General Geology and Phosphate Deposits of Concepción del Oro District, Zacatecas Mexico

GEOLOGICAL SURVEY BULLETIN 1037-A

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

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By CLEAVES L. ROGERS, ZOLTAN DE CSERNA, EUGENIO TAVERA, *and* SALVADOR ULLOA

GEOLOGIC INVESTIGATIONS IN THE AMERICAN REPUBLICS

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GENERAL GEOLOGY AND PHOSPHATE DEPOSITS OF CONCEPCION DEL ORO DISTRICT, ZACATECAS, MEXICO

By Cleaves L. Rogers, Zoltan de Cserna,[1] Eugenio Tavera,[1] and Salvador Ulloa [1]

ABSTRACT

The Concepción del Oro district comprises an area of about 1,300 square kilometers in northern Zacatecas and southern Coahuila, Mexico. The district lies near the southern margin of a broad belt of strongly asymmetrical mountains, which trend generally westward and are characterized by a moderately rugged terrain. Four small anticlinal ranges have been mapped. They are generally overturned toward the north and in some places are characterized by fan folding. They contain several important thrust faults and many normal faults, some of which have large displacement.

The stratigraphic sequence, about 3,600 meters in thickness, includes the Zuloaga limestone and La Caja formations of Late Jurassic age, and the Taraises formation, Cupido limestone, La Peña formation, Cuesta del Cura limestone, Indidura formation, Caracol formation, and Parras shale, of Cretaceous age. The rocks are predominantly calcareous up to the Cuesta del Cura limestone, above which they become increasingly clastic. Above these marine formations is the Mazapil conglomerate of early Tertiary age which consists of mixed sedimentary and pyroclastic material. Flows and pyroclastic rocks ranging in composition from rhyolite to basalt are considered to be mainly of middle to late Tertiary age. The Tertiary rocks are overlain by lacustrine deposits, conglomerate, and alluvium of Quaternary age.

Intrusive rocks are of Tertiary age and range from stocks of granodiorite and diorite to small stocks, sills, and dikes of andesite, dacite, rhyolite, and aplite. The deep-seated intrusive masses of granodiorite and diorite strongly metamorphosed the adjacent sediments and in places highly deformed them. Commercial deposits of copper, lead, zinc, silver, gold, and iron are associated with the stocks and contact metamorphic zones.

Marine phosphorites occur principally in one unit or member of the La Caja formation. Five lithologic types are present in this member, calcareous phosphorite being the most important commercially and containing the highest percentage of P_2O_5. The phosphate mineral is fluorapatite, occurring as primary pellets of generally structureless, cryptocrystalline collophane and as secondary material replacing pellets, fossils, and the rock matrix. The fluorapatite may

[1] Instituto Nacional para la Investigación de Recursos Minerales.

contain carbonate, and spectrographic analysis indicates the presence of 28 elements in addition to those reported in the chemical analyses. The principal impurities in the phosphatic rock are chert and calcite, the chert predominating in the lower part of the phosphatic member, and the calcite predominating in its upper part. The deposits probably accumulated very slowly in shallow clear agitated waters, and the richest material may have formed on a low submarine ridge.

The phosphatic member ranges from less than 1 meter to about 20 meters in thickness, and the grade of the phosphatic rock decreases in inverse proportion to its thickness. The phosphatic member is considered to have commercial possibilities only in the Sierra de Santa Rosa, where it averages 2.15 meters in thickness. In that area, reserves are calculated to amount to some 5,000,000 metric tons averaging 21.1 percent P_2O_5, or about 13,500,000 metric tons averaging 16.2 percent P_2O_5.

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

The primary purpose of the present study was to evaluate the phosphate deposits of the Concepción del Oro district, in the hope that a major phosphate field might be present in that area.

Although Mexico has a rapidly growing fertilizer industry, it can meet only a part of the country's needs. Large-scale production of superphosphates is contingent upon the discovery of an adequate source of raw material within the country. It is expensive to import phosphate rock or commercial fertilizers from the United States, and the deposits now being exploited in the State of Nuevo León are small and scattered, although they are high in grade.

The investigation was not limited to the phosphate deposits, but was extended to include areal geologic mapping of the district. The authors hope that the results of this work will be useful to the local mining industry, which produces a diversity of precious and base metals, including gold, silver, copper, lead, zinc, and iron. The geology in many of the principal mining areas is complex and difficult and, in large part, has never been adequately mapped. Also, it is hoped that this study may lead to a better understanding of some aspects of the regional geology.

GEOGRAPHIC FEATURES OF THE AREA

The area studied has an extent of about 1,300 square kilometers. Although it is situated mainly in the northern part of the State of Zacatecas, it extends a short distance into Coahuila. (See fig. 1.) The principal town in the district is Concepción del Oro, an important metal-mining and smelting center of 5,400 inhabitants. It is connected with the city of Saltillo, Coahuila by the narrow gage Coahuila and Zacatecas Railroad. Saltillo lies 125 kilometers to the northeast of Concepción del Oro. Branch lines connect Bonanza and Melchor Ocampo with the Coahuila and Zacatecas main line at Avalos, and the Compañia Minera de Peñoles operates a short narrow gage line connecting Avalos with their plants at Terminal. Although the Coahuila and Zacatecas Railroad is mainly a freight line servicing the local mining industry, it maintains passenger service operating daily, except Sunday, between Saltillo and Concepción del Oro.

The closest paved highway is in the vicinity of Saltillo, and roads within the mapped area are dirt or gravel and generally poor. Only the roads being used for trucking ore receive any maintenance, and

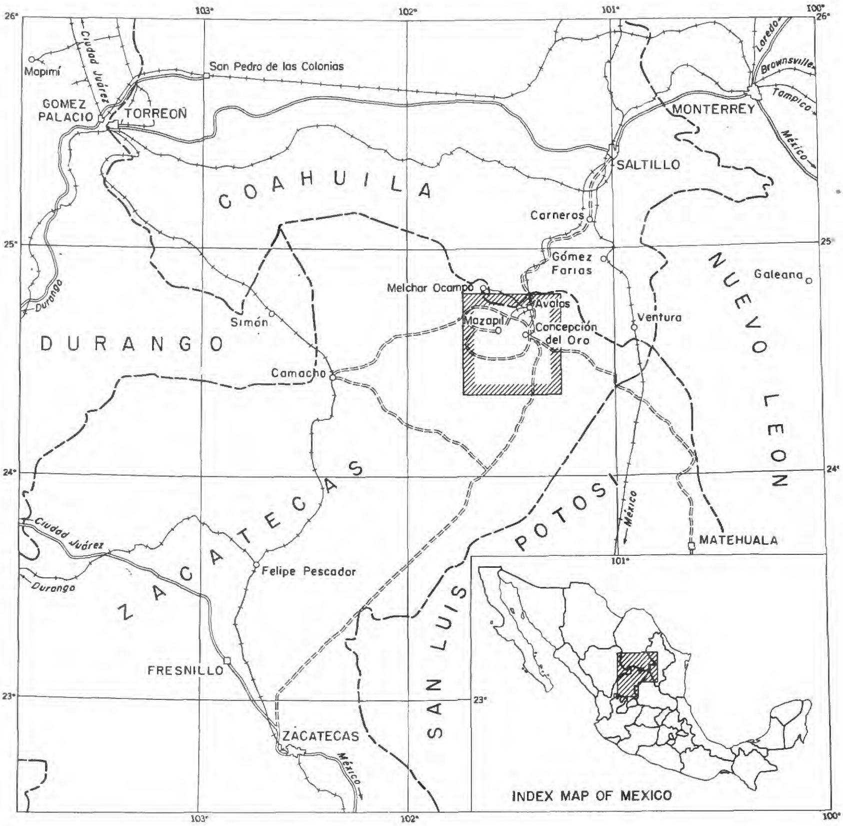

FIGURE 1.—Index map of Mexico showing location of the area studied.

some roads may be temporarily impassable during the rainy season. However, a modern highway from Saltillo to Concepción del Oro is under construction and will be completed in 1956. Eventually this road will be surfaced with asphalt and will become a part of the federal highway network. The area contains numerous foot and burro trails, which form important connecting links for the local inhabitants.

The area is situated in the northern half of the Mesa Central, a high semiarid plateau containing many scattered mountain ranges of relatively short extent. It lies close to the southern margin of a broad belt of closely spaced, westward-trending mountains and valleys

FIGURE 2.—Aerial view, looking westward, of northern part of the area mapped, showing the typical tightly folded anticlines separated by narrow synclines. From left to right: Sierras de La Caja, Canutillo, Zuloaga, and Sombreretillo. Photograph furnished by United States Air Force.

which form the dominant topographic features of the region (fig. 2). The mountains are characterized by a terrain only moderately rugged.

The mapped area is crossed by four parallel ranges, which from north to south are known as the Sierras de Canutillo, La Caja, Santa Rosa, and Santa Rita. The eastern part of the Sierra de La Caja is known as the Sierra de Concepción del Oro, while the eastern part of the Sierra de Santa Rosa is called the Sierra de San José. The Sierras de San José and Concepción del Oro are in part joined by a large granodiorite stock to form a continuous U-shaped range open toward the west. The area is bounded on the east and west by the Bolsones de San Carlos and Cedros, which are large, northwestward-trending intermontane basins.

The maximum relief in the area is about 1,400 meters, and the highest mountain summit, Cerro de La Sorpresa, has an altitude of 3,175 meters.

This region of Mexico has a semiarid climate, most of the precipitation occurring in the summer rainy season. Annual rainfall totals about 500 millimeters. The mapped area contains scattered shallow wells, and a few springs emanate from the igneous rocks and some of the larger fault zones, but the farmers are in many places precariously dependent upon the collection of surface water in small earth reservoirs known as tanques.

Diurnal changes in temperature are relatively great. In winter the days are pleasantly warm, while the nights are cool, and temperatures occasionally dip below freezing. The summers are generally hot. The mean annual temperature ranges between 11° and 13°C.

The plains and lower mountain slopes support a sparse vegetation, classed as xerophytic, containing a great variety of desert shrubs and cactus. At higher elevations there may be open pine or cedar forest.

The principal source of income in the area is the mining industry, which, directly or indirectly, supports a majority of the inhabitants and has resulted in a greater population density than characterizes the surrounding region. However, many settlements in the area are predominantly agricultural communities, which are engaged mainly in the cultivation of corn, beans, and wheat and in the raising of goats. Other activities include the gathering of fiber for rope, wood for charcoal, and candelilla for wax. Guayule has been another important resource, although the rubber factory in Cedros has been idle since the end of World War II. In general, the farming is on a bare subsistence level.

HISTORY OF THE DISTRICT

Although the Indians may have exploited the ore deposits of the Concepción del Oro district on a small scale, the mining history of the area really began in the early days of the Spanish conquest. The oldest known mines are the San Eligio and Albarradón in the Sierra de La Caja, which were discovered about 1530 by Francisco de Urdiñola, an officer in the army of Cortés. For his discoveries he was rewarded with a title and was known as the Marqués de Aguayo. About 1548 the Real de Minas de Mazapil was established.

The earliest ore bodies worked were mainly silver, but by the end of the 16th century gold had been discovered near the present site of Concepción del Oro. The rich copper ores of Aranzazú were left undisturbed, as the Spaniards were interested only in the precious metals.

During the 18th century some of the rich bonanzas were exhausted, and this, together with the War of Independence in the beginning of the 19th century, greatly reduced activity in the district. Recovery began about 1889, when the Mazapil Copper Co. was organized by a group of English investors. Old mines were reopened, new mines were discovered, and construction of the Coahuila and Zacatecas Railroad made the region easily accessible for the first time. By 1906, monthly production from Aranzazú amounted to 7,000 metric tons of ore averaging 5 percent copper. A number of smaller companies were also active in this period, and in 1915 the Compañía Minera de Peñoles, S. A., a subsidiary of the American Metals Co., undertook exploitation of the deposits of silver, lead, and zinc in the Providencia area.

During the Mexican Revolution, activity in the district was again greatly reduced and real prosperity returned only with the advent of World War II. This prosperity has continued, and although the rich oxide ores were exhausted long ago, many sulfide bodies remain, and new discoveries are still being made.

EARLIER WORK IN THE AREA

The first reference to the district to be found in the literature is a description by Joseph Burkart (1836) of a visit to Mazapil, which is believed to have been made about 1830. He describes briefly an iron deposit and some of the metalliferous deposits then being exploited to the northeast of Mazapil.

The first detailed geologic work in the area was done by Carlos Burckhardt, who mapped parts of the Sierras de La Caja, Concepción del Oro, and Santa Rosa. The results of his excellent studies were published in 1906 as excursion guides for the 10th session of the International Geological Congress (Burckhardt, 1906a, 1906b, 1906c). Although earlier workers refer to the presence of fetid and oolitic rocks in the area, Burckhardt (1907) was apparently the first to recognize the phosphorites, and he described them briefly. Additional material on the district is included in his volume on the Mexican Mesozoic (1930).

In the late 1930's, a phosphate sampling program was undertaken in the area by Ings. Jesús J. Falomir and Germán García Lozano on behalf of the Mexican Government. Although their investigation was rather limited, it produced additional information on the extent and grade of the deposits (Falomir and García, 1939).

In the course of the past 70 years many papers have appeared describing individual mines or camps, but these have contributed little to a knowledge of the regional geology.

FIELDWORK AND ACKNOWLEDGMENTS

This study is one of the projects carried on in Mexico under the joint auspices of the United States Geological Survey and the Mexican Instituto Nacional para la Investigación de Recursos Minerales. The project was originally suggested by Jenaro González Reyna, chief geologist of the Instituto. It was carried on under the overall supervision of Carl Fries, Jr., chief of the Geological Survey party in Mexico, in close cooperation with González Reyna. It was part of the geologic program in the American Republics sponsored at its inception, on the part of the United States, by the Interdepartmental Committee on Scientific and Cultural Cooperation of the Department of State, but in November 1951 it passed to the Technical Cooperation Administration and in 1953 to the Foreign Operations Administration.

The fieldwork was carried on intermittently between December 1949 and July 1952, and only the senior author was engaged continuously on the project. Field mapping was done on aerial photographs taken by the Comisión Cartográfica Militar of the Secretaría de la Defensa Nacional; these photographs have an average scale of 1:20,000. The Sierra de Canutillo, which lies along the northern border of the area, was mapped by Ulloa. The Sierra de La Caja was mapped by Rogers and Tavera, and its southeastern extension, known as the Sierra de Concepción del Oro, was mapped by Rogers. The Sierra de Santa Rosa was mapped by Rogers, Tavera, and Ulloa, and its southeastern extension, the Sierra de San José, was mapped by Rogers. The Sierra de Santa Rita and the basalt flows to the northeast of Terminal were mapped by de Cserna. A considerable amount of geologic reconnaissance in areas contiguous to the Concepción del Oro district was carried on during the same period.

The fieldwork was greatly aided by several residents of the area. Among these were Ing. Leonides González of the Mazapil Copper Co., Walter H. Triplett and Charles Y. Manderfield of the Compañía Minera de Peñoles, and John G. Barry, a consulting geologist with long experience in the district. The owners of the Santa Rosa mine, the Nochebuena mine, and the guayule rubber factory in Cedros hospitably provided living quarters during some parts of the work. Antonio Pardo and Daniel Rodríguez were loyal and capable helpers in the field, and Adolfo Interial M. was helpful and cooperative in many ways. Many other residents of the district were most generous in their assistance.

Much assistance has been given by colleagues of the United States Geological Survey. The triangulation necessary for the compilation of a planimetric map was begun by Kenneth Segerstrom of the Geological Survey and was later finished by Eugenio Tavera, Salvador Ulloa, and Pedro Reyes Soto of the Instituto Nacional para la Investigación de Recursos Minerales. R. W. Imlay visited the area briefly in March 1952 and studied the greater part of our invertebrate fossil collections. In June 1952 the party was visited by Carl Fries, Jr., and V. E. McKelvey, who offered many valuable suggestions. C. S. Ross, James Owens, Charles Milton, Norman Herz, and Richard Kellagher examined many of our thin sections and made helpful comments. Ruth Todd examined shale samples for microfossils. Specimens of fossil wood were identified by R. W. Brown.

Valuable assistance was also given by these persons: D. H. Dunkle of the United States National Museum examined our vertebrate material, S. A. Northrop of the University of New Mexico identified one specimen of fossil wood, a number of invertebrate fossils that were not studied by Imlay were identified by the late F. K. G. Mullerried of the Instituto de Geología and by de Cserna, and Eduardo Schmitter of the Instituto de Geología kindly assisted us in the solution of some petrographic problems.

SEDIMENTARY ROCKS

The sedimentary rocks exposed in the region are mainly offshore marine facies of Late Jurassic and Cretaceous age which were deposited in the Mexican geosyncline. The only younger sediments found in significant quantities are a few small masses of Tertiary continental rocks, consisting of conglomerate, arkose, siltstone, and tuff, and a thin alluvial mantle covering the valleys and lower mountain slopes. (See pl. 1.)

All but the uppermost part of the stratigraphic column was carefully worked out by Burckhardt, mainly based on ammonites, and is clearly described in his early reports on the area. Although the authors have adopted the nomenclature developed by Imlay and other geologists of the University of Michigan, who have carried on stratigraphic studies and reconnaissance mapping in a vast area lying to the north and northwest of the Concepcion del Oro district, the work of Burckhardt was useful in many ways. A correlation between the present writers' stratigraphic units and those of Burckhardt was easily made and is shown in figure 3, which also gives the approximate thickness of the formations.

	QUATERNARY	Alluvium	0–30 m
	TERTIARY	Mazapil conglomerate	200 + m
	UPPER CRETACEOUS	Parras shale	1300 + m
AGE UNDETERMINED Green sandstone with brownish and blackish shale. No fossils		Caracol formation	800 + m
UPPER CRETACEOUS Platy limestone and shale, alternating with bluish limestone. Some sandy beds. Many *Inoceramus, Turrilites,* and *Ammonites*		Indidura formation	180 ± m
MIDDLE CRETACEOUS Grayish laminated limestone with bedded and lenticular black chert. Many uncoiled ammonites	LOWER CRETACEOUS	Cuesta del Cura limestone	280 ± m
LOWER CRETACEOUS Alternation of yellow marl and marly limestone with grayish, bluish, or slightly brownish limestone. *Parahoplites* abundant		La Peña formation	140 ± m
Grayish limestone with interbedded irregular chert. Few identifiable fossils		Cupido limestone	300 ± m
Yellowish marl alternating with grayish or brownish limestone. *Holcostephanus* abundant		Taraises formation	140 ±m
UPPER JURASSIC Whitish marly limestone with bedded black chert	UPPER JURASSIC	Unit D	La Caja formation 40–150 m
Grayish phosphatic limestone Reddish phosphatic limestone		Unit C	
Claystone with *Waagenia* Black compact limestone with *Haploceras fialar* Brownish laminated limestone with *Aucella*		Unit B	
Claystone and shale with *Idoceras*		Unit A	
Massive grayish limestone with *Nerinea*		Zuloaga limestone	400+m

FIGURE 3.—Correlation of Burckhardt's stratigraphic units and those of the present writers.

Mexican and European geologists working in Mexico have generally separated the Cretaceous into Lower, Middle, and Upper divisions, whereas geologists from the United States separate it into two parts. Although this twofold division is still not universally accepted in Mexico, it has been adopted in this report as the more convenient usage.

According to Imlay,[2] the reasons for rejecting the usage of Middle Cretaceous in Mexico are that it does not reflect a natural lithologic division, it does not have any particular value in mapping or in dis-

[2] Written communication.

cussions of geology, it does not correspond exactly in time with the Middle Cretaceous in Europe, and it has not been generally used even in Europe. The beds in Mexico that Burckhardt (1930, tables 15 and 16, p. 210) called Middle Cretaceous are correlated on the basis of ammonites with the middle and upper Albian and the lower Cenomanian of Europe. The Middle Cretaceous in Europe has been employed generally for the Albian and Cenomanian stages, although some European geologists have included the Aptian, some have excluded the Cenomanian, and some have included even the Turonian. The controversy was settled as far as most geologists were concerned

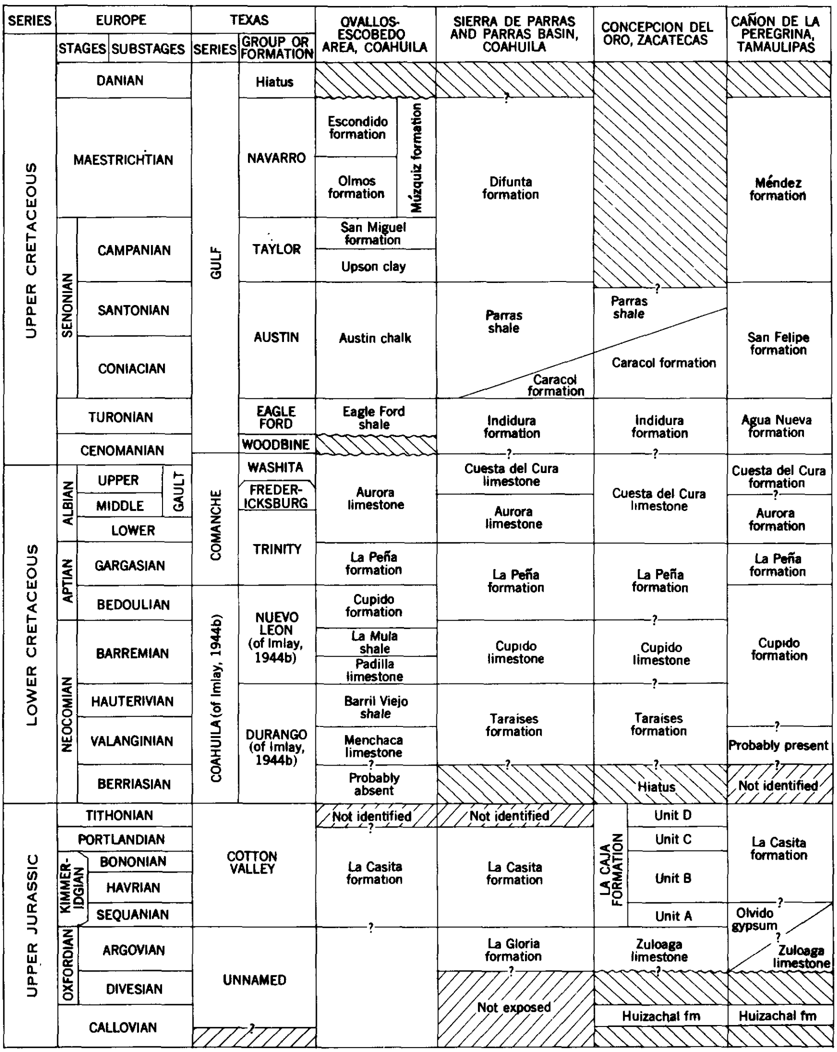

FIGURE 4.—Correlation of Jurassic and Cretaceous formations of north-central and eastern Mexico.

when the International Congress at Zürich in 1885 divided the Cretaceous into Lower and Upper subsystems and placed the Gault (middle and upper Albian) in the Lower Cretaceous. It was chance that both Carlos Burckhardt and Emil Böse (1923a, 1923b), who contributed greatly to the knowledge of the Cretaceous of Mexico, were educated under paleontologists who employed a threefold subdivision of the Cretaceous.

Figure 4 shows the correlation between the stratigraphic section in the Concepción del Oro district and sections in eastern and northern Mexico. Additional correlation charts are available in the writings of Imlay. Although broad stratigraphic studies have been carried on in many parts of the country, the matter of correlation is a difficult and continuing problem. As stratigraphic knowledge increases, adjustments will undoubtedly be made in correlations, and unnecessary and duplicating formational names will be discarded.

