MAYO ADIT

The Cinco de Mayo adit of the Las Animas claim is a west-northwestward trending excavation 150 meters long (fig. 49). It lies 120 meters above the Río Tolimán. It follows the contact zone of three quartz latite dikes which intruded Lower Cretaceous limestone. Along the contacts the limestone is highly metamorphosed and converted to tactite, so that underground it was difficult to distinguish from dike rock. Tactite mineral content was described in the section on metamorphism.

Pyrite occurs in the contact zone in thin stringers and disseminated through the altered limestone. Near the end of the adit a zone of tactite containing pyrite and sphalerite was cut and some ore was removed. The stope is now filled and inaccessible but it was apparently very small. No other stope was seen.

About 45 meters above the Cinco de Mayo adit, a weakly metallized tactite zone has been unsuccessfully explored by a pit 5 meters deep. The prospect is along the contact between a tactite zone 15–20 meters wide and isoclinally folded Lower Cretaceous limestone. Sphalerite, pyrite, and calcite occur in both tactite and limestone as thin veinlets, pods, and irregular stringers. They are accompanied by a little galena and chalcopyrite. Galena is formed later than the sphalerite-pyrite-calcite veinlets. None of the rock seen constituted ore.

Ninety meters above the Cinco de Mayo adit a manto 1 to 1.5 meters thick along the bedding of Lower Cretaceous limestone at the intersection with a dike has been stoped upward for about 20 meters and along the strike for about 5 meters. The limestone strikes N. 20° W. and dips 45° SW. The dike strikes N. 65° E. and dips 85° SE. Mineralization, which is very weak, produced pyrite, sphalerite, galena, and a little chalcopyrite disseminated in the limestone.

EL ESPIRITU MINE

The El Espíritu mine lies at an altitude of 1,980 meters on the precipitous northeast slope of Cerro de Los Lirios in the extreme northwest corner of the area mapped. Country rock is chert-bearing Lower Cretaceous limestone which strikes N. 45°–70° W. and dips 40°–60° SW. A manto 1–1.5 meters thick has been developed for some 50 meters southeast along the strike and 15–20 meters down the dip. The ore body pinched out at the southeast end. The mine workings downdip are filled with waste. A winze 10 meters deep along a N. 55° W. vertical fracture connects with a lower manto which strikes N. 45° W. and dips 20° SW. Workings along the lower manto extend 30–40 meters downdip into caved ground. The upper manto was largely plumbojarosite and iron oxide; the lower manto, about 1 meter thick, is largely iron oxide and jasper with a little interlaminated plumbojarosite. The fracture in the winze connecting the two mantos is a fault of small displacement filled with 10 cm or so of limonitic gouge.

Possibilities of finding additional ore by prospecting southeastward along the strike of the upper manto seem fair, but the great distance of the mine from transportation is a severe handicap. The mine appears to have been long abandoned and is badly caved.

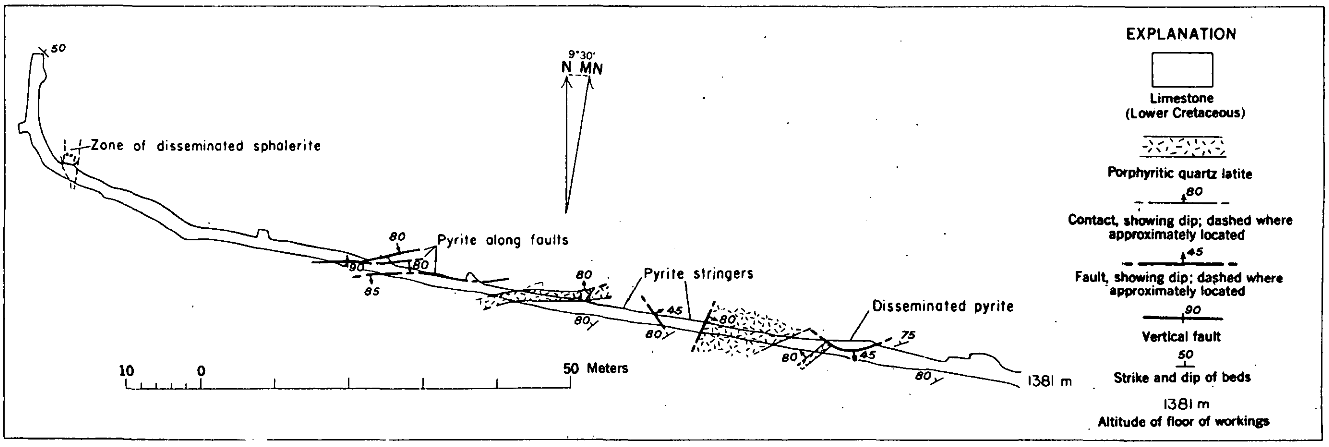

FIGURE 49.—Map of Cinco de Mayo adit.

LAS ESTACAS MINE

The Las Estacas mine is just above the bottom of Barranca de Tolimán about 400 meters downstream from the mouth of El Cajón. Mine workings, a single irregular stope, are shown in figure 50. The ore body

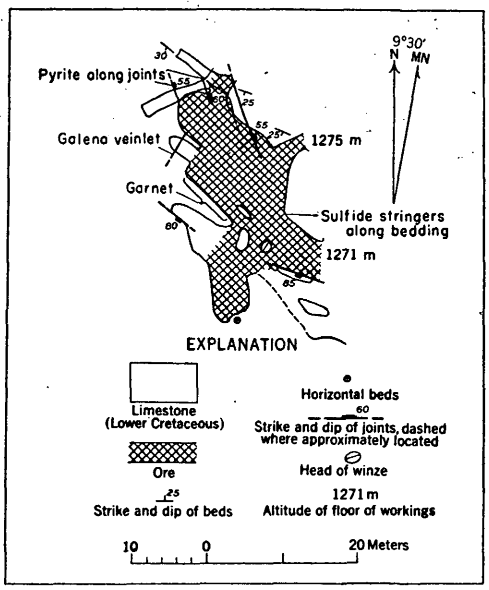

FIGURE 50.—Map of Las Estacas mine.

exploited was a sulfide manto partly enclosed in tactite. The walls of the stope in several places are solid tactite against which the ore terminated abruptly, but elsewhere ore feathers out into limestone in a series of thin stringers parallel to the limestone bedding. Country rock is Lower Cretaceous limestone which strikes northwestward and dips 25°–30° SW. The few northwestward-trending fractures seen had little apparent effect on localizing ore, although the northwesterly elongation of the ore body suggests that they may have exercised some control. Pyrite and galena were seen along some of the fractures.

The ore extracted was a high-grade sphalerite-galena ore with minor amounts of pyrite. Banding parallel to the bedding of the enclosing limestone is prominent in the ore. Layers of essentially solid sulfide alternate with tactite. The original ore body has been worked out, but the possibility of discovering additional ore along the same bed or series of beds seems good.

LA PAZ MINE

The La Paz mine is about 210 meters above Barranca de Tolimán at the foot of the great promontory of La Ortiga. Mine workings consist of a stope along a manto, and an irregular winze which followed an ore chimney. Country rock is Lower Cretaceous limestone which is gently folded and has dips of as much as 30°. A projection of the manto and chimney workings is given in figure 51.

The manto averaged about 2 meters in thickness over an area about 35 by 60 meters, and was more than 3 meters in thickness locally. Considerable ore came from a series of mineralized northwestward-trending fractures. All the ore mined was apparently oxidized, plumbojarosite being an important ore mineral. The chimney ore body averaged about 8 meters in diameter and was followed to a depth of at least 80 meters below the manto.

EL ROSARIO MINE

The El Rosario mine is on the northeast slope of Cerro de Los Lirios at an altitude of 2,150 meters, 170 meters above and southwest of the El Espíritu mine. The main excavation is a stope along a manto striking N. 70° W. and dipping 40° SW. The stope extends downdip for at least 100 meters and probably averages more than 10 meters in width.

Much of the stope is caved, but the ore body seems to have been completely mined out except for a pillar of plumbojarosite and iron-oxide ore half a meter thick near the lower end of the stope. The manto has a maximum thickness of 10 meters. According to a local miner, the ore was entirely lead and silver, no zinc, copper, or gold having been found.

A second parallel manto was found 15 meters below the upper manto. The two mantos are connected by a winze which appeared to be along a mineralized fault, but the ground was caved so badly that no close obser-

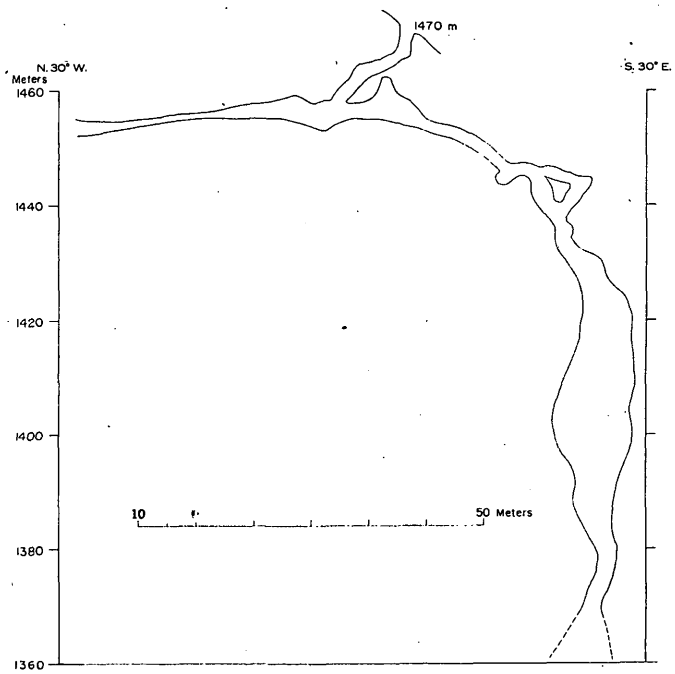

FIGURE 51.—Projection of workings of La Paz mine.

vations could be made. The lower manto was very thin and seems to have been of low grade. A few small northwestward-trending faults cutting the lower manto have thin veinlets of galena along them; elsewhere all the ore is oxidized. Exploration carried out along the strike of the known ore bodies did not discover ore, and the deposit appears to be completely worked out.

SAN GUILLERMO ADIT

The San Guillermo adit is 170 meters above the Río Tolimán, just above the highest outcrop of quartz monzonite on the west side of Barranca de Tolimán. The adit is 130 meters long and trends about N. 60° W. (fig. 52). A thin dikelike tactite mass forms the south wall of the adit for the first 65 meters from the portal; from that point to the end the wall is a fault dipping 85°–90° NE. A second tactite mass striking N. 20° E. traverses a cave intersected about 35 meters from the portal. Country rock is folded Lower Cretaceous limestone which strikes nearly parallel to the adit.

The limestone in the last 55 meters of the adit is metamorphosed and contains disseminated sulfides. Two raises and a stope along a thin manto have followed the sulfide-bearing limestone. The mineralogy of the metamorphosed limestone is described on p. 42.

Sulfide minerals recognized include pyrrhotite, pyrite, sphalerite, galena, and chalcopyrite. Only pyrite is abundant, although small pockets of galena-sphalerite and galena-pyrrhotite were seen. Pyrrhotite and pyrite are early-formed sulfides; chalcopyrite appears to be the latest formed. Wollastonite, calcite, and a little fluorite are the principal gangue minerals. Mineralized rock at the San Guillermo adit is highly pyritic, and the small quantities of sphalerite and galena in the tactite do not constitute minable ore.

SAN VICENTE MINE

The San Vicente mine is in the southwest part of the Carrizal mining area and will be described together with the San Cayetano and El Intermedio mines, with which it forms a natural unit.

Mine workings consist of a steep incline along a 50-cm andesite (?) dike which strikes N. 5° E. and dips 70° E., and a small stope in the hanging wall of a fault which intersects the dike 9.5 meters below the portal of the incline. The fault strikes N. 20° W. and dips 50° NE. A little galena and pyrite occur along the fault, but most of the ore extracted came from stringers along the bedding of Lower Cretaceous limestone in the hanging wall of the fault. The limestone strikes N. 60° W. and dips 35°–40° SW. The ore consists largely of galena and sphalerite; pyrite is common, and a little jamesonite occurs in places. Calcite is the only abundant gangue mineral, pale-green fluorite is subordinate, and quartz is rare. Mineralization generally is very weak, sulfides rarely composing as much as 10 percent of the metallized limestone.

The San Cayetano mine is 30 meters below and north of the San Vicente mine. Mine workings consist of a 10-meter adit along a southward-striking dike, and a

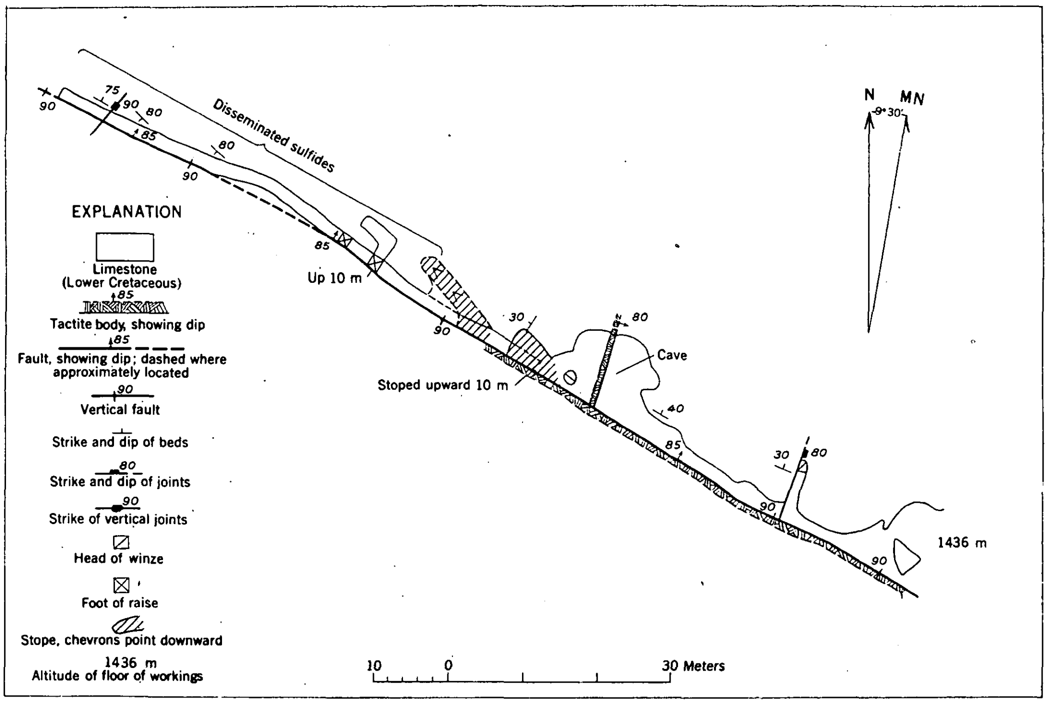

FIGURE 52.—Map of San Guillermo adit.

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small inaccessible stope to the southwest along a fault which cuts off the dike. The fault strikes N. 55° W. and dips 40° NE. Possibly the dike is the same as that of the San Vicente mine. A flooded winze, said to be 50–60 meters deep, was sunk at the intersection of dike and fault. According to local miners, small pockets of ore found in the winze assayed 12–15 percent lead and 3–4 kilograms of silver per ton. No ore was seen in the mine.

The El Intermedio prospect, 20 meters below the San Cayetano mine, consists of a shaft 8 meters deep in the footwall of a dike which strikes N. 80° W. and dips 80° N., and a short drift along the dike. In the drift a few sulfide stringers cut Lower Cretaceous limestone which strikes N. 15° W. and dips 15° NE. The ore is principally disseminated pyrite cut by veinlets of galena. One pocket of sphalerite was seen, and a little jamesonite was doubtfully identified.

None of the mines in the San Vicente group is particularly promising, because of the very low grade and small quantities of ore available. They have never yielded any significant production.

SANTA CLARA MINE

The Santa Clara mine workings are 130 meters above the Río Tolimán. They consist of an adit 95 meters long and two stopes along the footwall of premineralization faults. The portal is in quartz monzonite, but a short distance underground, metamorphosed Lower Cretaceous limestone is found and the rest of the workings are in that rock. Four porphyritic dacite dikes are cut in the adit. Workings are shown in figure 53.

Both ore bodies are tabular chimneys localized along faults. The ore body near the portal was apparently oxidized, but the main ore body is sulfide. Sulfide stringers locally follow the bedding of the limestone, which is contorted, but the shape of the main ore body has been determined to a large extent by the fault that forms its hanging wall.

Principal sulfides are pyrite, sphalerite, and galena, of which both coarsely crystalline galena and the fine-grained "steel" variety are found. A little arsenopyrite was seen in the metamorphosed limestone. Calcite and fluorite are the dominant gangue minerals. Crystals of light-green fluorite as large as 2 cm across were seen in vugs with calcite and galena. A significant but unknown production has come from the mine, which is the second largest producer among the west-side mines.

LA SIRENA PROSPECT

The La Sirena prospect is on the steep northwest slope of Cerro de Los Lirios in the gorge of the Río Moctezuma a short distance above its confluence with the Río Tolimán. The deposit lies about 600 meters above the Río Moctezuma and is extremely difficult and dangerous to reach. It was not seen during this survey but was examined by Lindgren in 1913. The following description is quoted from a paper published by Lindgren and Whitehead (1914, p. 458–459).

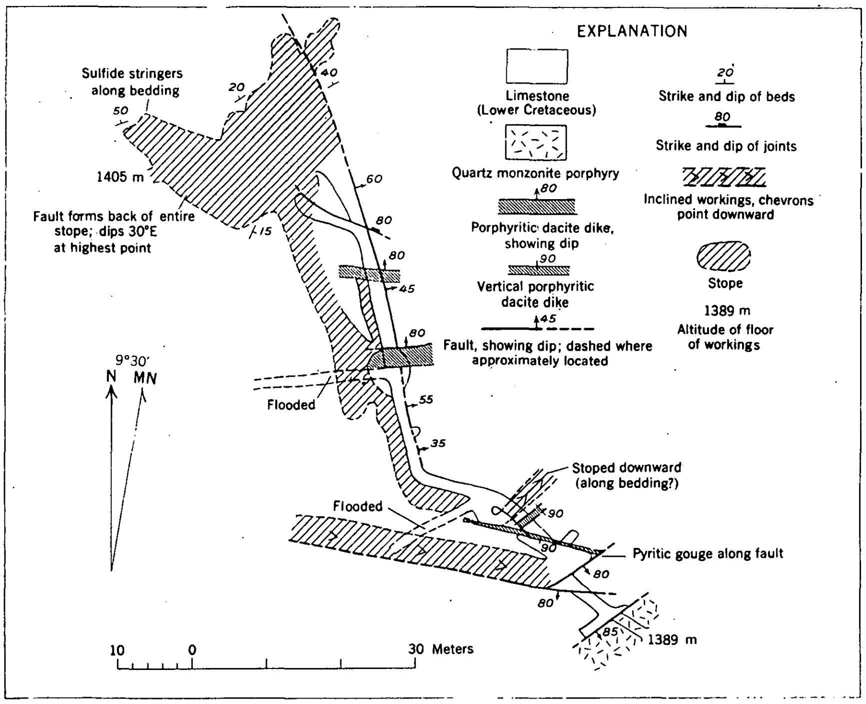

FIGURE 53.—Map of Santa Clara mine.

The deposit of La Sirena is formed by replacement of limestone. It occurs not more than 2,500 feet below the Cretaceous plateau of Sierra Madre Oriental. Though the depth of erosion of the peneplain of the plateau and the correlation of age of the deposit with this plain cannot definitely be determined, the ore body probably has not been formed at a depth greater than a few thousand feet below the surface. It is of large dimensions and constitutes a mass at least 1,000 feet long and from a few feet to probably over 100 feet in thickness. Its outlines cannot be ascertained from present developments, but it probably forms a flat body with a dip similar to that of the surrounding limestone, whose structure is not disturbed at the contacts of the deposit. The bulk of the deposit is formed by a heavy sulfide ore with up to 50 per cent of gangue. This gangue consists of albite feldspar and quartz with some fluorite, apatite and some residual and recrystallized calcite, the albite being the oldest and fluorite the youngest of the constituents. The metallic ore minerals all of which are probably later than the gangue minerals are, in the order of their formation, arsenopyrite, pyrrhotite, zincblende and jamesonite ($2PbS.Sb_2S_3$). At the eastern end of the deposit where it is of much smaller dimensions two exposures of a basic dike appear, which has been extensively altered.

Near this dike the limestone is somewhat metamorphosed and the products of recrystallization include calcite, quartz, grossularite, albite, danburite, fluorite and actinolite. Of the metallic minerals in this narrow part of the deposit below Punta David pyrite predominates and is older than any of the other gangue or ore minerals. The other sulphides consist of arsenopyrite, zincblende, pyrrhotite and jamesonite. All of the gangue minerals, with the exception of an amphibole which was found deposited in calcite and quartz just before the jamesonite, are here also older than the ore minerals. On the whole the ore formation began by silicification and the development of albite, danburite and fluorite under the influence of boron and fluorine mineralizers. Then followed the introduction of iron, sulphur, and arsenic and the formation of arsenopyrite and pyrrhotite. Finally came zinc, lead, antimony and sulphur to form zincblende and jamesonite.

The dike at the two places where samples could be taken was altered by the introduction of calcite, siderite, pyrrhotite and pyrite; actinolite and pargasite were developed from primary ferromagnesian silicates. The dike specimens also contain some sericite, hydrargillite and chlorite but no ore minerals except the two mentioned were found in the dike.