BASEMENT ROCKS

Although the Zuloaga limestone is the oldest formation exposed within the mapped area, the underlying rocks must come close to the surface at some points. In two deeply eroded mountain ranges a few kilometers to the west, known as the Sierras de Candelaria and El Borrego, the Zuloaga limestone rests unconformably upon the Huizachal formation, a series of predominantly reddish siltstone, sandstone, and conglomerate beds that lack identifiable fossils but may be late Callovian or early Oxfordian in age, or possibly both. The redbeds have remarkable differences in thickness, probably owing mainly to erosion, and farther to the northwest, in the vicinity of Caopas, they appear to be lacking over a fairly extensive area in which the Zuloaga limestone rests directly upon older phyllitic and schistose rocks of undetermined age.

Redbeds have been reported by Imlay (1938b, p. 1659) as underlying the Zuloaga limestone in an area 40 kilometers to the east of Concepción del Oro. A section approximately 6 meters thick is exposed along an anticlinal axis in the mountains lying immediately to the west of La Ventura, Coahuila.

JURASSIC SYSTEM

Most of the index fossils that were used by Burckhardt in dating the Upper Jurassic sedimentary rocks in Mexico were previously known in Europe or in South America. His ideas concerning these fossils were applied to his Mexican studies without a thought for possible discrepancies in age in such widely separated regions. As a result, the work by later paleontologists has slightly modified the findings of Burckhardt, as shown in figure 5, which, with some simplifications, is adapted from Mullerried (1951).

368566—56——2

BURCKHARDT, 1930				IMLAY, 1943b				
	STAGES		FAUNAL ZONES	FAUNAL ZONES		STAGES		
UPPER JURASSIC	TRANSITION ZONE		*Steueroceras*	*Substeueroceras* and *Proniceras*	*Micracanthoceras* and *Hildoglochiceras*		TITHONIAN	UPPER JURASSIC
			Hoplites koellikeri					
	UPPER	PORTLANDIAN	*Kossmatia*	*Kossmatia* and *Durangites*			PORTLANDIAN	
			Proniceras					
	LOWER		*Aulacosphinctes*	*Subplanites*	*Aulacosphinctoides*			
			Mazapilites	*Mazapilites*		KIMMERIDGIAN	BONONIAN	
			Waagenia	*Waagenia*			HAVRIAN	
	KIMMERIDGIAN		*Haploceras fialar*; *Aucella pallasi*	*Glochiceras fialar; Idoceras duranguense*				
			Idoceras	*Idoceras balderum*			SEQUANIAN	
				?				
			Sutneria	*Sutneria platynota*				
	UPPER	OXFORDIAN	*Ochetoceras*	*Dichotomosphinctes*		OXFORDIAN	UPPER	
			Perisphinctes plicatilis	NONE				
	LOWER		NONE	NONE			LOWER	

FIGURE 5.—Age determinations of index fossils of the Upper Jurassic of Mexico, according to Burckhardt and Imlay.

ZULOAGA LIMESTONE

The Zuloaga limestone was defined by Imlay (1938b, p. 1657), who designated the Sierra de Sombreretillo as the type locality. About 550 meters of this limestone formation is exposed in that area, and about 400 meters is exposed in the Concepción del Oro district. The unit apparently thins to the west, for the complete section above the redbeds in the Sierra de Candelaria is only 275 meters, and it may thin to the east as well, for in the vicinity of La Ventura the complete

FIGURE 6.—Flat-lying Zuloaga limestone close to an anticlinal axis in the western part of the Sierra de La Caja. The small cave is formed in a calcareous siltstone layer.

section above the redbeds is only about 365 meters. Within the mapped area the Zuloaga limestone forms the cores of the anticlinal ranges and composes most of the high central ridges and mountain summits (fig. 6).

The upper part of this formation is predominantly a massive dark-gray limestone, whose beds range generally from 0.3 to 3 meters in thickness; whereas the middle and lower parts contain many light- to medium-gray beds, which may be reddish to yellowish weathering and in many places show incipient brecciation. In general, the middle and lower parts are thinner bedded than the upper limestone and contain several argillaceous beds. The latter are only rarely exposed, but in many places their contacts with the adjacent limestone are characterized by a relatively dense growth of vegetation and the beds are thus easily traced. These argillaceous beds appear as sharply defined lines on the aerial photographs and may be utilized in many places as structural guides in the field. They are as much as 4 meters thick and consist generally of a brownish poorly indurated calcareous siltstone, which may be fossiliferous. Gray to brownish shales are found in some places, and in several localities the lower part of the formation was found to contain platy dark-gray limestone with intercalated lenticular black chert. Scattered relatively small nodules of gray to black chert are found in many beds throughout the formation, but they are quantitatively unimportant. Some limestone beds contain a host of coral fragments, which are poorly preserved and can rarely be identified. They are never found in place but have clearly been abraded and transported. Although the coral-bearing layers are not confined to a particular horizon, they have not been observed within a hundred meters of the La Caja contact. The massive limestone composing the upper part of the formation is characterized by many stylolitic partings of relatively large amplitude.

In a few localities the Zuloaga limestone contains small areas of dark-reddish-gray to brownish finely crystalline dolomite. The dolomitization may follow individual beds but it is commonly irregular and clearly seems to be a result of secondary alteration, probably by hydrothermal solutions.

It is difficult to obtain fossils from the limestone, but they are easily obtained from a few argillaceous beds in the middle and lower parts of the formation. With the exception of *Thamnasteria* and *Nerinea*, those listed below were collected from the calcareous siltstone.

Thamnasteria imlayi Wells
Astarte aff. *A. smackoverensis* Imlay
Astarte sp.
Astarte (*Coelastarte*) cf. *A. ratheri* P. de Loriol
Gryphaea sp. juv.
Trigonia? sp.
Nerinea sp.
Harpagodes sp.
Arcid pelecypod
Terebratulid brachiopod

The Zuloaga limestone is apparently overlain conformably by units A, B, C, and D of Oxfordian, Kimmeridgian, and Portlandian ages of the La Caja formation, and on the basis of its stratigraphic position it has been assigned to the upper Oxfordian. Although it is lacking in characteristic fossils that might allow it to be dated more accurately, it has a faunal assemblage closely resembling those of the upper Oxfordian units of other parts of the Gulf region (Imlay, 1943b, p. 1446–1450).

The mollusks and coral fragments in the Zuloaga limestone indicate deposition in an epineritic environment, and the corals are indicative of warm waters. According to Imlay (1943b, p. 1484), "the uniform appearance of this unit throughout most, if not all, of the Mexican geosyncline indicates a uniform climate, few rivers emptying into the sea, and few highland areas."

LA CAJA FORMATION

The La Caja formation is composed mainly of calcareous siltstone, but it contains other rock types, including the phosphorite beds that were studied in detail in this examination.

The type locality of the formation has been designated by Imlay (1938b, p. 1659) as the Vereda del Quemado on the southern flank of the Sierra de La Caja. That section was described by Burckhardt (1906b, and 1930, fig. 14) and was visited and restudied by Imlay.

The formation occurs in many widely separated areas of Mexico and will probably be found throughout much of the central part of the Mexican geosyncline. It has been found in the Sierrita del Chivo of southeastern Durango; near Simón and in the Sierra de Ramírez, which lie to the west of Concepción del Oro in the Durango-Zacatecas border area; in the Sierra Madre Oriental west of Linares, Nuevo León; in the vicinity of Ciudad Victoria, Tamaulipas; and in the Sierra de Catorce of northern San Luis Potosí. It is the offshore equivalent of the La Casita formation, into which it is gradational in the area to the north of Concepción del Oro. Much of the available information concerning these formations has been summarized by Ruiz Elizondo (1950), but many other data, obtained largely by petroleum geologists, have not been published. Little or nothing is known of the sedimentary rocks of Kimmeridgian and Portlandian ages in the several parts of the geosyncline that have not received even reconnaissance studies.

Within the area mapped the La Caja formation comprises a series of predominantly thin- to medium-bedded rocks ranging in composition from argillaceous limestone to shale but consisting mainly of siltstone; many chert layers occur in its middle and upper parts. The formation is sharply set off from the underlying Zuloaga limestone and the limestone beds of the overlying Taraises formation.

The La Caja formation is exposed generally in two narrow parallel belts flanking the Zuloaga limestone of the anticlinal cores, and, being easily eroded, it is characterized by the formation of saddles and strike valleys. It weathers rapidly, and exposures are generally poor. In most places the formation supports a scantier vegetation than the adjacent limestone and appears as relatively barren strips, which may generally be identified from great distances (figs. 7 and 8.).

The La Caja formation has been measured in many places, although such measurements are difficult to make, owing partly to a lack of exposures and partly to the incompetent nature of the rocks, which in many places are highly squeezed and contorted. It has a thickness ranging from 40 to 150 meters. In general the thickest sections are in the Sierra de Santa Rosa, from which the formation thins gradually

FIGURE 7.—View of the north flank of the Sierra de Santa Rita southeast of San Francisco. The barren strip is underlain by the La Caja formation (Juc) and the ridge above is composed of Zuloaga limestone (Juz). White areas are caliche.

in all directions. In a northerly direction the formation averages about 80 meters in thickness in the Sierra de La Caja, 50 meters in the Sierra de Canutillo, and between 40 and 90 meters in the Sierras de Zuloaga and Sombreretillo. In the Sierra de Santa Rita to the south it has an average thickness of about 65 meters.

In his studies of the Sierras de Santa Rosa and La Caja, Burckhardt (1906a, 1906b, 1906c) divided the formation into seven units, which are based primarily on faunal divisions, whereas the authors have established four lithologic divisions based upon mappability. Although these divisions are in this report referred to as units A, B, C, and D, it is believed that they may eventually be designated as members. A correlation between these units and those described by Burckhardt is given in figure 3.

UNIT A

Unit A has a thickness ranging from 12 to 44 meters, and, like the formation as a whole, it reaches its maximum thickness in the Sierra de Santa Rosa.

The lowermost beds, in at least part of the district, are Oxfordian in age. They consist of a thin section of gray to brownish poorly indurated siltstones overlain by more resistant thin- to medium-

FIGURE 8.—View of a typical contact between the La Caja (left) andTaraises (right) formations. The La Caja formation is characterized by poor exposures.

bedded siltstones and cherts. As the base of the La Caja formation is generally concealed by talus or alluvium, these rocks are rarely exposed. In the sections measured, however, they ranged from less than 1 meter to about 8.5 meters in thickness. Near the top of the cherty rocks is a 10-centimeter bed of lustrous black crystalline limestone, which locally is highly bituminous. This bed is apparently persistent over a wide area, and Imlay has suggested that it may represent extremely slow deposition, perhaps being equivalent stratigraphically to the gypsiferous beds of the Olvido formation. These beds are moderately fossiliferous in places, the lower siltstone beds yielding several species of small pelecypods and the upper section containing *Trigonia* aff. *T. hudlestoni* Lycett.

The remainder of the unit is of early Kimmeridgian age. It consists mainly of thin-bedded brownish to grayish-brown poorly lithified calcareous siltstone containing numerous large spherical to discoidal limestone concretions. The concretions are as much as 1 meter in longest dimension and are composed of dark-gray to black, hard to brittle limestone. They may be fossiliferous, and some have furnished remarkably well preserved specimens of *Idoceras*. One concretion has yielded a fragmentary fossil that has been tentatively identified by S. A. Northrop of the University of New Mexico as fossil wood. It is a segment with an indicated diameter of about 10 centimeters, and its surface is covered with gypsum crystals. Although similar concretions may be found in other parts of the formation, they are abundant only in this unit. The siltstone generally contains a few beds of grayish to brownish often slightly reddish weathering laminated argillaceous limestone, which emits a fetid odor when freshly broken. The siltstone is also characterized by thin partings of a friable rust-brown claystone. Wherever exposed, this rock is broken into innumerable small fragments with smooth curving surfaces and a slightly waxy luster. A mineralogical examination shows it composed mainly of mica and montmorillonite, and some quartz and calcite and small reddish-brown nodular masses containing manganese and iron. It is similar in appearance to some bentonitic shales, but C. S. Ross of the Geological Survey reports that it is not of volcanic origin.

The siltstone is thin- to medium-bedded and of varied shades of medium gray and brown. It ranges from soft and crumbly to medium hard and is strongly calcareous, as shown by chemical analysis (table 1, sample 6). It is similar in composition to the siltstone of the middle and upper sections of the formation.

UNIT B

Unit B has a thickness ranging from 20 to 65 meters and averaging about 35 meters. Like the underlying unit A, it reaches its maximum thickness in the Sierra de Santa Rosa. It is middle and late Kimmeridgian in age, and over most of the area mapped it contains a diversity of types of rock.

The lowermost part of the unit is composed of a thin series of brownish to grayish-brown argillaceous limestone beds of a thickness of 1.5 to 4.0 meters. The limestone is medium to thick bedded and medium hard, generally offering better exposures than the adjacent siltstones. Some beds are only moderately fossiliferous, whereas others are composed in large part of ammonite remains. The fossil material is largely a single ammonite species, *Glochiceras fialar* (Oppel), although *Aucella*, a pelecypod, was found by Burckhardt in the lower part of the section. The limestone emits a strongly fetid odor when freshly broken and is described by Burckhardt as marking the base of the phosphorite. Sampling, however, has shown the rock to be only feebly phosphatic, having approximately the same tenor as the siltstone lying above and below it. The limestone may be interbedded with calcareous siltstone and gray to brown friable claystone, and in many places it contains lenticular layers of a granular crumbly rock consisting mainly of coarsely crystalline calcite in an argillaceous groundmass. Also present in places are lenses of coarsely fibrous fetid calcite, whose crystals lie normal to the bedding. Both types of calcite are found in other parts of the formation, but they occur most commonly at this horizon.

TABLE 1.—*Chemical analyses of rock samples from the La Caja formation, Puerto Blanco, Sierra de Santa Rosa*

[Analyses made in laboratories of the Instituto de Geología by Alberto Obregón, reported Apr. 22, 1953]

	Sample no.					
	1	2	3	4	5	6
Laboratory no.	10581	10582	10583	10584	10586	10589
SiO_2	8.40	39.44	85.40	63.37	67.86	65.23
Al_2O_3	.70	1.01	2.06	2.36	2.12	3.72
Fe_2O_3	1.15	.86	1.43	1.13	1.43	2.02
FeO	.11	.09	.14	.13	.13	.19
MnO	.02	.01	.01	.03	.02	.01
MgO	.25	.08	.12	.54	.41	1.12
CaO	49.21	31.48	4.56	17.22	14.04	13.20
Na_2O	.21	.29	.25	.29	.39	1.03
K_2O	.11	.20	.35	.10	.18	.37
TiO_2	.20	.15	.15	.11	.24	.36
P_2O_5	.58	.65	1.62	.18	.29	.48
CO_2	37.95	23.73	2.06	13.35	10.47	9.30
H_2O-	.14	.17	.10	----------	.22	.16
H_2O+	.89	1.74	1.80	1.45	2.11	2.44

1. Silty limestone from upper part of unit D, from bed 2.9 meters below contact with the Taraises formation.
2. Highly calcareous siltstone from basal part of unit D, from bed 3.5 meters above phosphatic member.
3. Calcareous chert from upper part of unit B, from bed 2.1 meters below phosphatic member.
4. Hard calcareous siltstone from central part of unit B, from bed 14 meters below phosphatic member.
5. Soft calcareous siltstone from lower part of unit B, from bed 26.2 meters below phosphatic member.
6. Calcareous siltstone from lower part of unit A, from bed 24 meters below unit B.

The argillaceous limestone is overlain by a section of thin-bedded gray to brown calcareous siltstone (table 1, sample 5) 5 to 20 meters thick. This rock is rather similar lithologically to the underlying member, although it contains relatively few concretions and a smaller number of shaly partings. Since much of the siltstone is soft to crumbly, exposures in most places are poor. This material is succeeded rather abruptly by a hard medium- to thick-bedded medium-brown calcareous siltstone, which breaks with a blocky subconchoidal fracture. It is similar in composition to the rest of the formation (table 1, sample 4) but has undergone a higher degree of lithification.

The hard brown siltstone grades upward into a heterogeneous series of rocks containing many cherty layers. The chert and calcareous chert (table 1, sample 3) are thin-bedded to massive dark brownish-black to black hard to brittle rocks, which crop out in many localities where the rest of the formation is concealed. Although it is easy to obtain an exaggerated impression of their abundance, they actually compose only 25 to 30 percent of the member. The cherty rocks are interbedded with cherty limestone, calcareous siltstone, phosphorite, and gray to brown friable claystone, and they generally contain many small limestone lenses and concretions. Near the top of the series these lenses are composed of a hard dark-gray to reddish-gray finely crystalline phosphatic limestone, which is characterized by a smooth light- to medium-gray weathered surface. At a lower horizon the cherty rocks generally contain several yellow- or brownish-weathering lenses of hard to brittle finely crystalline dark-gray to brownish limestone, which is largely nonphosphatic. Unlike the overlying lenses, these are generally unsymmetrical and may be characterized by a pronounced irregularity of form. Large concretions similar to those of the underlying unit are also rather common at this horizon. Although the cherty rocks contain relatively little phosphate, the interbedded siltstone and limestone may be moderately to strongly phosphatic, and a few cherty limestone layers contain 10 to 15 percent of phosphorus pentoxide. The phosphorite beds are thin, and many are highly conglomeratic, being composed of fragments of black phosphatic limestone in a matrix consisting mainly of coarsely crystalline calcite and massive apatite.

Unit B, as described above, is thickest in the Sierra de Santa Rosa. Outward from that area the cherty facies tends to disappear gradually, and the member grades into a relatively homogeneous series of calcareous siltstone beds similar to those of the underlying unit A. The fossiliferous argillaceous limestone persists at the base of the member, however, and the limestone lenses characteristic of the upper part of the member are also found over a wide area. The cherty facies disappears within a relatively short distance in an easterly direction and is almost completely lacking in the Sierra de Concepción del Oro. To the north and south it diminishes more gradually, and to the west it has been traced as far as Pico de Teyra, where it is fairly thick. Pico de Teyra lies approximately 40 kilometers to the west of the area mapped.

UNIT C

Unit C contains the highest concentration of phosphatic material, the grade of the rock generally decreasing in inverse proportion to thickness of the member. Where it is thick the phosphate is dispersed and beds of commercial grade are lacking. It ranges from early to late Portlandian age.

In the Sierra de Santa Rosa the unit ranges from 1.35 to 3.40 meters in thickness and averages about 2.20 meters. It contains three general lithologic types, which are only briefly described here but are discussed more fully in a later section of the report. The lower beds are composed mainly of hard to brittle medium- to dark-gray phosphatic calcareous chert and cherty phosphorite, while the overlying beds are medium-hard reddish-gray calcareous phosphorite. Both sections contain numerous lenses of gray to reddish-gray finely crystalline phosphatic limestone. In some localities these lenses change into fairly persistent beds, which may be characterized by pinching and swelling. All the rocks described above give off a strongly fetid odor when freshly broken. One of the phosphorite beds has yielded fossils which have been examined by D. H. Dunkle of the United States National Museum and identified as reptile bones. They closely resemble various reptilian ribs of Jurassic age but cannot be classified even as to order. The structure of the bones, however, suggests a terrestrial rather than a marine reptile.

Outward from the Sierra de Santa Rosa the phosphatic unit thickens within a short distance, reaching a maximum of about 20 meters, and it grades into a series of thin- to medium-bedded phosphatic siltstone and phosphatic calcareous chert beds, having only a few scattered layers that can be classed as phosphorite. The lenticular phosphatic limestone is abundant everywhere.

The phosphatic facies diminishes in an easterly direction, and in the Sierra de Concepción del Oro it can hardly be distinguished from the underlying beds of unit B. It persists, however, and has been recognized in the vincinity of Iturbide, Nuevo León, a village in the Sierra Madre Oriental which is situated 150 kilometers to the east of the area mapped. It also diminishes to the north and south but is more persistent in a westerly direction.

UNIT D

Unit D is the uppermost member of the La Caja formation and has a thickness ranging from 2 to 50 meters. Like the other members, it reaches its maximum thickness in the Sierra de Santa Rosa. It is late Portlandian and Tithonian in age.

Most of the unit is thin- to medium-bedded medium hard brownish to brownish-gray calcareous siltstone (fig. 9), which contains many thin beds and lenses of black chert. The siltstone becomes increasingly calcareous toward the top, and the uppermost beds are medium- to thick-bedded silty limestone (table 1, samples 1 and 2). In some localities the member contains a few concretionary bodies and beds of reddish-gray laminated fetid argillaceous limestone. The siltstone has an ashy-white weathered surface, which is its most distinctive feature.

In the Sierra de Santa Rosa the rocks immediately overlying the phosphorites are soft thin-bedded brownish to grayish-brown phosphatic calcareous siltstone beds with a total thickness of from 2 to 8 meters. They contain some beds of calcareous phosphorite and fetid argillaceous limestone, but such layers are relatively rare. These beds grade upward almost imperceptibly into the harder, more calcareous

FIGURE 9.—View showing typical lithology of unit D of the La Caja formation. The rock is calcareous siltstone with numerous layers of black chert. The picture was taken in the northwest corner of Valle de Santa Rosa.

siltstone described above. Beyond the Sierra de Santa Rosa this facies is only poorly developed, if present at all.

Unit D has little lithologic variation in the Concepción del Oro district and has apparently been found over a wide area. The rocks that weather whitish have been noted in the Sierrita del Chivo, the Sierra de Ramírez, in the vicinity of La Ventura, and even farther to the east in the Sierra Madre Oriental. The chert is less persistent, however, and may not extend far beyond the boundaries of the area mapped.

PALEOECOLOGY

A list of representative fossils collected from the La Caja formation within the area mapped is given below.

Unit A

Taramelliceras sp.
Idoceras cf. *I. santarosanum* Burckhardt
Belemnopsis? sp.
Fossil wood(?). A segment with an indicated diameter of about 10 centimeters; surface covered with gypsum crystals

Unit B

Hybonoticeras (*Waagenia*) sp.
Torquatisphinctes sp.
Idoceras cajense Burckhardt
? sp. juv.
Subdichotomoceras? sp. juv.
Glochiceras fialar (Oppel)
Isocyprina sp.
Aucella sp.
Vermetus (*Burtinella*) *cornejoi* Castillo and Aguilera

Unit C

Aspidoceras? sp.
Mazapilites zitteli (Burckhardt)
Epivirgatites? cf. *E. nikitini* Michalski
Virgatosphinctes cf. *V. aguileri* (Burckhardt)
Aptychus sp.
Lamellaptychus sp.
Meleagrinella sp.
Cucullaea phosphoritica Burckhardt
Lucina sp.
Astarte sp.
Aucella sp.
Isocyprina? cf. *I. coteroi* (Castillo and Aguilera)
Grammatodon sp.
Corbis sp.
Anomia? sp.
Vermetus (*Burtinella*) *cornejoi* Castillo and Aguilera
Cap-shaped gastropods
Cerithioid gastropods
Fish vertebrae
Reptile bone fragments suggesting terrestrial forms
Coniferous wood fragment

Unit D

Proniceras? sp.
Substeuroceras sp.
Berriasella aff. *B. calisto* (D'Orbigny)
Kossmatia sp.
Cylindroteuthis cf. *C. clavicula* Anderson
Belemnite not determined
Aucella cf. *A. elderensis* Anderson

The predominance of ammonites in most of the La Caja formation suggests deposition in an infraneritic environment. Imlay (1943b, p. 1495) believes that the abundance of ammonites and relative scarcity of benthonic mollusks may be due to an excessively muddy environment, however, rather than to any great depth of water. He suggests that the large amount of shale and organic matter in the sedimentary rocks of Kimmeridgian-Portlandian age of the Mexican geosyncline was the result of climatic changes in the bordering land area. The climate may have been less arid than during Oxfordian time.

The authors have found several lines of evidence in their studies of the La Caja formation which strongly indicate deposition in shallow waters, which during some periods were strongly agitated. These include the occurrence of conglomeratic layers in the phosphatic member and the upper part of unit B, and the occurrence of cap-shaped gastropods in the phosphatic member. These small gastropods are abundant in some beds. The marked differences in thickness that characterize the various members of the formation may be due to diastems, which would also reflect temporary shallow-water conditions, or may be the result of deposition on an undulating surface which lay close to sea level and may actually have been emergent in places.

CRETACEOUS SYSTEM

TARAISES FORMATION

The Taraises formation, which contains limestone and some subordinate siltstone, was defined by Imlay (1936, p. 1111) and is named for Cañón de Taraises in the western part of the Sierra de Parras. It is Valanginian and Hauterivian in age. Within the area mapped it has an average thickness of 140 meters.

It appears to rest conformably upon the silty limestone with intercalated black chert that forms the upper part of the La Caja formation. The contact with the underlying rocks may represent a diastem, however, as no Berriasian rocks have been found. Valanginian fossils are present in the lowermost Taraises beds.

The formation consists of alternate thick-bedded to massive limestone and poorly lithified gray to yellowish or brownish siltstone. The limestone is generally light to medium gray and weathers to a characteristic shade of blue or bluish gray. In many places weathered surfaces also show yellowish discoloration. The limestone beds contain many rosettes of oxidized pyrite and a small proportion of nodular gray and black chert, which is sparsely distributed through the formation. The siltstone is highly calcareous and locally contains a small proportion of noncalcareous friable brown claystone. Some beds are fossiliferous.

In general, the limestone beds have a thickness averaging about 30 centimeters. In some localities, however, the formation contains a unit of thicker bedded limestone at or near the base. In this unit the beds may be as much as a meter in thickness, and the siltstone layers are largely or wholly lacking.

The fossils collected from the Taraises formation are

Distoloceras aff. *D. michaelis* (Uhlig)
   ? sp.
Crioceras sp.
Olcostephanus aff. *O. raricostatus* (Böse)
   aff. *O. atherstoni* (Sharpe)

All are ammonites which, along with the lithology, may indicate deposition in an infraneritic environment.

CUPIDO LIMESTONE

The Cupido limestone was first described by Imlay (1937, p. 606) from exposures in the middle part of the Sierra de Parras. Paleontologic evidence is scant, but the stratigraphic position indicates a late Hauterivian and Barremian age.

The formation comprises about 300 meters of massive limestone and is one of the most important ridge formers in the region. The beds range generally from 0.25 to 1 meter in thickness, and the rock is a medium-gray limestone with a slight pinkish to reddish coloration on weathered surfaces. The formation contains many pyritic concretions and a large proportion of nodular to lenticular gray chert, which becomes increasingly abundant from the base upward. A few nodules contain various amounts of coarsely crystalline limestone. The limestone beds are characterized by well-developed stylolites of relatively large amplitude. Locally, a few thin layers of calcareous siltstone occur.

The Cupido limestone is almost completely lacking in fossils; the few ammonites found are too poorly preserved for generic identification. The lithologic character indicates normal limestone deposition in an infraneritic environment.

LA PEÑA FORMATION

The La Peña formation, which consists mainly of alternate limestone and siltstone beds, was defined by Imlay (1936, p. 1119), who designated the north flank of the Sierra de Taraises in the vicinity of Hacienda de La Peña as the type locality. The Sierra de Taraises is in the western part of the Sierra de Parras.

The formation is more easily eroded than the underlying Cupido limestone and the overlying Cuesta del Cura limestone, and it is commonly marked by a strong development of arroyos and saddles. It contains several types of rock, and the resulting differences in vegetation may be apparent on the aerial photographs as fairly well defined lines or bands. In the field the formation is generally easily identified at a distance by a brownish or reddish coloration, which offers a sharp contrast to the gray of the adjacent limestones. Within the area mapped it has an average thickness of about 140 meters.

The lower and middle parts of the formation consist of alternate massive limestone and poorly lithified siltstone beds. The limestone is light- to medium- and dark-gray, weathers reddish to yellowish, brownish, or olive green, and contains a considerable proportion of gray to black chert in irregular nodular masses and lenses. Some nodules contain carbonate, and where this has been leached the remaining chert has a spongy appearance. Pyrite concretions are common in the limestone. In general, the limestone is thicker bedded at the base than in the rest of the formation and contains fewer argillaceous beds. The siltstone is highly calcareous, is soft and crumbly to medium hard, and is yellowish to buff and gray. It contains a few partings of a fissile yellow green to rusty-brown shale. The siltstone is subordinate to the limestone and in most places is not exposed. The upper part of the formation contains limestone and siltstone similar to the underlying material, but it also includes a large proportion of thin-bedded to platy light-gray argillaceous limestone, and occasional layers of light- to medium-gray medium- to thick-bedded laminated limestone. The platy limestone and the thicker bedded laminated limestone contain thin lenses of black chert, giving the formation an appearance similar to the upper part of the La Caja formation. The sequence contains a few thin layers of fissile greenish to brownish shale.

The La Peña formation contains a few fragmentary external molds of ammonites, one of which was identified as *Parahoplites* sp. The stratigraphic position and fossil evidence indicate that the formation represents probably the entire Aptian. The lithologic character and ammonite fauna suggest deposition in moderately deep water. According to Imlay (1938b, p. 1690), the black chert represents a type of sedimentation which in northern Zacatecas continued almost without interruption until the end of the Albian.

CUESTA DEL CURA LIMESTONE

The Cuesta del Cura limestone was first described by Imlay (1936, p. 1125) from exposures in the western part of the Sierra de Parras, where it lies between the Aurora limestone and the Indidura formation. It is a resistant formation and is inferior only to the Zuloaga and Cupido limestones as a ridge former. At the same time, it is highly incompetent and almost everywhere is characterized by extensive drag folding. It has an average thickness of 270 meters.

Within the area mapped the formation contains two well-defined units. The lower one is composed predominantly of a laminated wavy-bedded medium- to dark-gray limestone with fairly common thin lenses of black chert, but it also contains many layers of a massive light- to medium-gray limestone (fig. 10). This unit has a thickness of 50 to 60 meters and may be equivalent to the Aurora limestone of the Sierra de Parras, which is described by Imlay (1936, p. 1124) as a reef facies.

The upper unit of the formation is composed almost wholly of laminated wavy-bedded limestone and lenticular black chert, but it

FIGURE 10.—Cuesta del Cura limestone, showing wavy bedding and lenticular black chert.

also contains many partings of a platy argillaceous limestone, which may show reddish to violet tints when weathered. The beds range generally from 15 to 30 centimeters in thickness and are the only rocks in the stratigraphic section which have wavy bedding.

Fossils were observed in the upper part of the formation in many localities, but few were collected, as they are poorly preserved. They consist mainly of small uncoiled ammonites, with some high-spired gastropods.

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The ammonites were identified as follows

Hysteroceras? sp.
Crioceras? sp.
Ancyloceras cf. *A. zacatecanum* Burckhardt

On the basis of its stratigraphic position, in addition to the ammonites that were found in the formation, the Cuesta del Cura limestone probably ranges in age from early Albian into the Cenomanian. The lithologic character and faunal evidence suggest deposition in waters of moderate depth in the infraneritic zone.

INDIDURA FORMATION

Within the Concepción del Oro district the Indidura formation consists mainly of siltstone, shale, and platy or laminated limestone. The unit was first defined by Kelly (1936, p. 1028) from exposures in the Las Delicias region of Coahuila, where the name was applied to about 30 meters of shale, rubbly limestone, and platy limestone directly overlying the Aurora limestone and containing fossils of late Albian, Cenomanian, and Turonian age. It has been described by Imlay (1936, p. 1126) in the western part of the Sierra de Parras, where it lies between the Cuesta del Cura limestone and the Parras shale and has a total thickness of about 650 meters. Imlay (1938b, p. 1665) has also described it in the Melchor Ocampo area, where it overlies the Cuesta del Cura limestone and underlies the Caracol formation, as in the Concepción del Oro district. It is clear that the sedimentary rocks that have been placed in the Indidura formation include not only several different facies but are not everywhere stratigraphically equivalent, and probably the nomenclature should be revised, as suggested by Imlay (1938b, p. 1692).

In the Concepción del Oro district the Indidura formation is generally set off from the Cuesta del Cura limestone by an abrupt change from wavy-bedded limestone to thin-bedded highly argillaceous rocks. In some areas, however, the boundary may be represented by a transitional zone 20 to 30 meters thick. The formation appears mainly along the lower mountain slopes or at the base of the ranges. Where it occurs at higher elevations, the exposures are generally better and are characterized by scanty vegetation, which may render the formation easily visible in the field and also on the aerial photographs.

The formation has an average thickness of about 180 meters, and, in the area mapped, it contains two distinct lithologic units. The lower one is mainly thin-bedded or platy argillaceous limestone and calcareous siltstone, having many layers of medium- to thick-bedded laminated dark-gray to brownish limestone (fig. 11). The platy argillaceous limestone is light gray and may weather to pinkish, red, or violet. It is commonly interbedded with a relatively soft, gray to yellow-gray or brownish siltstone, which may contain partings of a fissile rusty-brown shale. The upper unit has an average thickness of 50 meters and is largely a homogeneous highly fissile dark-gray calcareous shale that weathers yellow. It is easily eroded and in many places is marked by the formation of shallow saddles.

FIGURE 11.—View showing lower beds of the Indidura formation cropping out on the north flank of the Sierra de Santa Rosa. The Sierra de La Caja is in the background.

Fossils are limited mainly to the lower unit; the best specimens are external molds of bivalves from the beds of laminated dark-gray limestone. The following were identified

Inoceramus cf. *I. labiatus* Schlotheim
Inoceramus sp.

Several species of foraminifera were found in the shale of the upper unit and were identified as

Gümbelina? sp.
Globigerina sp.
Globorotalia? sp.
Globotruncana sp.

On the basis of faunal evidence and stratigraphic position, the Indidura formation is probably Cenomanian and Turonian in age.

The fauna and lithology indicate a shallowing of the sea after deposition of the Cuesta del Cura limestone.

CARACOL FORMATION

The Caracol formation was named by Imlay (1937, p. 616) for exposures in the middle part of the Sierra de Parras. He described it as a series of devitrified tuff, shale, and limestone directly overlying the Indidura formation. It occupies the same stratigraphic position in the Concepción del Oro district, and its boundary with the Indidura formation is drawn at the lowest bed of arkosic sandstone.

FIGURE 12.—View of the Caracol formation cropping out on the south flank of the Sierra de Canutillo, showing differential erosion between shale and resistant sandstone beds.

The formation is found only in the synclinal valleys separating the mountain ranges and has a minimum thickness of about 800 meters. It is mainly an alternation of shale and resistant sandy beds, the shale predominating. (See fig. 12.) The shale is dark gray to black, weathers yellowish or yellowish gray, and breaks characteristically into sharp splintery fragments. It is slightly to moderately calcareous and locally may contain some admixture of sandy material.

Although the hard beds have been described as tuff in the type locality (Imlay, 1937, p. 616), the specimens collected in the Concepción del Oro district and examined petrographically by the authors can be more accurately described as calcareous arkosic sandstone, perhaps approaching graywacke in composition. This view is confirmed by C. S. Ross,[3] of the Geological Survey, who reviewed several of the slides. The thin sections contain no material that is demonstrably volcanic in origin but are composed mainly of angular to moderately rounded quartz and feldspar grains embedded in a carbonate matrix. The feldspar exhibits considerable variation in the degree of alteration, and some grains appear to have been completely kaolinized. The sections also contain scattered rock fragments of quartzite, slate, or fine-grained schist, and small quantities of biotite, chlorite, sericite, magnetite, and limonite.

In the field the sandstones are hard thin-bedded to massive rocks, which on fresh surfaces range from gray to brown and greenish brown or green, but generally weather to a distinctive shade of brown.

The sandstone beds are more abundant in the lower part of the formation than toward the top and seem to be more numerous between the Sierras de Zuloaga and Santa Rosa than in the areas to the north and south. On the north flank of the Sierra de La Caja they compose about 50 percent of the lower part of the formation, and individual layers may be as much as 3 or 4 meters in thickness. In one area on the northeast flank of the Sierra de Concepción del Oro the middle part of the Caracol formation contains a zone of lenticular dark-gray to blackish limestone, which weathers light gray. Some of the limestone is thin to medium bedded, with slightly wavy laminations, and some is massive and characterized by a rough, peculiarly pitted, weathered surface.

The first megafossils to be found in the Caracol formation were collected by Ulloa in the valley to the north of the Sierra de Canutillo, but they have proved to be of little stratigraphic value. They include fragmentary oysters and echinoids, and a few ammonites which probably belong to the family Peroniceratidae and suggest a Coniacian or Santonian age for the formation.

Shale samples yielded only a few specimens of Foraminifera. These were identified as

Globorotalia? sp.
Haplophrogmoides? sp.
Globigerina? sp.
Gümbelina? sp.

Although the fossil evidence is inconclusive, the Caracol formation, according to Imlay (1944a, p. 1160), is probably of Coniacian and Santonian age and is correlative in its lowest part with the upper

[3] Written communication.

part of the Indidura formation near Parras, Coahuila. The lithology seems to indicate rapid deposition in shallow water, and the apparent scarcity of marine life may reflect unfavorable bottom conditions.

PARRAS SHALE

The Parras shale was described by Imlay in the western part of the Sierra de Parras, where it lies between the Indidura and Difunta formations. In the Concepción del Oro district it is the uppermost Cretaceous unit and is present only in the Bonanza Valley. The formation is difficult to measure, as the bedding is indeterminable in

FIGURE 13.—View of the Parras shale near village of Bonanza. The shale is overlain by lake-bed deposits and conglomerates of probable Pleistocene age.

many places, but it appears to have a thickness of about 1,300 meters. The boundary with the underlying Caracol formation is transitional and is drawn where the sandstone beds become relatively scarce. The formation is made up mainly of a splintery black calcareous shale, which may weather slightly yellowish (fig. 13). The sandstone layers occur in zones or groups sparsely distributed through the formation.

No megafossils were found in the formation, but shale samples yielded a few specimens of Foraminifera. The following were identified.

Bulimina? sp.
Virgulina? sp.
Globigerina? sp.

The Foraminifera are all minute and apparently do not represent the type of planktonic population that is characteristic of the Indidura and Caracol formations. The apparent lack of abundant planktonic species would suggest that, although the shale was deposited under marine conditions, it was not in an area to which oceanic currents had access.

The Parras shale of the Concepción del Oro area probably corresponds to only the upper part of this formation in the Parras Basin. It represents the same type of deposits as the Caracol, except that it contains less sandy material. It is probably largely Santonian in age.

TERTIARY SYSTEM

MAZAPIL CONGLOMERATE

Six small to moderately large areas within the Concepción de Oro district are underlain by a sequence of continental deposits that contain tuffaceous material and are of Tertiary age. Originally the beds may have formed a continuous mantle over the region, but they are now present only where they have been downfaulted into the older rocks and have thus been preserved from erosion.

The largest area is that underlying the northern part of the Mazapil valley to the north of Mazapil and extending east to within about 1.5 kilometers of Salaverna. Outcrops are relatively scarce except in the large reentrant on the south flank of the Sierra de La Caja, where several of the deeper arroyos expose most of the sequence. The authors refer to the unit as the Mazapil conglomerate, and this area is designated as the type locality. The rocks have a minimum thickness of 200 meters.

Along the northern side of the area, where the rocks are in fault contact with the older Mesozoic sedimentary rocks, the lowest exposed beds consist mainly of yellowish to brownish loosely consolidated calcareous siltstone or impure sandstone, but include some layers of lenticular and concretionary limestone, which is generally medium dark to dark brownish-gray and is probably of fresh-water origin. One of the beds observed was highly conglomeratic.

Overlying the yellow sedimentary rocks and separated from them by an angular unconformity is a poorly sorted reddish conglomerate, which in the exposures along the Mazapil-Novillos trail has a thickness of about 40 meters. The rock fragments in the conglomerate range from pebble size to boulders but are generally coarse, the boulders having a maximum diameter of about 1 meter. The rock fragments are angular to moderately rounded and are mainly limestone, although in places the conglomerate contains platy fragments from the La Caja formation and fragments of sandstone and shale, which have apparently been derived from the Caracol formation or Parras shale. The matrix is generally a reddish material consisting mainly of calcite stained by hematite, although it may contain some sandy and argillaceous material, and close to the fault boundary it may contain secondary silica. On the south side of the area, and in the grabens, this conglomerate forms the lowest beds exposed, and in the area northwest of Mazapil it has been seen resting directly upon the Caracol formation.

The red conglomerate is overlain by a considerable thickness of loosely consolidated green arkose or arkosic sandstone, which consists mainly of rounded quartz and feldspar grains, andesitic rock fragments, and an interstitial green earthy mineral that has been identified as celadonite by C. S. Ross.[4] The materials are essentially those of a reworked volcanic ash. Some of the rock is calcareous and in some places it contains a few thin conglomeratic layers in which rounded pebbles and cobbles of limestone are common. Crossbedding has been observed in several localities.

The green arkose is overlain by a varicolored heterogeneous sequence of sedimentary rocks which range from green or bluish green to yellow, reddish brown, and red, and include conglomerate, arkose, siltstone, mudstone, and tuff, all fairly calcareous. The arkosic rocks contain angular to rounded grains of quartz, feldspar, calcite, epidote, and magnetite in a predominantly carbonate matrix. The siltstone is generally reddish and probably much of it contains reworked highly altered volcanic material. The mudstone is gray to greenish and only a few centimeters in thickness. The tuff is predominantly reddish highly acid rock and is probably rhyolitic in composition.

The sedimentary rocks are gently folded, extensively faulted, and in one graben area are overlain by a rhyolite flow. All these criteria indicate a Tertiary age, and the rocks may well correlate with the red conglomerate at Guanajuato and similar deposits in various parts of central and southern Mexico, as well as with red conglomerates near the city of Zacatecas (Edwards, 1954) and in the Santa María del Oro district of northern Durango. The red conglomerate at Guanajuato has yielded a few vertebrate fossils which indicate a late Eocene or early Oligocene age (Fries, Hibbard, and Dunkle, 1955, p. 8–9).

QUATERNARY SYSTEM

LAKE BEDS AND CONGLOMERATE

In the Bonanza valley, near Bonanza, a few remnants of lake beds are overlain by conglomerate (fig. 13). The lake beds consist of poorly consolidated calcareous mud or silt about 4.5 meters thick. The conglomerate, which has a maximum thickness of about 14 meters, is composed of strongly cemented pebbles and cobbles of limestone and igneous rocks and contains several layers of lake-bed

[4] Written communication.

material. These deposits dip slightly to the north but are otherwise undisturbed. They may be Pleistocene in age, and possibly they represent the same humid cycle of erosion as the Mayran formation, which was described by Imlay (1936, p. 1135) in the western part of the Sierra de Parras. Remnants of a strongly cemented conglomerate have been found in other parts of the area mapped, but it is impossible to prove whether they are all of one age.

ALLUVIUM

A thin mantle of alluvium covers the floors of the synclinal valleys within the area mapped. It consists of silt, sand, and gravel washed down from the adjacent mountain ranges. Most of the alluvium is moderately well bonded by an argillaceous lime cement.

IGNEOUS AND METAMORPHIC ROCKS

TERTIARY INTRUSIVE ROCKS

Many intrusive bodies, in the form of stocks, sills, dikes, and possibly one phacolith, are found in the three southerly ranges of the Concepción del Oro district. In composition they range from rhyolite to andesite, and in size from sills to bodies having an area of 10 square kilometers or more. Many small bodies that were found in the field could not be mapped on the scale employed, and others may have been overlooked. The various lithologic types are described below in probable chronological order of intrusion.

GRANODIORITE AND DIORITE

Granodiorite and diorite are the oldest igneous rocks to be found in the district and are quantitatively the most important. Occurrences are limited mainly to the Sierras de La Caja and Santa Rita, where these rocks form three major stocks, a possible phacolith, and a large number of smaller bodies, which may be sills or dikes but are generally irregular in form.

CONCEPCION DEL ORO AND PROVIDENCIA STOCKS

The Concepción del Oro and Providencia stocks are found in the Sierra de Concepción del Oro, and, although they have invaded mainly the anticlinal core, they extend locally into the adjacent synclinal structures. At the surface, they are separated only by a thin septum of Zuloaga limestone, and they probably coalesce at a relatively shallow depth to form a single large intrusive body.

The fresh granodiorite is a gray to greenish-gray or slightly pinkish predominantly medium-grained rock, with fairly common small plagioclase phenocrysts whose maximum length is about 1 centimeter. These phenocrysts are subhedral and, along with some large- to medium-sized grains of quartz and mafic minerals, are in many places enclosed in a finer grained groundmass composed mainly of quartz, plagioclase, and orthoclase. In some places the rock is nearly equigranular. On weathered surfaces it is generally reddish to brownish. The modal composition is shown in table 2.

TABLE 2.—*Modal composition of granodiorite*

[Very small amount indicated by letter x]

Composition of representative specimens

	R-953	R-984	R-986	R-826	R-759	R-777
Plagioclase	61.6	61.6	70.6	61.5	61.2	73.5
Orthoclase	6.1	6.4	10.9	15.3	10.9	8.6
Quartz	22.8	8.1	14.8	14.4	12.6	6.2
Clinopyroxene	----------	10.6	1.5	7.7	----------	6.2
Hornblende	3.1	----------	----------	----------	14.2	.5
Biotite	2.6	9.4	1.6	.4	----------	2.3
Magnetite-ilmenite	3.5	3.6	.3	.6	1.0	2.6
Apatite	.2	.2	x	x	x	x
Sphene	x	x	.2	x	x	x
Zircon	x	x	x	x	x	x

Average composition of six thin sections

Plagioclase	Orthoclase	Quartz	Mafic minerals	Magnetite-ilmenite	Other accessories
65.0	9.7	13.0	10.1	2.0	0.2

R-953 and R-984 are from the central part, and R-986 is from the border area of the Concepción del Oro stock. R-826 and R-759 are from the central part, and R-777 is from the border area of the Providencia stock.

In general, these stocks are granodioritic in composition, although in some areas close to the borders they may grade to tonalite or diorite. Some of the rock may be more silicic, however, as suggested by Triplett (1952, p. 585), who reports that a specimen taken from the Providencia mine workings was identified as quartz monzonite by Frank F. Grout. The predominant mineral is andesine plagioclase, which has an average composition of An_{40}. Some of the phenocrysts are strongly zoned. Most of the simple twins observed are the Carlsbad type, but polysynthetic twinning is more common. Much of the plagioclase has been rather highly altered under hydrothermal conditions, and this makes accurate determination of the composition difficult. The potash feldspar is orthoclase, which is also extensively sericitized and kaolinized. In one thin section it contained a meager microperthitic intergrowth. The quartz content is much more variable than the feldspar content, and in the specimens studied it ranges from 6.2 to 22.9 percent and averages about 13.0 percent. The commonest mafic minerals are biotite and pyroxene, and hornblende is relatively scarce. The pyroxene, which is mainly diopside, ranges from neutral to pale green and may be slightly pleochroic. The hornblende is relatively light and is generally pleochroic from yellow green to a medium dark green, although it may be brownish or bluish locally. It may be intergrown with biotite, which, in part at least, seems to be an alteration product. Biotite is also closely associated with the pyroxene in many places. In the thin sections containing both pyroxene and hornblende, much of the hornblende seems to be a magmatic mineral formed later from the diopside. There is some chloritization and other alteration of the mafic minerals, but such changes are not extensive, and the minerals remain relatively fresh. The commonest accessory minerals are magnetite, ilmenite, sphene, apatite, and zircon. Epidote occurs in a few sections.