The development of the replacement in the limestone thus involves the addition of much silica, boron, fluorine, soda, alumina, iron, arsenic, zinc, sulphur, antimony and lead.

TODOS SANTOS MINE

The Todos Santos mine is 630 meters above the Río Tolimán on the top of the great promontory of La Ortiga. Mine workings are in Lower Cretaceous limestone which strikes about north and dips 20°–60° W. All the workings are inaccessible or so badly caved as to be dangerous. Workings lie either along a series of northwest steeply dipping fractures or along the bedding of the limestone. One partly caved stope on a manto deposit is 30 meters long on the surface. The only ore minerals seen on the dump were a little plumbojarosite and scarce cerussite. Calcite and a little quartz were noted as gangue minerals. According to a local resident, sulfides were found at depth. The mine has not been operated for many years, owing, in part at least, to the great distance to truck transportation and the difficulty of access.

LOS TRES ALCANGILES MINE

The Los Tres Alcangiles mine is near the San Vicente mine in the southwest corner of the Carrizal mining area. Mine workings consist of a 10-meter inclined shaft along a fault which strikes N. 70° E. and dips 80°–85° SE. The entire mine is in the footwall of a rhyolite dike which strikes N. 35° W. and dips 65° NE. (fig. 54). A little disseminated sphalerite, galena, and pyrite were found in the footwall of the fault and along the intersection of fault and dike. Calcite and a little garnet were the only gangue minerals seen. The mine shows little promise, for although pockets of high-grade ore have been found, the average grade of the material mined was very low and little ore is expected in the future.

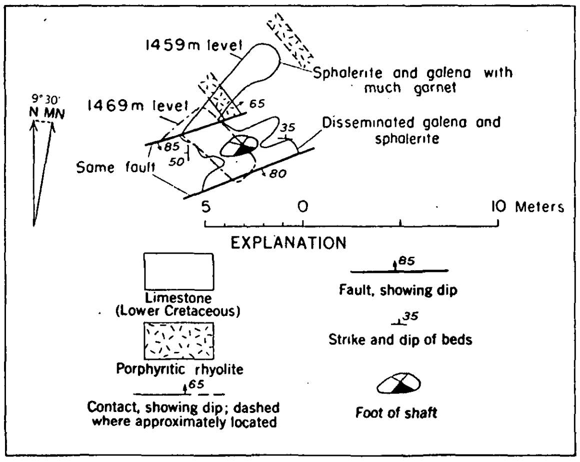

FIGURE 54.—Map of Los Tres Alcangiles mine.

LAS VENTANAS MINES

The Las Ventanas mines are in the northwest corner of the Carrizal mining area about 130 meters above the Río Tolimán on the old trail from the river to La Ortiga. The workings are also known as the Dos Amigos and Santa Cecilia mines. Three workings seen were a lower adit and winze, an upper adit and winze, and an upper stope on a chimney.

The lower adit trends southwest along a latite dike which follows a fault dipping 85° NW. Seventeen meters from the portal a 15-meter winze was sunk in the hanging wall of the dike along a zone of very weak galena mineralization in limestone striking northeastward and dipping 35° NW. A little iron oxide was found in the winze, but the tonnage of ore seen was negligible.

The upper adit and winze workings are on a 2-meter tactite mass which strikes N. 25° W. and dips 80° SW. This mass is unique in the district in that it is composed largely of graular axinite. At about 5 meters from the bottom of the 9-meter winze a little pyrite, sphalerite, and galena form irregular small pockets in Lower Cretaceous limestone striking northward to northeastward and dipping 25° W. to 25° NW. The workings were abandoned at the time of our study.

A contact of ore and limestone is well exposed near the head of the winze. At the contact the ore consists of a layer of strongly banded pyrite-galena-calcite rock 10 cm thick. The layer is succeeded by 5–8 cm of banded calcite-sphalerite ore cut by veinlets of pyrite. The last exposure is 30 cm of coarse cubic pyrite with thin layers of sphalerite. Banding is parallel to the contact, which is very sharp. Sphalerite is the earliest sulfide formed and it was followed by pyrite and galena.

The upper chimney is about 15 meters south-southeast of the upper adit and is localized along the intersection of the same tactite mass seen in the adit and a deeply weathered 2-meter igneous dike striking N. 65° E. and dipping 70° NW.; the two dikes intersect at nearly right angles. The chimney is from 10 to 20 meters long along its northwest axis, 5 to 8 meters wide, and has been stoped to the surface about 40 meters above. The chimney was apparently oxidized. A small manto was found along the southwest side of the chimney in limestone striking N. 65° E. and dipping 25° NW.

EAST SIDE OF BARRANCA DE TOLIMAN

The most important producing area in the Zimapán mining district is the east side of Barranca de Tolimán. Production from the Los Balcones and Lomo de Toro mines accounts for more than 90 percent of the district's output.

Plate 4 is a geologic map of the Lomo de Toro-Los Balcones mine area. The Los Balcones mine is in the northern part of the area, close to the quartz monzonite dike believed to be the source of the fluids that deposited the ore bodies of the Carrizal mining area. The Lomo de Toro mine, by far the largest in the district, is in the southeastern part of the area, 400 meters or more from the nearest outcrop of the main quartz monzonite dike. The difference between the two mines in type of ore and ore bodies is believed to be related directly to their position with regard to the quartz monzonite. The Los Balcones ore bodies are almost all crosscutting, nearly vertical chimneys of sulfides, among which pyrrhotite is abundant and arsenopyrite and chalcopyrite are common. The ore bodies of the Lomo de Toro mine are either mantos or chimneys that lie parallel to the bedding of the enclosing limestone. Most of the ore produced thus far from the Lomo de Toro mine has been oxidized. The sulfides are dominantly galena, sphalerite, and pyrite; pyrrhotite and arsenopyrite are absent except in the El Barreno and San Damián workings, and chalcopyrite is rare. Both mines have several adits, which will be described separately. Four mines on the east side of Barranca de Tolimán are described below.

LOS BALCONES MINE

The Los Balcones mine was the largest producer in the Zimapán district during the years 1948–49, although its total production is much less than that of the Lomo de Toro mine. Production data for 1947–49 are given below:

	Metric tons
1947	4,275
1948	14,339
1949 (6 mo.)	10,512
Total	29,126

Ore from the Los Balcones mine was almost entirely sulfide and averaged about 9 percent lead, 19 percent zinc, and 300–400 grams of silver per ton.

The workings of the Los Balcones mine may be divided into two groups, each of which represents a separate ore trend. The southwestern group includes, in ascending order, the La V2, La V, Los Balcones, and La Palmita workings; the northeastern group is composed of the San Rafael Nuevo, San Rafael Viejo, and San Miguel de Los Palacios workings. Both groups of workings have a northwesterly trend, which corresponds roughly to the regional strike of the country rock, Lower Cretaceous limestone. The northeastern group lies along the northwest extension of the Lomo do Toro ore bodies.

LA V2 ADIT

The La V2 adit (fig. 55) is the lowest working of the Los Balcones mine. Workings consist of a 330-meter drift, for the most part along a northwestward-striking vertical rhyolite dike, and a 130-meter crosscut to the south.

Sulfide ore has been found along a vertical rhyolite dike 3.5 meters thick that strikes N. 48° W. This dike is the same one that appears in the La V adit above. The sulfide ore occurs mainly in the limestone along both sides of the dike, in a layer that ranges from 0.5 to 2 meters in thickness. At one place, about 120 meters from the portal, the ore branches from the north wall of the dike and lies along a limestone bed about 40 cm thick; this manto had not yet been explored in August 1953. At the point where the south crosscut branches,

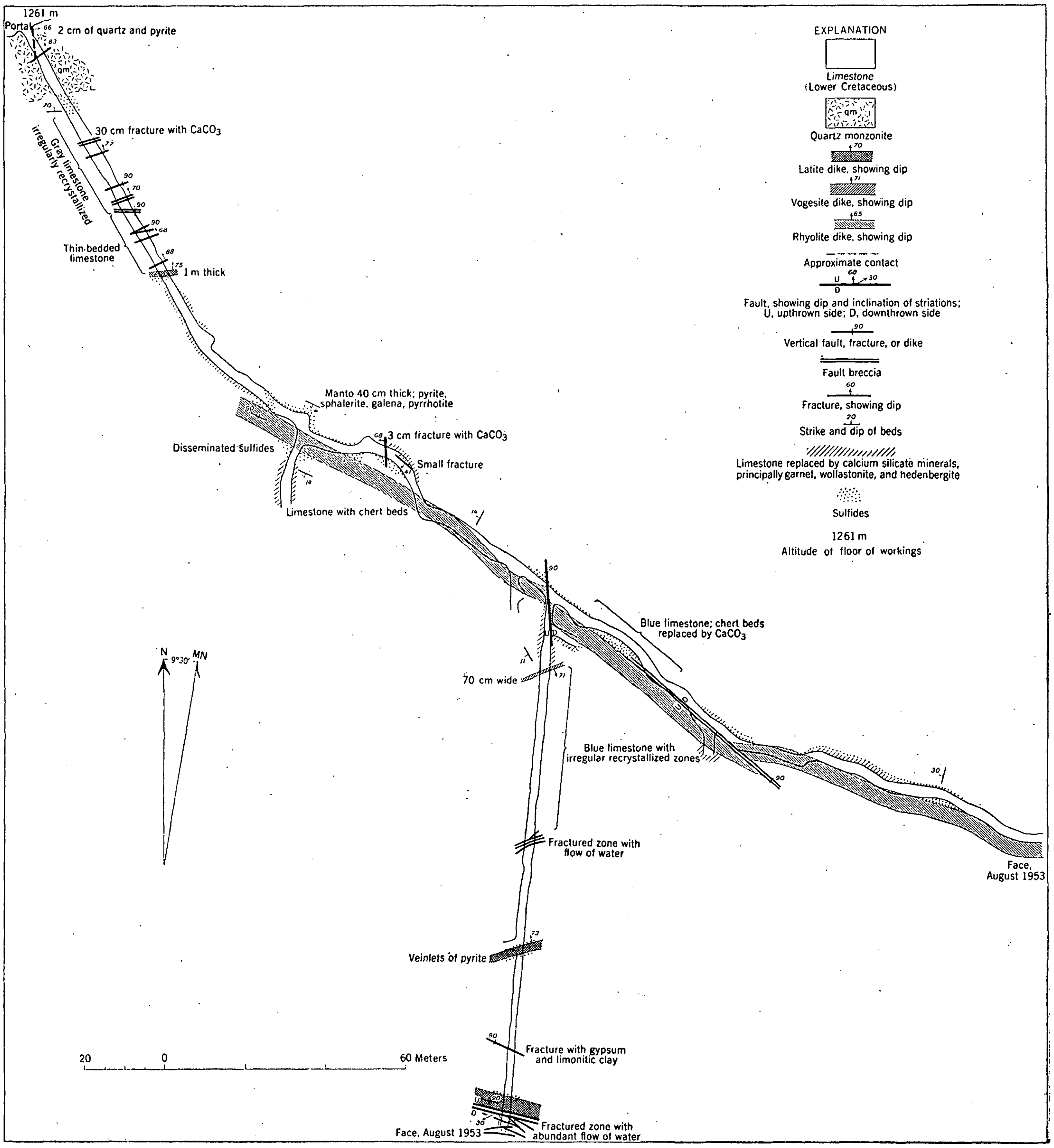

FIGURE 55.—Map of La V2 adit, Los Balcones mine.

the dike is slightly displaced by a small vertical fault. Approximately 35 meters to the southeast of the south crosscut, the dike is cut by another vertical fault striking N. 50° W., which seems to be strong. The fault first follows the north wall of the dike for a short distance and then cuts the dike at an acute angle. The limestone along the fault is intensely crushed and brecciated in a zone 70 cm wide. The north side seems to be downthrown.

A vogesite dike some 70 cm thick was cut at a point about 17.5 meters from the entrance of the south crosscut. This dike strikes N. 70° E. and dips 71° S. The only alteration noted along it was a little recrystallization of the limestone.

At about 85 meters from the entrance of the south crosscut, a latite dike 2 meters thick striking N. 75° E. and dipping 73° N. was cut. This dike is bounded by only a little recrystallized limestone and has small veinlets of pyrite along its contacts. It was also found in the workings of the La V adit above.

Almost at the end of the crosscut, 124 meters from its entrance, another vertical latite dike 4 meters thick striking N. 75° W. was found. This dike is the same one along which the productive chimney of the La V adit occurred. At this lower level, however, only small quantities of disseminated ore occur along its contacts. Strong faulting took place along the south wall of the dike, and the limestone in a zone 30 cm thick is severely crushed and brecciated. The striations on the dike walls pitch 30° W. and indicate that the south side is downthrown. To the south of this fault the limestone is intensely fractured by what seem to be feather joints, through which large quantities of water drain.

The ore is composed mainly of pyrite, sphalerite, and galena. Calcite, garnet, and a little quartz are the only abundant gangue minerals. The sulfides seem to be formed later than the garnet. Sphalerite and galena are probably contemporaneous, but pyrite was everywhere seen to cut these minerals in veinlets and is therefore formed later.

Pyrrhotite and arsenopyrite in small quantities are confined to the metamorphosed limestone in the vicinity of the rhyolite dike. They are accompanied by a little pyrite and abundant garnet, wollastonite, hedenbergite, and diopside. The lime silicates occur generally in irregular patches replacing limestone, but in at least one place a limestone bed 80 cm thick was seen to be completely replaced by lime silicates. Elsewhere the limestone is dark blue, has interlayered chert, and shows irregular areas of recrystallization. In the vicinity of the rhyolite dike, some chert layers are replaced by calcite.

LA V ADIT

The portal of the La V adit is 143 meters above and 168 meters southeast of the La V2 portal. Workings consist of an irregular adit and a stope connected to the Los Balcones adit above. Figure 56 is a map of the adit. Sulfide ore has been found in small quantities along and within an eastward-trending latite dike 20 meters from the portal and along a northwestward-striking premineralization rhyolite dike that begins at a fault some 55 meters from the portal and has been explored for 95 meters along the strike to the southeast, but the only sizeable ore body is a nearly eastward-trending tabular chimney at the south end of the workings. The chimney at the La V level is more than 80 meters long and averages 4–5 meters in thickness. It lies along the footwall of a latite dike 4 meters thick and has been stoped downward 24 meters below the adit level and upward almost to the Los Balcones level, 64 meters above. Ore pinched out at the lowest and most westerly part of the stope. Near the center of the ore body a few meters of limestone lies between dike and ore, but elsewhere the ore is in direct contact with the dike.

The ore is composed of pyrite, sphalerite, and galena, some of which show beautiful banding and faithful following of minor plications in the limestone country rock. Calcite and yellow-green garnet are the only abundant gangue minerals. Garnet is abundant only in the deeper parts of the ore body and becomes scarce nearer the Los Balcones level; it is seen also in the wall rocks near the ore body, where it occurs as thin stringers along the bedding of the limestone. Sulfides are formed later than garnet. Sphalerite and galena are probably formed simultaneously; pyrite seems to be formed later than galena and sphalerite in most places and is definitely formed later at a place near the east end of the ore body, where calcite-pyrite veinlets cut massive sphalerite.

Pyrrhotite, arsenopyrite, and chalcopyrite are confined to metamorphosed limestone along the rhyolite dike; none is abundant. They are accompanied by a little pyrite, which is formed earlier than pyrrhotite, and considerable sphalerite, which is the latest sulfide formed. Chalcopyrite was seen only in veinlets cutting pyrrhotite.

A northeastward-trending crosscut about 110 meters from the portal follows a manto of zinc carbonate and iron oxide 5 to 200 cm thick. The manto occurs along the intersection of the bedding with a steeply dipping northeastward-trending fracture, which is cut off by a northwestward-striking fault 25 meters from the mouth of the crosscut. According to Sr. Jorge Preisser, the

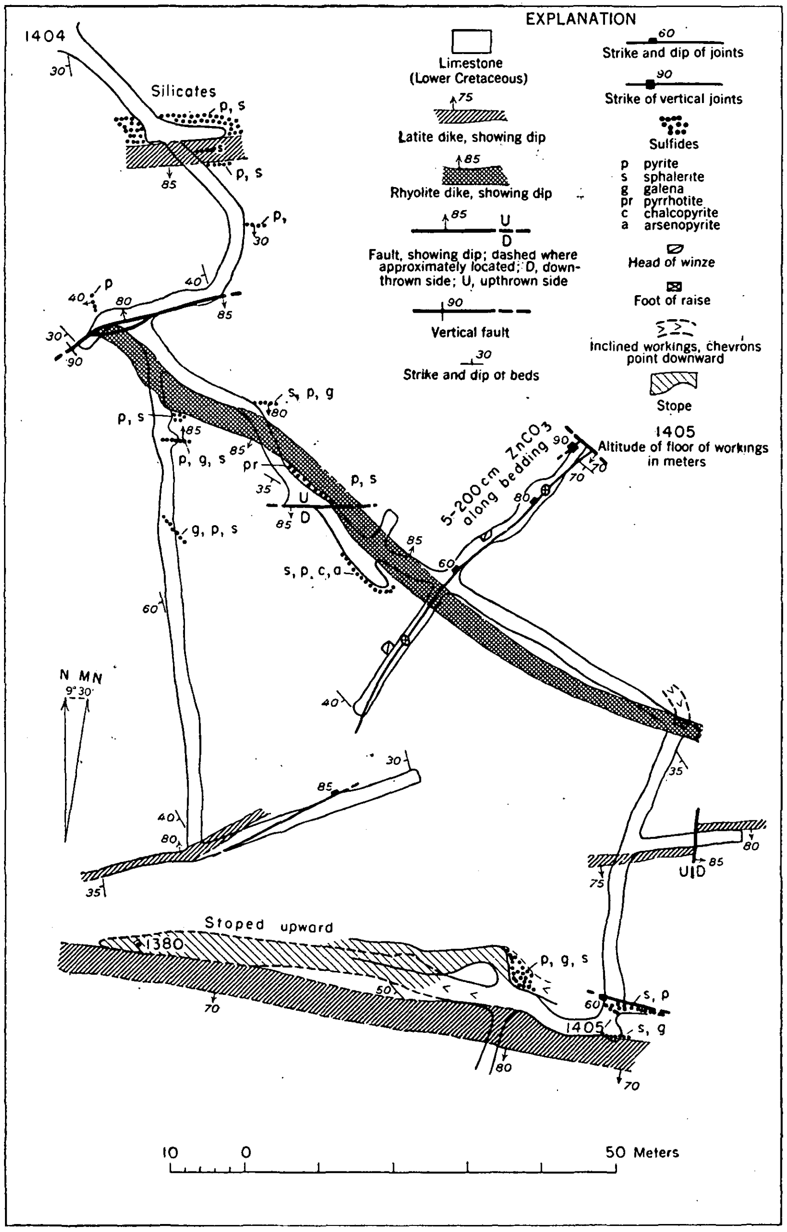

FIGURE 56.—Map of La V adit, Los Balcones mine.

mine operator, the ore averages 33 percent zinc. A little malachite accompanies the zinc ore.

LOS BALCONES ADIT

The portal of the Los Balcones adit is 64 meters above and 72 meters east of the La V portal. Mine workings consist of a 60-meter drift along an eastward-striking latite dike, and a 210-meter irregular drift to the south. Workings are shown in figure 57.

The original Los Balcones ore body was an irregular manto found about 50 meters along the south drift; it was a nearly northward-trending manto dipping 40°–60° W. and was followed 70 meters south to its intersection with the La V-Los Balcones chimney and a 4-meter latite dike. The manto averaged about 5 meters thick and had a maximum thickness of about 16 meters at its intersection with a rhyolite dike, which is probably the same one seen in the La V working. A narrow tonguelike manto of oxidized ore dipping 40°–55° W. was opened by an incline 26 meters deep along the south wall of the rhyolite dike. Ore at the thickest part of the manto was oxidized, but at both the north and south ends of the manto the ore is sulfide, largely deep reddish-brown sphalerite. According to Brinsmade (1921), 400,000 pesos worth of ore averaging 25–26 percent of lead and 1,250 grams of silver per ton was extracted from this ore body. The latite dike that forms the south wall of the La V-Los Balcones chimney was weakly mineralized along its south wall also; ore was oxidized, but it was apparently of low grade.