The granodiorite stocks contain a large amount of alaskite in dikes and small to moderately large bodies of different shapes. The dikes are found in various parts of the intrusive bodies, and, although they are fairly common, they are relatively small, usually measuring only a few centimeters in thickness. The larger bodies are generally found along or close to the borders of the stocks, either in the stocks or in the adjacent country rock. In most places the alaskite is light gray to white, but it may be yellow or buff. It is fine to medium grained, but predominantly fine grained, and in many places it has a granulitic texture. It is composed mainly of quartz and orthoclase and contains subordinate plagioclase, mostly as phenocrysts. The feldspars may be highly altered. The rock is cónspicuously deficient in mafic minerals. Small amounts of biotite and muscovite, and a little magnetite, sphene, and zircon were found in the thin sections that were studied. The alaskite is clearly younger than the granodiorite and probably represents a late-stage acid differentiate.

No pegmatites or lamprophyres have been observed in association with the Concepción del Oro and Providencia stocks, or with any of the other granodiorite bodies in the area mapped.

The granodiorite contains many dark-gray dioritic inclusions, which are rounded to somewhat angular and are generally small, measuring less than 30 centimeters long. One thin section of this rock was found to consist mainly of andesine, with rather abundant biotite and some clinopyroxene and magnetite. Only a very little quartz and potash feldspar were present. According to Bergeat (1910, p. 20), these inclusions are not xenoliths but are segregations of the early-formed minerals and have a composition closely corresponding to that of the enclosing rock, except they are more basic. He reports that they contain relatively abundant magnetite, sphene, and apatite.

NOCHEBUENA STOCK

The Nochebuena stock is in the western part of the Sierra de La Caja and is elongated, measuring about 4.5 kilometers in length and about 1.5 kilometers in maximum width. Unlike other stocks, it has not invaded the anticlinal core but is found on the northern limb of a fold.

The rock is predominantly medium grained and is medium gray to greenish gray or slightly pinkish. Although it contains feldspar phenocrysts, they are relatively small and scarce, and the porphyritic texture is not pronounced. The rock is diorite, as shown in table 3.

TABLE 3.—*Modal composition of representative specimens of diorite*

[Very small amount indicated by letter x]

	R-652	R-634
Plagioclase	78.5	57.6
Orthoclase	3.4	6.5
Quartz	5.2	2.2
Clinopyroxene	6.9	13.0
Hornblende	3.1	14.9
Biotite	.7	1.7
Magnetite-ilmenite	2.1	4.0
Apatite	x	x
Sphene	x	x
Zircon	x	x

R-652 is from the interior, and R-634 is from the border area of the Nochebuena stock.

The plagioclase is andesine, having a composition of about An_{40}. Potash feldspar and quartz are present only in small quantities. In one thin section the orthoclase was found to be microperthitic. The hornblende seems to be mainly uralite formed by the alteration of a pale-green clinopyroxene.

In some places close to its margins, the diorite contains many small areas of recrystallized and silicated limestone, although nearly all are too small to be shown in plate 1.

Several smaller granodiorite and diorite bodies are found in the Sierra de La Caja, some in the vicinity of the large intrusive masses and some in the area between the Providencia and Nochebuena stocks. A few in the second area have invaded the breccia zone along the La Caja thrust. These rocks have not been studied in thin section, but megascopically they are similar to the large igneous masses. The number and wide distribution of the granodiorite intrusive bodies suggests that the greater part of the La Caja anticline may be underlain by a batholith.

SAN FELICIANO PHACOLITH(?)

The San Feliciano phacolith(?) is in the axial region of the Santa Rita anticline, and field evidence suggests that it is largely concordant with the overlying Zuloaga limestone. The authors suggest that it may have been intruded between the Zuloaga limestone and the underlying redbeds. It may be considerably larger, however, than is indicated by the exposures. Limestones to the southeast are partly altered for a distance of about 2 kilometers from the intrusive mass, possibly reflecting the presence of an underlying igneous mass. In this area the rocks have a strongly reddish coloration, owing to an abundance of finely disseminated hematite. It is also possible that

San Feliciano valley, a large reentrant, is underlain by granodiorite, and granodiorite has been reported as underlying the synclinal valley in the area immediately to the east. It was found by diamond drilling close to the Gemelos gold prospect,[5] and a granodiorite exposure is present on the northeast side of the valley near the base of the Sierra de San José. If a single igneous body actually underlies this extensive area, it is not a phacolith but a stock only locally concordant with the overlying sediments.

The intrusive mass ranges in composition from granodiorite to diorite and is a medium-gray fine- to medium-grained rock with a hypidiomorphic texture. The plagioclase, which has a composition ranging from An_{65} to An_{40}, forms phenocrysts or relatively large subhedral grains in a finer groundmass consisting mainly of quartz, orthoclase, plagioclase, and mafic minerals. The phenocrysts may be strongly zoned, having a labradorite core rimmed by andesine, although a few grains appear to contain a labradorite zone lying between a core and an outer shell of andesine. Clinopyroxene, biotite, and hornblende are found in subhedral prismatic grains, the first two somewhat more abundant than the last. The pyroxene is a pale-green diopside, which may be slightly pleochroic, and the hornblende is generally pleochroic from yellow green to a medium dark green or bluish green. The accessory minerals include magnetite, hematite, apatite, sphene, and zircon. The hematite occurs as irregular grains and in small veinlets cutting the other minerals. The feldspars are extensively altered, and the biotite is generally much chloritized. Epidote was noted in several thin sections, and in one section the chlorite contains small aggregates of dark nearly opaque needlelike crystals which may be rutile.

HORNBLENDE-PYROXENE ANDESITE AND ASSOCIATED APLITE

An area on the north flank of the Sierra de La Caja and extending into Bonanza valley contains many sills and a few dikes of andesite and some aplite. The area is indicated on plate 1 by a special symbol because the sills are too numerous and small to map individually on the scale employed. The area has a length of 8.5 kilometers and a maximum width of 2.5 kilometers and lies mainly within the Caracol formation and Parras shale. Although the igneous rock is largely confined to the region described, a few sills occur in other parts of the valley and have been found as far east as Concepción del Oro.

The sills range from a few centimeters to 12 meters or more in thickness, and in many places they cut across the adjacent sediments on a small scale. Minor brecciation of the country rock occurs locally along the borders of the sills, which may contain many angular fragments of shale. Most country rock immediately adjacent to the

[5] Oral communication from W. H. Triplett, Cía. Minera de Peñoles.

andesite is altered to a hornfels. The most extensively metamorphosed area is in the Cerros Colorados, rugged isolated hills west of Bonanza. There are many sills in that area, and the consequent metamorphism has produced a rock highly resistant to erosion.

The andesite sills are medium dark gray to dark greenish gray and highly porphyritic. Specimens of only four were examined petrographically and of this number only one appears to be a fairly fresh andesite, whereas the others are highly altered. The first is composed of plagioclase phenocrysts and altered mafic grains in a fine-grained groundmass containing mainly plagioclase with a little accessory magnetite and little or no quartz. The phenocrysts are relatively fresh and consist of sodic andesine or calcic oligoclase, but the mafic minerals are wholly altered to aggregates of carbonate and chlorite.

The remaining sills were found to contain phenocrysts of plagioclase, hornblende, and pyroxene in a fine-grained groundmass consisting mainly of plagioclase, and minor amounts of quartz and carbonate and some accessory magnetite, limonite, sphene, apatite, and zircon. Some of the feldspar may be andesine or oligoclase, but a large part of it, including both the phenocrysts and the material in the groundmass, has apparently been albitized by magmatic solutions introduced later. It is rather strongly sericitized. The hornblende is pleochroic from yellow green to olive green and may form well-developed prismatic crystals, which in one sill have a preferred orientation, reflecting the direction of flowage. The pyroxene is a pale-green augite and may be slightly pleochroic. Both of the mafic minerals are extensively altered, largely to an aggregate of chlorite, carbonate, and some quartz. Much of the quartz in these sections is obviously secondary, and possibly none is an original rock constituent. The limonite is probably derived from the weathering of pyrite, which is sparsely disseminated through the rock. These highly altered sills differ texturally from the first sill described above. Individual grains in the groundmass are poorly defined, and the original texture seems to have been largely or wholly obliterated by the alteration processes.

The phenocrysts make up a large proportion of the rock, perhaps forming more than 50 percent by volume of some sills, and the magma must have been a highly viscous mixture of crystals and liquid injected under high pressure. This may account for the brecciation that is frequently seen along the borders of the rock, and may serve to explain several small sills in which foreign material, including shale and igneous rock fragments, is actually predominant.

The eastern part of the area contains several sills of a light-gray or buff to creamy-white color. One was examined petrographically and was found to contain a few plagioclase phenocrysts, largely kaolinized, in a fine-grained equigranular groundmass consisting mainly of sodic plagioclase with a little quartz and many isometric grains of pyrite.

Perhaps these sills represent a slightly acid differentiate of the andesitic magma and can be classed as aplites.

The Cerros Colorados and surrounding area contain many gold prospects, probably related genetically to the igneous rocks.

The sills here described may be related to sills described by Imlay (1938b, p. 1671) as intruding the Caracol and Indidura formations to the north and northeast of Melchor Ocampo, which lies in the synclinal valley separating the Sierras de Zuloaga and Sombreretillo. An area of about 13 square kilometers contains vertical or nearly vertical thin sills identified as andesite porphyry and a light-colored felsite porphyry.

FIGURE 14.—View of the dacite intrusive body of Las Parroquias, Sierra de Santa Rosa. The picture was taken from Puerto Blanco.

Imlay suggests that these sills may mark the position of a fairly large igneous body lying at depth.

DACITE PORPHYRY

Dacite is found mainly in the Sierra de Santa Rosa, where it forms 14 sills or sill-like intrusive bodies sufficiently large to be mapped. It occurs in both limbs of the anticline and has invaded mainly the comparatively thin-bedded rocks of the La Caja and Taraises formations, although one large sill has intruded the Cuesta del Cura limestone and another has intruded the Zuloaga limestone. The rock differs somewhat in composition from place to place and may actually range from a dacite to a latite.

The intrusive body of Las Parroquias is by far the largest and measures approximately 5 kilometers in length by 900 meters in maximum width (fig. 14). Although grossly sill-like in form, it has strongly crosscut the adjacent formations. Unlike the granodiorite, it has not invaded the sedimentary rocks by magmatic stoping, but has forced its way in by pushing the rocks aside, as can be clearly observed on the geologic map (pl. 1). The body has crosscut the La Caja and Taraises formations and the Cupido limestone, which have been offset a maximum distance of about 750 meters. If the offset segments could be restored to their original position, however, little, if any, of the section would be found to be missing. The magma emplacement was responsible for two moderately large faults, one at each end of the intrusive mass.

The fresh dacite is a light- to medium-gray rock, easily weathered to a soft, rotten material with a brownish or reddish coloration. It contains many large lath-shaped phenocrysts of plagioclase, which are enclosed in an aphanitic groundmass. The phenocrysts have a maximum length of 4 or 5 centimeters and commonly are zoned from labradorite in the core to an outer shell of andesine or calcic oligoclase. They seem to have a largely random orientation, and no primary flow structures could be clearly determined. Petrographic study shows that the plagioclase phenocrysts, along with a few large grains of quartz and moderately large subhedral grains of hornblende and biotite, are enclosed in a finely crystalline groundmass of potash feldspar, plagioclase, and quartz. The biotite is partly altered to chlorite and epidote. The potash feldspar is probably sanidine. A little magnetite, sphene, and zircon are present, but accessory minerals are relatively scarce. Calcite is found in most thin sections. Rosenbusch (Burckhardt, 1906a) reports that the groundmass may contain secondary feldspar and quartz, which have formed through devitrification of an original glass.

The limestone adjacent to the dacite is bleached or finely recrystallized, but the metamorphic zone is generally narrow. There is little or no evidence of ore mineralization in the vicinity of the Parroquias intrusive body or other dacite bodies.

The only other mass of dacite in the Sierra de Santa Rosa studied petrographically by the authors was the westernmost sill on the north flank of the anticline, which has a length of 1.75 kilometers and a maximum thickness of about 300 meters. It is a medium-gray to reddish-gray or violet rock containing small phenocrysts of plagioclase, quartz, and biotite in an aphanitic groundmass consisting of a finely crystalline mixture of potash feldspar, plagioclase, and quartz. The feldspar is approximately 60 percent plagioclase and 40 percent potash feldspar.

A thin section from the compound sill that is exposed in Cañón de La Canela was studied by Rosenbusch (Burckhardt, 1906a, p. 26), who described it as a highly altered rock composed of irregular angular fragments of mica dacite having a glassy or cryptocrystalline groundmass, angular quartz grains, and fragments of a hornfelslike mixture of biotite, quartz, and feldspar. It also rather commonly contains calcite. Rosenbusch could not determine whether the rock was a dacite with many inclusions or a breccia. However, field study has shown this body to be clearly intrusive.

A few small dacite bodies, including sills and dikes, have intruded the loosely consolidated rocks of the Mazapil conglomerate in the Santa Rosa graben and in the downfaulted area lying along the north side of the Mazapil valley. In the second area only two bodies were sufficiently large to map, and a specimen from only one was studied in thin section. A few wholly altered plagioclase phenocrysts and a few biotite grains are enclosed in a fine-grained, highly altered groundmass containing plagioclase, potash feldspar, and quartz.

ANDESITE

The only body of later formed andesite to be found within the area mapped is that exposed on the crest of the Sierra de La Caja and lying immediately to the west of the high summit known as Cerro de Los Carneros. This body is roughly circular and has a diameter of about 525 meters. The rock ranges from grayish violet to yellow and yellowish white and seems to have a slightly porous texture, which is accentuated on weathered surfaces. The single thin section obtained by the authors is composed of very small, highly altered, plagioclase phenocrysts and some muscovite laths in a glassy or cryptocrystalline groundmass with a strongly developed flow banding. The plagioclase could not be determined. Rosenbusch also studied the rock petrographically (Burckhardt, 1906a, p. 27) and described it as a highly altered vitrophyric amphibole andesite. The flow structure strikes approximately parallel to the borders of the intrusive body and dips inward at moderate to steep angles. The rock is closely jointed parallel to the flow structure, imparting a platy appearance. The mass has intruded the Zuloaga limestone, which is almost completely unmetamorphosed. It is believed to have filled a volcanic vent, although there is no trace of the andesitic volcanic rocks which must have been ejected. Apparently they have been completely eroded.

RHYOLITE

A small rhyolite stock crops out in Cañón del Potrero on the north side of the Sierra de Santa Rita. It may be considerably larger than is indicated by the exposure, for apparently it underlies the Zuloaga limestone immediately to the west. A second small rhyolitic mass is present on the northeast flank of the Sierra de San José about 0.8 kilometer southwest of the La Laja mine. A few additional minor rhyolitic intrusive masses are present in the Sierra de La Caja

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but have not been indicated on the geologic map (pl. 1). They are closely associated with rhyolitic flow remnants which have been mapped in the Salaverna-Providencia area.

The rock in Cañón del Potrero is light reddish brown and has a porphyritic texture. The phenocrysts are potash feldspar and quartz. They range in size from 0.5 to 1.0 millimeter and are contained in a finely crystalline groundmass. The feldspar is highly altered but was probably sanidine. Biotite and hornblende can be recognized, as well as accessory hematite. Petrographic study shows that the rock underwent some brecciation before crystallization was complete, and this was followed by the introduction of silica, probably as chalcedony.

CONTACT METAMORPHISM AND MINERALIZATION

The deep-seated intrusions of granodiorite and diorite strongly metamorphosed the adjacent sediments. Since the authors were able to make only a cursory investigation of the contact metamorphism and ore mineralization, these subjects are discussed only briefly in the present report. However, they would like to recommend that a detailed study be made of the district, for they believe that it would greatly benefit the local mining industry.

To date the only careful investigation of the contact metamorphism is that made by Bergeat (1910). His study was limited to a small area in the vicinity of Concepción del Oro, however, and although his paper is based on a great deal of careful petrographic and analytical work, he devoted relatively little time to field observations.

CONCEPCION DEL ORO AND PROVIDENCIA STOCKS

Contact metamorphism formed a thin garnetized border in the limestone adjacent to the Concepción del Oro and Providencia stocks. This belt occurs only intermittently around the edges of the stocks and ranges in thickness from a few centimeters to 15 meters or more. The predominant mineral is andradite, which is generally green to yellow green, but locally may be red or brownish. The garnet may be accompanied by calcite, quartz, wollastonite, diopside, tremolite, vesuvianite, epidote, scapolite, and more rarely, zoisite and hornblende. Although the boundary between the garnetite and granodiorite is generally sharp, in some places it is poorly defined. The garnet rock in places has been invaded by small apophyses or small isolated bodies of the intrusive rock.

In the garnetite zone, or close to it, are found some of the most important ore deposits. These contain mainly chalcopyrite (with gold and silver), pyrite, chalcocite, magnetite, hematite, and sphalerite, together with a little tetrahedrite and other minerals in small amounts. Some deposits are irregular in shape and apparently independent of structural controls, and others form pipes or chimneys lying along fractures, fracture intersections, or the intersections of fractures with beds favorable to replacement.

Beyond the garnetite border is a metamorphic aureole in which the limestone is recrystallized and is replaced only locally by silicate minerals. The aureole has a width ranging from several hundred meters to more than 1 kilometer, and toward the outer border the metamorphic effects die out gradually and almost imperceptibly. Most limestone is transformed into medium- to coarse-grained white marble, although in some areas away from the contact, black or alternately black and white recrystallized limestones are relatively common. Certain limestone beds, such as those of the Taraises formation or those in the lower part of the Zuloaga limestone, seem especially to produce black marble. This color is probably related in part to the carbonaceous content of the rock, which is recrystallized to graphite. In the white marble the carbonaceous material may have been burned off rather than recrystallized and preserved. As Bergeat (1910, p. 46) has pointed out, however, the intense black coloration does not always correspond to a relatively high carbon content. For example, the uppermost unit of the La Caja formation, which in the areas close to the granodiorite contact is generally a recrystallized black limestone rich in wollastonite, contains very little carbonaceous material. The lower units of the La Caja formation, which differ little in composition from unit D, except they are less calcareous, are transformed into hard buff-colored hornfels rich in wollastonite and quartz, which contrasts sharply with the overlying black rocks.

The silicates within the metamorphic aureole may be sparsely disseminated through the limestone, but in many places they form thin discontinuous layers along the bedding planes, and possibly along some stylolitic partings. In cherty formations, such as the Cuesta del Cura limestone, many chert lenses are completely garnetized. In some areas close to the igneous contact the thin garnet layers formed along bedding planes appear to have been folded and crumpled and are broken into many discontinuous segments (fig. 15). Bergeat (1910, p. 49) believes this may have taken place during recrystallization of the limestone and may be the result of pressure exerted by the ascending magma.

Within or close to the aureole there are many mesothermal ore deposits consisting mainly of galena, sphalerite, and pyrite, which carry silver and gold. Although contemporaneous with the contact metamorphic deposits, they were formed at lower temperatures. Many of these mesothermal deposits are associated with fractures and various types of flexures and may occur where such structural elements are found in conjunction with beds favorable to replacement or sedimentary contacts.

According to Bergeat (1910, p. 35), the margin of the granodiorite in the Concepción del Oro stock is in many places transformed into a thin garnetiferous selvage, whose thickness is only a few centimeters, in which the garnet, diopside, wollastonite, quartz, and minor calcite are pseudomorphic after plagioclase, hornblende, and pyroxene.

FIGURE 15.—View showing crumpled, metamorphosed Cuesta del Cura limestone close to contact with granodiorite in Sierra de Concepción del Oro. *g*, garnet; *c*, bleached chert.

NOCHEBUENA STOCK

Along the limestone contacts of the Nochebuena stock there is considerable replacement by garnet and other contact-metamorphic minerals, but there is no strongly developed garnetite zone comparable to that bounding the Concepción del Oro and Providencia stocks. A wide metamorphic aureole is present, however, and within or close to this zone are several metalliferous deposits that are being mined for silver, lead, and gold. At the east end of the intrusive body the Caracol and Parras sedimentary rocks are metamorphosed to yellow or buff and, locally, greenish masses of hornfels and argillite.

The east end of the stock, along with the small intrusive body lying adjacent to it and invading the La Caja thrust, has produced a wide belt of fairly massive wollastonite in the Cuesta del Cura limestone. The wollastonite ranges from fine grained to coarsely crystalline, and the grains are as much as 2 centimeters in length. The fibers may form radial aggregates or lie roughly parallel, but more often they seem to have a random orientation. They may contain disseminated calcite, garnet, diopside, and possibly other minerals, but for the most part these silicates are concentrated along the chert lenses, which may be almost completely garnetized. In general, the wollastonite close to the contact is white, coarse grained, and contains relatively few impurities, and that occurring away from the contact is gray to bluish gray, fine grained, and contains a large quantity of foreign material, particularly calcite. Partial chemical analyses of grab samples of these two general lithologic types are given in table 4.

TABLE 4.—*Partial chemical analyses of two samples of wollastonite from the Sierra de La Caja*

[The analyses were made in the laboratories of the Instituto de Geología by Alberto Obregón P., reported June 20, 1953]

	Laboratory no.	
	10700	10701
SiO_2	47.36	26.76
Al_2O_3	4.69	5.29
Fe_2O_3 (total iron)	.63	.79
CaO	41.79	55.83
MgO	.12	.05

No. 10700 represents a thickness of about 10 meters and was taken immediately adjacent to the diorite contact.
No. 10701 represents a thickness of about 20 meters and was taken immediately above the first sample.

The authors believe that the rock represented by no. 10700 may have commercial possibilities. Wollastonite and garnet are easily separated by high-intensity magnetic- or gravity-separation methods, and the garnet might be salvaged as a byproduct for the abrasives industry.

SAN FELICIANO PHACOLITH(?)

The granodiorite in the Valle de San Feliciano has recrystallized the adjacent limestone to a distance of a few meters from the contact, but it has not strongly silicated it. The only metallization in the vicinity of the intrusive body produced hematite, found mainly along fracture zones and along the high-angle thrust fault lying immediately to the northwest. It is being mined on a very small scale for use in the paint industry in Monterrey. The granodiorite contains many inclusions of Zuloaga limestone, which in general have been marmarized only close to the margins.

TERTIARY EXTRUSIVE ROCKS

Extrusive rocks occupy several small areas in the Sierras de La Caja and Santa Rosa, and in the adjacent valleys. They include flows, agglomerate(?), and some tuff, and they range in composition from rhyolite to basalt.

AGGLOMERATE(?)

In the center of the Santa Rosa anticline (fig. 16) an area slightly oval in shape and about 2.75 kilometers long is underlain by a highly altered rock that has been described as an altered porphyry stock (Burckhardt, 1906a, p. 23–24; Barrera, 1927, p. 53–54). Field study and petrographic examination of this material, however, strongly suggest a volcanic origin.

In one area on the western margin of the Valle de Santa Rosa the rock is characterized by well-developed layering, which dips away from the fault contact at an angle of 25° to 30°. However, most of the material seems to be relatively massive, with layering only faintly defined or wholly lacking, and in many places it is obviously composed of angular rock fragments ranging from less than a centimeter to more than a meter in longest dimension. The fragmental structure lends credence to the theory that the rock is an agglomerate or volcanic breccia. The fresh rock is generally white to pinkish, but weathered surfaces are strongly reddish. A few xenolithic blocks of marmarized limestone have been seen in the material, and one very large limestone block was penetrated by a diamond drill in the western part of the area.

The rock is so strongly altered that little idea of the original composition and texture can be gained from a petrographic examination. The thin sections that were studied consist mainly of quartz and chalcedony grains, with considerable muscovite and sericite, in a groundmass composed of fine-grained secondary silica. A few outlines of original feldspar grains can be observed, but these have been completely altered to sericite or kaolin, and the quartz, which occurs as large, irregular grains, may be the only original rock constituent. Several of the specimens studied by Rosenbusch (Burckhardt, 1906a, p. 26–27) appear to have been similar, although another one he describes is mainly an allotriomorphic quartz and feldspar aggregate formed by alteration of a spherulitic matrix. This material has a few large crystal outlines filled by chlorite; these probably represent original grains of feldspar and biotite.

Kaolin and secondary silica may be deposited along fractures in the agglomerate(?) or in larger, more irregular areas. The kaolin is apparently of good quality and might possibly merit a brief investigation to determine commercial possibilities. On the south side of Cerro Colorado the agglomerate(?) contains deposits of turquoise, which occur along fractures close to the fault contact and must have been formed by hydrothermal solutions. The phosphoric acid required for the deposition of turquoise may have been derived from the phosphatic beds of the La Caja formation.

The authors believe that the agglomerate(?) may occupy the site of a volcanic orifice and may have been dropped down into the sedi-

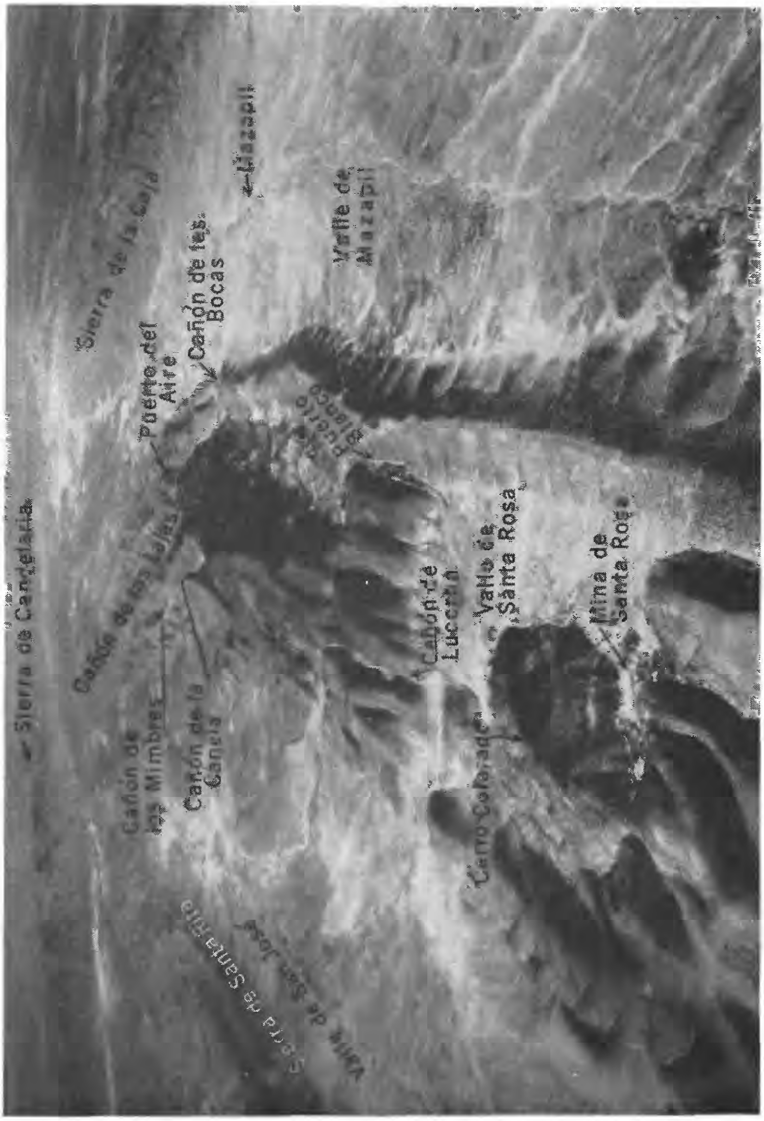

FIGURE 16.—Aerial view, looking westward, of the Sierra de Santa Rosa. Photograph furnished by United States Air Force.

mentary rocks by cauldron subsidence. It has a known thickness of about 400 meters but continues to an unknown depth in the central part of the valley. Since all the intrusive rocks in the vicinity are dacite, perhaps this rock was also dacitic in composition, and possibly this was the only point at which the dacite magma reached the surface.

Along the eastern margin of the agglomerate(?), the Zuloaga limestone is partly marmarized and in some areas is mineralized, containing gold, silver, and lead ores. However, along the remainder of tbe contact there is evidence of only minor alteration or mineralization. This would suggest that the ore-bearing solutions moved upward locally along the fault contact but may have had no genetic relation to the volcanic rock. There are little or no mineralization effects associated with the dacite, but, on the other hand, some features of the ore in the agglomerate(?) and adjacent limestone at Santa Rosa, such as the presence of fluorite and manganese, suggest an origin during the metallogenetic epoch that later accompanied widespread extrusion of rhyolite.

RHYOLITE FLOWS

A thin rhyolite flow lies unconformably above the Mazapil conglomerate in Valle de La Caja, and small remnants of other flows cap several hill summits on the south limb of the La Caja anticline in the vicinity of Salaverna. The rocks are generally reddish or pinkish but locally may be gray or yellowish gray. Phenocrysts are relatively rare and consist mainly of quartz grains enclosed in a finely crystalline groundmass containing sanidine, plagioclase, and quartz. Mafic minerals are very rare. Most of the rock is slightly vesicular, but it has no strongly developed flow structure. One thin section appears to be a leucotrachyte, containing mainly sanidine and a considerable amount of hematite and some quartz. No mafic minerals are present.

BASALT FLOWS

Basic volcanic rocks appear in two rather widely separated areas. They underlie the flat-topped hills, which are known as Las Mesas, at the western end of the Sierra de Santa Rosa, and they form a range of low but rather conspicuous hills in the Bonanza valley northeast of Terminal. In both localities a series of basalt flows overlie loosely consolidated arkose, which may be a reworked volcanic ash.

In the Las Mesas area the volcanic rocks have a maximum exposed thickness of more than 200 meters and dip to the west at an angle of about 5°. There is no evidence of faulting in the area, and the dip probably represents an original slope. The arkosic sediments are covered by talus from the overlying flows and are rarely exposed. Those which were seen are light-gray to reddish or yellowish crumbly poorly cemented rocks, and only two specimens were examined petrographically. One was found to be composed of rounded grains of plagioclase, quartz, and chalcedony, and rounded rock fragments in a chalcedonic cement. The rock fragments consist of basalt or basalt and chalcedony. The other rock is a well-sorted loosely consolidated sand containing angular to moderately rounded grains of highly altered feldspar, chalcedony, and quartz, and some carbonate and magnetite. One flow was examined in thin section and proved to be a basalt containing phenocrysts of twinned basic plagioclase and a few grains of olivine that are largely replaced by iddingsite.

In the western part of the Mazapil valley several low hills are composed of arkose resting upon beds of Caracol age. The flows are missing, but the hills are littered with bombs of scoriaceous lava, which in places have been cemented by caliche.

In the Bonanza valley the volcanic rocks dip to the northeast at an angle of 15° to 20°. They are bounded on the north by a large normal fault known as the Canutillo fault (p. 54), have a total thickness of about 300 meters, and apparently rest upon beds of the Caracol formation, although the actual contact is covered by alluvium. Five basalt flows cap the hills and have a total thickness of about 150 meters. They range in color from dark reddish to gray or almost black. One examined petrographically was found to contain abundant phenocrysts of plagioclase, olivine, and hypersthene in a finely crystalline groundmass. The plagioclase forms euhedral grains, which are generally twinned according to the albite law and may be strongly and intricately zoned. The olivine is pale greenish and relatively fresh. Magnetite or ilmenite is very common. The groundmass consists mainly of plagioclase in microlites and small irregular grains. Locally, the microlites appear to define flow lines, although the flow structure is poorly developed.

STRUCTURAL GEOLOGY

FOLDS

The Concepción del Oro district is near the southern margin of a broad belt of closely spaced asymmetrical folds which extend in a westerly direction across the southern part of Coahuila and the northern part of Zacatecas. The area mapped contains four anticlinal ranges separated by narrow synclinal valleys. The three southerly ranges, which are arcuate and convex to the northeast, occur on a major curve in the regional trend from northwest to west, or slightly south of west.

The three southerly ranges, Sierra de La Caja, Sierra de Santa Rosa, and Sierra de Santa Rita, are moderately to strongly overturned toward the north and northeast and in part are fan shaped. The Sierra de Canutillo, however, is slightly overturned toward the south with a tendency toward fan folding in the anticlinal core. The Sierra de Zuloaga, which lies to the north of the Sierra de Canutillo and which has been mapped by Imlay (1938b, p. 1675, pl. 7), is rather strongly overturned toward the south. All these anticlinal folds plunge to the west beneath the Bolsón de Cedros, a narrow alluvial basin bounded on the west by a series of anticlinal ranges with a northwestward trend. These folds lie at a sharp angle to those found within the area mapped and must reflect another abrupt change in the regional strike. The Santa Rita anticline plunges to the southeast beneath the Bolsón de San Carlos, a second northwestward-trending alluvial basin. The other ranges, however, terminate abruptly on the east, and it is possible that the Santa Rosa and La Caja anticlines may continue under the basin in a southeasterly direction, to reappear beyond the basin in the form of other anticlinal ranges. The authors believe that the Bolsón de San Carlos may be a structural basin formed by block faulting, although little attention has been given to this problem.

The folds in the Concepción del Oro district and adjacent areas are small and rather tightly packed and may extend only to a relatively shallow depth. The redbeds of the Huizachal formation have been involved in the folding, but clearly to a lesser extent than the overlying sediments, and for that reason they are only rarely exposed in the anticlinal cores in this region. During the Laramide orogeny there must have been widespread slippage along the surface separating the Huizachal rocks from the overlying Zuloaga limestone, which permitted décollement in these anticlines.

FAULTING

Faulting is more common in the Concepción del Oro district than in the surrounding region and has produced a complex structural pattern in some places. Three important thrust faults have been found within the area. They occur along the north flanks of the Sierras de La Caja and Canutillo and in the center of the Santa Rita anticline; they dip southward. A similar fault has been mapped by Imlay (1938b, pl. 7) on the north limb of the Zuloaga anticline, but apparently thrusting is rare in the broad folded belt to the north and northwest in the Sierra de Parras. Only three overthrusts have been mapped in the Sierra de Parras (Imlay, 1937, pl. 10), and they are all in the western half of the region.

Most of the faults in the district are normal faults which appear to fall into three general categories; faults associated with major intrusions, transverse faults, and block faults with associated graben structures.

Many faults in the vicinity of the major igneous bodies apparently were formed by the pressure of upwelling magmas during the period of emplacement. Most faults of this type have small displacements, and many are found on the immediate periphery of the igneous bodies. They may have random orientation but in most places fall into fairly well defined sets. Such fracture sets may be parallel to the borders of the intrusive bodies, may lie perpendicular to the borders, or may have some orientation between these two extremes. In the mineralized areas these faults have played an important part in the localization of ore. A few large faults close to the intrusive masses may have displacements of as much as several thousand meters.

Many vertical or steeply dipping transverse and oblique faults are present in the district. In general, they are small, although they may have effected lateral offsets of formational boundaries amounting to 100 meters or more. Most are simple gravity faults, probably formed during the tensional phase that followed folding. A few can be classed as tear faults, which are related to the dominant overturning of the anticlinal flanks.

Several long, relatively narrow grabens, nearly parallel to the regional trend, are bounded by longitudinal faults dipping at moderate to high angles. The three smallest grabens are comparatively short and broad and are completely bounded by faults. The largest structure, which occupies a part of the Mazapil valley, is bounded on the north by a fault but may not be on the south. The authors believe that the small fault troughs or grabens, which are among the most noticeable structural features of the Concepción del Oro district, as well as the younger Canutillo fault, belong to a major system of block faulting in the northern part of the Mesa Central. Although this type of faulting has not been widely recognized, much of the previous geological work in the region has been of a reconnaissance nature, and it may simply have been overlooked.

MAJOR STRUCTURAL UNITS

CANUTILLO ANTICLINE

The Sierra de Canutillo is the smallest of the anticlinal structures within the area mapped. It has a trend of approximately N. 80° W. and lies along the boundary between the States of Zacatecas and Coahuila. It has a length of 17.5 kilometers and a maximum width of about 4 kilometers. It ends abruptly on the east, but on the west it plunges steeply under an alluvial plain. The fold is slightly asymmetrical, the axial plane dipping steeply to the north. Dips on the north limb are generally 65° to 70° N., but on the south limb they are as much as 80° S. The anticlinal core, which is composed of massive Zuloaga limestone, shows a tendency toward fan folding. This folding is present in the Cerro del Guayabo, immediately to the west of Puerto de Canutillo, and can be seen from the road that goes through the pass.

In the eastern part of the range a thrust fault has been traced for approximately 3.5 kilometers. It terminates on the east against the younger Canutillo fault and on the west against a second normal fault. Exposures in the area are poor, but the fault appears to dip to the south at a low angle, possibly not more than 10° or 15°. Maximum displacement occurs at the base of Cerro del Guayabo, where Zuloaga limestone is apparently resting upon beds of the Caracol formation.

The Canutillo fault is a large normal fault which can be traced for 14 kilometers along the south flank of the anticline and is responsible for the fault-line scarp that forms such a conspicuous topographic feature in that area (fig. 17). Two kilometers west of Puerto de

FIGURE 17.—View of the scarp formed along Canutillo fault north of Novillos. Cuesta del Cura limestone (Klcc) is in contact with the Zuloaga limestone (Juz). The saddle is formed on La Caja formation (Juc).

Canutillo the fault has dropped beds of Caracol age against the Zuloaga limestone, a stratigraphic throw of more than 1,100 meters. The fault dips 80° to 85° S. Although the fault disappears under alluvium at the east end of the Sierra de Canutillo, it must curve to the southeast and persist for 10 kilometers or more, for it is this structure that has tilted the volcanic rocks lying to the northeast of Terminal. The volcanic rocks form a range of low but rather conspicuous hills, and the basaltic flows capping these hills dip to the north at an angle of 15° to 20°.

The Canutillo fault belongs to the youngest group of faults to be found within the area mapped. They must be Pliocene in age, as they are younger than the basic volcanic rocks, which were probably extruded in late Tertiary time. The character of the Canutillo fault-line scarp indicates an early stage of evolution.

In addition to the faults described above, the Canutillo anticline contains several transverse faults, and in two localities the incompetent bends of the La Caja formation have been squeezed and faulted out for appreciable distances by reverse faults.

LA CAJA ANTICLINE

The La Caja anticline is represented topographically by the Sierras de Concepción del Oro and La Caja, which are actually a continuous range with different names for the eastern and western segments. This structural feature has a length of about 45 kilometers and is arcuate in shape, curving gradually in a westerly direction from N. 45° W. to approximately west. The anticline ends abruptly on the southeast, at the edge of the Bolsón de San Carlos, but on the west it plunges at a low angle beneath the Bolsón de Cedros.

The Sierra de Concepción del Oro, the part of the fold southeast of Providencia, is the more complex segment of the anticline, owing largely to the intrusion of two large granodiorite stocks. This segment is strongly overturned toward the northeast, and in the vicinity of Concepción del Oro it is nearly recumbent, the north limb of the fold dipping 5° to 20° SW. (fig. 18). In this area the south limb has an average dip of about 45° SW., and on both limbs the dips steepen gradually outward from the anticlinal core until they reach a maximum of 75° to 80° SW. Both limbs of the fold steepen gradually to the west, and in the vicinity of Terminal and Providencia the north limb is dipping generally 70° to 80° S.

In the part of the Sierra de La Caja lying between the Providencia stock and the Nochebuena granodiorite stock, the fold is not strongly overturned in either direction, although locally, in and close to the anticlinal core, there may be fan folding, and locally there is overturning of the limbs of the fold. Much of the north limb is concealed beneath the La Caja overthrust, but in exposed areas the rocks dip generally 50° to 80° N. In part, the south limb has approximately the same range of dips to the south. As elsewhere, dips in the Cuesta del Cura limestone and the Caracol formation differ in many places, owing to the extensive drag folding. The same is true, although to a lesser extent, of the Indidura formation and the incompetent sections of the remaining stratigraphic units.

The west end of the anticline, extending from the Nochebuena stock to Cedros, is known locally as the Sierra de Cedros; it is a normal symmetrical anticline, with the dips on both limbs generally ranging from 45° to 70°. In the axial region of the fold the rocks are nearly horiztontal, although the axis plunges from 5° to 10° W.

The La Caja thrust extends about 15 kilometers along the north flank of the Sierra de La Caja, although the actual fault outcrop is sinuous and considerably longer. For most of its length the edge of

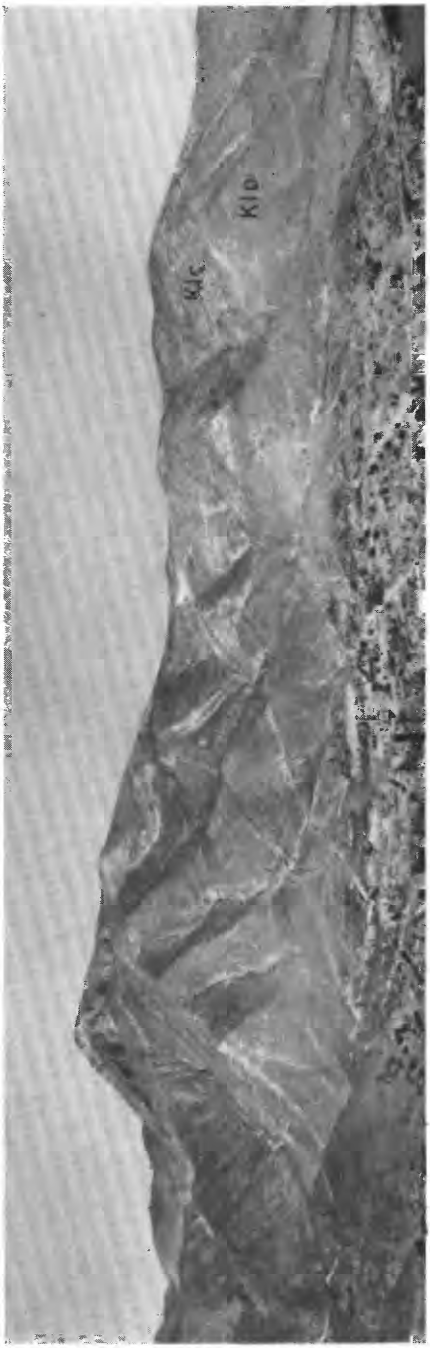

FIGURE 18.—View of Cerro de La Campana, with Concepción del Oro in foreground. The peak is composed of Zuloaga limestone, while the narrow belt lying below the cliffs and containing no visible exposures is underlain by the La Caja formation. On the right, the La Peña formation (Klp) is overlain by Cupido limestone (Klc). The beds dip from 5° to 15° to the southwest and are overturned.

the overthrust plate forms a prominent fault-line scarp, one of the most noticeable topographic features of the range. On the west the fault apparently ends at the Nochebuena stock, although, owing to poor exposures, it cannot be traced all the way to the edge of the stock. On the east it dies out rather abruptly only 0.5 kilometer short of the Providencia stock. However, several smaller related faults in this area may continue to the granodiorite stock. Four of these faults are intersected by the El Tesoro adit, which runs in a southwesterly direction from the stock through the Taraises and La Caja formations and continues for about 170 meters into the Zuloaga limestone. The faults have southwesterly dips ranging between 55° and 70°, and the two largest have breccia zones measuring several meters in thickness. At the surface, several of the fault zones contain dikes or small lenticular bodies of alaskite.

In general, the La Caja fault appears to dip 45° to 50° S., although locally the dip may steepen to 75° or 80°, and in one relatively small area lying to the south of Novillos the thrust plainly dips to the north at a very low angle. The fault is everywhere characterized by a large breccia zone, which ranges generally from 30 to 100 meters in thickness. A few small to moderately large granodiorite bodies occur along the fault zone; only the largest of these have been mapped. They are clearly formed later than the thrusting, although one has been brecciated, owing apparently to localized later movement along the fault. Maximum displacement occurs in the vicinity of Cañón del Gato, where Zuloaga limestone rests upon the Caracol formation, thus indicating a stratigraphic throw of more than 1,100 meters.

A peculiar reverse fault is found along the crest and southern flank of the La Caja range to the southwest of Providencia. It appears to be a high-angle thrust dipping to the north and may owe its origin to emplacement of the Providencia stock.

The principal area of large-scale normal faulting is found in the vicinity of the Concepción del Oro granodiorite stock, which apparently exerted an active upward thrust that strongly disrupted the overlying sediments. The Concepción del Oro fault is a peripheral fault, somewhat arcuate in form, which lies to the northeast of the stock and runs nearly parallel to the igneous contact. The rocks on the northeast side of the fault have low southwestward dips and represent the strongly overturned limb of the anticline. On the other side of the fault the rocks are generally steeply inclined, and this segment represents a part of the underlying recumbent syncline, which was pushed upward by the invading magma. The fault plane is nearly vertical, and the fault may have a maximum throw of 900 meters or more.

The Concepción del Oro stock invaded the core of the La Caja anticline mainly, but a part of the igneous mass extended into the adjacent syncline, and in this area also, the invading magma disturbed the overlying sediments in a highly complex manner. The rocks lying along the trough of the syncline were thrust upward and disrupted, and the fold axis was offset about 1,200 meters to the southwest. These dislocations have resulted in a peculiar topographic feature. The La Caja and Santa Rosa anticlines are now connected by a ridge which crosses the intervening synclinal valley and divides it into two segments. The major segment is that lying to the west, which is known as the Mazapil valley. The ridge has a width of 2 kilometers, and in this upthrust area the synclinal trough is occupied by Cuesta del Cura limestone, the younger beds of the Indidura and Caracol formations having been eroded. The ridge has been dissected by headward erosion from the small valley to the southeast, and the divide separating this system from the Mazapil valley is little more than 100 meters in width. The synclinal axis has been offset along a fault zone that extends for about 5 kilometers S. 65° W. from Cañón de Los Angeles and then turns sharply to the northwest to follow the La Caja formation. The offset was not effected along a single fault, but along a complex zone containing several large faults. Several large sedimentary blocks were rotated and moved along the zone for considerable distances. The La Caja formation has been offset for more than 2 kilometers along the zone.

Two small grabens are present along the crest of the La Caja anticline. A high relatively broad, shallow valley, known as Valle de La Caja, has been developed upon the larger graben, and to the west this valley drains into a narrow steep-walled canyon cut along the anticlinal axis. The fault block has a length of about 2.25 kilometers and a maximum width of 1.5 kilometers; the fault has dropped Mazapil conglomerate into the Zuloaga limestone. The Tertiary rocks are folded into a gentle westward-trending syncline, with maximum dips of about 35°. The folding may have been effected earlier than the formation of the graben structure, but it seems more likely that the gentle syncline is a product of drag along the faults bounding it. In the northern half of the valley the conglomerate, siltstone, and tuff are covered by a thin rhyolite flow, which has been breached by the larger arroyos crossing it. The flow antedates the fault and is tilted to the south along with the underlying rocks. Cañón del Gato, a deep, relatively narrow valley, has been cut along the second graben, which has a length of only 1 kilometer. Tertiary conglomerate, siltstone, and tuff have been dropped deep into the Zuloaga limestone of the anticlinal core and have been tilted to the south or southeast. The lowest rock exposed is a coarse boulder conglomerate with a gray to slightly reddish matrix. Exposures are poor, as most of the Tertiary rocks are covered by alluvium.