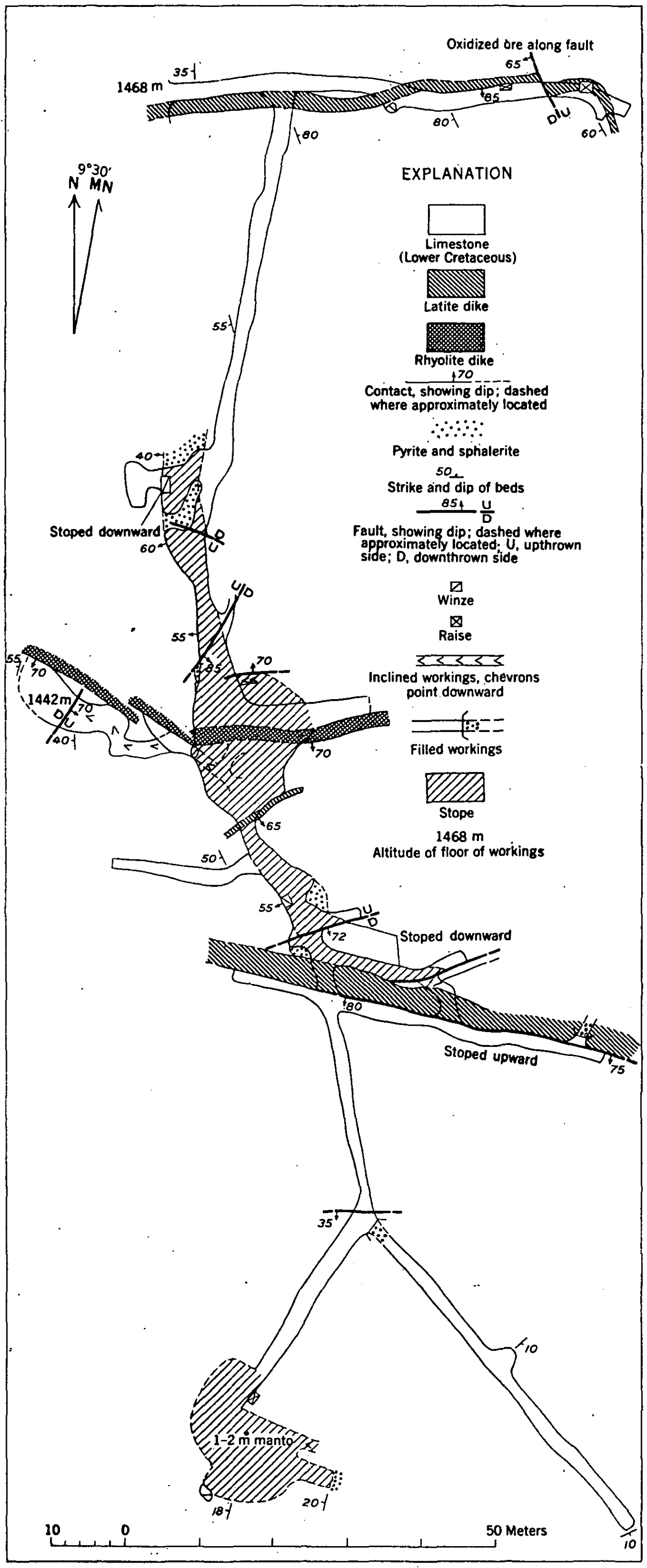

FIGURE 57.—Map of Los Balcones adit, Los Balcones mine.

A second manto was disclosed in a diamond-drill hole at the Los Balcones level 50 meters south-southeast of the latite dike and has been exploited from a stope above and a winze below. The manto strikes about N. 10° E. and dips 18°–20° NW.; it averages 1–2 meters thick and is 18 meters in length along the strike at the level. It seems likely that the manto will be found to connect with the La Palmita ore bodies above and to the east. The ore is largely sphalerite and pyrite. At a depth of 15–16 meters in the winze the ore is nearly solid pyrite whereas at the Los Balcones level and above, it is practically solid sphalerite, some of it in large crystals. The sphalerite is a reddish-brown mineral cut by pyrite veinlets. Calcite is the only gangue mineral. In the stope above, beautiful crystals of galena as much as 2 cm across were found in a vug associated with coarsely crystalline calcite; both galena and calcite were coated with tiny tabular crystals of cream-colored dolomite.

LA PALMITA ADITS

The La Palmita adits are about 150 meters S. 15° E. of the Los Balcones adit and are 47 and 62 meters, respectively, above the Los Balcones level. Workings are shown in figure 58.

The upper La Palmita adit is short, leading to the great La Palmita chimney, a triangular ore body measuring about 25 by 25 by 30 meters at its base and worked from the outcrop to an estimated depth of about 40 meters. The chimney is under the gable formed by the acute intersection of two dikes, one of which strikes N. 85° W. and dips 85°–90° S., the other striking about N. 60° E. and dipping 50°–60° NW. The Lower Cretaceous limestone is flat lying but isoclinally folded. One of the limestone walls is very regular and practically vertical. The chimney has the appearance of a huge triangular nail punched upward into limestone, with a total disregard for structure within the limestone.

The bottom of the stope is floored with rubble, but small pockets of plumbojarosite left in the walls indicate that the ore body was at least partly oxidized. Extraction of the ore body took place many years ago and nothing is known about the type or grade of ore.

A manto averaging about 1 meter in thickness formed an offshoot along the south wall of the chimney at about 5–10 meters above the adit level. Galena and sphalerite disseminated in limestone were seen in the few remaining pillars.

The lower La Palmita adit is an incline that leads under the upper chimney. At the level where the chim-

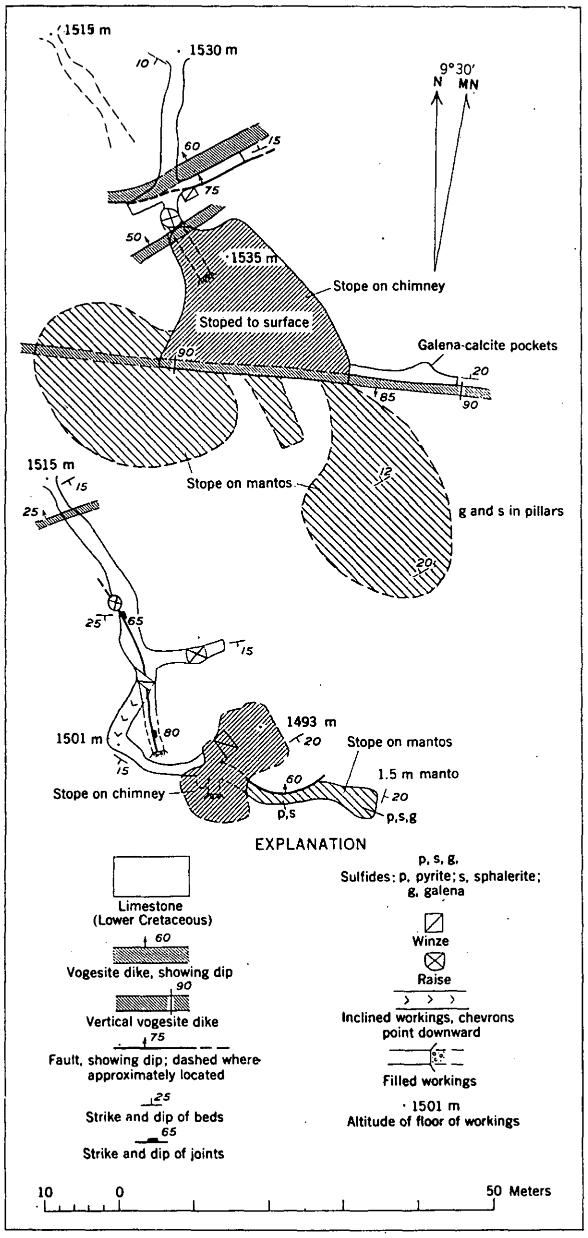

FIGURE 58.—Map of La Palmita adits, Los Balcones mine.

ney was intersected (about 40 meters below the base of the chimney in the upper adit), it was much smaller than above, measuring a maximum of 10 by 17 meters and averaging only about 5 by 8 meters. The northeastward-striking dike of the upper adit was cut near the portal of the lower adit but no ore was found; the eastward-striking dike was not seen underground. A 1.5-meter manto was found branching off the chimney to the east. All the ore in the lower working is sulfide. The manto is rather low-grade banded ore composed of layers of pyrite-sphalerite and galena-pyrite-calcite interbedded with unreplaced limestone. Galena is commonly coarse grained and has cleavage faces as much as 2 cm across. Pyrite appears to be the earliest sulfide formed, and galena is definitely formed later than either pyrite or sphalerite. The working was abandoned in July 1949, because of the low grade of the ore and decreasing metal prices.

If Prescott's generalization (1926, p. 248–253, 289–296) that a limestone replacement ore body maintains a rather uniform cross-sectional area over considerable distances but gradually diminishes in size with distance from its source is valid (and it is surely valid in the examples described by him from Santa Eulalia, Ojuela, and Naica in Mexico), then the possibilities of discovering other ore bodies below the main La Palmita chimney seem good. Almost certainly the manto at the south end of the Los Balcones adit is related to the La Palmita ore bodies, but its small cross-sectional area suggests that another mineralized channel of circulation may occur elsewhere. Exploration by diamond drilling has been planned by the mine operator.

SAN RAFAEL NUEVO ADIT

The San Rafael Nuevo adit is the lowest of the northeastern adits, lying at an altitude of 1,495 meters, or 27 meters above and 120 meters east-northeast of the Los Balcones adit. The adit trends south-southeastward for 115 meters, then southward for 55 meters, where it splits into southwestward and eastward-trending branches. Workings are shown in figure 59. The San Rafael Nuevo adit is used principally as a haulageway for ore from the San Rafael Viejo workings above, but a small amount of ore comes from workings in the adit itself.

Three ore bodies have been cut in the adit. An inclined pipe was found in a crosscut to the southwest at a point 102 meters from the portal; its structure and mineral composition have been discussed in the section on ore bodies and will not be repeated here.

An essentially vertical ore body, the San Rafael chimney, was intersected about 130 meters from the portal. At the San Rafael Nuevo level the chimney is slightly elongated in an east-northeasterly direction and measures about 12 meters long by 3–5 meters wide. It is a few meters north of an eastward-striking dikelike tactite body, which in the San Rafael Viejo working above becomes the south wall of the chimney. A little pyrite and sphalerite were seen in the walls of the stope, but most of the information on the type of ore comes from exposures in the San Rafael Viejo working.

A second chimney was found in the east branch at the south end of the adit. It was a roughly equidimensional ore body about 8 meters in average diameter, which has been exploited by two winzes, now flooded. The south wall of the chimney is a 30-cm eastward-

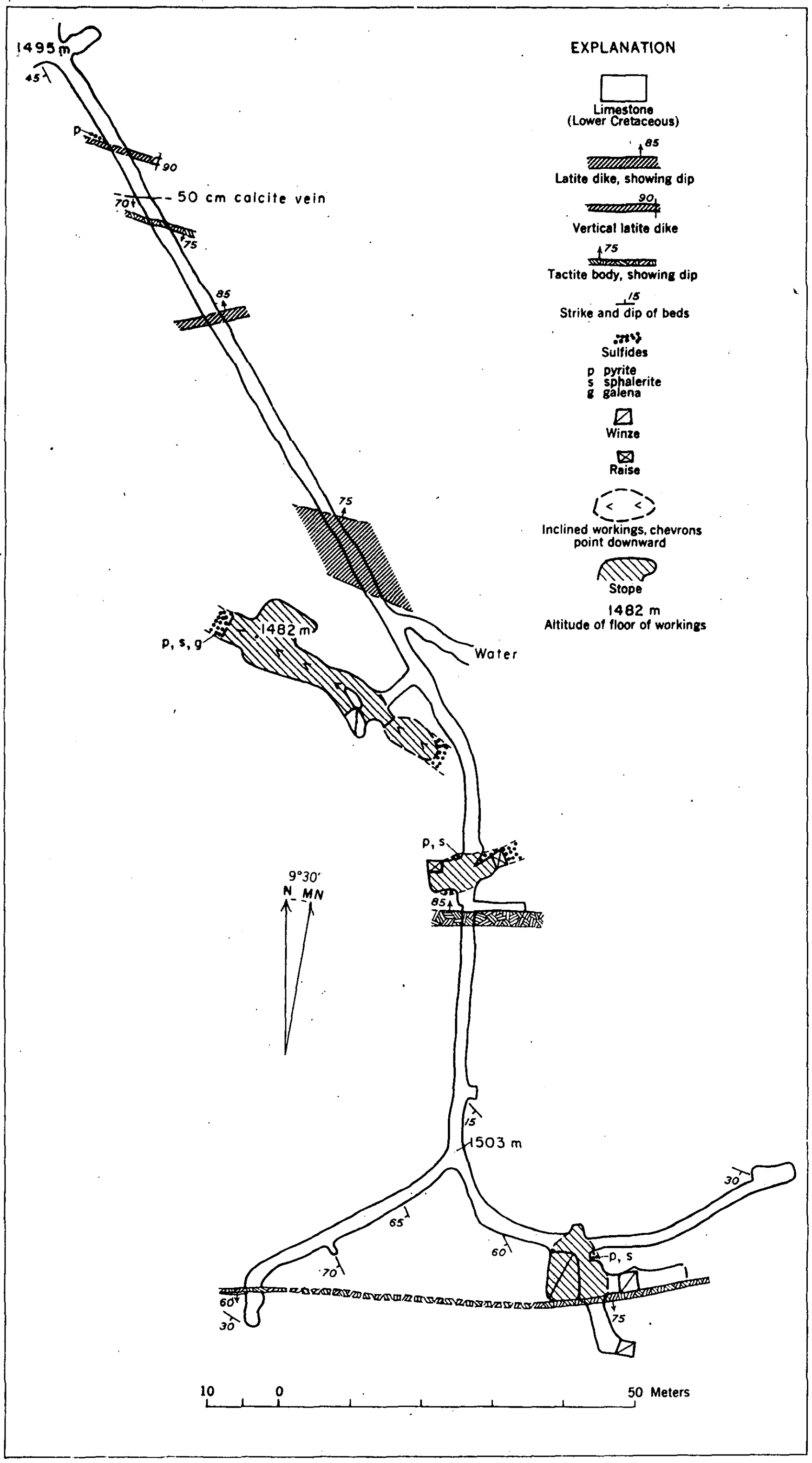

FIGURE 59.—Map of San Rafael Nuevo adit, Los Balcones mine.

trending tactite body which dips 75° S. The chimney seems to be controlled in part by the bedding of the limestone, which strikes north-northwestward and dips steeply westward, but few observations can be made as most of the stope is inaccessible. The ore body was stoped a maximum of about 5 meters above the level, where the ore appears to become rather lean. Possibly the chimney is connected with the manto at the south-east end of the San Miguel de Los Palacios workings above and to the notheast, but the area between has not been explored as yet.

Three latite dikes and a tactite body were cut between the portal and the inclined pipe. Except for a little pyrite along the contact of the dike nearest the portal, no mineralization effects related to the dikes were seen.

SAN RAFAEL VIEJO ADIT

The San Rafael Viejo adit is one of the oldest workings of the Las Balcones mine. It is 46 meters above the San Rafael Nuevo adit. The mine workings are essentially a southeastward-trending incline along a fracture zone which terminates in an ore chimney about 70 meters from the portal. Most of the tortuous workings are shown in figure 60.

The ore body originally exploited was a manto localized by the intersection of a favorable bed, striking about N. 30° W. and dipping 40°–45° NE., with a northwestward-trending system of fractures dipping steeply northeastward. The ore body terminated to the northeast against a nearly eastward-trending dike dipping 75° S. The manto was extremely irregular and was thoroughly oxidized. Most of the workings along it are inaccessible. At the intersection of the manto and a dike 40 to 50 cm thick found 60 meters from the portal, a few remnants of sphalerite-pyrite-galena ore were seen, but the main ore body now exploited is a vertical chimney bounded on the south side by a dikelike tactite body which strikes about east and dips 75°–90° S. The chimney has been stoped upward about 15 meters above the level of the portal, and downward to the San Rafael Nuevo level, or through a total vertical distance of some 60 meters. At the highest accessible level the chimney is about 25 meters in length along the tactite body and 3–4 meters in width. Thirty-five meters below, at the next accessible level, it is 12 meters long parallel to the tactite body and about 15 meters wide. At the San Rafael Nuevo level, 20 meters farther down, the chimney is 12 meters long by 3–5 meters wide. The chimney is extremely irregular in shape, except for its smooth south wall; one large horse of unreplaced limestone was seen near the south wall.

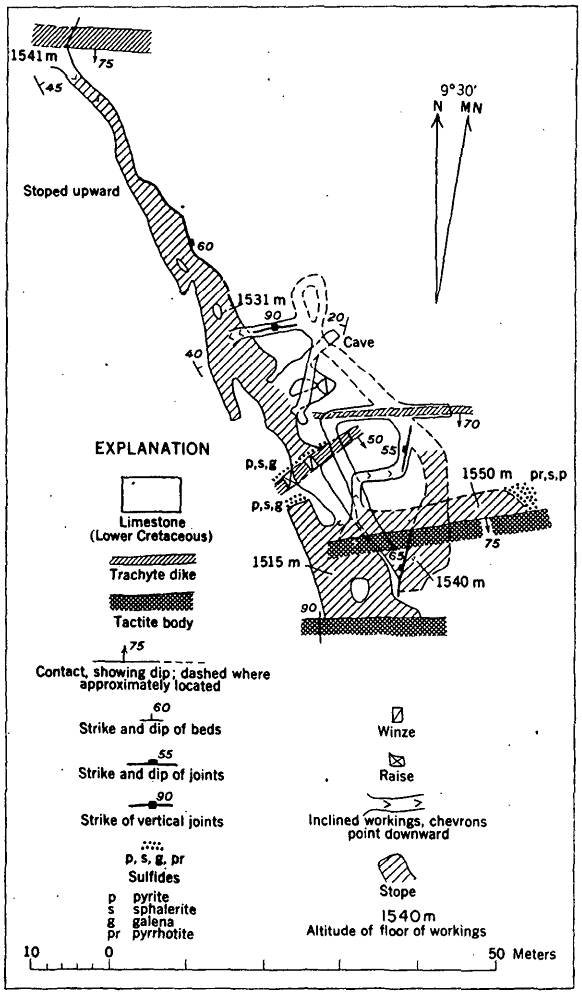

FIGURE 60.—Map of San Rafael Viejo adit, Los Balcones mine.

The ore of the chimney has characteristics of both pyrometasomatic and hypothermal-mesothermal deposition. Near the wall of the tactite body, and locally at the limestone contact, the ore is metallized tactite with abundant pyrrhotite and some arsenopyrite. Locally a thin layer of silicates lies between limestone and ore. The silicates were not studied in detail, but hedenbergite is known to be a prominent constituent of the tactite. The contacts of tactite with limestone are very sharp, the only noticeable metamorphism in unsilicated limestone being very slight recrystallization. In the tactitic ore, sphalerite and pyrite are the earliest sulfides formed and are followed by pyrrhotite. Galena and a little chalcopyrite are late-formed sulfides. The position of arsenopyrite in the paragenetic sequence is not known, but the mineral seems to be formed early, possibly the earliest of the sulfides. The tendency of early-formed pyrrhotite to accompany silicates along the walls of the chimney, and the common tendency, noted in other ore bodies, of galena to be concentrated along the walls, have resulted in a common association of the two minerals, the galena being apparently invariably formed later than the pyrrhotite. Where no tactite is present the ore is the common pyrite-sphalerite-galena assemblage, banded parallel to the chimney walls. Colorless fluorite is the commonest gangue mineral; calcite is scarce.

Together with the La V-Los Balcones chimney, the San Rafael chimney has been the major source of ore of the Los Balcones mine for some time. The ore body was almost mined out in 1949.

SAN MIGUEL DE LOS PALACIOS ADIT

The San Miguel de Los Palacios adit is the highest in the Los Balcones mine. It is 38 meters above and 90 meters south of the San Rafael Nuevo portal. Mine workings, shown in figure 61, consist of an adit that

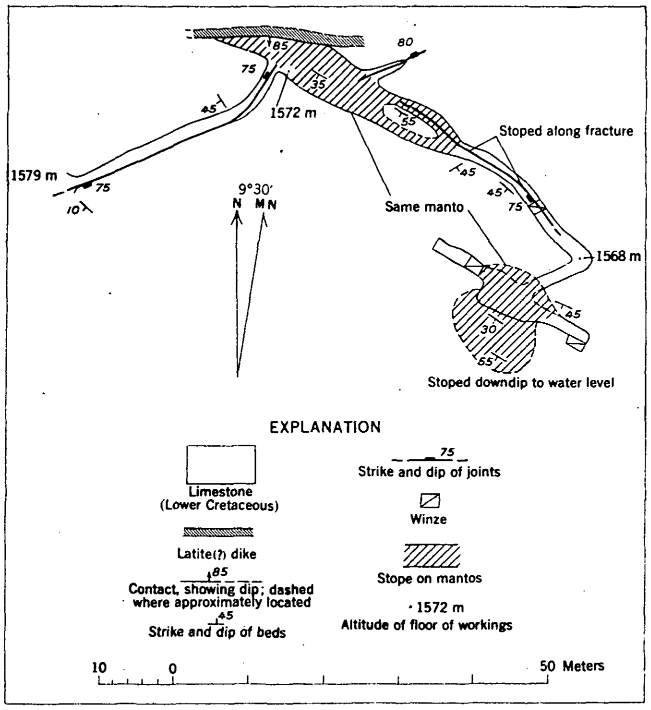

FIGURE 61.—Map of the San Miguel de Los Palacios adit, Los Balcones mine.

connects with a stope along a manto, and an incline connecting the manto with a lower manto. The adit is driven through contorted Lower Cretaceous limestone striking northwestward and dipping southwestward.

The stope on the manto is about 35 meters long and averages about 10 meters in width in the plane of the manto, which strikes about N. 60° W. and dips 35°–55° SW. The maximum thickness of the manto was about 5–6 meters. An eastward-trending dike dipping 85° S. forms the north wall of the stope. The ore of the manto was oxidized and was apparently largely plumbojarosite and iron oxide. The working is very old and nothing is known about the type of ore produced.

At the southeast end of the stope an incline along a mineralized northwestward-trending fracture leads southeastward to a thin sulfide manto about 5 meters below the upper manto. The lower manto strikes northwestward and dips 30°–55° SW. The two mantos may be along the same bed. A few remnants of low-grade pyrite-galena ore were seen in pillars in the accessible part of the lower stope.

The lower or southeast manto is probably connected with the chimney at the south end of the San Rafael Nuevo adit, although the connection has not been proved by exploration. The two workings are rather close together, but apparently the ore in the area of the connection was not minable.

UNNAMED PROSPECT

An unnamed prospect below the Los Balcones mine has been driven south along a fracture striking N. 5° W. and dipping 60° E. The lower Cretaceous limestone in the vicinity strikes N. 45° E. and dips 15° SE. Ore on the dump consisted of pyrite and a little sphalerite disseminated in calcite.