The largest of the downfaulted blocks containing Mazapil conglomerate is found along the south flank of the range. It underlies the northern side of the Mazapil valley in the area directly north of Mazapil and may be about 9 kilometers long by 2 to 2.5 kilometers wide. The area is bounded on the north by a fault or fault system, which in part is easily traced, but the southern border of the area is covered largely by alluvium. In one area to the northwest of Mazapil, however, the red conglomerate rests unconformably upon beds of the Caracol formation, and the yellowish siltstone, sandstone, and limestone which underlie the conglomerate along the north side of the structure are wholly lacking. In this locality, at least, there is no fault bounding the southern margin of the formation. The Tertiary rocks have a thickness of about 200 meters and are fairly well exposed in the large reentrant lying to the north of Mazapil. They have been folded into a shallow westward-trending syncline. Close to the fault on the north, dips may be 60° or more to the south or southwest, but away from the fault they are 15° or 20°. Along the southern edge of the area the rocks dip 5° to 30° N. Although it is probable that the folding is due in large part to drag along the faults at the boundary, there may have been some folding of the Tertiary rocks before the graben was formed. In one locality on the north side of the valley the beds are overturned, and such overturning is difficult to explain by faulting alone. Around the borders of the reentrant the conglomerate and associated rocks are bounded by a relatively complex system of faults, of which the largest are shown on the regional map (pl. 1). The rocks have been intruded by a few small dikes and one sill of highly altered gray to violet dacite. Some dikes have invaded fault zones.

SANTA ROSA ANTICLINE

The Santa Rosa anticline is represented by a small mountain range 45 kilometers long. The western part of the range is known as the Sierra de Santa Rosa (fig. 16), and the eastern section is called the Sierra de San José. The fold is arcuate in shape, curving gradually in a westerly direction from a strike of N. 40° W. to a strike averaging a little south of west. The anticline ends abruptly on the southeast, at the edge of the Bolsón de San Carlos, but on the west it appears to plunge beneath the Bolsón de Cedros at a low angle, although in that area it is partly concealed beneath basic volcanic rocks.

The anticline is moderately overturned toward the north along its entire length. The strata on the northern limb of the fold dip from 50° to 75° to the south and southwest and average about 65°. In most of the Sierra de San José the anticlinal core, which is composed of Zuloaga limestone, is fan folded, the southern half of the core dipping generally 40° to 45° NE. This overturning extends outward to the La Peña formation, but the younger rocks in most places dip normally to the southwest. On the west the fan folding largely dies out in the vicinity of Santa Rosa, and to the southeast it dies out a few kilometers short of the end of the range. In the Sierra de Santa Rosa there is a tendency toward fan folding in some areas, but it is less strongly developed. In general, the rocks on the south limb of the fold are steeply inclined toward the south, although they flatten gradually away from the anticlinal core. They may have an average dip of about 65° S.

The Zuloaga limestone is believed to be compressed into a double anticline along the entire length of the fold. The formation contains no characteristic key beds that would furnish definite proof of this, but the distribution of the siltstone layers and coral-bearing beds would seem to bear it out. Furthermore, the Zuloaga limestone, which is tightly and even isoclinally folded, forms a belt with an average width of 1,800 meters. As the total thickness of the formation may be little more than 400 meters, the section would appear to be repeated four times, rather than twice as in the normal single fold.

In the southern half of the Mazapil valley, about 1.5 kilometers to the north of the Sierra de Santa Rosa, is an isolated hill known as Cerro Gordo. The hill is 2.5 kilometers long and has an average width of about 1.25 kilometers. Structurally, the hill is a small anticline (section *A–A′*, pl. 1) slightly overturned toward the south. On the south side of the hill the rocks are partly altered and slightly mineralized near the contact of the Cuesta del Cura limestone and the Indidura formation. Possibly the fold was formed by the upward pressure of an unexposed intrusive body.

A long, narrow graben is present in the core of the Santa Rosa anticline. It can be traced for about 6.5 kilometers, mainly along Cañón de Las Lajas, and on the west it disappears under the alluvium that floors the valley. It is very narrow, having a maximum width of about 375 meters. The rocks within the trough are poorly exposed, but seem to consist mainly of red Mazapil conglomerate, with only a small proportion of siltstone or tuffaceous material. Bedding is obscure, although in one locality adjacent to the southern boundary fault the conglomerate is clearly dipping 45° N. In general, the graben structure appears to lie along a synclinal axis in the Zuloaga limestone.

In the eastern part of the Sierra de Santa Rosa an oval area 2.75 kilometers long occupying the center of the anticline is underlain by altered volcanic agglomerate(?). The broad depression known as Valle de Santa Rosa has been eroded in this material, and the agglomerate(?) forms a conspicuous reddish hill known as Cerro Colorado (fig. 16) that rises about 400 meters above the level of the valley. The contact of the volcanic material and the surrounding sedimentary rocks is largely concealed by alluvium or other debris, but where exposed it is a fault zone. In the Santa Rosa mine the fault plane dips 30° to 50° W. and appears to steepen gradually with depth. The agglomerate(?) may once have blanketed a large region, but it is now wholly eroded except in this single area, where it has been preserved by faulting. The reason for the faulting is unknown, although the authors suggest that a volcanic vent may have been present in the area, and that the peculiar structure was caused by collapse of an underlying magma reservoir. No ring dikes have been observed in the area.

SANTA RITA ANTICLINE

The Santa Rita anticline is represented by a small arcuate mountain range known as the Sierra de Santa Rita, which has a length of 46 kilometers. It lies parallel to the Santa Rosa anticline and has a strike curving in a westerly direction from N. 20° W. to approximately west.

The fold is an asymmetrical doubly plunging anticline, in part moderately overturned toward the north. The south limb of the fold, however, has a normal inclination and an average dip of about 50° to the south and southwest. In the vicinity of San Feliciano valley the fold is overturned to the southeast, although in a southeasterly direction this limb steepens gradually to the vertical and then assumes a normal inclination to the east. This section of the fold plunges steeply beneath an alluvial plain at an angle of 30° to 35°. To the west of San Feliciano valley the amount of overturning toward the north decreases gradually until the fold is nearly symmetrical. The western end of the fold plunges beneath the Bolsón de Cedros at an angle of approximately 5°.

To the west of the San Feliciano phacolith(?) the Zuloaga limestone, which occupies the anticlinal core, seems to develop a double fold similar to that in the Sierra de Santa Rosa. The more northerly anticline is overturned toward the north and is generally isoclinal except in the area to the west of the rhyolite stock in the Cañon del Portrero, where it is asymmetrical and may have been modified by intrusion of the rhyolite, which apparently continues into the anticlinal structure to the west of the outcrop. The other anticline is also overturned toward the north and is generally isoclinal, except in the vicinity of the rhyolite stock, where it develops a fan structure.

The hills in the vicinity of La Cigüeña represent a part of the west limb of a small northward-trending anticline. The fold is asymmetrical, the axial plane dipping steeply to the east.

The granodiorite in the Valle de San Feliciano is believed to be much larger than is indicated by the outcrop area. During the process of emplacement the overlying sediments were probably arched strongly upward, thus producing the small to moderately large normal faults present in the vicinity of the body.

A major fault can be traced from the San Feliciano intrusive body on the east to the lower end of Valle de Santa Rita on the west, a distance of about 19 kilometers. It is believed to be a high-angle thrust dipping to the south, although, except on the west, stratigraphic displacement has been relatively small. A thick breccia zone is seen in the few places where the fault is exposed.

The upper part of Valle de Santa Rita, a troughlike valley with a length of 7.5 kilometers and a maximum width of about 400 meters, is an anomalous topographic feature within the Zuloaga limestone, the principal ridge former in the region. It is apparently a graben structure, similar to a parallel structure in the Sierra de Santa Rosa, which formed along the zone of weakness created by the thrust fault. A few outcrops of Mazapil conglomerate occur along the southern margin of the valley, but exposures of arkose, siltstone, or tuffaceous beds are wholly lacking. The valley may have been thoroughly scoured, and all the rocks overlying the basal conglomerate, as well as most of the conglomerate itself, were removed by erosion.

GEOLOGIC HISTORY

The redbeds of the Huizachal formation, which do not crop out in the Concepción del Oro district, are widely exposed in the area lying immediately to the west. They seem to have been deposited in arid basins in many sections of Mexico and elsewhere in both North and South America (Imlay, Cepeda, Alvarez, and Díaz, 1948, p. 1753–1761). The source of the redbeds in central and eastern Mexico was probably in moist uplands in the western and north-central parts of the country. Imlay suggests that deposition was not necessarily continental but may have been in large basins of highly saline waters. Such an origin is suggested by the generally even bedding and by the association of redbeds with salt deposits in southern Mexico.

During the Late Jurassic the formation of the Mexican geosyncline began as a mobile belt or trough along the outer margin of the Coahuila Peninsula, a southerly extension of the North American continent in Mesozoic time and perhaps a continuation of the Ouachita orogenic belt. Although the Coahuila Peninsula must have had its origin in late Paleozoic time, it was probably rejuvenated in the Mesozoic, and it was this foreland area which formed the source of the Jurassic and Lower Cretaceous sedimentary rocks represented within the area mapped. Upper Cretaceous sedimentary rocks were derived from the west, however, as the foreland was covered by Late Cretaceous seas.

Marine transgression began in late Oxfordian time, when the Zuloaga limestone was deposited on an erosion surface truncating the redbeds. The Zuloaga sediments were laid down in a shallow epicontinental sea and consisted mainly of limestone, with a relatively small proportion of clastic material. In Kimmeridgian and Portlandian time the character of the deposits changed and became predominantly clastic, possibly reflecting climatic changes in the adjacent land areas. During this period intermittent orogenic movements may have affected the geosyncline as well, as Burckhardt (1930, p. 72–73) has suggested in discussing the area west of San Pedro del Gallo, Durango, where the vertical or steeply inclined beds of Kimmeridgian age are overlain by Portlandian and Cretaceous sedimentary rocks dipping at a low angle toward the west. This orogeny may have been related to the Nevadan disturbance, which probably had a widespread influence in the region of the geosyncline. According to Imlay,[6] however, the apparent unconformity near San Pedro del Gallo should be thoroughly verified in the field, as there has been tight folding and some thrusting in the area, and this feature may actually be a thrust plane.

Although no erosional unconformity separating the beds of Kimmeridgian and Portlandian ages has been found within the Concepción del Oro district, exposures are generally poor, and local unconformities might well exist. The marked differences in thickness of the La Caja formation, and of the units within the formation, suggest that the sediments were deposited on an uneven surface (fig. 19), and that the sea bottom was characterized by a series of gentle valleys and ridges, which may have been the product of minor tectonic movements. The ridges must have had low relief, and a few may have emerged and formed low, relatively small islands from which the reptile remains in the La Caja formation may have been swept. This type of submarine topography may have impeded the circulation of sea water in some areas. Imlay reports that in the Sierras de Parras, Atajo, and Jimulco which lie to the north and northwest of the area mapped, the Upper Jurassic sedimentary rocks contain abundant gypsiferous and carbonaceous beds, which imply lagoonal conditions and, therefore, some sort of barrier to the south. Within a limited area such as the Concepción del Oro district, it is difficult to determine whether the hollows and ridges were elongated in a particular direction or were irregular in form, although there is some suggestion of a northwestward trend.

Apparently there was no emergence at the end of the Jurassic, although the boundary with the Cretaceous seems to be marked by a diastem, for sediments representing the Berriasian are absent. This diastem, like the earlier oscillations, may be related to the Nevadan orogeny. During the Early Cretaceous, normal limestone was deposited in a moderately deep sea, with some layers of clastic materials being deposited from time to time, probably reflecting temporary changes in climate or elevation of the adjacent land areas. At the beginning of the Late Cretaceous there was an abrupt change to predominantly clastic sedimentation, and from that time onward

[6] Written communication.

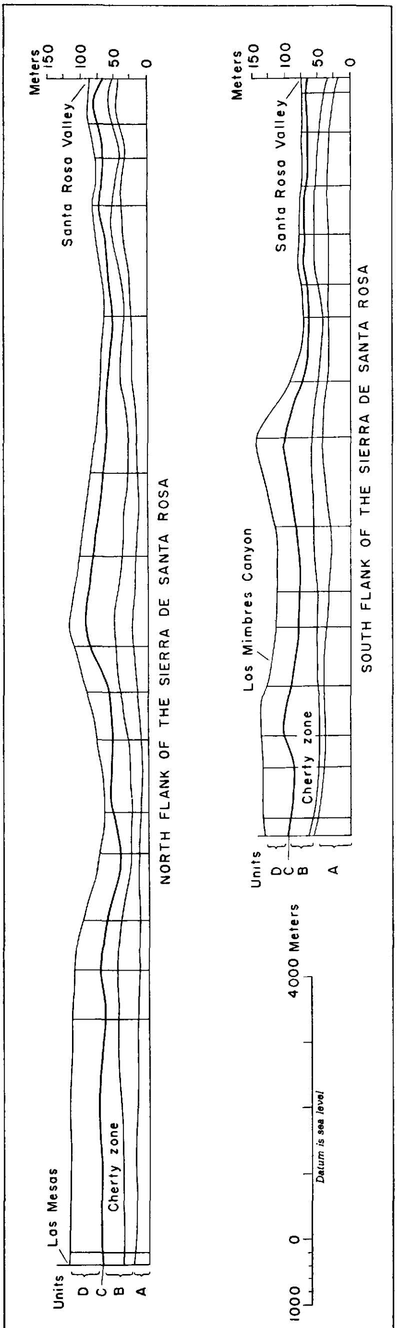

FIGURE 19.—Longitudinal sections showing differences in thickness of the La Caja formation in the Sierra de Santa Rosa. Based on measurements at phosphate sample localities (indicated by vertical lines).

the ratio of clastic material to chemically or biochemically precipitated lime continued to increase. During this period the land masses to the west must have been rising slowly, providing increasingly greater quantities of mud and silt for the shallow seas. From Coniacian to Campanian time, but mainly in the Coniacian, large quantities of arkosic sand were added to the calcareous muds then being deposited.

During the Laramide orogeny, probably started in latest Cretaceous time and continuing into the middle Eocene (Muir, 1936, p. 140), the Mexican geosyncline was compressed by forces acting from the south and west, almost at right angles to the margin of the Coahuila Peninsula, which served as a stable buttress. The sedimentary rocks were thrown into a series of narrow, elongated folds, most of which were parallel to the borders of the old land masses and were overturned toward the north and east, although the deformation also produced many fan structures and some overturning toward the south and west. The strong overturning culminated with some thrusting. Toward the end of the orogeny some anticlinal structures were invaded by large masses of granodiorite or diorite, which metamorphosed the surrounding sediments and in some areas strongly deformed them. Following emplacement and cooling of the magmas many localities were mineralized. As the compressional phase subsided, mountain building ended and was succeeded by a phase in which tensional stresses predominated. These stresses produced first many relatively small transverse faults, but during later stages were responsible for fairly extensive graben and block faulting.

Block faulting began in late Eocene time and formed basins in which the red conglomerates and associated sediments accumulated. Fault movements continued into the early part of the Oligocene but probably halted soon after deposition ended. The unconformity separating the red conglomerate from the underlying rocks in the area north of Mazapil is evidence that fault movement occurred during deposition of the Mazapil conglomerate.

The last major chapter in the diastrophic history of the region was a second period of major block faulting that occurred in late Miocene or early Pliocene time and that started deposition of middle Pliocene to Pleistocene valley fills. The Canutillo fault, formed after the extrusion of basalt, is probably Pliocene in age and related to these relatively recent fault movements. Other contemporaneous faults may have formed the basins that bound the area mapped on the east and west, as well as several other basins in the region.

Although graben structures apparently originate in several different ways (Taber, 1927, p. 581–590), those associated with anticlines, domes, and monoclinal flexures are probably the product of tensional stresses due to differential uplift. Generally, such structures are relatively small and extend only to a shallow depth.

Since the end of the Laramide orogeny the geosynclinal belt has remained above sea level, and the anticlinal ranges within the geosynclinal belt have been subjected to continuing strong erosion. Although this time period has generally been characterized by increasing aridity, it may have been punctuated by occasional brief humid cycles. Such a humid cycle may be represented by the red limestone-boulder Mazapil conglomerate, which has been preserved in several of the graben areas. This conglomerate may be correlative with the red conglomerate at Guanajuato, which apparently is late Eocene or early Oligocene in age.

At some time in the Eocene and following emplacement of the deep-seated granodiorite stocks, many sills of andesite, along with some associated aplite, intruded the rocks of the Caracol formation and Parras shale on the south side of the Bonanza valley. Similar rocks in the Melchor Ocampo district have been described by Imlay (1938b, p. 1671), who presents evidence indicating that the intrusion occurred toward the end of folding, but before final overturning. Deposition of the Mazapil conglomerate was accompanied by volcanic activity, which added andesitic and rhyolitic ash to the sediments.

Following deposition of the Mazapil conglomerate the region was intruded by a magma ranging in composition from dacite to latite. This rock is found mainly intruding limestones in the Sierra de Santa Rosa, although a few sills and dikes of dacite have been found intruding the loosely consolidated rocks of the Mazapil conglomerate in the Santa Rosa graben and in the downfaulted area lying on the north side of the Mazapil valley. The dacitic magma may have reached the surface through a volcanic vent at the present site of Valle de Santa Rosa. If the continental deposits of the Mazapil conglomerate are late Eocene or early Oligocene, as a tentative correlation with the red conglomerate at Guanajuato seems to indicate, the dacites are probably Oligocene in age.

The remnants of the other igneous rocks present in the Concepción del Oro district suggest three major periods of volcanic activity. The first is represented only by the round andesitic body that occurs on the crest of the Sierra de La Caja, in the area lying immediately to the east of the high summit known as Cerro de Los Carneros. This rock may fill a volcanic orifice, suggesting that andesitic rocks reached the surface. None of the ejected material has been found, however, and it may have been completely eroded.

During the second period of eruption small rhyolitic bodies intruded the Santa Rita, Santa Rosa, and La Caja anticlines, and thin flows covered at least part of the Sierra de La Caja. One flow unconformably overlies rocks of the Mazapil conglomerate in the Valle de La Caja graben and has been downfaulted with those rocks. The other flows occur only as small remnants capping several mountain summits in the eastern part of the range.

During the last stage of volcanic activity a series of basalt flows was extruded and may have covered much of the district, although the flows now remain only in two relatively small areas. The age of these rocks is unknown, but they are certainly more recent than the acid volcanic rocks and may have been extruded in late Miocene or early Pliocene time. They seem to have originated after the topography had largely assumed its present form, and although they have been downfaulted in the Bonanza valley, there is no evidence of faulting in the Las Mesas area. Since the volcanic rocks in the Las Mesas area have not been preserved by graben faulting, it seems doubtful if they could have survived erosion for a long period of time. They are underlain by loosely consolidated arkose, which is easily eroded, and the flows are continually being undermined and reduced in size.

The possible sequence of igneous rocks and tentative age assignments are summed up as follows

Pliocene.	
?	Basalt flows
Miocene	Rhyolite intrusive and flow rocks
?	Andesite
Oligocene	Dacite and agglomerate(?)
?	Pyroclastic rocks (Mazapil conglomerate).
Eocene	Hornblende-pyroxene andesite and associated aplite.
Eocene	Granodiorite, with dioritic and alaskitic facies.

PHOSPHATE DEPOSITS

THE PHOSPHATE MINERAL (FLUORAPATITE)

The phosphate mineral in the Concepción del Oro rocks is dense cryptocrystalline material with a concretionary habit. This material, which contains various impurities, is generally known as collophane. Part of it is primary, and the rest is secondary. Primary phosphate forms small generally structureless pellets ranging in size from 0.05 millimeter to more than 1 millimeter; secondary phosphate replaces primary pellets and fossils and is disseminated through the rock matrix. The phosphatic material ranges in color from light gray or almost colorless to pinkish, brown, and intensely black. The color, and also a characteristic fetid odor, may be dependent upon the quantity of organic matter present. The material has a hardness of from 3 to 4 and a specific gravity ranging from 2.5 to 2.9. In thin section the phosphatic material is commonly light to medium dark brown and, owing perhaps to its color and fine grain, appears to be isotropic. Only occasional grains are anisotropic.

The phosphate mineral belongs to the apatite series, which has the general formula $Ca_5(PO_4)_3(F, Cl, OH)$ (Palache, Berman, and Frondel, 1951, p. 882), and can be classed as the member fluorapatite, $Ca_5(PO_4)_3F$. Fluorine is present in a proportion equal to 10.1 percent of the P_2O_5 content. Altschuler and Cisney (1952) have found that marine phosphorites are generally composed of carbonatian fluorapatite, and a study of several chemical analyses of the Concepción del Oro deposits indicates that they also may be slightly to moderately carbonatian. Possibly the anisotropic material seen in thin sections contains more carbonate than the bulk of the phosphatic material.

Owing to the presence of a simple cation, usually calcium, and an anionic radical, PO_4, as well as a simple anion, usually fluorine, apatite is particularly susceptible to substitutions. Minor quantities of magnesium, manganese, strontium, lead, sodium, uranium, and the rare earths may substitute for calcium, and these and other substitutions largely explain the abundance of the minor metals found in many phosphorites, including those of the Concepción del Oro district. The presence of the carbonate may result by substitution of $CO_3\,OH$ for PO_4 (Palache, Berman, and Frondel, 1951, p. 882).

Many phosphatic samples collected in the Concepción del Oro district were analyzed semiquantitatively by spectrograph by the United States Bureau of Mines and the Geological Survey. Twenty-eight elements were identified in addition to those found in chemical analysis. All are present in minute quantities, and apparently all are too dilute to have commercial value. Table 5 summarizes spectrographic analyses of 30 samples, including 10 samples each of the calcareous phosphorite, phosphatic calcareous chert, and phosphatic limestone. The rarer elements show little variation in percentage in these different lithologic types. The table brings out several points, among which are the almost complete lack of potassium in the phosphate rocks and the relative abundance of lanthanum, strontium, and yttrium. Other spectrographic analyses, not included in the table, show that some phosphorite also contains the elements beryllium, cobalt, bismuth, columbium [niobium], niobium, and ytterbium.

Twelve samples of phosphate rock that were analyzed by radiation and chemical methods specifically for uranium ranged from less than 0.001 to 0.006 percent in equivalent uranium (eU). Uranium and the rare earths are present in the phosphate mineral and are therefore most abundant in the highest grade phosphorites. Zinc, nickel, and molybdenum probably also occur in part in the phosphate mineral, although they seem to be almost as abundant in the weakly phosphatic rocks as in the phosphorites.

TABLE 5.—*Results of spectrographic analyses of 30 samples of phosphate rock from the Concepción del Oro district*

[Analyses by P. R. Barnett and R. G. Havens, Geological Survey]

Element	Number of analyses with indicated range in percent					
	>10	1–10	0.1–1.0	0.01–0.1	0.001–0.01	0.0001–0.001
Si	11	19				
Al		3	27			
Fe		6	24			
Ti				26	4	
Mn				21	9	
P		30				
Ca	28	2				
Mg			23	7		
Na			3	25	2	
K			1			
Ag					3	20
B			1	1	11	4
Ba				16	14	
Cr				3	27	
Cu					26	4
Ga						2
La				10	11	1
Mo					2	8
Ni					28	2
Pb					5	3
Sc					6	13
Sn						5
Sr			8	22		
V				22	8	
Y				19	11	
Zn				18		
Zr					29	1

NOTE.—Looked for but not found: As, Au, Be, Bi, Cd, Ce, Co, Ge, In, Ir, Hf, Hg, Li, Nb, Os, Pd, Pt, Re, Ru, Sb, Sm, Ta, Te, Th, Tl, U, W.