LA CUÑA MINE

The La Cuña mine is just north of the Los Balcones mine. Workings consist of a 60-meter shaft along a steep-dipping northwestward-striking bed of Lower Cretaceous limestone. Ore is disseminated sulfide which has to be carefully hand cobbed and sorted. Sphalerite is the most abundant sulfide; galena and pyrite were the only other sulfides noted. Calcite is the only gangue mineral. The mine was maintaining a small but steady production in 1948.

LOMO DE TORO MINE

The Lomo de Toro (so named because of the fancied resemblance of the profile of the mountain east of the mine to that of a bull's shoulders and back) mine consists of seven workings on the steep east side of Barranca de Tolimán. Vertical distance from lowest to highest workings is 453 meters. Only the San Guillermo adit was being mined during our work in the district. Mining in the San Damián adit ceased in 1943 when heavy rains flooded the winze. The other workings have been abandoned for periods ranging from 10 or 20 years (San Antonio, La Bota, La Maravilla?) to probably more than a century (El Barreno, La Mora?).

The workings are described in ascending order. Production for 1945–49 is given below.

Production data, Lomo de Toro mine, 1945–49

Year	Tons	Pb (percent)	Ag (g/ton)	Au (g/ton)	Remarks
1945	2, 597	45. 5	795	1	
1946	2, 149	27. 2	614	1–1. 5	Oxidized ore
1947	6, 233	22. 7	575	1. 5	
1948	7, 984	21. 4	580	1–1. 5	
1949	2, 843	19. 5	636	-------	
	1, 142	24. 0	800	------	Partly oxidized ore, 3–5 percent S
	351	18. 2	592		
Total	23, 299				

EL BARRENO ADIT

The El Barreno adit is at an altitude of 1,381 meters, about 90 meters above the Río Tolimán. It was driven from a narrow platform jutting from the steep cliff below the San Guillermo adit and is reached by descending the cliff with the aid of a series of ropes and ladders. The workings, shown in figure 62, consist of two nearly parallel eastward-trending adits connected at short intervals, four drifts, and irregular workings extending northeastward from the first drift to the north. The adit slopes upward at an angle of about 11°. Country rock is highly folded Lower Cretaceous limestone which in general strikes northward to northwestward.

The drifts followed rusty oxidized zones along north-northwestward-striking joints, but no appreciable amount of ore was found except in two small mantos at the south end of the drifts. Exploration northeastward from near the end of the first north drift along a rusty zone in limestone uncovered a manto of nearly solid sulfide ore 1 meter thick composed largely of fine-grained sugary sphalerite accompanied by pyrite, pyrrhotite, galena, and a little chalcopyrite and arsenopyrite. Sphalerite appears to be the earliest sulfide formed and is followed by pyrite, pyrrhotite, galena, and chalcopyrite in approximately that order. A little white dolomite was the only gangue mineral seen. Sparce cerussite, melanterite, and chalcanthite occur as oxidation products. An assay of the El Barreno sulfide ore gave the following results.

Pb	percent	5. 5
Zn	do	23
Fe	do	24
Cu	do	0. 4
Ag	g/ton	330
Au	do	0. 1

The El Barreno working was apparently intended as a haulageway for ore extracted from higher workings, but so far as we know, no connection was ever made. A steeply inclined massive masonry trough was constructed between the El Barreno portal and some higher point, probably the small platform now occupied by the ruins of the generator shack of a concentrating plant. Ore was probably to be hauled by rope in sacks or buckets up the trough to where it might be loaded on

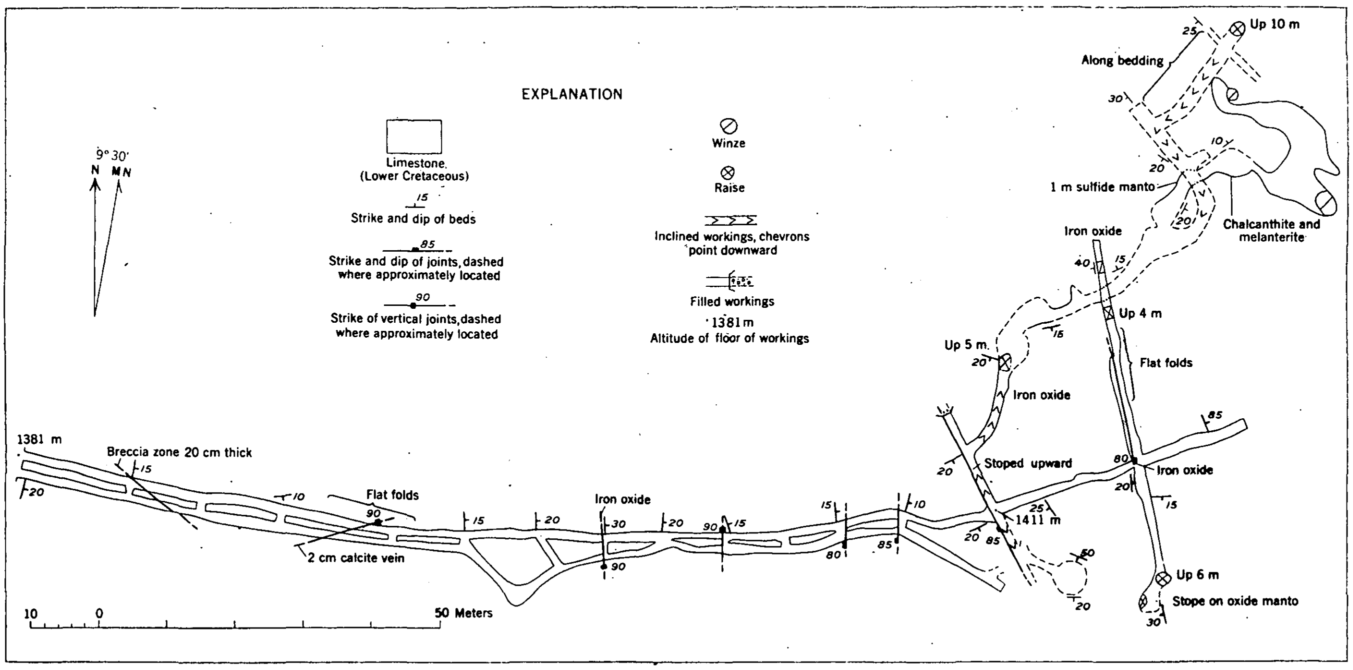

FIGURE 62.—Map of El Barreno adit, Lomo de Toro mine.

burros for shipment. An interesting sidelight on the El Barreno adit is that there is no evidence that rock drills were used in driving the adit. Possibly the rock was broken by heating the face to a high temperature and then quenching it with water.

LEVEL 3

Level 3 is 79 meters above the El Barreno adit and 29 meters below level 2. Mine workings consist of a northwestward-striking irregular level connected to the level 2 workings by means of a vertical shaft and three raises. A map of this level is shown in plate 5. Sulfide ore has been found along the north contact of an eastward-trending almost-vertical latite dike. This dike is undoubtedly the same as the one seen in the Santa Luisa ore body in the San Guillermo adit above, and the sulfide ore therefore represents the continuation of the oxidized ore mined in the Santa Luisa stope. Thus far (August 1953), the rhyolite dike along which the vertical Santa Luisa chimney occurs in the San Guillermo adit has not been found at this level, but the chances of finding it with a little more exploration are good. Another large body of sulfide ore was found in a crosscut to the south. Ore consists of disseminated sulfides of zinc, lead, and iron in a calcitic gangue. This ore corresponds to the ore from a projection of the vertical San Pedro chimney, and both ore localities therefore have possibilities of large tonnage.

In the neighborhood of the shaft, a 1.5-meter latite dike was found. This dike is probably the same one seen on level 2 and in the San Pedro stope. No ore has yet been found along it, however.

The southeastern part of this level has intersected a series of parallel eastward-trending small fractures mostly filled with calcite and a little pyrite. One of them, however, strikes southeastward and seems to be fairly strong; it contains a vein of disseminated sulfide ore in a calcitic gangue about 1 meter wide. This fracture may be the same one seen in the workings of level 2.

LEVEL 2

Level 2 is 29 meters above level 3 and 42 meters below the San Guillermo adit. Mine workings consist of an irregular level connected to the upper workings of San Guillermo by means of three stopes, a shaft, and several raises. A map of this level is shown in plate 5. Ore has been found in the vertical projection of the Santa Luisa and San Pablo ore bodies, along the northwestward-striking San Pedro fault some 12 meters east of the shaft, and in a small winze some 15 meters northwest of the Santa Luisa stope. The ore from the Santa Luisa, San Pedro, and San Pablo bodies has been stoped upward to the San Guillermo level 42 meters above. Stoped ore was largely plumbojarosite with a little cerussite, anglesite, and galena, but at level 2 the sulfides are more abundant than the oxides. Sulfides are sphalerite, pyrite, and galena in a calcitic gangue.

Mine workings on this level cut an eastward-trending latite dike 1.5 meters thick, probably the same dike seen in the southwestern end of the San Pedro stope of the San Guillermo level. Only small pyrite veinlets were found along this dike.

SAN GUILLERMO ADIT

Ore bodies developed in the San Guillermo adit have been the principal source of production from the Lomo de Toro mine in recent years. The adit was driven in the 1890's, and the winzes of San Agustín and Los Bronces were sunk around 1900. No large amount of ore was extracted through the adit, however, until 1945, when the first of the important oxide ore bodies, San Pablo, was discovered. From 1945 to 1951 all the ore from the mine came from the San Guillermo ore bodies.

The San Guillermo workings are extremely complicated and are difficult to describe adequately in writing. A generalized map of the most important workings (pl. 5) and a longitudinal vertical projection of the main stopes (pl. 6) have been prepared.

Some of the workings are very old. The discovery of the outcrop of the El Claro ore body in 1632 initiated mining in the Zimapán district. Modern mining began in 1945, after a period of more than 100 years of inactivity. The boundary between the old and new workings is the inconspicuous fault between the San Vicente and San Pablo stopes. South of the fault the only relatively modern workings are the winzes of San Agustín and Los Bronces, and levels 2 and 3 driven to explore the main ore bodies at depth. Although the fault has a displacement of only about 5 meters, it completely cuts off the San Vicente ore body at its north end. Apparently the mine was abandoned after all the oxidized ore south of the fault had been extracted. It seems strange that no exploration was carried out north of the fault by the old miners, but their inexplicable oversight has proved very fortunate for the present mine owners, who found the great ore bodies of San Pedro and Santa Luisa, and the many smaller deposits such as San Pablo and Pepito, after prospecting toward the north on the downthrown side of the fault.

The structural controls of the San Guillermo ore bodies have been discussed elsewhere and will be summarized here. The ore bodies occur along a north-northwestward-trending zone which is roughly parallel to the regional strike of the Lower Cretaceous limestone and to the strike of a series of discontinuous steep-dipping fractures. All the major ore bodies lie approximately parallel to the bedding of the enclosing limestone, whether they are chimneys (Santa Luisa, San Pedro Nuevo, La Piedad, El Claro) or mantos (La Victoria, Pepito, San Vicente, San Pedro Viejo, Ave María). The major control, then, appears to be a bed or series of beds favorable to replacement. A second widespread structural feature of the mine is the series of north-northwestward-trending fractures, some of which are seen in all of the workings. Only a few of the fractures are shown on the map. Many of the fractures are mineralized. An ore body 2–3 meters wide was found along the fault between the Pepito and San Pedro ore bodies. Another control, of importance only in the Santa Luisa chimney, is a group of premineralization dikes. A rhyolite dike forms the northeast wall of the Santa Luisa ore body, and a thin altered dike forms part of the south wall; the second dike is a prominent ore control at the lowest level in the mine, where ore is also largely confined to its north side. The last control recognized is highly contorted bedding, which was prominently displayed in the walls of every accessible chimney (El Claro, San Pedro Nuevo, Santa Luisa). Its importance in the manto deposits could not be evaluated, but in every manto stope, minor folds were seen in the walls or back.

A short description of the principal stopes will be given in order from north to south; a long description of all the workings would serve no useful purpose, as the interested reader may gain far more information from the map and projection (pls. 5 and 6).

Santa Luisa.—A nearly vertical chimney approximately 35 meters long and 10 meters wide, exploited to a maximum depth thus far (August 1953) of about 70 meters. Lies parallel to strike of highly contorted limestone but transects bedding markedly at southeast end, where ore body ends abruptly. Connected to San Pedro by a complex series of mantos and chimneys shown in a diagonal broken line pattern on the plan. Ore largely plumbojarosite with a little cerussite, anglesite, and galena at upper levels; cerussite, anglesite, and galena are more abundant in deeper parts of the ore body. A 2- to 3-cm veinlet of galena-pyrite was seen within the rhyolite dike that bounds the chimney on the northeast side.

Pepito.—An as yet unexploited manto about 2 meters thick, overlain by a 1-meter shrinkage space. Strikes northward, dips 30°–50° E. in upper part, overturned to 30°–45° W. in lower part. Connected to San Pedro Nuevo along a mineralized northwestward-striking pivoted normal fault with no displacement at last exposure to southeast. Ore seems to be solid plumbojarosite.

San Pedro Nuevo.—A very irregular, essentially vertical chimney lying parallel to the strike of contorted limestone and locally strongly transecting the bedding. Maximum dimensions 60 meters long, 30 meters high; average width about 15 meters, but less than half of the volume indicated was ore, the rest being limestone. Ore largely plumbojarosite, with a little cerussite.

San Pablo.—A small very irregular manto striking northward and dipping 10°–20° E. The original discovery ore body in modern mining at Lomo de Toro. Ore body continuous with San Pedro Nuevo. Ore was cerussite with minor plumbojarosite; very high grade, averaging 45–50 percent lead and 750–850 grams silver per ton.

La Victoria.—A thin, tonguelike manto trending north-northwestward, about 130 meters long, maximum width 15 meters, average thickness about 2 meters. Connected to San Vicente by an irregular chimney. Ore was plumbojarosite of very high grade.

San Vicente.—A large manto, maximum dimensions 60 meters in length, 45 meters in width. Thickness 5–6 meters, maximum perhaps 10 meters. Strikes northeastward, dips 10°–45° SE. Separated from San Pablo by a premineralization fault. Ore was probably largely plumbojarosite, as a few remnants were seen in the walls.

La Piedad.—Inaccessible chimney 60 meters high, 40 meters long, maximum width about 19 meters. Connected above to El Claro, but connection now caved. Probably connected below to San Vicente, but connection has been filled. The third largest of the old stopes.

El Claro.—The largest ore body yet discovered in the Zimapán mining district. A northwestward-trending chimney dipping steeply southwestward. Maximum dimensions 65 meters long, 35 meters wide, 105 meters high from outcrop to bottom of stope. Lies parallel to contorted limestone overturned to northeast. Northwest and southeast walls are clean straight faces crosscutting bedding of limestone. Small mantos lead off chimney at northeast, southeast, and southwest corners. Ore was apparently largely plumbojarosite, remnants of which are left in short drifts along the mantos. Was connected below to La Piedad. Estimated volume of ore removed somewhat more than 100,000 cubic meters; estimated tonnage, 350,000 tons.

San Pedro Viejo.—Manto averaging perhaps 2 meters in thickness connected along bedding through small stope of La Dicha to San Vicente to the north; continuous ore body with Ave María to the south.

Ave María.—Second largest of the old stopes. A very irregular manto measuring about 75 meters long by 40 meters wide, maximum thickness perhaps 15 meters, but floor is deeply buried by rubble and sulfide ore from Los Bronces winze. Manto is roughly domical, dips 45°–60° E. along east side, 20°–30° W. along west side, irregular dips to south along south side. Oxidized ore was apparently largely plumbojarosite. Sulfide ore found in San Agustín winze to northeast of stope.

Los Bronces.—Flooded working, apparently along a sulfide manto. Connected by a winze to Ave María. Average grade of 163 samples from Los Bronces sulfides and 23 samples of San Agustín sulfides was lead, 13.35 percent; zinc, 12.48 percent; silver, 433 grams per ton; gold, 0.2–1.5 grams per ton. The average width was 1.4 meters. Sulfides are sphalerite, pyrite, and galena in a sparse calcite gangue. Sphalerite and pyrite appear to be formed contemporaneously; galena is the latest sulfide formed.

LA MORA ADIT

The La Mora adit is 140 meters above and 130 meters northeast of the San Guillermo portal. Mine workings

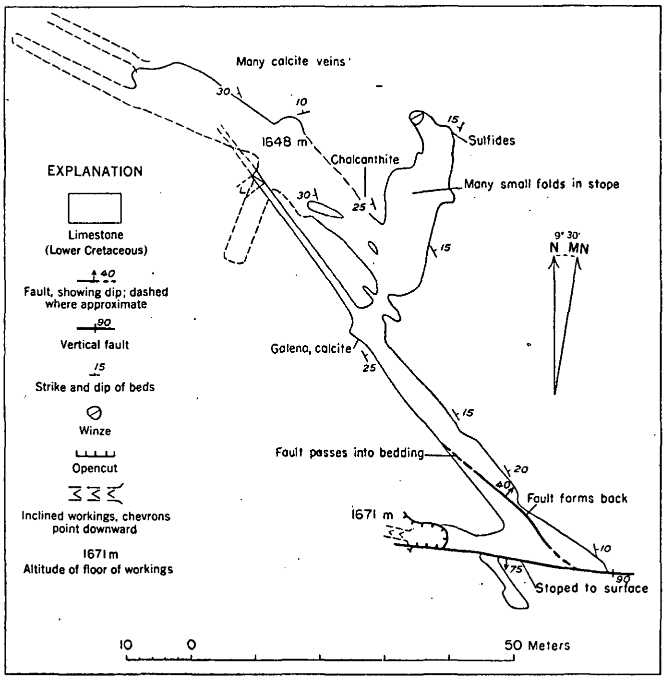

FIGURE 63.—Map of La Móra adit, Lomo de Toro mine.

consist of a stope on a chimney and a long irregular stope on a northwestward-trending undulating manto (fig. 63).

The chimney was a rather small wedge-shaped ore body found at the acute intersection of a thin eastward-trending dike dipping 75° S. with a northwestward-striking fault which dips 40° NE. It was about 30 meters long and reached a maximum width of about 5 meters. Stope height is variable; at one point the ore body was stoped to the surface, perhaps 10 meters above the chimney. To the northwest the fault passes into the plane of the bedding and the chimney becomes an irregular manto which has been mined for at least 110 meters along the strike to the northwest. The manto reached a maximum width of about 10 meters and averaged perhaps 1.5–2 meters in thickness. The Lower Cretaceous limestone is thrown into numerous small folds, faithfully followed by the ore body. Most of the ore was oxidized, but a few sulfide remnants are in the walls of the northeast branch of the manto stope. Sulfides are sphalerite, pyrite, and a little galena disseminated in calcite. Plumbojarosite was apparently the dominant oxide mineral; a little chalcanthite was also noted.

The La Mora ore body was extracted many years ago. According to old maps of the mine owner, the working was connected to the northwestern part of the El Claro stope, but the connection has never been found by the present miners and is probably inaccessible.

SAN DAMIAN ADIT

The San Damián adit is 170 meters above and 190 meters northeast of the San Guillermo portal. It is a northeastward-trending adit 157 meters long which was driven to extract ore from a chimney discovered in the San Antonio and La Bota workings above. The adit was driven in the 1890's and was worked until 1910 and also from 1929 until 1943. The Lower Cretaceous limestone, the country rock, strikes north-northwestward and dips 20°–50° NE. throughout the workings. A map of the adit is shown in figure 64.

The Santa Luisa dike is cut 22 meters from the portal, but no ore was found at the San Damián level. A little over 100 meters from the portal a 30-cm dike which forms the southeast wall of the San Damián chimney was intersected. Between the two dikes the limestone country rock is tightly folded (fig. 64). The second dike strikes N. 70° E. and is essentially vertical; it is intruded along a fault whose northeast side is downthrown. The stope along the dike at the adit level is about 35 meters long and averages 3–4 meters in width; it is connected above to the San Antonio and La Bota workings but the connection is inaccessible. From the San Damián level the chimney has been stoped downward toward the northeast for about 25 meters horizontally and 70 meters vertically. Near the bottom of the stope the chimney passes into a sulfide manto 1.5 to 2 meters thick which strikes N. 20° W. and dips 30° NE. The dike pinches out to the northeast, but the fault along which the dike was intruded continues to the bottom of the stope. The manto appears to be localized by the intersection of the fault and a favorable bed. At the extreme northeast end of the stope the manto is along the crest of a tightly folded anticline which plunges 60° NE.

Heavy rains in 1943 flooded the stope and caused suspension of work. The stope was drained in 1948 through a diamond-drill hole from the San Guillermo level, but as a result of the flooding the walls of the stope are heavily plastered with mud nearly everywhere and practically no information can be obtained as to the type of ore mined. However, the manto at the bottom of the winze is exposed in a few places; it is composed largely of arsenopyrite and a little pyrite veined by sphalerite and minor galena. Arsenopyrite occurs both as a dense mat of tiny needles and in massive form; it commonly has inclusions of pyrite. Calcite is very scarce. Oxidized ore from the upper part of the chimney is said to have carried considerable vanadinite, but none was seen during our study of the deposit.

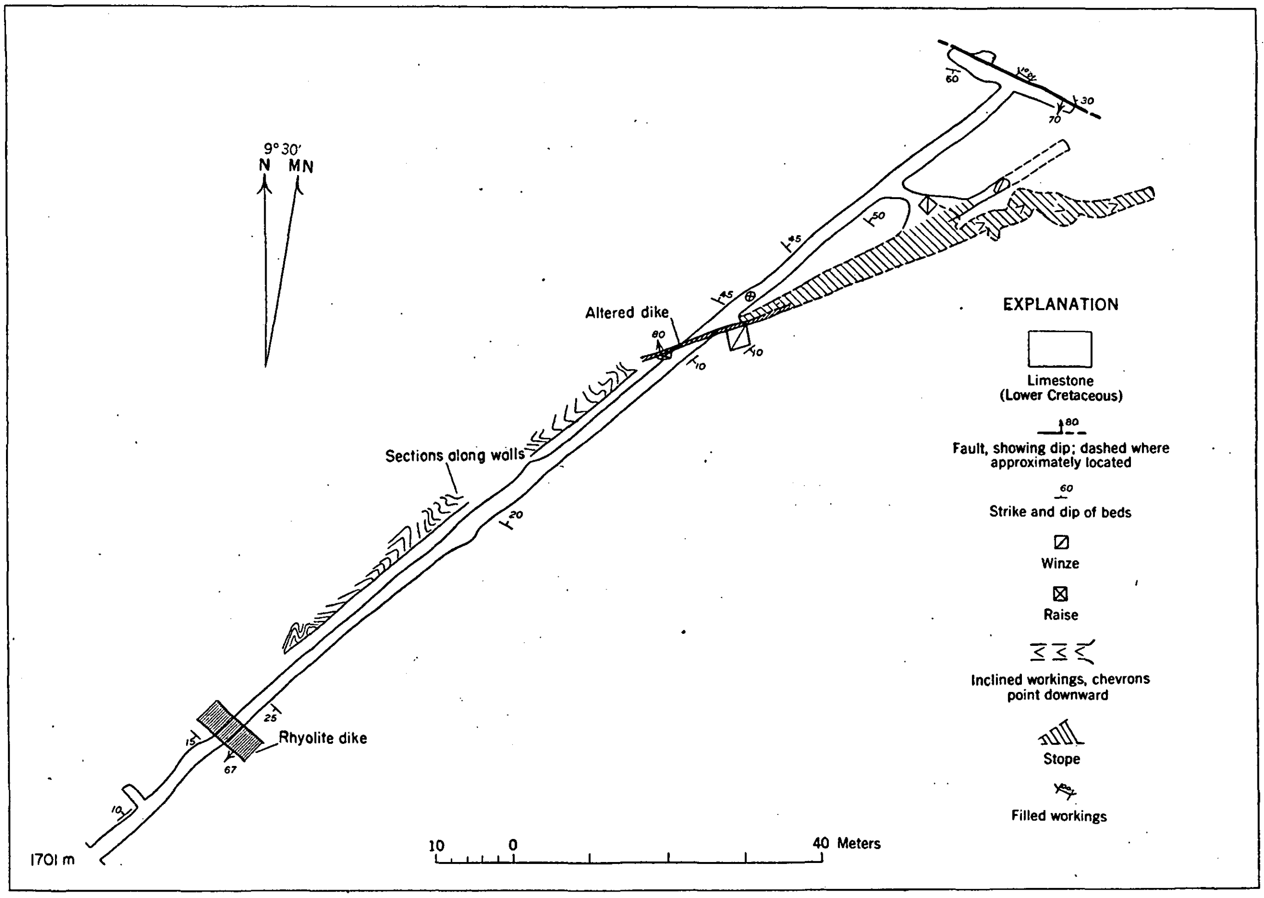

FIGURE 64.—Map of San Damián adit, Lomo de Toro mine.

Assays of four shipments of ore from the San Damián ore body are presented below.

Tons	Pb (percent)	Zn (percent)	Fe (percent)	Ca (percent)	Ag (g/ton)	Au (g/ton)	S (percent)
13.2	31. 6	1. 3	12. 6	7. 6	884	1. 4	9. 3
33.7	33. 8	1. 1	15. 1	3. 4	1160	1. 8	17. 5
5.6	29. 0	2. 1	14. 6	8. 0	880	1. 3	8. 0
26.8	32. 8	1. 7	14. 0	3. 1	1064	1. 6	15. 6

The ore was apparently composed largely of partly oxidized argentiferous galena and iron sulfide. The low zinc content is unusual in a sulfide ore body at Zimapán.

A long exploration crosscut on the San Guillermo level was driven in an unsuccessful search for the downward continuation of the San Damián chimney. The working was driven well past the projected position of the bottom of the San Damián stope, but no evidence of mineralization was found. It is possible, however, that the northeastward dip of the San Damián ore body has carried it beyond the projected position.

SAN ANTONIO ADIT

The San Antonio adit is 64 meters above the San Damián working and is connected with it by an inaccessible winze. A map of the adit is given in figure 65. A north-northeastward-trending adit 50 meters in length leads to a weakly mineralized manto which strikes northwestward and dips 15°–45° SW. Veinlets and irregular pods of galena and a few malachite stains were the only evidence of mineralization seen. Near the northwest end of the working along the manto is a small stope on an oxidized manto about 1 meter thick. A short branch to the east leads to the winze to the San Damián adit. The San Antonio ore body has contributed only a very small part of the output of the Lomo de Toro mine and has been abandoned for more than 10 years.

LA MARAVILLA INCLINE

The La Maravilla incline was inaccessible at the time of this survey. It is 70 meters west of and 26 meters below the La Bota incline. It is a northwestward-

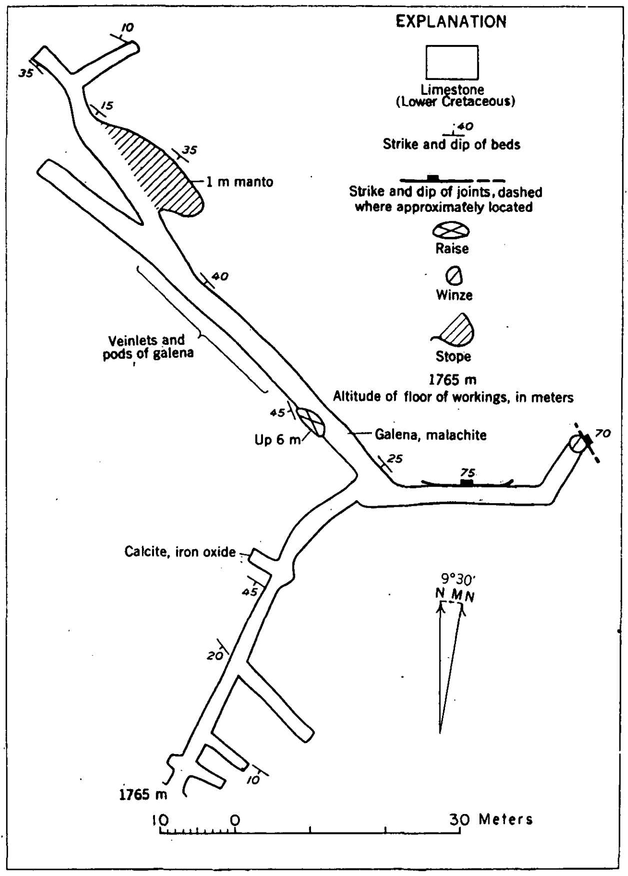

FIGURE 65.—Map of San Antonio adit, Lomo de Toro mine.

trending incline parallel to the La Bota incline, and is about 160 meters long and 75 meters deep. Old maps show no stopes, and apparently it has not been productive.

LA BOTA INCLINE

The incline of La Bota is the highest of the workings of the Lomo de Toro mine. Its portal is at an altitude of 1,834 meters, 303 meters above the San Guillermo level and about 400 meters east-northeast of the San Guillermo portal. It is an incline 300 meters long toward the northwest along a tonguelike manto whose maximum width is about 20 meters; the lower end of the incline is 77 meters below the portal. A winze 210 meters from the portal connects with the San Damián working below. A map of the incline is shown in figure 66. The entire incline from the main stope to the portal is along an ore body. Ore was first found as a thin manto along the rather flat troughs of two synclines plunging gently northwestward. In the main stope, ore occurred in a manto 1 to 5 meters thick which strikes northwestward and dips southwestward at angles as much as 55°. Beyond the main stope a few stringers of galena were seen along the manto horizon, but no minable ore was found to the end of the incline.

The ore extracted from the La Bota ore body was largely oxidized. Remnants of plumbojarosite and iron oxide were seen in several places. Apparently the ore body was a manto offshoot from the top of the San Damián chimney, although the precise relationship between the two ore bodies cannot be established because the intervening workings are inaccessible. The incline was abandoned some years ago, probably in the early 1930's.

EL VAQUERO MINE

The El Vaquero mine is in the northeast corner of the Carrizal mining area at an altitude of 1,560 meters. Mine workings, an adit and stope along a vertical bed of Lower Cretaceous limestone striking N. 40° W., are inaccessible. Ore on the dump is nearly solid sphalerite cut by pyrite veinlets, but this may represent zinc-rich rejected ore. Nothing is known about past production; the mine has been closed for many years.

CALCITE MINE

A small deposit of pure calcite on the southeast slope of Cerro del Muí 3.5 kilometers east-northeast of Zimapán has long been utilized by local smelters. A quarry 25 meters long has been opened on a flat-lying deposit of calcite about 2 meters in maximum thickness. Calcite has replaced steep-dipping Lower Cretaceous limestone. Figure 67 is a sketch of the southeast face of the quarry, showing the irregular contact between calcite and limestone.

The hanging-wall limestone is somewhat fractured, and locally as much as 1 meter of the hanging wall is a replacement breccia of angular limestone fragments imbedded in calcite. Calcite is very coarse grained; a perfect rhombic cleavage face 45 cm on a side was seen, and one cleavage face was 105 cm across. The coarse calcite is cut by vertical veins of white sugary calcite; these veins strike N. 50°–60° W. and have a maximum thickness of 30 cm. Another quarry 50 meters northeast of the main quarry appears to be on the same calcite deposit.

SLAGS

Much of the ore extracted during the early periods of activity was smelted at or near Zimapán. Inasmuch as some of the slag contains a relatively high proportion of valuable metals, it was considered worthwhile to make an estimate of the tonnage and grade of easily available slag within the district. Accordingly, the ten largest slag piles were mapped by plane table, volumes and tonnages were calculated, and a 15-kilogram grab sample of each slag pile was analyzed. In addition, estimates were made of tonnages available in three small slag piles. Results of the calculations and analyses are given in the following table.

Tonnages and analyses of slags

[Analyses by Geological Institute of Mexico. No analysis made of El Carmen slag pile]

Slag pile	Tonnage (metric tons)	Pb (percent)	Zn (percent)	Ag (g/ton)	Fe_2O_3 (percent)	FeO (percent)	S (percent)	SiO_2 (percent)
La Aurora-La Trinidad	113, 765	3. 57	4. 50	62	0. 00	30. 70	1. 29	36. 76
El Carmen	[1] 600							
Cerrito Romero (La Cruz)	25, 050	2. 55	4. 00	58	. 70	31. 42	2. 45	37. 18
La Equitativa	34, 915	2. 04	3. 60	150	. 00	26. 13	1. 17	37. 54
La Llave	53, 205	4. 59	4. 80	142	2. 15	32. 84	2. 58	33. 14
Loreto	33, 350	4. 59	4. 30	76	. 00	30. 99	1. 20	35. 60
Monserrat	[1] 3, 550	2. 55	4. 80	56	. 39	32. 56	. 82	35. 88
San Antonio	28, 145	6. 12	5. 40	195	4. 70	41. 41	3. 79	30. 66
San Francisco	32, 695	3. 32	4. 90	66	7. 02	33. 13	1. 00	34. 44
San José-Purísima	195, 030	2. 81	4. 50	95	1. 99	32. 84	1. 47	33. 04
San Miguel	[1] 2, 815	5. 36	4. 40	84	. 00	28. 99	. 84	36. 74
San Nicolás	8, 325	3. 06	6. 40	95	. 07	31. 56	1. 54	23. 10
La Soledad	33, 260	3. 06	5. 80	48	. 00	31. 56	. 98	34. 72
Total	564, 705							

[1] Estimated only.

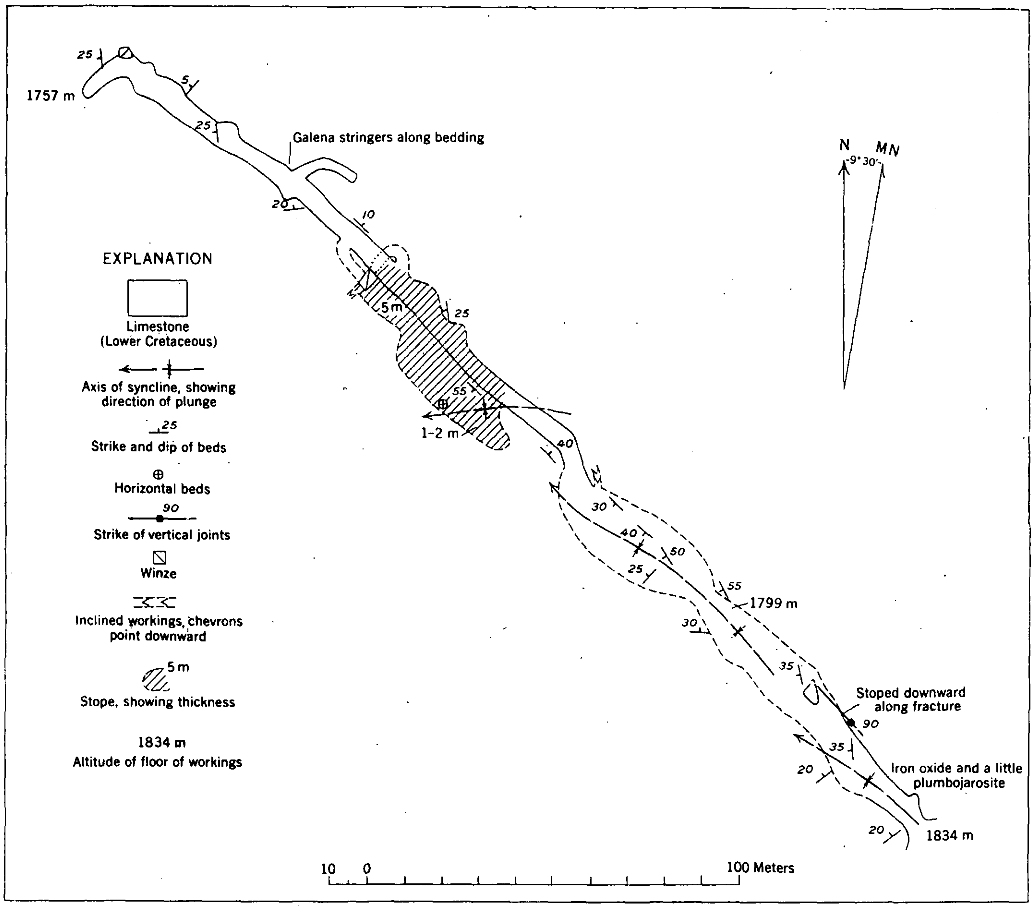

FIGURE 66.—Map of La Bota incline, Lomo de Toro mine.

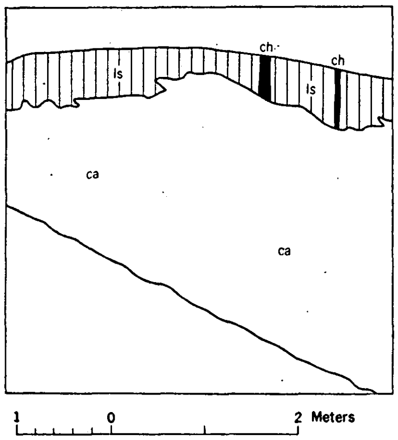

FIGURE 67.—Sketch of southeast face of calcite quarry, Cerro del Muf. Shows irregular replacement contact between calcite (*ca*) and Lower Cretaceous limestone (*ls*). Lower line is bottom of quarry. Calcite has replaced impartially limestone and chert (*ch*).

PETROGRAPHIC NOTES ON THE LAS ESPINAS VOLCANIC ROCKS

CERRO DE LA ESTANCIA SECTION

The columnar section for the Cerro de La Estancia volcanic rocks (fig. 68) is numbered from the bottom. The colors and color numbers are from the Rock-color chart of the National Research Council, Washington, D. C., 1948.

1. Soft friable red andesite tuff, the only identifiable mineral in hand specimens is plagioclase.

2. Pyroxene andesite, a grayish-red-purple platy aphanitic rock with irregular rusty red patches representing a zone of alterations around some iron-rich mineral. Microlites of plagioclase can be distinguished in hand specimens. In thin section the rock has a microporphyritic texture of altered pyroxene(?) phenocrysts as long as 0.3 mm set in a very fine grained hyalopilitic groundmass of andesine (An_{40}) microlites, pyroxene prisms, a little iron ore, and abundant slightly devitrified glass. Flow structure is obscure. The pyroxene(?) in both phenocrysts and groundmass is altered to a fine-grained fibrous aggregate which is probably a chlorite.

3. Andesite, in hand specimen, a brownish-black cryptocrystalline amygdaloidal rock. No crystals are visible with the hand lens. Amygdules are of opal. Flow banding is well developed. No thin section was made.

4. Andesite, a greenish-black rock similar to unit 3, but more massive.

5. Quartz latite tuff, a dusky-red welded tuff showing quartz, potash feldspar, and soda-lime feldspar crystals as much as 3 mm long imbedded in a dense glassy groundmass. The rock is characterized by grayish-pink lithophysae as much as 1.5 cm in diameter; grains of quartz and feldspar are enclosed within the lithophysae. Some of the lithophysae are partly enveloped by open cavities, a few of which have been filled with opal. For microscopic features, see description of rock unit 11.

6. Olivine andesite, a very dusky red-purple amygdaloidal volcanic rock with good flow structure and stretched amygdules. The only minerals visible in hand specimen are phenocrysts of an altered ferromagnesian mineral and, rarely, plagioclase microlites in the aphanitic groundmass. Under the microscope, crystals of olivine as much as 1.5 mm across are imbedded in an intergranular matrix of andesine (An_{45}) microlites 0.2–0.3 mm long, augite granules, a few tiny olivine grains, scattered iron ore, and a little devitrified brown glass. The olivine of both phenocrysts and groundmass is altered to a core of very fine grained irresolvable pale-brown material with considerable iron ore and a rim of iddingsite. Some crystals have been converted entirely to clear red-orange iddingsite.

7. Quartz latite tuff, same as unit 5.

8. Andesite, same as unit 2.

9. Red andesite agglomerate, fragments of red andesite as much as 8 cm across in a tuffaceous matrix.

10. Olivine basalt, a grayish-black porphyritic rock with rude flow banding. A few phenocrysts of an altered ferromagnesian mineral and plagioclase, as well as plagioclase microlites, can be distinguished in hand specimen. Microscopically the rock contains euhedral crystals of labradorite (An_{60}) as much as 2 mm across, in an intergranular base of andesine (An_{45}) laths, augite grains, a little olivine and iron ore, and some brown glass. The olivine is completely altered to iddingsite, and in places it has a rim of augite.

11. Quartz latite tuff, like unit 5, except that the top 70 cm is free of lithophysae. This rock is a dusky-red vitric-crystal tuff with a stony groundmass. Crystals of quartz, potash feldspar, and plagioclase feldspar can be seen in hand specimen. The microscope reveals crystals of sanidine and oligoclase as large as 2 mm across, and quartz grains as much as 1 mm in diameter, set in a slightly devitrified groundmass composed of glass shards and pumice fragments which are bent and flattened to simulate flow structure (pl. 9*C*). Crystals of all minerals are corroded and plagioclase grains are partly melted. A few tiny grains of apatite, numerous minute euhedral crystals of sphene, and a little iron ore, as well as a few grains of altered pyroxene(?) complete the mineral assemblage.

12. Olivine-hypersthene basalt, in hand specimen, a grayish-brown platy aphanitic rock in which plagioclase and some tiny reddish crystals are visible. Under the microscope slender crystals of andesine-labradorite

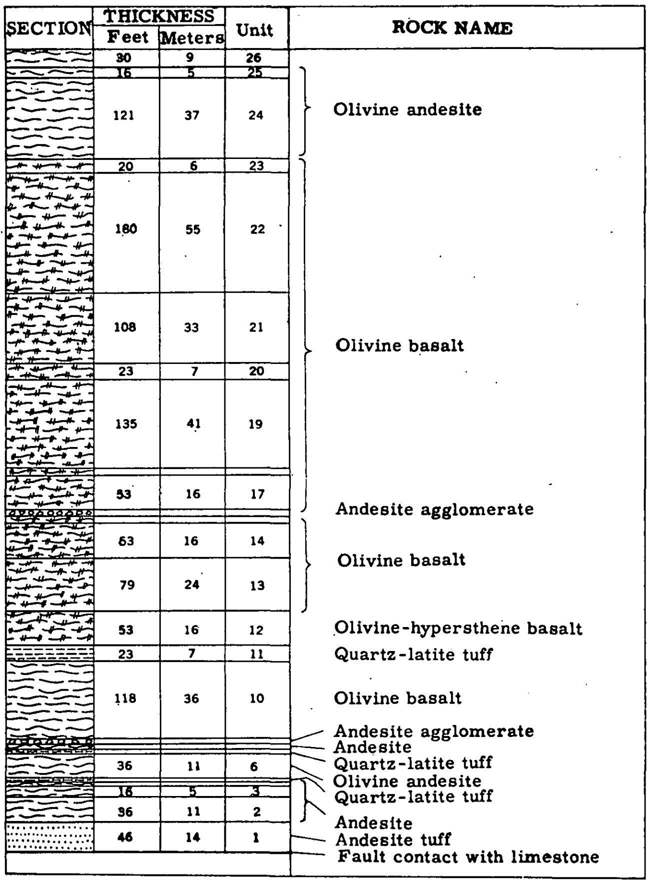

FIGURE 68.—Columnar section of volcanic rocks, Cerro de La Estancia.