Although sampling has shown that nearly all the La Caja formation is at least feebly phosphatic (table 1), by far the greatest concentration of phosphatic material is in unit C. In general, the grade of the rock decreases in inverse proportion to the thickness of the member. Where it is thick the phosphate is so dispersed that beds of commercial grade are lacking. Although the unit may range from less than 1 meter to 20 meters in thickness, the total phosphate present generally ranges only from 20 to 40 meters-percent (thickness in meters times percent of P_2O_5). The overall range within the area mapped, however, is from 10 to 70 meters-percent.

In the Sierra de Santa Rosa, which contains the only deposits with commercial possibilities, unit C ranges from 1.35 to 3.30 meters in thickness, and has an average thickness of 2.15 meters.

Outward from the Sierra de Santa Rosa, the phosphatic member thickens within a short distance, having a maximum thickness of about 20 meters in several places, and the phosphorites grade into a series of thin- to medium-bedded siltstones containing many lenses of phosphatic limestone. The siltstones are highly calcareous, and many are cherty as well. They are soft to moderately hard brown to grayish-brown rocks containing differing proportions of phosphate and are commonly interbedded with scattered thin layers of calcareous phosphorite. Such rocks rarely average more than 5 or 6 percent P_2O_5.

LITHOLOGY, PETROGRAPHY, AND CHEMICAL COMPOSITION

The phosphate deposits are predominantly chemical or biochemical sediments, containing very little detrital material. The lower part of the phosphatic member consists mainly of phosphatic calcareous chert, phosphatic cherty limestone, and cherty phosphorite; the upper part is calcareous phosphorite (fig. 20). Both parts contain many lenses of phosphatic limestone and locally may contain phosphatic siltstone.

The phosphate occurs mainly in small round to oval or irregular pellets, which are embedded in a matrix consisting of calcite, silica,

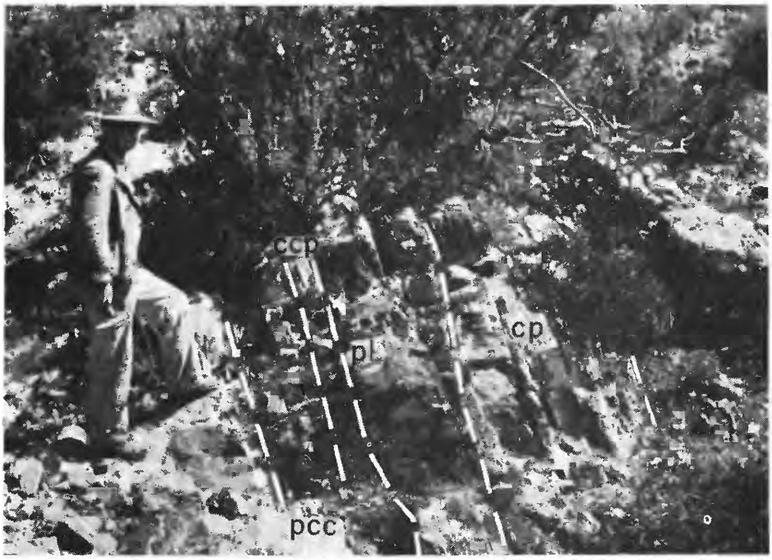

FIGURE 20.—Exposure of phosphatic unit of La Caja formation in Cañón de La Canela, Sierra de Santa Rosa. *cp*, calcareous phosphorite; *pl*, phosphatic limestone; *ccp*, cherty calcareous phosphorite; *pcc*, phosphatic calcareous chert.

and apatite. The silica has probably migrated in part from adjacent cherty sediments.

The principal lithologic types present in the phosphatic member and adjacent rocks are described in order of importance.

CALCAREOUS PHOSPHORITE

Calcareous phosphorite, which is the most abundant rock type in the phosphatic member, as well as the richest in P_2O_5, composes the upper section of unit C in the Sierra de Santa Rosa, where it reaches its greatest size. It has a maximum thickness of 1.25 meters and an average grade, within the reserve areas, of 21.1 percent P_2O_5. It disappears within a short distance to the east of Valle de Santa Rosa and diminishes to the north and south as well. In places on the south flank of the Sierra de La Caja it may appear in two or three beds rather widely separated by phosphatic siltstones and other rocks. Such layers have a maximum thickness of 85 centimeters, but in most places they range only from 10 to 25 centimeters. The calcareous phosphorite has not been seen farther to the north, and on the south it occurs only on the north flank of the Sierra de Santa Rita, where it reaches a maximum thickness of about 55 centimeters.

Most of the calcareous phosphorite is thick bedded to massive and moderately hard. It is medium dark reddish gray and has a strongly speckled appearance, owing to an abundance of light-pinkish or pinkish-white phosphate pellets, which are enclosed in a groundmass consisting mainly of very dark crystalline calcite. Secondary calcite commonly occurs in small veinlets, which may carry free fluorite. The rock has a strongly fetid odor when freshly broken.

In most places the rock is somewhat conglomeratic and contains small scattered fragments of phosphate rock darker than the host rock. These fragments may be sharply angular but are generally subangular to rounded or somewhat tabular in form, and, although they are easily visible on weathered surfaces, they are never conspicuous.

Petrographic study reveals that the rock consists mainly of small apatite pellets or replacement oolites embedded in a coarsely crystalline calcite matrix (figs. 21, 22, and 23). The pellets are well sorted and range from 0.1 to 1.0 millimeter in diameter, although they are generally not much larger than 0.5 millimeter. Many are wholly or partly replaced by calcite or chert, or both. This replacement was apparently followed by redeposition of apatite as matrix material and, in many places, as concentric laminations on the pellets, giving them an oolitic appearance. Many pellets have a rounded or oval form, but some are irregular, and they are lacking in nuclear impurities. The apatite is brown massive cryptocrystalline material, which is almost uniformly isotropic. The brown color may be due to the inclusion of organic matter. The chert seems to be present almost wholly as a replacement of apatite and may have migrated from the adjacent sediments, where it is relatively abundant. The rock is extensively fractured, and in thin sections many minute fractures were filled with secondary calcite.

The rock fragments were found to have the same constituents as the host rock, although generally in widely different proportions. They are mainly a fairly intimate mixture of apatite, calcite, and chert, although apatite is predominant. They contain fewer pellets than the host rock. They may be well defined, but in many places they have indefinite outlines and appear to merge gradually into the matrix, owing apparently to the movement and redeposition of apatite and other minerals. Some are partly rimmed by calcite or by a sheath of secondary apatite. Probably many of these fragments are

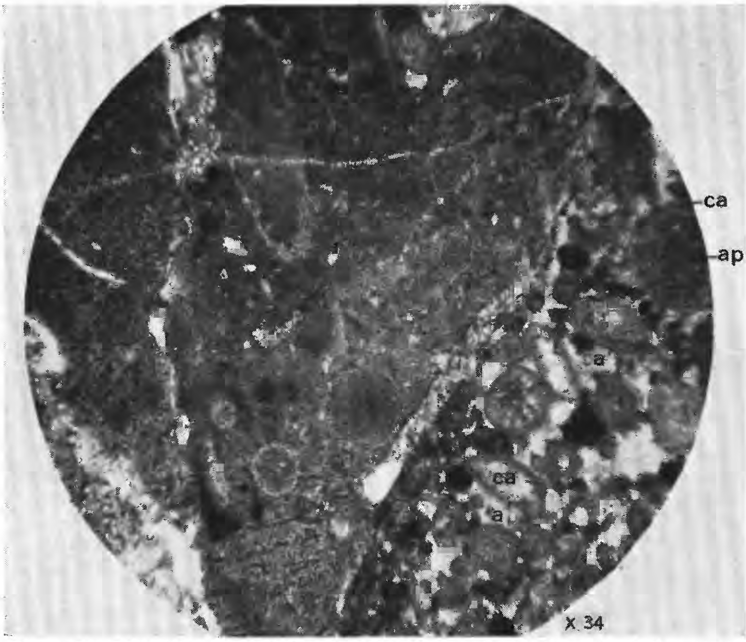

FIGURE 21.—Photomicrograph of calcareous phosphorite. A part of a large rock fragment or nodule can be seen on the left. The fragment contains a few apatite pellets but is composed mainly of massive apatite, with minor calcite and chert. The remainder of the picture shows round to oval apatite pellets in a coarsely crystalline calcite matrix. Some of the pellets exhibit replacement by calcite, *ca*, or secondary apatite, *ap*.

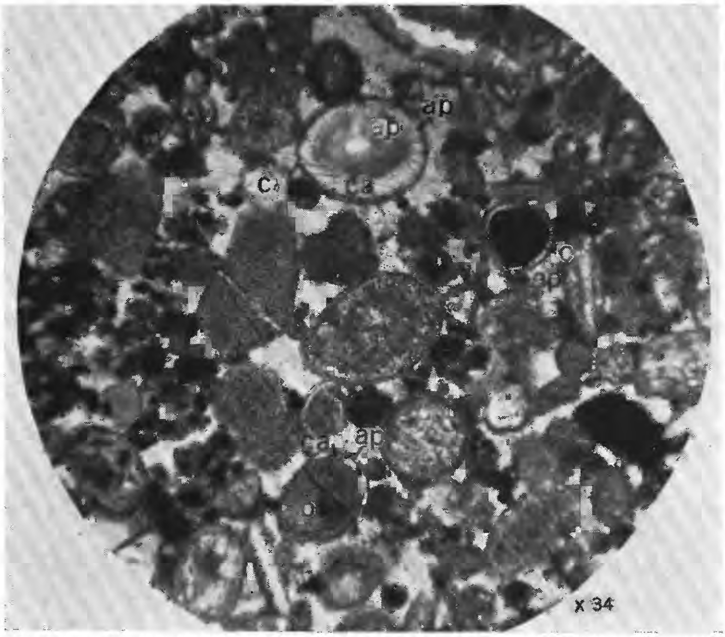

FIGURE 22.—Photomicrograph of calcareous phosphorite. Apatite (*ap*) pellets in a matrix which is predominantly calcite but contains a considerable amount of massive apatite. The pellets show replacement by calcite, *ca*, chert, *c*, and secondary apatite, *ap*.

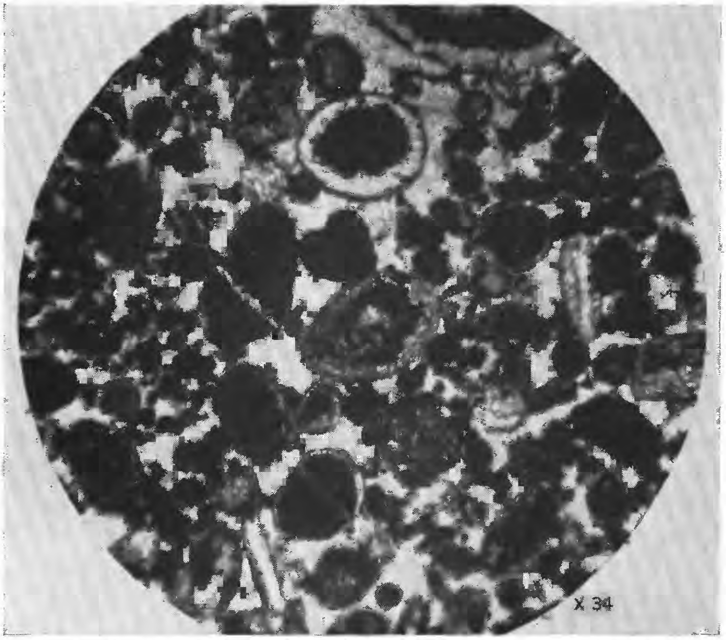

FIGURE 23.—Photomicrograph of calcareous phosphorite. Like figure 22, but with crossed nicols. The apatite is dark under crossed nicols.

nodules that, in varying degrees, have been transported and subjected to abrasion.

The calcareous phosphorite contains fairly abundant ostracodes and some Foraminifera (Globigerinids?),[7] which are generally phosphatized. None could be identified specifically.

The chemical composition of the calcareous phosphorite is shown in table 6. These and other analyses indicate that the principal mineral constituents of the calcareous phosphorite may have the average percents given below. No detrital minerals, except very minor quartz, were recognized in the thin sections.

Apatite	54. 8
Calcite	33. 1
Chert	10. 5
Miscellaneous material	1. 6
Total	100. 0

In the area immediately east of the dacite intrusive body of Las Parroquias the phosphatic member contains a calcareous phosphorite not found elsewhere. It occurs in two layers totaling 77 centimeters in thickness, separated by a lens of phosphatic limestone. The layers are composed of a soft to moderately hard, thin- to medium-bedded,

[7] The calcareous phosphorite and other phosphatic rocks were examined for microfossils by C. Téllez-Girón de A. and A. Ayala of Petróleos Mexicanos, and by Ruth Todd of the U. S. Geological Survey.

light- to medium-gray rock having a strongly speckled appearance and containing an abundance of gray to black apatite pellets in a light-colored highly calcareous groundmass. Petrographic study reveals that the rock consists of light-gray oval to ellipsoidal apatite pellets in a calcite and chert matrix. The pellets are well sorted in some beds and poorly sorted in others. They have a size range of 0.05 to 0.8 millimeter and an average diameter of about 0.3 millimeter. They differ from the pellets in the usual calcareous phosphorite, which overlies this rock, in their pale-gray color, which perhaps indicates a low organic content, and in their lack of concentric laminations. The pellets are discrete, and there is relatively little evidence of alteration in the thin sections, although a few of the pellets have been partly or wholly replaced by calcite or chert. The matrix is a mixture of carbonate and chert, which occur in varying proportions in different beds. Some fossil material is present and is largely replaced by apatite. One thin section contains rotaliform Foraminifera, in addition to the usual megafossils. The rock has an average grade of 24.7 percent P_2O_5 and an average acid-insoluble content of 29.0 percent. The grade falls off very rapidly toward the east, and the rock is transitional to a phosphatic calcareous siltstone. Only 800 meters to the east it has a total thickness of 1.52 meters and an average grade of 14.9 percent P_2O_5.

TABLE 6.—*Partial chemical analyses of five samples of calcareous phosphorite from the Sierra de Santa Rosa*

[U. S. Geological Survey analyses by Guttag, Caemmerer, Barlow, Rowe, and Tucker; reported June 13, 1951]

Sample no.	Laboratory no.	Stratigraphic thickness (meters)	P_2O_5	CaO	CO_2	Acid insoluble	F	Al_2O_3	Fe_2O_3	V_2O_5
PR5-1	36970	1.25	19.7	47.50	14.92	15.5	2.06	1.10	0.35	0.01
PR9-2	36999	1.10	22.7	47.50	14.30	10.2	2.26	1.10	.40	.01
PR14-1	37042	1.05	21.1	48.75	17.84	6.6	2.25	.67	.23	.02
PR30-4	51280	.90	20.1	48.25	16.86	9.8	2.01	.67	.46	.02
PR33-3	51292	.90	20.9	48.75	14.20	11.6	2.28	.86	.58	.03

CHERTY CALCAREOUS PHOSPHORITE

The cherty calcareous phosphorite is limited mainly to the south flank of the Sierra de Santa Rosa. On the east it disappears beyond Valle de Santa Rosa, and on the west it lenses out in the upper part of Cañón de Los Mimbres. It has a thickness ranging from 16 to 40 centimeters, averaging 25 centimeters, and has an average grade of 20.1 percent P_2O_5.

The rock is medium dark reddish gray to dark reddish black and obviously siliceous. No bedding is discernible, but the rock parts easily along irregular closely spaced planes which are roughly parallel with bedding in the adjacent sediments. It is hard and only moderately fetid. It contains an abundance of black pellets and fossil remains in a lighter colored groundmass.

Petrographic study shows that the rock is composed of brown apatite pellets, fragments of phosphate rock or nodules, and phosphatized fossil remains in a matrix consisting mainly of cryptocrystalline isotropic chert with subordinate calcite (fig. 24). The pellets are oval to ellipsoidal and poorly sorted. In sections examined they range from 0.05 to 0.9 millimeter in diameter and average about 0.25 milli-

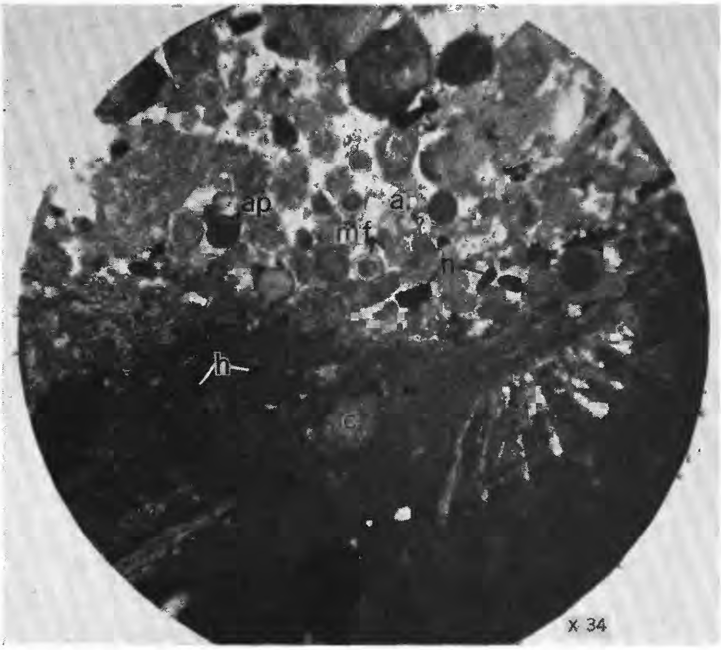

FIGURE 24.—Photomicrograph of cherty calcareous phosphorite. A part of a rock fragment or nodule can be seen in the lower part of the photograph. The fragment is composed of a few apatite pellets, one chert, *c*, pellet and a fossil fragment, *f*, in a matrix of massive apatite. The groundmass is composed of apatite, *ap*, pellets and several phosphatized microfossils, *mf*, in a predominantly chert matrix. Small hematite, *h*, grains are visible in both the rock fragment and groundmass.

meter. Like the calcareous phosphorite, this rock is slightly conglomeratic. The foreign fragments are small and scattered, however, and are very inconspicuous except under magnification. They are subrounded to rather angular, and some are composed essentially of apatite and chert pellets cemented by brown finely crystalline apatite. Others contain little or no pelletal material, but may be composed of rather intimate mixtures of apatite, calcite, and chert. These constituents occur in varying proportions, but apatite is generally greatly predominant. Reddish iron-oxide fragments are in many places associated with the cementing material in the rock fragments, but they are also fairly abundant in the rock matrix.

The rock contains many fossils largely replaced by apatite. They are mainly small pelecypods, but the rock includes a number of cerithioid gastropods. Microfossil study reveals an abundance of Radiolaria, which are altered and cannot be identified specifically.

A partial chemical analysis of one sample of cherty calcareous phosphorite is given in table 7. This and many additional analyses for phosphorous pentoxide and acid insoluble indicate that the principal mineral constituents of this rock may form the average percents given below. No detrital material was recognized in thin sections.

Apatite	52
Chert	27
Calcite	18
Miscellaneous material	3
Total	100

PHOSPHATIC CHERTY LIMESTONE

The phosphatic cherty limestone can be traced along the southern flank of the Sierra de Santa Rosa for about 9 kilometers. It does not occur to the east of Valle de Santa Rosa, and on the west it lenses out in the lower part of Cañón de La Canela. It has a thickness

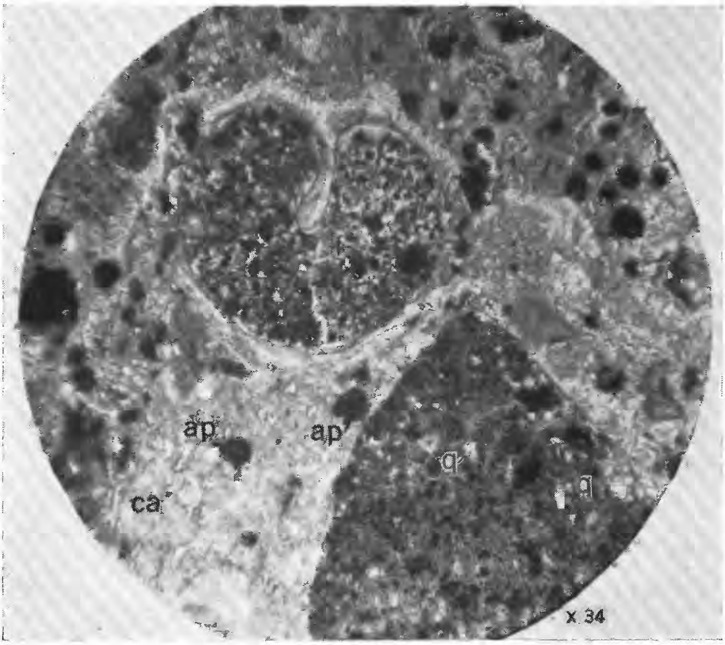

FIGURE 25.—Photomicrograph of phosphatic cherty limestone. A partially phosphatized fossil, *f*, and a part of a rock fragment or nodule appear in a groundmass containing scattered apatite, *ap*, pellets in a rather intimate mixture of calcite, *ca*, and apatite, with the calcite predominating. The rock fragment or nodule is mainly massive apatite, with some calcite and scattered small detrital quartz, *q*, grains.

ranging from 10 to 25 centimeters and averaging about 17 centimeters, and has an average grade of 14.0 percent P_2O_5.

The rock is medium gray with reddish or brownish tints. It is soft to moderately hard and is generally easily broken with a hammer. It contains an abundance of black pellets and fossil material in a lighter colored groundmass and is moderately fetid.

Petrographic study shows the rock to consist of dark-brown apatite, small oval apatite pellets, fossil remains, and irregular rock fragments or nodules, all cemented by a mixture of crystalline calcite, chert, and light-brown apatite (fig. 25). The rock fragments are composed of phosphate pellets and detrital quartz grains in an apatite matrix. The fossils are generally phosphatized, but some are partly replaced by calcite, and some are partly replaced by secondary silica, commonly as feathery fringes.

No microfossils were found in the specimens studied, although megafossils are abundant, consisting mainly of small cerithioid gastropods and small pelecypods. Fish and reptile remains also occur in this rock.

Analyses indicate that the principal mineral constituents of the phosphatic cherty limestone may form the average percents given below. The quartz occurs in part as detrital material, but mainly as secondary chert, which may have migrated from the adjacent sediments.