(An_{45-55}) as long as 1 mm, and numerous crystals of altered olivine as much as 0.3 mm across, as well as a few small prisms of faintly pleochroic hypersthene are set in an intersertal groundmass of plagioclase laths, pyroxene (largely augite) granules, scattered iron ore, and considerable glass. A poor flow structure is developed in the groundmass. All olivine is altered to iddingsite. Locally there are large patches of glass.

13. Olivine basalt, a grayish-brown rock similar to unit 12. No thin section was made.

14. Olivine basalt, a grayish-red (10*R*4/2) amygdaloidal lava with a few small reddish phenocrysts in an aphanitic groundmass. This is the uppermost flow, about 16 meters thick, of a sequence of similar flows beginning with unit 12. Microscopically the rock consists of phenocrysts of olivine as much as 1 mm across in an intergranular base of andesine-labradorite (An_{50}) laths with interstitial pyroxene granules, a little iron ore, and some slightly devitrified brown glass. One phenocryst of augite was noted. Olivine is completely altered to iddingsite. Amgdules are of brownish chlorite. The rock exhibits fair flow structure.

15. Olivine basalt, a platy amygdaloidal lava similar to unit 19.

16. Red andesite agglomerate.

17. Olivine basalt, a fine-grained amygdaloidal lava similar to unit 19.

18. Olivine basalt, a flow 2.4 meters thick with a clinkery base. Similar to unit 19.

19. Olivine basalt, a grayish-red (10*R*4/2) platy rock with light-colored spots, possibly local concentrations of feldspar. A few rusty phenocrysts of an altered ferromagnesian mineral are the only megascopic crystals. The microscope shows crystals of olivine and a few plagioclase phenocrysts in an intergranular matrix of labradorite microlites with interstitial pyroxene, a little iron ore, and some brown devitrified glass. The groundmass shows prominent flow structure. Olivine is entirely altered to iddingsite and iron ore. Both augite and hypersthene are present in the groundmass; the largest grains are hypersthene, but augite predominates.

20. Olivine basalt, similar to unit 19. This flow is very massive and forms a prominent cliff about 7 meters high.

21. Olivine basalt, similar to unit 19. A sequence of thin flows; poor exposures prevented determination of the exact number of flows.

22. Olivine basalt, similar to unit 19. A sequence of four nearly identical cliff-forming flows.

23. Olivine basalt, similar to unit 19.

24. Olivine andesite, a sequence of four flows of grayish-brown platy lava. Small rusty phenocrysts of an altered ferromagnesian mineral are the only megascopic crystals. Under the microscope phenocrysts of altered olivine as much as 0.7 mm across are set in an intersertal groundmass of andesine laths averaging 0.2 mm long, interstitial pyroxene and a little iron ore, and pale-brown glass. Flow structure is noticeable but not well developed. Hypersthene predominates in the pyroxene groundmass; much of it has a rim of augite.

25. Olivine andesite, a grayish-red (10*R*4/2) vesicular platy lava similar to unit 24.

26. Andesite, a thick flow of dusky-red vesicular lava without phenocrysts. Vesicles are lined with opal.

CERRO GRANDE SECTION

The columnar section for the Cerro Grande volcanic rocks (fig. 69) is numbered from the bottom.

1. Olivine basalt, a blackish-red porpyhritic rock consisting of numerous reddish phenocrysts of a completely altered ferromagnesian mineral, probably olivine, and a few stubby pyroxene crystals in an aphanitic groundmass in which a few plagioclase laths are visible. The dark color and abundance of olivine(?)

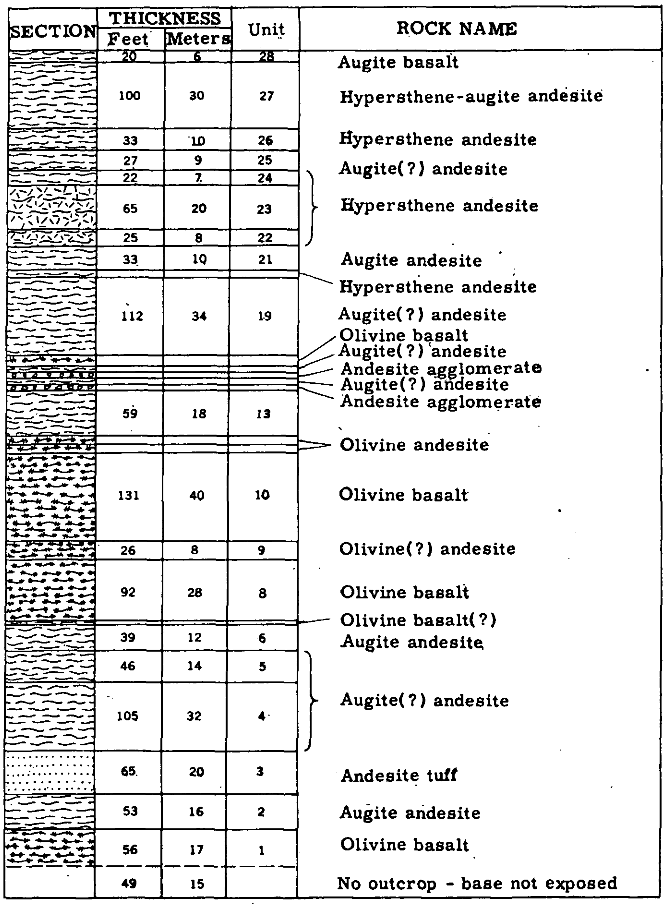

FIGURE 69.—Columnar section of volcanic rocks, Cerro Grande.

phenocrysts indicate that the rock is probably a basalt. No thin section was examined.

2. Augite andesite, in hand specimen a dusky yellowish-brown amygdaloidal rock without phenocrysts. Amygdules are of dark-green chlorite, generally with a core of opal. The rock shows prominent flow banding. Under the microscope the rock shows a few microphenocrysts of plagioclase and pyroxene in a hyalopilitic base of andesine (An_{45}) laths, pale-green pyroxene needles, a few scattered reddish grains of hematite(?), and somewhat devitrified brown glass. The phenocrysts of plagioclase are corroded and saussuritized, and all the pyroxene is altered to an aggregate of yellow-green chlorite. The groundmass is very fine grained, the andesine prisms averaging about 0.3 mm

3. Andesite tuff, a coarse red tuff with a thin agglomerate bed at the top. Plagioclase and pyroxene are the only identifiable minerals. No thin section was made.

4. Augite(?) andesite, an olive-gray lava with prominent flow banding and pronounced fissility. Tiny red phenocrysts, probably altered pyroxene, and a few plagioclase crystals are set in an aphanitic glassy groundmass in which a few plagioclase microlites can be distinguished. The rock is very similar to unit 5 and was not examined in thin section.

5. Augite(?) andesite, a dark yellowish-brown fine-grained rock with prominent flow banding. A few reddish prisms of altered pyroxene and an occasional grain of pyrite are the only identifiable minerals. The rock is somewhat less fissile than unit 4, but otherwise very similar. It is the commonest rock in the Cerro Grande section. The microscope shows a few phenocrysts, as long as 0.6 mm, of a pale-green-brown mineral, probably augite altering to chlorite, in an extremely fine grained felsitic groundmass of andesine (An_{40}) needles averaging less than 0.05 mm long, many tiny hexagonal plates of a brown mineral (hematite?), a little iron ore, and interstitial slightly devitrified colorless glass.

6. Augite andesite, similar to unit 2.

7. Olivine basalt(?), in hand specimen the rock is a grayish-red (10*R*5/2) porphyritic lava with red phenocrysts of an altered ferromagnesian mineral in an aphanitic glassy groundmass. No minerals can be identified with certainty. The microscope reveals crystals of a highly altered ferromagnesian mineral as long as 4 mm, a few small crystals of augite, and iron-ore grains as much as 0.5 mm across, set in a very fine grained hyalopilitic base of andesine-labradorite laths (An_{50}) and tiny augite granules with interstitial devitrified glass, pale-brown chlorite, and iron-ore dust. The phenocrysts are altered to an irresolvable fine-grained aggregate with a rim of iron oxide; the shape of the crystals and the degree of alteration are atypical for the Cerro Grande volcanic rocks. Probably the best name for the rock is olivine basalt.

8. Olivine basalt, a pale-brown porphyritic rock showing many tiny phenocrysts of altered olivine and a few plagioclase laths imbedded in a glassy groundmass. A few plagioclase laths can be identified. The microscope reveals phenocrysts of olivine as large as 4 mm across and a few smaller augite grains in a hyalopilitic matrix of labradorite (An_{65}) rods with interstitial pale-brown glass, iron-ore dust, and a few minute granules of olivine. The olivine phenocrysts are altered to a core of serpentine and iddingsite(?), an intermediate rim of iddingsite, and an outer rim of iron oxide.

9. Olivine(?) andesite, a moderate-red fine-grained platy rock with a few dark-brown phenocrysts of an altered ferromagnesian mineral. No other minerals can be distinguished in the hand specimen. Microscopically, the rock is seen to have phenocrysts of a completely altered ferriferous mineral, probably olivine, in a hyalopilitic groundmass of andesine prisms imbedded in a dark-brown nearly opaque base of glass, iron-ore dust, and tiny brown rods of what may be basaltic horn-

blende. There are numerous small amygdules of brownish chlorite. The phenocrysts are altered to a brownish-black irresolvable aggregate; the shape of the crystals suggests that the original mineral was olivine, but it could also have been a pyroxene.

10. Olivine basalt, a pale-brown porphyritic rock showing red-brown phenocrysts of an altered ferromagnesian mineral in a fine-grained felted groundmass. It seems to be a single flow about 40 meters thick. Under the microscope the rock is nearly holocrystalline and has an intergranular texture and readily apparent flow structure. Olivine crystals as much as 1 mm across, completely altered to a fine-grained felted aggregate with a rim of iddingsite, are the only phenocrysts. Microlites of labradorite (An_{65}) averaging about 0.4 mm long with interstitial granules and rods of augite, iron-ore particles, and a little slightly devitrified glass compose the groundmass.

11. Olivine andesite, a dark-gray porphyritic lava with a very few red-brown phenocrysts of an altered ferromagnesian mineral in an aphanitic groundmass. The microscope shows a few phenocrysts of nearly opaque, thoroughly altered olivine, set in an intergranular groundmass of andesine (An_{40}) laths, augite granules, iron-oxide dust, and patchy brown devitrified glass. No flow structure is visible. A few ghostlike largely resorbed poikilitic remnants of what was probably hornblende are scattered through the groundmass.

12. Olivine andesite, a dark-gray aphanitic rock similar to unit 11, except that there are fewer phenocrysts. Microscopically, the rock consists of scarce phenocrysts of altered olivine as much as 2.5 mm across in a nearly holocrystalline intergranular groundmass of andesine prisms with interstitial augite granules, iron-ore dust, and a little brown devitrified glass. A rude flow structure has been formed. Olivine is altered to carbonate and chlorite with a rim of iddingsite; a little zeolite is also present. The groundmass is flooded with carbonate which has replaced feldspar and glass, and, to a lesser extent, augite.

13. Augite(?) andesite, similar to unit 5.

14. Red andesite agglomerate.

15. Augite(?) andesite, similar to unit 5.

16. Red andesite agglomerate.

17. Augite(?) andesite, similar to unit 5.

18. Olivine basalt, a grayish-brown scoriaceous lava in which the only visible minerals are a few plagioclase prisms. Under the microscope the rock is seen to have a few small phenocrysts of olivine in a hyalopilitic base of labradorite (An_{65}) laths imbedded in a nearly opaque matrix of devitrified glass, iron-ore dust, and a highly altered mineral of prismatic habit which may be an amphibole. Olivine is altered to an irresolvable brownish core with a rim of iron oxide. The rock is very similar to unit 9.

19. Augite(?) andesite, similar to unit 5.

20. Hypersthene andesite, a dark reddish-brown platy aphanitic lava in which the only identifiable mineral is microlitic plagioclase feldspar. Under the microscope the only phenocrysts, less than 1.0 mm long, are prisms of nearly colorless hypersthene. Microlites of andesine-labradorite (An_{50}) averaging 0.1 mm in length, hypersthene needles, iron-ore dust, a few plates of hematite(?), and brown devitrified glass make up the intersertal groundmass.

21. Augite andesite, similar to unit 2.

22. Hypersthene andesite, a dark greenish-gray (*5GY4/1*) platy porphyritic rock with prominent phenocrysts of plagioclase and a little pyroxene. The groundmass is aphanitic. This rock appears to be a single flow about 8 meters thick, with a scoriaceous base. The microscope shows phenocrysts of andesine (An_{35}) as much as 1 mm long, a few crystals of augite, and some highly altered remnants of what was probably hypersthene set in an extremely fine grained intersertal groundmass of plagioclase needles, augite rods and granules, iron-ore grains, and glass.

23. Hypersthene andesite, similar to unit 22.

24. Hypersthene andesite, similar to unit 22, but phenocrysts are less prominent. Microscopically, the rocks are nearly identical, except that there is a little unaltered hypersthene and the plagioclase is slightly more calcic.

25. Augite(?) andesite, similar to unit 5.

26. Hypersthene andesite, a grayish-red (*10R4/2*) platy rock with large phenocrysts of plagioclase and smaller crystals of pyroxene set in a very fine grained groundmass. The rock is similar to unit 20. It was not studied in thin section.

27. Hypersthene-augite andesite, a brownish-gray lava with small phenocrysts of plagioclase and some pyroxene in an aphanitic groundmass. Under the microscope, phenocrysts of plagioclase and pyroxene are set in a fine-grained felsitic groundmass of oligoclase-andesine (An_{30}) laths, iron-ore dust, and devitrified glass. Both augite and hypersthene are present in about equal amount; the hypersthene is faintly pleochroic and occasionally is jacketed by augite. A few rounded quartz grains are present, always with a rim of augite granules; they seem to be xenocrysts, exhibiting the well-known reaction rim of pyroxene (pl. 9*D*).

28. Augite basalt, a grayish-red (*5R4/2*) platy aphanitic rock with only plagioclase laths as identifiable crystals. The microscope shows microphenocrysts of labradorite (An_{65}) and augite in a hyalopilitic groundmass of minute plagioclase microlites, scarce

iron ore, and pale-brown devitrified glass. The augite phenocrysts are all fairly altered; the principal result has been a decrease in birefringence and the production of considerable residual iron oxide.

CERRO DE LAS ESPINAS AREA

The volcanic rocks of Cerro de Las Espinas are dominantly dark, conspicuously porphyritic lavas of andesitic or dacitic composition. Exposures are inadequate to permit delineation of individual flows, but in general the flows appear to be rather thick.

A typical andesite from the lower part of the section is a dark-gray to greenish-gray porphyritic rock with phenocrysts of pale-greenish feldspar as much as 3 to 4 mm across and tiny dull ferromagnesian grains in an aphanitic groundmass. In thin section the rock shows slightly rounded euhedral plagioclase phenocrysts, a few altered ferromagnesian crystals and scattered quartz xenocrysts in a hyalopilitic matrix of albite-oligoclase needles, iron-ore dust, and pale-brown glass. Iron ore is an abundant accessory. Plagioclase has sericitized cores and kaolinized rims; the few unaltered remnants are albite. Ferromagnesian crystals are completely altered, either to carbonate or to an aggregate of penninite, iron oxide, and a little sphene; the original mineral may have been titaniferous augite. A few grains of what may have been olivine as much as 1 to 2 mm across are altered to penninite, carbonate, iron ore, and a little quartz. Many tiny amygdules have rims of penninite and carbonate and cores of quartz. Secondary chlorite, quartz, and carbonate occur in veinlets.

Porphyritic dacite flows totaling about 60 meters in thickness crop out between Puerto de Los Bronces and the Mercedes adit. In hand specimen the rock is a very dusky red-purple lava showing phenocrysts of greenish-white feldspar as much as 2 to 6 mm across, abundant small deep-red crystals of altered ferromagnesian minerals, and many tiny quartz grains in a fine-grained matrix. Under the microscope the rock shows phenocrysts of plagioclase feldspar, pale brownish-green hornblende prisms as much as 1 mm in length, and a few rounded microphenocrysts of fresh augite set in a hyalopilitic base of albite-oligoclase laths, minute grains of orthoclase, iron-ore dust, a little apatite, and abundant glass. Euhedral and slightly embayed plagioclase phenocrysts are altered to zoisite, strongly pleochroic epidote, and kaolinite; the unaltered remnants are albite. Hornblende is slightly altered to iron oxide. A few grains of some ferromagnesian mineral, probably biotite, are completely altered to iron oxide, serpentine, and a fine-grained colorless aggregate. Many small irregular patches of quartz dot the groundmass. The rather small quantity of potash feldspar observed suggests that the rock is more likely a dacite than a quartz latite.

The summit of Cerro de Las Espinas is composed of a dark greenish-gray porphyritic lava in which small crystals of rusty feldspar and a little quartz are the only minerals identifiable in hand specimen. The microscope reveals grains of completely sericitized plagioclase feldspar as much as 0.4 to 3 mm across and a few crystals of some highly altered ferromagnesian mineral as much as 0.5 mm across in a groundmass of sericitized plagioclase laths, granular quartz, and much devitrified glass. Abundant apatite and a little iron ore are accessory minerals. The rock is probably a dacite, but it is too altered for accurate identification.

A moderate-red fine-grained porphyritic lava from the low hill about 500 meters west of Cerro de Las Espinas proved to be too thoroughly altered for identification. Sericitized orthoclase phenocrysts as much as 4 mm long and a few oligoclase laths were the only minerals identifiable in thin section. The rock is probably a latite.

ROCKS FROM OTHER AREAS

Trachyte.—The only trachyte lava recognized in the Las Espinas volcanic rocks is an isolated remnant on the ridge of El Morro fanglomerate north of the San Pascual mine. It is yellowish-gray fine-grained rock in which tiny whitish feldspar phenocrysts and a few minute plagioclase rods are visible with a hand lens. In thin section, ragged kaolinized orthoclase crystals as much as 1 mm in length and a few albite microphenocrysts are set in a groundmass of devitrified glass with an average refractive index near that of orthoclase. A little quartz replaces orthoclase. Iron ore is a scarce accessory mineral.

Olivine basalt.—A few flows of fresh olivine basalt are intercalated in Las Espinas volcanic rocks near Temoté. They are dark-gray to grayish-black porphyritic rocks which everywhere contain megascopic olivine and in places show plagioclase and pyroxene phenocrysts as well. A thick flow of grayish-black olivine basalt forms a cliff along the southwest side of Barranca de El Suspiro, 750 meters east of Temoté. Many grains of glassy olivine and pyroxene are visible in hand specimen. In thin section, phenocrysts of olivine and augite are set in a very fine grained intersertal groundmass of pyroxene rods, minute laths of labradorite (An_{55}), considerable iron ore, and much colorless glass. A few microphenocrysts of labradorite as much as 0.5 mm long are scattered through the rock. Olivine is the most abundant phenocrystic mineral; it occurs as slightly serpentinized subhedral grains from 1 to 3 mm in length. The olivine is chrysolite, optically (−) with 2V near 90°. Augite forms euhedral crystals as much as 1 to 2 mm in length. It is strongly and discontinuously zoned, the extinction angle $Z \wedge C$ in 010 ranging from 44° to 47° in the cores to 49° to 55° at the rims. The average difference in extinction angle from core to rim is 6°, and the maximum difference is 8°. Cores are colorless, passing into pale brownish red toward the edges; zoning is evidently from magnesian augite in the cores to ferriferous aguite in the rims. Multiple twinning on 100 is common.

Apatite and a little sphene were noted as accessory minerals in a thin section of an olivine basalt flow exposed southwest of Cerro del Potrero; slides of the other basalts have iron ore as the only accessory mineral.

The most calcic plagioclase found in the Las Espinas volcanic rocks occurs as phenocrysts in an olivine basalt flow that crops out on the south side of Cerro del Melchor. In hand specimen the rock is a grayish-red-purple porphyritic amygdaloidal lava with small phenocrysts of feldspar set in a dense aphanitic groundmass. Microscopically, the feldspar is labradorite-bytownite (An_{70}) in rounded and corroded crystals, partly replaced by groundmass. Olivine grains averaging 0.4–0.5 mm across are completely altered to serpentine and iron ore. The hyalopilitic base consists of andesine (An_{45}) microlites averaging 0.15 mm in length and a few augite granules set in a matrix of nearly opaque glass. Amygdules consist of thin opal rims and chalcedony cores.

Tuffs.—The tuffs of the Las Espinas volcanic rocks were not studied in detail, as they form a relatively small part of the formation. They are abundant only in the basal part of the formation at the contact with the El Morro fanglomerate. The tuffs are commonly coarse-grained poorly consolidated rocks ranging in color from brownish-gray to grayish-green. A few fine-grained tuffs form lenses in the El Morro fanglomerate; in thin section these tuffs consist largely of carbonate with tiny fragments of quartz, plagioclase feldspar, apatite, and a little iron ore. The coarse-grained tuffs are dominantly feldspathic and usually contain quartz and abundant rock fragments; in a number of coarse tuffs, biotite is an abundant accessory mineral. In general, ferromagnesian minerals are scarce in the tuffs, although abundant tiny prisms of augite appear in a few tuffs. A light brownish-gray coarse tuff consisting of glassy plagioclase, greenish altered feldspar, biotite, and quartz crops out in the southern part of the town of Zimapán.

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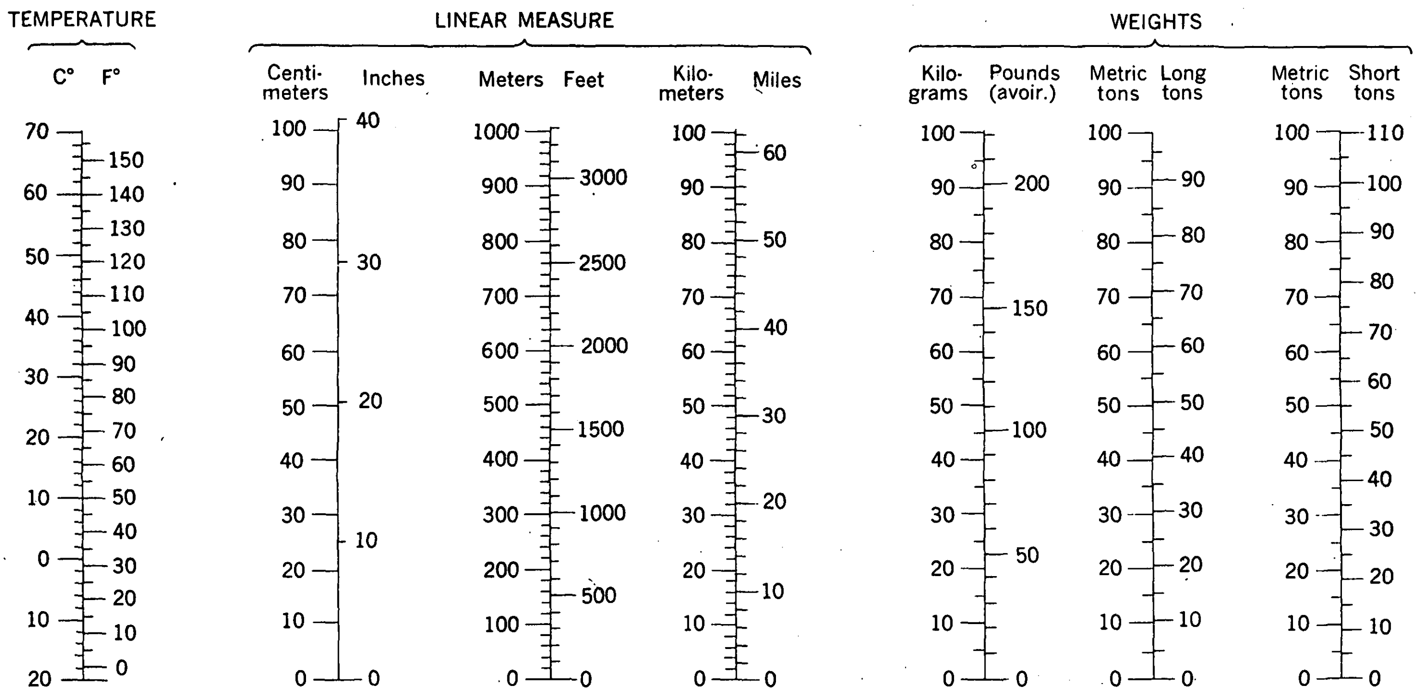
METRIC EQUIVALENTS



1 cm. = 0.3937 inch
1 inch = 2.5400 cm.

1 meter = 3.2808 ft.
1 ft. = 0.3048 meter

1 km. = 0.6214 mile
1 mile = 1.6093 km.

1 sq. meter = 1.20 sq. yd.
1 hectare = 2.47 acres
1 cu. meter = 1.31 cu. yd.

1 kg. = 2.2046 lbs.
1 lb. = 0.4536 kg.

1 metric ton = 0.9842 long ton
1 metric ton = 1.1023 short tons
1 metric ton = 2205 lbs.
1 long ton = 1.0161 metric tons
1 short ton = 0.9072 metric ton

INDEX

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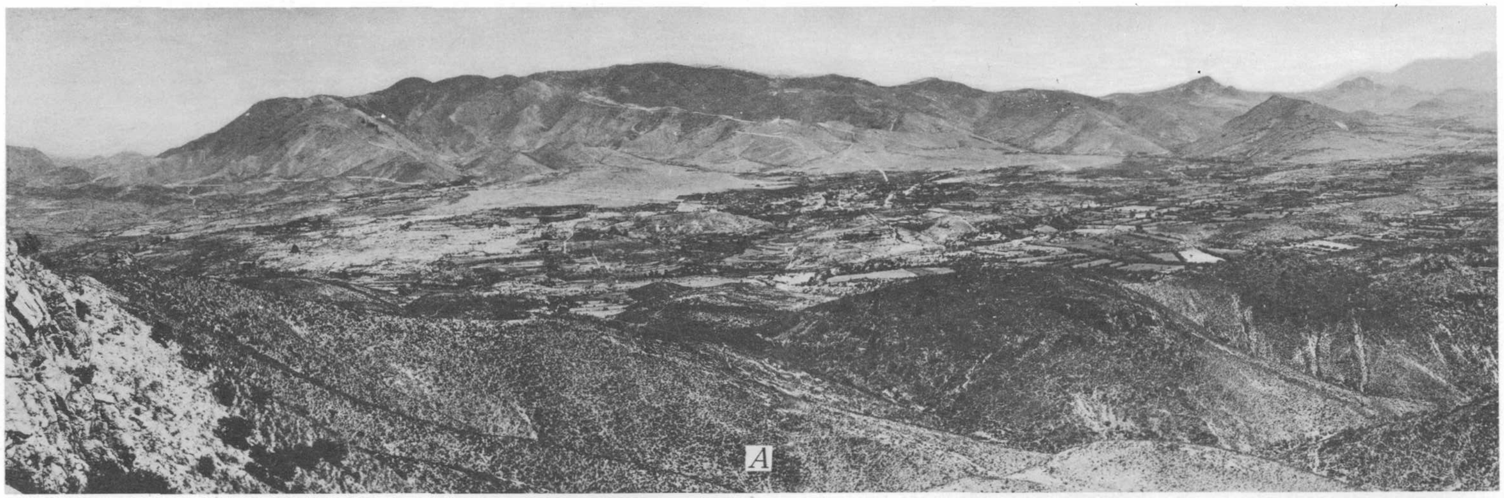
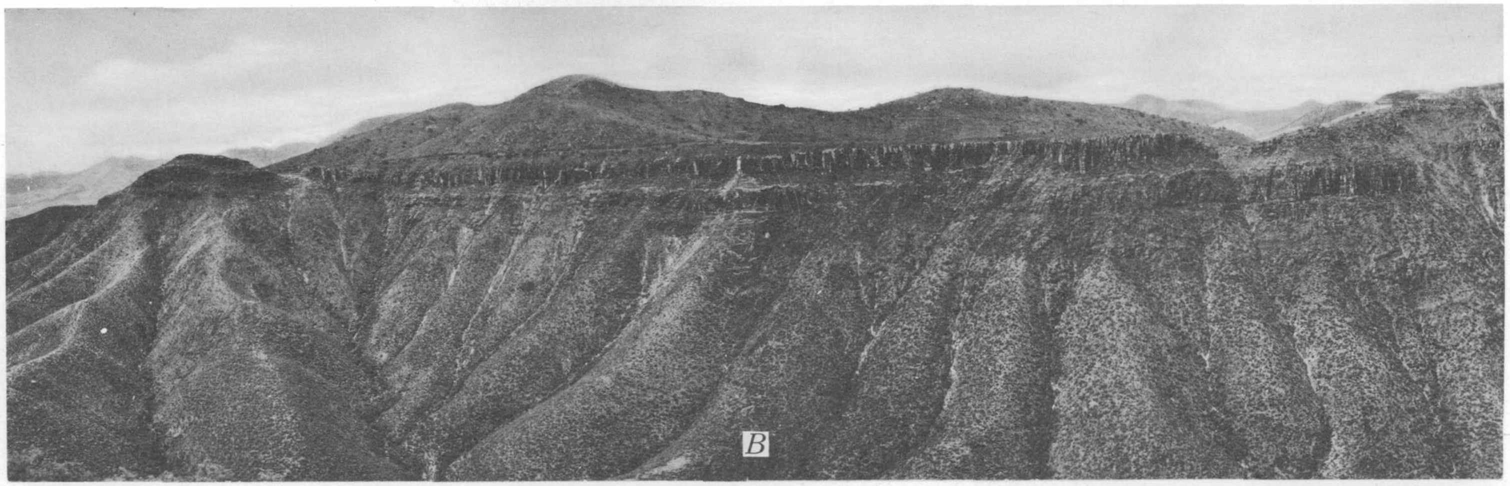
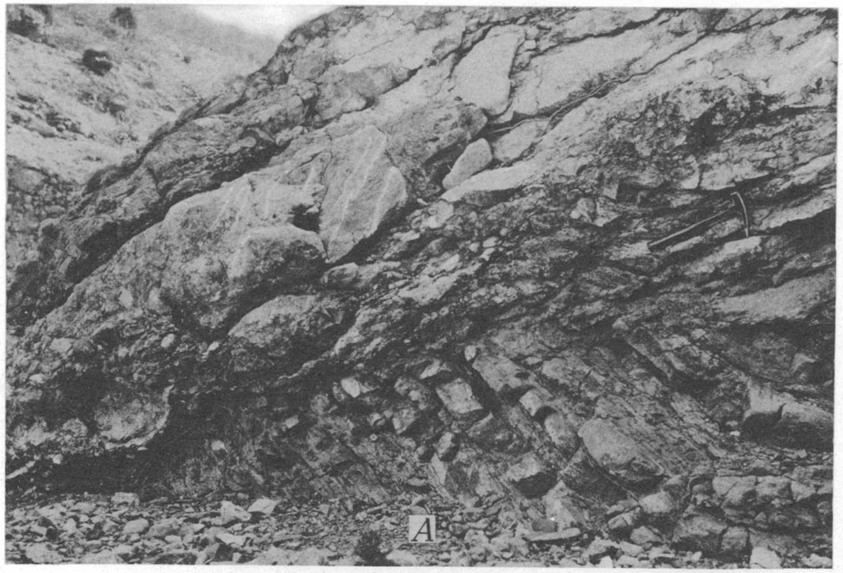


A. Panorama of Zimapán Valley and Sierra de El Monte. Dark rock in right center foreground is El Morro fanglomerate, which overlies lighter colored Upper Cretaceous rocks. Light rock at left is rhyolite felsite dike. Road to Lomo de Toro and Los Balcones mines skirts west (left) end of Sierra de El Monte, which consists of Lower Cretaceous limestone. View to northeast.



B. Cliff-forming El Morro fanglomerate overlying soft Upper Cretaceous beds. Top of upper cliff-forming bed is base of Las Espinas volcanic rocks, which form rounded skyline hills. Note rapid thickening of fanglomerate toward northwest (right). Road to San Pascual mine area passes through notch at right. View from Cerro del Malacate southwest across Barranca del Malacate.

FORMATIONS IN ZIMAPAN DISTRICT

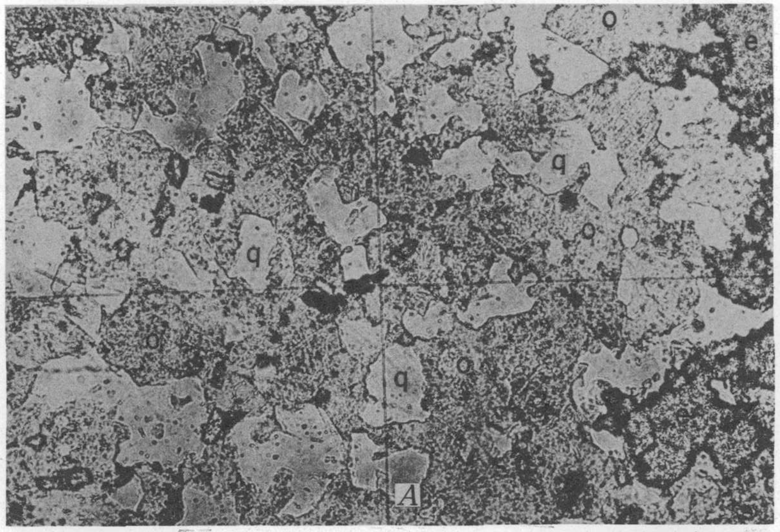


A. Unconformity between Upper Cretaceous strata and overlying El Morro fanglomerate. Base of El Morro fanglomerate is marked by chaotic jumble of poorly sorted boulders and cobbles of gray fossiliferous limestone. Outcrop in Arroyo del Portrero.

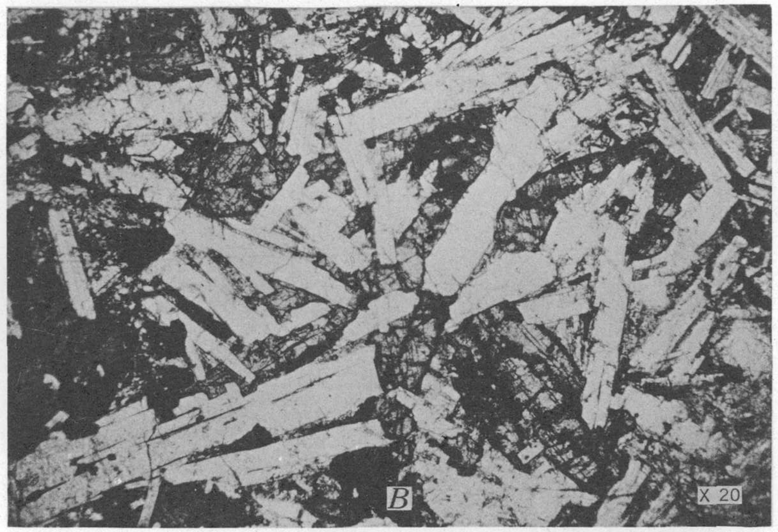
B. Outcrop showing texture of El Morro fanglomerate. All fragments are gray limestone. Note thin bed of finer grained material just below pick, and nearly total lack of sorting elsewhere. Fanglomerate dips about 30°. Outcrop southwest of Zimapán.

C. View along axis of Puerto Angel anticline. Northeast (left) limb of anticline is vertical; southwest limb forms dip slope of about 35°. Note sharpness of flexure at anticlinal crest. Massive beds are reef limestone. View looking southeastward from point 1 kilometer northwest of Cerro del Juaxidó, highest point in photograph.

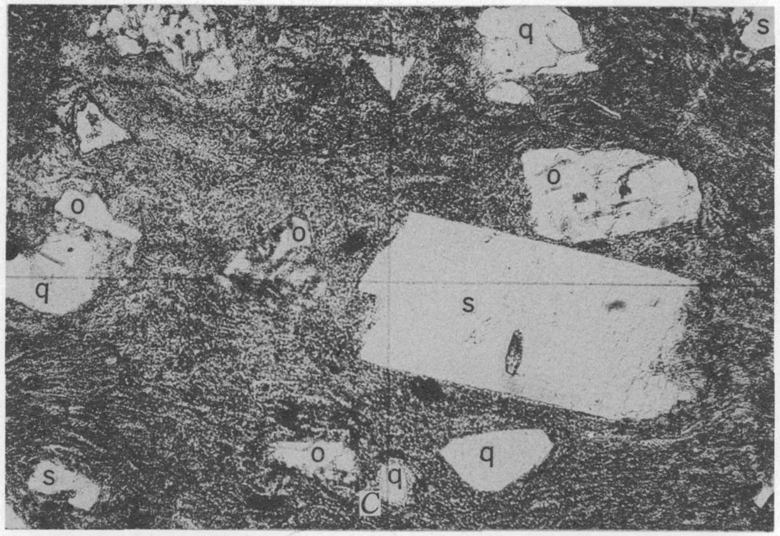
VIEWS OF TERTIARY EL MORRO FANGLOMERATE AND OF ANTICLINE IN CRETACEOUS ROCKS



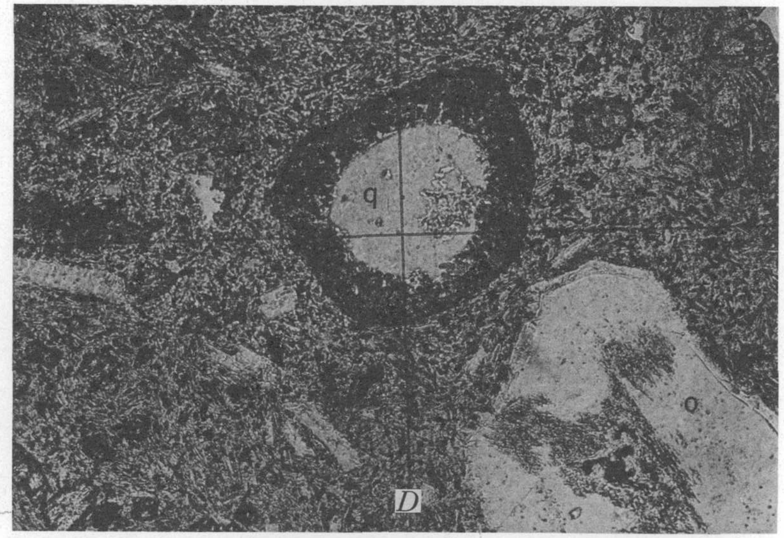
A. Orthoclasized quartz monzonite, Barranca de Tolimán. Early-formed epidote and quartz are replaced by orthoclase, which floods rock. The slide is slightly below focus. *q*, quartz; *o*, orthoclase; *e*, epidote. Plane-polarized light, × 72.



B. Augite diabase, Barranca Seca. White, andesine-labradorite; gray, titaniferous augite. Plane-polarized light, × 20.

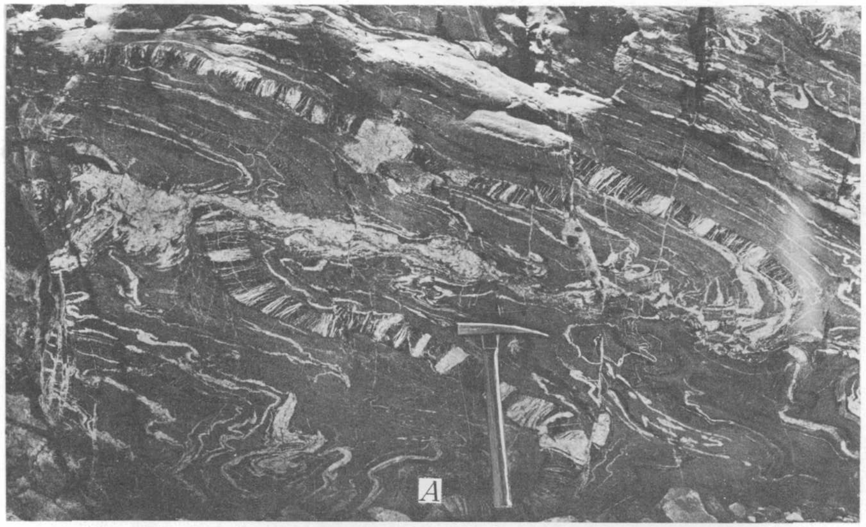


C. Quartz latite, Cerro de La Estancia. Note prominent flow lines in glassy groundmass. *s*, sanidine; *o*, oligoclase; *q*, quartz. Plane-polarized light, × 37.

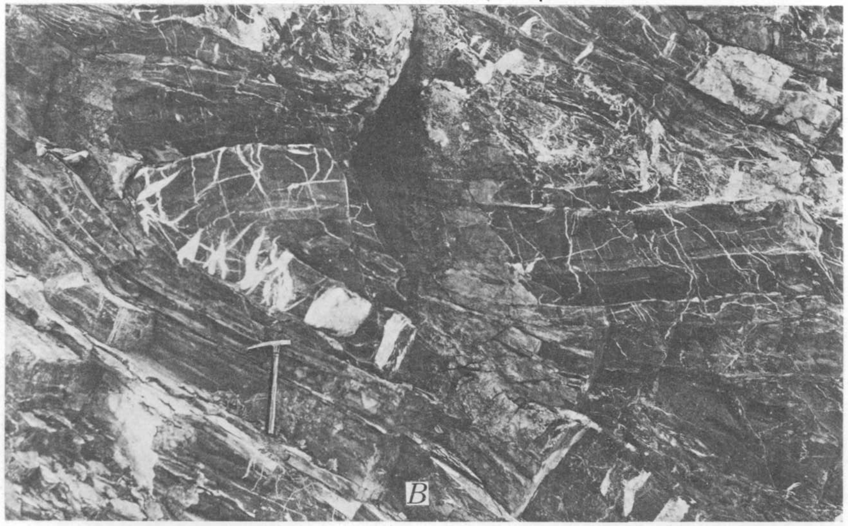


D. Hypersthene-augite andesite, Cerro Grande. Note reaction rim of augite granules around quartz xenocryst. *o*, oligoclase-andesine; *q*, quartz. Plane-polarized light, × 72.

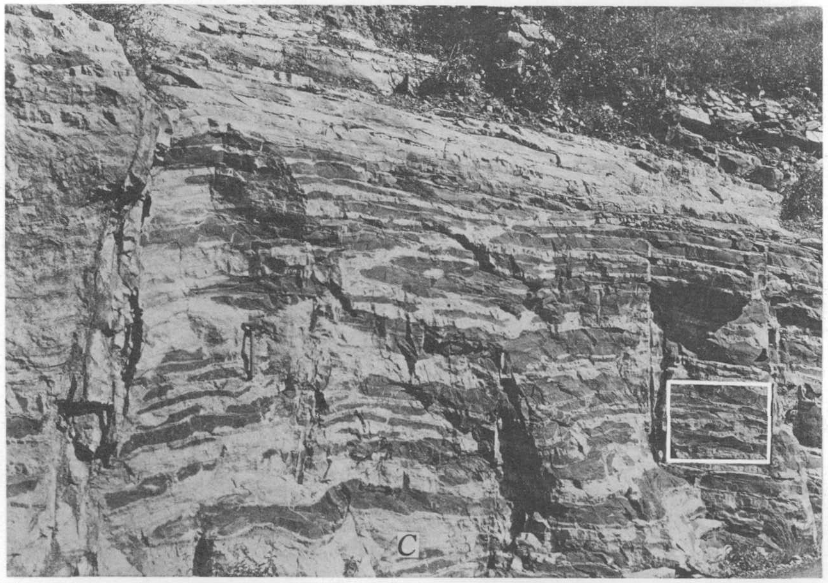
PHOTOMICROGRAPHS OF IGNEOUS ROCKS



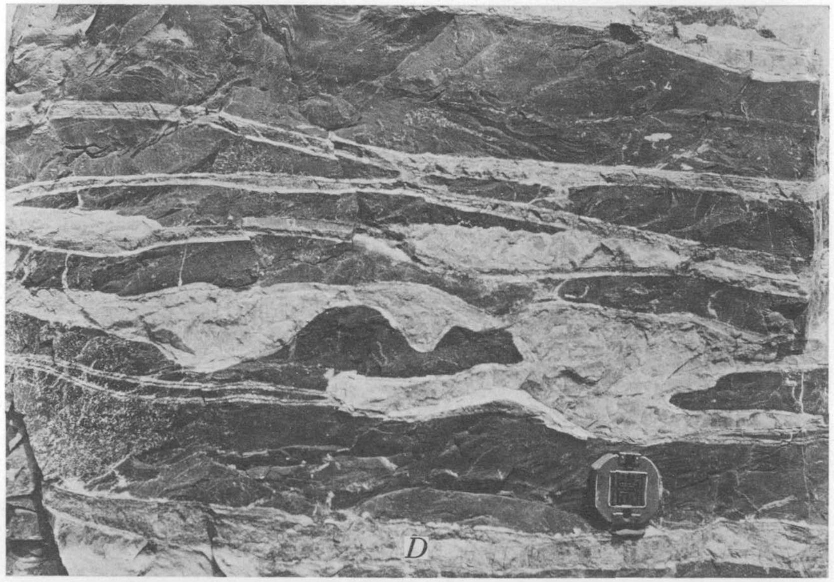
A. Contorted and faulted beds. Layer of black chert has been broken along small underthrust and is offset about 80 cm. Thrust is marked by irregular calcite stringer. Chert was fractured roughly perpendicular to bedding, and fractures were filled with calcite. Note steep reverse fault which postdates thrust, and also extreme contortion of bedding. View looking southeastward just upstream from bend in El Cajón, Barranca de Tolimán.



B. Recumbent folds. Axial planes of recumbent folds dip gently southwestward. Fractures in lower limb of lower fold are filled with calcite. Note breccia-tion along axial plane of upper fold. View looking southeastward about 350 meters south of San Guillermo adit along Lomo de Toro and Los Balcones road.

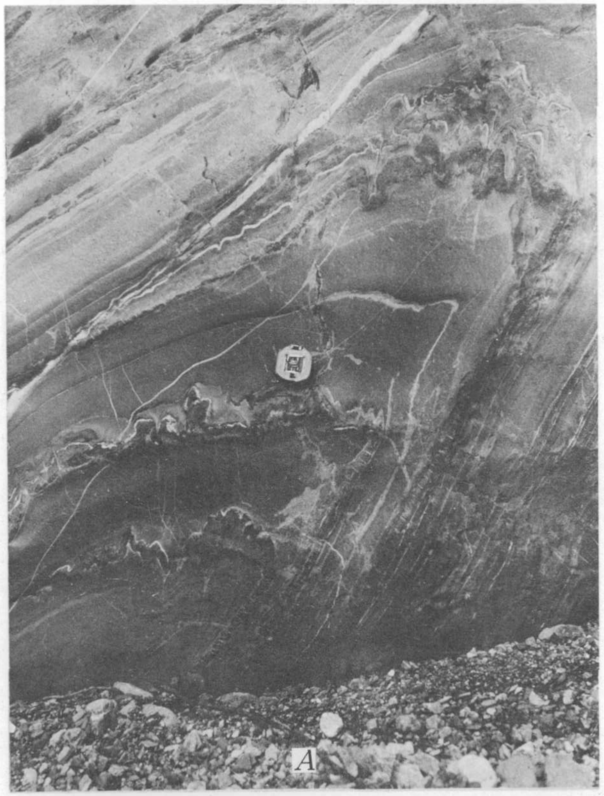


C. Metamorphosed Lower Cretaceous limestone with chert near Lomo de Toro mine. White, metachert and recrystallized bleached limestone; gray, limestone. Latite dike 30 cm thick appears near left edge of photograph. Alteration is more intense near dike, dying away at right.



D. Closeup of part of *C* marked by rectangle. Dark gray, limestone; light gray, metachert; white, bleached limestone bordering chert. Thin darker chert bands are garnetized and have lighter colored selvage of bleached limestone.

VIEWS OF LOWER CRETACEOUS LIMESTONE

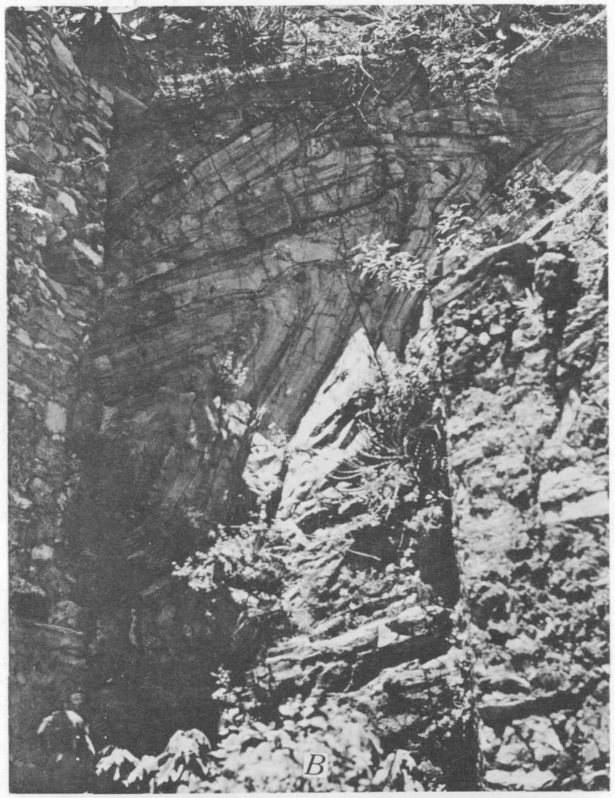


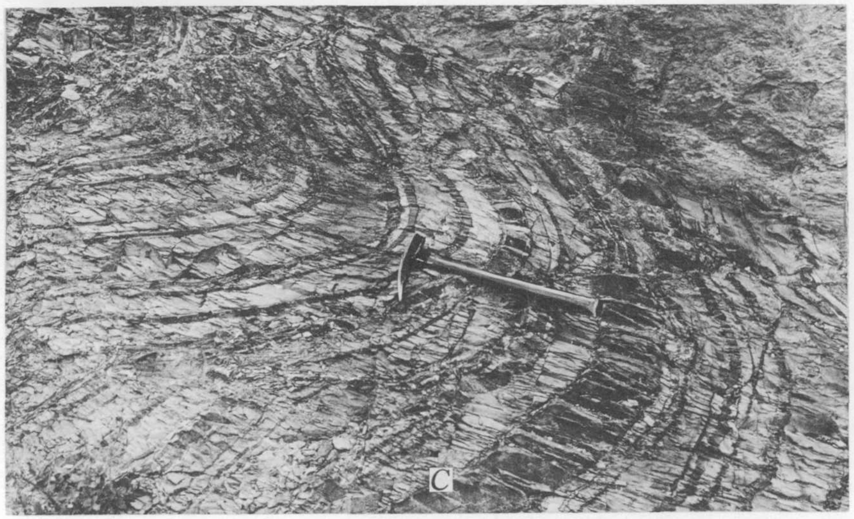
A. Overturned anticline. Note crumpling of chert layers (black), extreme thickening of limestone at crest of fold, and thinning of limestone along inverted limb. White streaks in upper left are calcite veins nearly parallel to axial plane of fold. View looking northwestward in Barranca de Tolimán 2 kilometers north of Lomo de Toro mine.

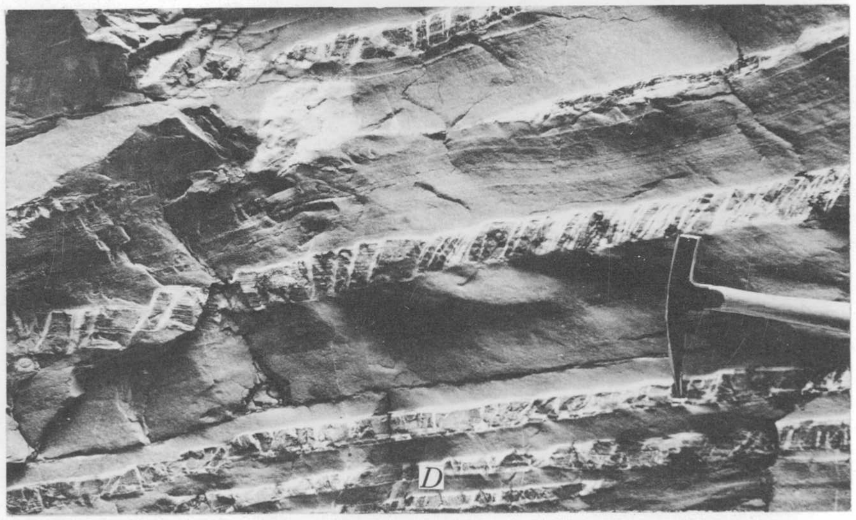
B. Tight folds. Axial planes dip 30°–40° SW. View at portal of El Claro stope of Lomo de Toro mine, looking northwestward.

C. Fracture cleavage in Upper Cretaceous shale. Hammer handle is along fracture cleavage cutting overturned fold; cleavage strikes northwestward and dips 20° SW. Shale outcrop in Arroyo de Chametla southwest of Zimapán, looking southeastward.

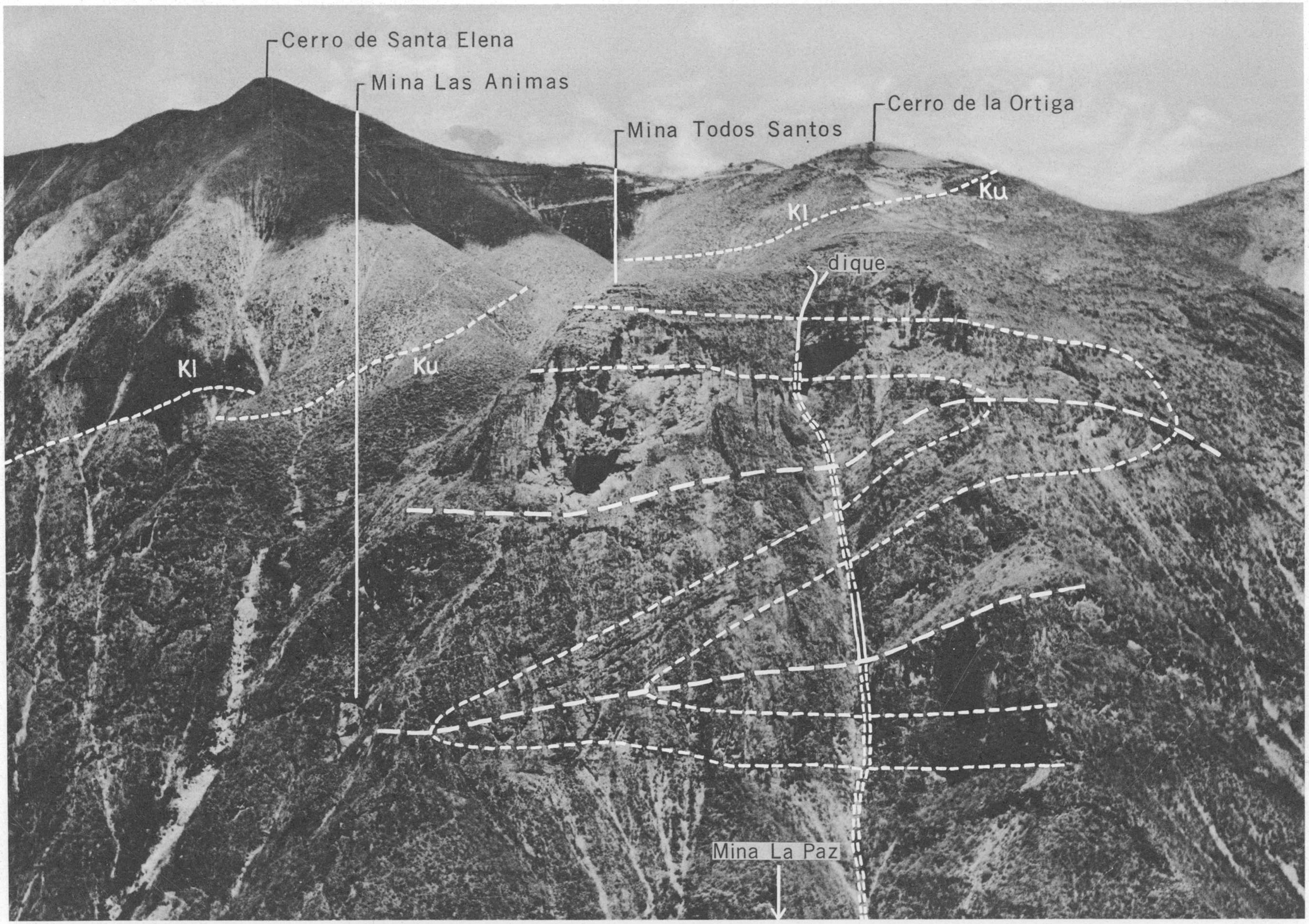
D. Fractured and deformed chert bed in Lower Cretaceous limestone. Chert bed in center is broken along series of fractures inclined 60°–70° to bedding, and blocks are rotated through maximum of 25°. White material is secondary calcite. Deformation has been absorbed plastically by the limestone. At right edge, fractures are so closely spaced as to resemble rude cleavage. Outcrop in El Cajón in Barranca de Tolimán, looking N. 50° W. along strike of beds dipping 17° SW.





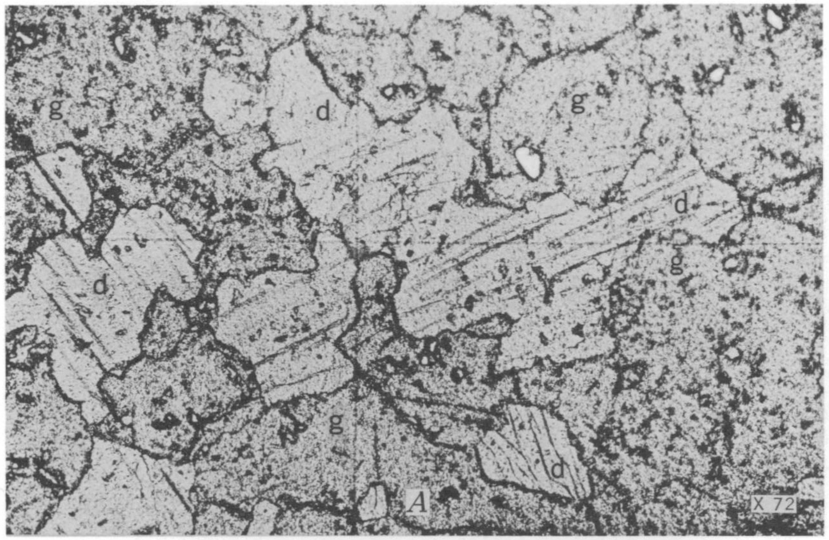


DEFORMED LOWER CRETACEOUS LIMESTONE AND UPPER CRETACEOUS SHALE

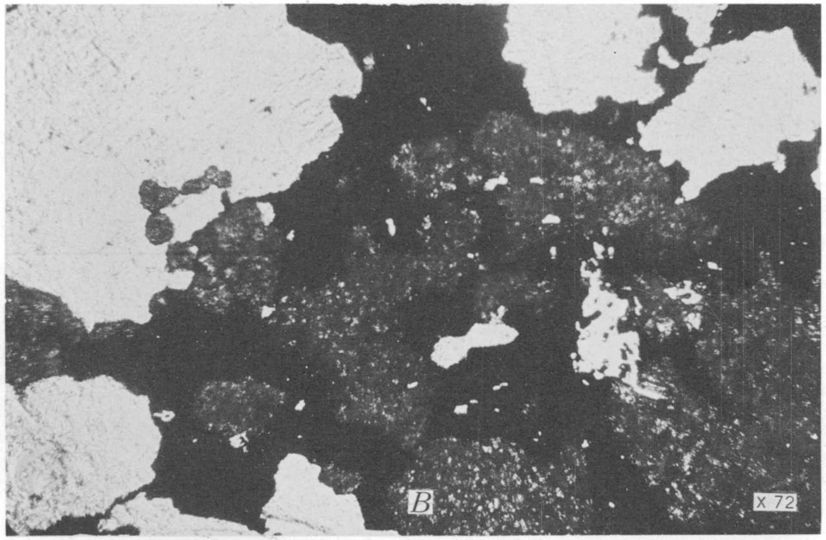


RECUMBENT FOLD IN LOWER CRETACEOUS LIMESTONE IN CLIFF ABOVE LA PAZ MINE

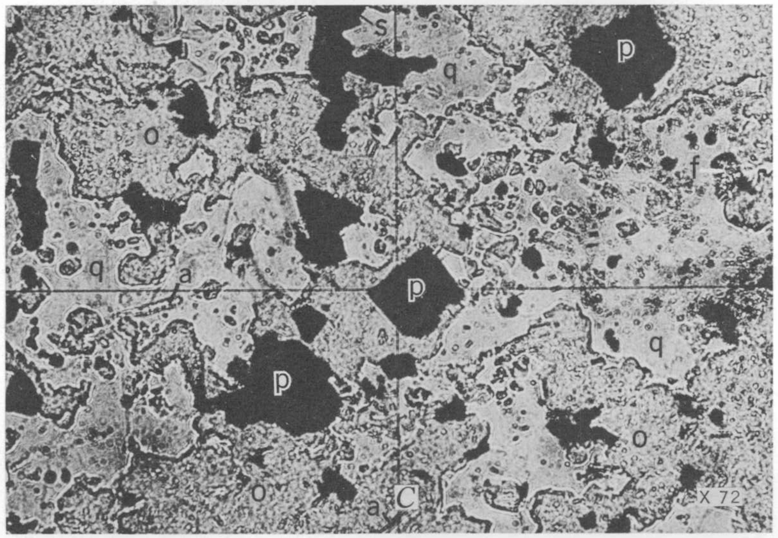
A prominent limestone bed and the contact between the Upper Cretaceous (Ku) and Lower Cretaceous (Kl) strata are outlined by light dashes; traces of axial planes of the folds, which dip gently southwestward, are shown by heavy dashed lines. Solid line indicates dike (dique). Vertical distance from La Paz mine to Todos Santos mine is 420 meters. View looking westward from 1 kilometer north of Lomo de Toro mine.



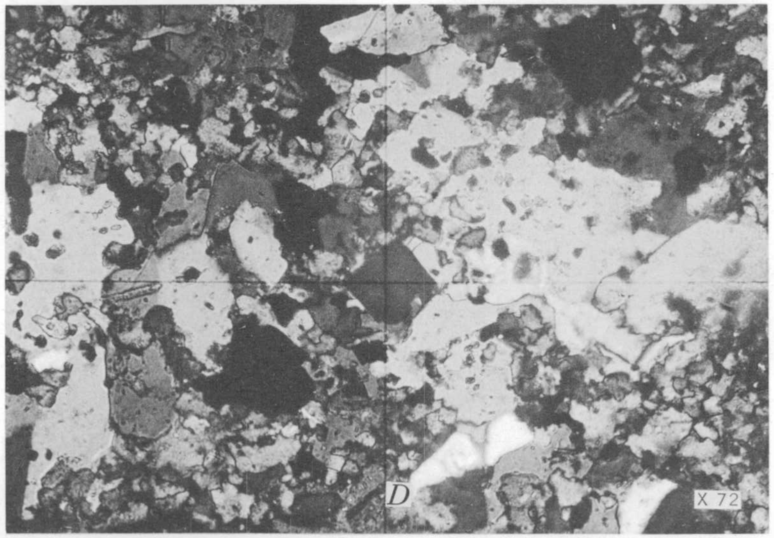
A. Tactite in Barranca de Tolimán near El Cajón. Garnet is replacing diopside. *g*, garnet; *d*, diopside. Plane-polarized light, × 72.



B. Tactite from Chiquihuites mine. White, fluorite; dark gray, sphalerite; black, galena. Sequence of mineralization is fluorite-sphalerite-galena. Plane-polarized light, × 72.



C. Orthoclasized quartz monzonite from Concordia mine. Early-formed fluorite and sulfides were followed by quartz and then by orthoclase, which partly replaces all minerals formed earlier. Slide slightly below focus. *q*, quartz; *o*, orthoclase; *a*, apatite; *s*, sphalerite; *p*, pyrite; *f*, fluorite. Plane-polarized light, × 72.



D. Same as *C*, between crossed nicols. Coarse-grained quartz contrasts strongly with fine granular orthoclase.

PHOTOMICROGRAPHS OF TACTITE AND ORTHOCLASIZED QUARTZ MONZONITE