Calcite	38
Apatite	36
Quartz	24
Miscellaneous material	2
Total	100

TABLE 7.—*Partial chemical analyses of phosphatic rock from the Sierra de Santa Rosa*

[U. S. Geological Survey analyses by Guttag, Caemmerer, Barlow, Rowe, and Tucker, reported June 13, 1951]

Rock type	Sample no.	Laboratory no.	Stratigraphic thickness (meters)	P_2O_5	CaO	CO_2	Acid insoluble	F	Al_2O_3	Fe_2O_3	V_2O_5
Cherty calcareous phosphorite	PR4-7	33434	0.28	22.5	39.75	7.22	24.0	2.14	1.90	1.29	0.03
Phosphatic calcareous chert	PR16-4	37067	1.10	8.4	27.50	13.14	47.3	.82	1.60	1.19	.01
Phosphatic limestone	PR9-3	37000	.20	5.1	50.25	35.18	6.9	.50	.64	.24	.01
Phosphatic limestone	PR4-8	33435	.60	11.5	42.25	21.28	18.4	1.21	1.70	1.38	.02
Phosphatic calcareous siltstone	PR25-7	51249	.40	10.4	29.25	13.38	38.3	1.12	2.20	.74	.06
Phosphatic calcareous siltstone	PR4-6	33433	.20	17.4	31.25	6.46	32.3	1.55	4.90	2.27	.15

PHOSPHATIC CALCAREOUS CHERT

Phosphatic calcareous chert occurs mainly in the Sierra de Santa Rosa. It disappears to the east of Valle de Santa Rosa, but on the west it can be traced to the end of the range. A similar rock is found on the southern flank of the Sierra de La Caja and on the northern flank of the Sierra de Santa Rita, but it forms relatively thin layers and is clearly transitional to other rock types. It ranges in thickness

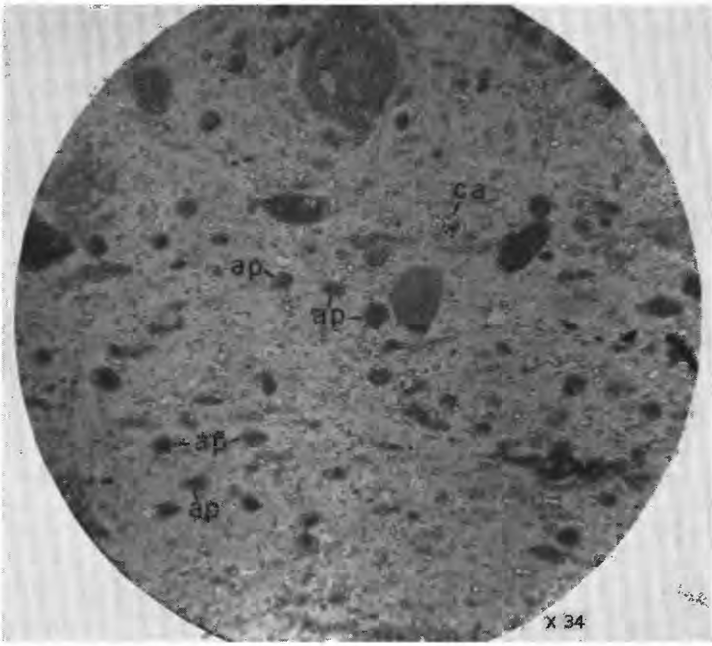

FIGURE 26.—Photomicrograph of phosphatic calcareous chert. Scattered, irregular apatite, *ap*, pellets in a matrix of calcite and isotropic chert. Several apatite pellets have been replaced by calcite, *ca*.

from a few centimeters to 1.68 meters and has an average grade of about 12.5 percent P_2O_5.

The rock is medium bedded to massive and is medium gray, although much of it exhibits slight reddish or brownish tints. It is hard to brittle and moderately fetid when struck with a hammer. It contains an abundance of black pellets and many black phosphatized fossils, which are enclosed in a hard, gray matrix. In general, the rock becomes increasingly phosphatic and calcareous, and less siliceous, from the base upward. It contains many short lenses of phosphatic limestone, particularly in the lower part of the zone.

Petrographic study reveals that the rock is composed of small pellets, fossil remains, and phosphatic rock fragments or nodules in a matrix of chert and calcite (fig. 26). The pellets are oval to irregular and are poorly sorted. They have a size range from 0.05 to 0.7

millimeter and average about 0.2 millimeter. They consist mainly of dark-brown apatite, but some have been extensively replaced by chert. The fossils are replaced by brown apatite, and in a few places by chert. The rock fragments or nodules are small, scattered, and rounded to subangular. They are inconspicuous except in thin sections and resemble the fragments found in the cherty calcareous phosphorite. Some consist of phosphate pellets cemented by finely crystalline apatite, but others contain little pelletal material and may have variable proportions of chert and calcite intimately mixed with the apatite. The matrix of the phosphatic calcareous chert is predominantly a light-brown to colorless cryptocrystalline chert, which is generally isotropic but may be anisotropic. Crystalline calcite is common but rather variable in proportion. A small quantity of detrital quartz was seen in the matrix in one thin section.

The silica in the cherty calcareous phosphorite and phosphatic calcareous chert may be primary in origin, but to some extent it has migrated within these layers and has been redeposited, for it is found replacing the apatite pellets, and less commonly the fossils. Perhaps it has migrated also to adjacent layers of calcareous phosphorite and phosphatic limestone.

The faunal assemblage in the phosphatic calcareous chert appears to be similar to that in the cherty calcareous phosphorite, including fairly numerous small pelecypods and small cerithioid gastropods. Radiolaria are also present but cannot be identified specifically.

A partial chemical analysis of one sample of phosphatic calcareous chert is given in table 7. This analysis and many additional analyses for P_2O_5 and acid insoluble indicate that the principal mineral constituents of the rock may form the following average percents.

Quartz	45. 0
Apatite	32. 5
Calcite	19. 5
Miscellaneous material	3. 0
Total	100. 0

PHOSPHATIC LIMESTONE

Phosphatic limestone occurs abundantly throughout the area mapped and in the surrounding region as well. It may be found in any part of the phosphatic member and is commonly present in the cherty beds forming the upper section of unit B. It is a medium-dark to dark-gray or reddish-gray phosphatic limestone, which develops a characteristically smooth light-gray or bluish-gray weathered surface. In many places it forms short, relatively thick lenses, and in some localities these develop into fairly persistent beds, which are commonly characterized by pinching and swelling. The beds range from a few centimeters to more than a meter in thickness.

The phosphatic limestone has the lowest phosphate content of all the rock types within the phosphatic member, and, unlike the other rocks, the lenses and beds of phosphatic limestone may have great differences in the total phosphate present. The phosphate content not only differs from one bed to the next, but also laterally within a

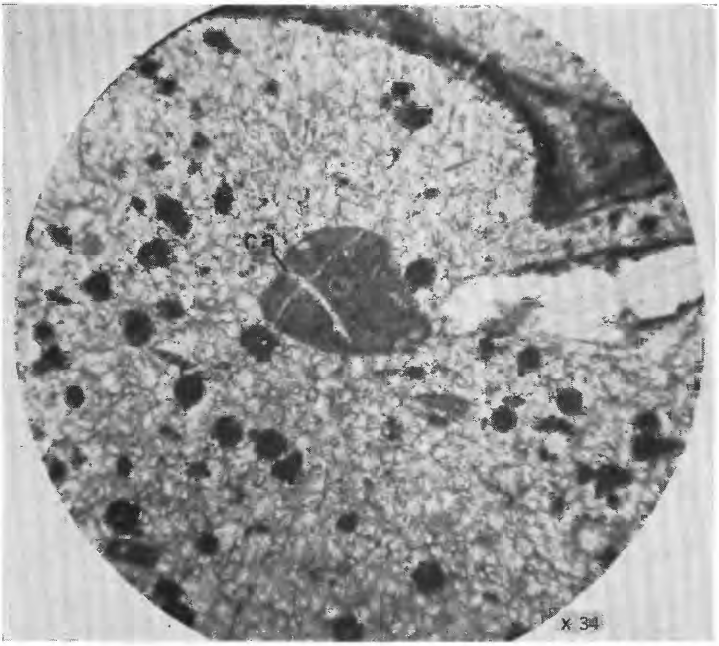

FIGURE 27.—Photomicrograph of phosphatic limestone. Small round apatite pellets in a finely crystalline calcite matrix. The small rounded rock fragment or nodule near the center is largely massive apatite, which is cut by a calcite, *ca*, veinlet.

given bed. The phosphatic limestone is the most strongly fetid rock in the phosphatic member.

Petrographically, the rock is a finely crystalline limestone containing scattered small apatite pellets, a little chert, and a minor proportion of detrital quartz fragments (fig. 27). The apatite ranges from pale brown to almost black. Many pellets have been replaced by calcite.

The rock contains many fossils replaced by apatite. None of the microfossils could be identified specifically, but they are largely Radiolaria. Small cerithioid gastropods are present in some beds.

Partial chemical analyses of two samples of the phosphatic limestone are given in table 7. The acid insoluble is mainly silica and is present partly as detrital quartz and partly as secondary chert which may have migrated from adjacent cherty rocks.

PHOSPHATIC CALCAREOUS SILTSTONE

Although the phosphatic member in the Sierra de Santa Rosa is almost wholly composed of the five lithologic types described above, phosphatic calcareous siltstone may be interbedded with them locally. This rock is not markedly different in appearance from other siltstones in the formation, except that it is relatively rich in apatite pellets and may contain a few thin beds of calcareous phosphorite.

Partial chemical analyses of two samples of phosphatic calcareous siltstone are given in table 7. Sample PR25–7 represents a layer 40 centimeters thick of a moderately hard, thin- to medium-bedded, grayish-brown phosphatic calcareous siltstone containing scattered thin beds of calcareous phosphorite. Sample PR4–6 represents a layer 20 centimeters thick which lies between a lens of phosphatic limestone and a layer of cherty calcareous phosphorite. It is a soft, brownish, predominantly thin-bedded, phosphatic calcareous siltstone. Both samples are noticeably higher in vanadium content than the phosphorites and phosphatic cherts. They are also higher in content of alumina and iron oxide.

PHOSPHATIC ROCKS ADJACENT TO PHOSPHATIC MEMBER

In the Sierra de Santa Rosa the calcareous siltstones immediately overlying the phosphatic member have been sampled in a few localities and were found to be weakly to moderately phosphatic. Nowhere are they sufficiently rich to have commercial possibilities, however. They grade upward into normal siltstones containing little more than a trace of phosphatic material.

The upper section of unit B, which underlies the phosphatic member, also contains many phosphatic layers, of which only a few were sampled, as they are too thin and too low in grade to be exploited. They differ in lithologic character and include phosphatic cherts, phosphatic calcareous cherts, phosphatic limestones, phosphatic siltstones, and a few thin calcareous phosphorites. Some of the phosphorites are highly conglomeratic. One conglomeratic bed was examined petrographically and was found to be composed of large brown phosphatic rock fragments in a matrix of apatite and calcite. The rock fragments are phosphatic limestone composed of poorly sorted apatite pellets, fragmental pellets, and fossil remains in a cement of coarsely crystalline calcite. A few of the pellets are replaced by chert. The rock matrix is composed of massive brown secondary apatite and coarsely crystalline calcite, with abundant apatite pellets and fossil remains disseminated throughout. Small quantities of chert and brown iron oxide are also present in the matrix. The rock was examined for microfossils and may contain rotaliform and agglutinated Foraminifera and globigerinids, although none could be identified generically.

ORIGIN

The outstanding work of recent years on the formation of marine phosphorites has been that of Kazakov (1937, 1950), who has discarded the traditional theory of biolith-diagenetic origin and substituted the hypothesis that phosphate is chemically precipitated from sea water. The deep waters of the ocean basins contain an enormous store of phosphate, and he believes that where these waters well up onto the continental slopes, the phosphate may be precipitated by an increase in the pH of the ascending waters as the temperature increases and the partial pressure of carbon dioxide decreases. He states that calcium carbonate reaches the saturation point first and is precipitated, and this is followed by simultaneous precipitation of calcium carbonate and calcium phosphate. He believes that phosphate is formed between depths of 50 and 200 meters. It is not precipitated in shallower waters, where most of the available phosphorus is utilized by the planktonic population, and conditions of supersaturation are not attained at depths greater than 200 meters.

Kazakov's theory has been accepted in large part by McKelvey (McKelvey, Swanson, and Sheldon, 1953) and other geologists of the U. S. Geological Survey working on the Phosphoria formation of the Northwestern United States, and, with some important modifications, it has been used by them to explain the origin of those deposits. McKelvey and his associates made the following three modifications of his theory. First, the solubility curves of apatite and carbonate overlap but do not coincide precisely, so that either apatite or carbonate may be precipitated independently. Also, apatite is generally precipitated at a lower pH and temperature than is calcium carbonate, rather than the reverse as indicated by Kazakov. Second, phosphorites are not completely a product of chemical precipitation, but a significant amount of phosphate is probably derived through the decay of organic matter. When sea water is essentially saturated with phosphate, the phosphate derived from decaying ogranisms is not resorbed by the water and probably accumulates with the bottom sediment. And third, the depths at which phosphate is being deposited on the present sea bottom (Dietz, Emery, and Shepard, 1942) suggest that the zone of phosphorite formation may lie between 200 and 1,000 meters, rather than in the shallower area described by Kazakov.

Marine phosphorites include two major facies: the platform deposits, which are associated mainly with limestone and glauconitic sandstone, and the geosynclinal deposits, which are associated mainly with chert, black carbonaceous shale, and smaller quantities of limestone.

McKelvey and his associates have pointed out that in the geosynclines, areas of bedded chert correspond fairly closely to the areas in which phosphorites are found, a point that was overlooked by Kazakov. The significance of the chert and phosphorite relationship is still unknown, although some important information may be furnished by studies now under way. Facies relationships in the Phosphoria formation suggest that the chert may have formed by diagenetic recrystallization of silt-sized quartz, which is most abundant in a zone intermediate between nearshore sandy detritus and deepwater argillaceous detritus. Yet, the silica may have been precipitated directly from sea water, owing to the physicochemical environment, or precipitation from sea water may have been brought about by organisms.

Calcium phosphate probably accumulates very slowly on the sea floor, and the formation of phosphorites is dependent upon a slow rate of deposition of clastic sediments and the inhibiting of other chemical precipitates, such as calcium carbonate, by the physicochemical environment. Clastic material may be scarce owing to distance from the shoreline, or to the low elevation or arid climate of the adjacent land masses, or because some areas are not reached by silt-bearing currents.

Kazakov's theory may apply equally well to most other major areas of marine phosphorites, although it is not yet widely known or accepted. The present writers believe that this theory, with some of the modifications suggested by McKelvey and others, may also apply to the Mexican deposits. Since their knowledge of the Mexican phosphorites is limited to a small area of several thousand square kilometers, it is impossible to test adequately many of Kazakov's ideas. A reconnaissance study is recommended of the phosphatic facies of the La Caja formation in a broad area extending from the longitude of Torréon, Coahuila, on the west, to Monterrey and Linares, Nuevo León, on the east. This study should reveal to what extent those ideas are applicable to the Mexican phosphates.

The Mexican phosphorites are a geosynclinal facies, and in the Concepción del Oro district they are associated mainly with highly calcareous siltstone and chert, containing some limestone. This suggests that higher grade deposits might be found in areas of lower lime content, where the terrigenous material is finer and accumulated more slowly, and this idea should be thoroughly tested. It is interesting that the Concepción del Oro deposits, like many similar deposits, are accompanied by a cherty facies, which is in large part coextensive with the richest phosphorite beds.

At the present time the writers would disagree with Kasakov and McKelvey in only one important respect. There is abundant evidence that the Mexican deposits were formed in shallow waters rather than in the zone lying between 50 and 200 meters as suggested by Kazakov, or in the still-deeper zone proposed by the Geological

Survey geologists. McKelvey [8] agrees, however, that the depth of water is still an open question, and he points out that many of the phosphorites in other parts of the world show signs of shallow-water deposition.

In the Concepción del Oro area the La Caja formation was apparently deposited on an uneven surface, as previously suggested (p. 63 and fig. 19), and the sea bottom may have been characterized by a series of gentle valleys and ridges, which were perhaps the product of minor tectonic movements related to the Nevadan orogeny. The ridges must have had low relief, and a few may have emerged to form relatively small low islands. No direct evidence for the existence of islands can be presented, as no erosional unconformities have been found within the area mapped. Good exposures of the beds of Kimmeridgian and Portlandian ages are generally rare, however, and local unconformities might well exist. Two lines of evidence suggest the presence of islands during deposition of the beds. One of the large limestone concretions in unit A has yielded a fragment of fossil wood, and one of the phosphorite beds in unit C has yielded bone fragments that were probably derived from a terrestrial rather than a marine reptile. As the Concepción del Oro area must have lain 100 kilometers to the south of the mainland during Kimmeridgian and Portlandian time, it is difficult to see how the presence of plant and land-reptile remains could be explained except by islands.

Imlay reports that in the Sierras de Parras, Atajo, and Jimulco, which lie to the north and northwest of the area mapped, the Upper Jurassic sediments contain abundant gypsiferous and carbonaceous beds, which imply lagoonal conditions and, therefore, some sort of barrier to the south. Perhaps such a barrier was furnished by the type of submarine topography here described.

The writers' fossil collections from the phosphatic member have been studied by Imlay, and his opinions on the ecology provide valuable information regarding the conditions under which the phosphorites must have been deposited.

The phosphatic material contains representatives of a great variety of free-swimming and benthonic organisms (see p. 23). Free-swimming forms include ammonites, belemnites, and fish, the fish represented by vertebrae and perhaps also by fragments of teeth and bone. The benthonic forms include various pelecypods, brachiopods, gastropods, worms, and many irregular worm tubes. The shells of all the free-swimming organisms are broken or smashed; whereas the shells of most of the benthonic organisms are entire and undeformed.

The pelecypods and the cap-shaped gastropods indicate a firm substratum and shallow agitated marine waters. The absence of such burrowing pelecypods as *Pleuromya* and *Trigonia* is also evidence,

[8] Written communication.

even though indirect, of a firm sea bottom. *Grammatodon* in the western interior of the United States and in Alaska is generally associated with thin beds of limestone or sandstone in a softer claystone or siltstone sequence. *Aucella* is most abundant associated with conglomerate, sandstone, or thin limestone. Its occurrence in limestone is as a coquina in a mass of siltstone, and some of the Aucellas in conglomerate and sandstone appear to have been reworked by wave action in much the same manner as pebbles. The cap-shaped gastropods, by comparison with similar living genera, indicate shallow much-agitated waters. The presence of many broken or smashed remnants of swimming organisms, including fish, also suggests agitated water and slow deposition.

Some of the phosphatic beds contain a host of rather minute gastropods and pelecypods, which the authors originally believed to be strongly suggestive of a dwarf fauna. However, this assemblage has been studied by Imlay, who describes it as containing an abundance of tiny immature forms. The mature pelecypods are normal in size, and the mature gastropods, consisting of cap-shaped varieties and various high-spired gastropods, including specimens of the family Cerithidae as well as smooth species, although very small, are also normal in size. The abundance of immature forms suggests that there was little, if any, winnowing action by currents. The presence of many cerithioid gastropods is indicative of clear waters and, therefore, a scarcity of clayey material.

Although the phosphatic sediments must have been formed in shallow waters, the complete absence of *Gryphaea* and *Exogyra* from these beds and their abundance elsewhere in the nearshore deposits of the Mexican sea suggests either that the phosphatic sediments were formed below the shallowest part of the neritic zone or that there was some factor which inhibited the growth of these oysters in areas where phosphate was being formed.

Deposition of the phosphatic beds in central Mexico appears to have been extremely slow, if their relatively slight thickness is compared with equivalent beds in the gulf region of the United States or in Cuba or California. The presence of many fossils in such thin strata is not good evidence that there was an abundance of life at any one time that might have completely utilized the phosphatic material in the sea water. Such an abundance of fossils merely proves that conditions were favorable for the preservation of fossils.

An interesting faunal relationship that may bear on the origin of the phosphate is the presence of the pelecypod *Aucella* and the absence of the gastropod *Nerinea* in the phosphorite beds. It is well known that *Nerinea* was characteristic of reefs and reeflike deposits of the Mediterranean region during Late Jurassic and Early Cretaceous time and that *Aucella* was characteristic of littoral and shallow-water deposits of the Boreal region during Late Jurassic and early Neocomian time. During those times *Aucella* rarely ranged south of central Europe and California and *Nerinea* rarely ranged north of about the same latitudes. Therefore, the occurrence of *Aucella* at two levels in the beds of Kimmeridgian to Portlandian ages in Mexico and the scarcity of *Nerinea* (except in the Kimmeridgian of the Malone Mountains of Texas) in beds above the Oxfordian in Mexico, might be construed as evidence that the waters of the Mexican sea were cooler during Kimmeridgian to Portlandian times than they had been earlier in the Jurassic.

As described in the foregoing pages, many of the phosphatic beds, particularly the calcareous phosphorite forming the upper part of unit C, are somewhat conglomeratic and contain small rounded to angular rock fragments or reworked nodules which may contain essentially the same constituents as the host rock but are clearly foreign in origin. This feature would appear to support the paleontological evidence and to indicate deposition of the phosphorites in shallow agitated waters. The sediments accumulating on the sea bottom must have been subjected to strong wave action and perhaps at times were actually exposed to the air.

It seems evident then, that the phosphate beds were deposited extremely slowly in shallow clear waters that may have been slightly deeper than the shallowest part of the neritic zone. There was probably considerable wave action but little current action. The life on the sea bottom where the phosphorite was forming includes genera that prefer or tolerate a firm substratum and probably were not abundant at any one time.

The concentration of phosphate in the Concepción del Oro district seems to be related more to nondeposition of clastic material than to any other factor. Perhaps the site of the Sierra de Santa Rosa, where the concentration is greatest, remained above wave base longer than the surrounding areas, and for that reason received less silty material.

RESERVES

The phosphatic member of the La Caja formation was sampled in 73 localities within the area mapped, and also in several adjacent areas which will be reported in future studies. In addition, other parts of the formation, particularly the sections immediately underlying and overlying the phosphatic member, were sampled in several localities, and in one area in the Sierra de Santa Rosa the full thickness of the formation was tested. The sample localities are not evenly spaced, as only natural exposures of the phosphatic rocks were utilized, and the material taken consisted of chip samples, as the extreme hardness of the cherty rocks and the moderate hardness of some of the other rock types make channel sampling difficult. The sample localities and sampling results are shown in plate 2. The analyses were made by the United States Bureau of Mines in its laboratories at Albany, Oreg., and by the United States Geological Survey in its laboratories at Washington, D. C.

Deposits of possible commercial value are limited to five areas in the Sierra de Santa Rosa (pl. 2), and the discussion of reserves that follows is therefore limited to those areas.

Computing reserves is a simple matter, and the results obtained are believed to be reliable, for, with the exception of the phosphatic limestone, individual beds within the phosphatic member are consistent in thickness and grade for fairly long distances. In calculating the tonnages, each sample locality was considered the center of a block. The volumes were obtained by multiplying the length of the block by the average width by a depth of 150 meters downdip, and the resulting figures were converted to metric tons by multiplying by the average specific gravity of the rock composing the block. The authors do not know whether it would be feasible to mine the phosphatic zone commercially to an average depth of 150 meters down the dip, and hence that figure must be considered as arbitrary until a study is made of mining conditions and costs. Specific gravities of the principal lithologic types occurring in the phosphatic member were determined in the laboratories of the Instituto Nacional para la Investigación de Recursos Minerales. The average specific gravity of the phosphatic member was found to be 2.64.

Until beneficiation or metallurgical tests have been made of the phosphate rock of the Concepción del Oro district, and a detailed analysis has been made of the costs involved in mining, processing, and marketing the rock, it is impossible to determine what the cutoff grade would be. For this reason, the reserves have been estimated in three ways. First, the full thickness of the phosphatic member was used in the calculations; this gave a total of 13,505,000 metric tons averaging 16.2 percent P_2O_5 or 35.3 percent tricalcium phosphate. Next, it was assumed that the full thickness of the phosphatic member would be mined, but that the lenses and beds of phosphatic limestone would be discarded as waste. This gave a total of 11,043,000 metric tons of rock averaging 18.3 percent P_2O_5 or 39.9 percent tricalcium phosphate. Finally, it was assumed that only the calcareous phosphorite would be mined and that 90 centimeters would be considered a minimum mining width. This gave a total of 5,036,000 metric tons of rock averaging 21.1 percent P_2O_5 or 46.0 percent tricalcium phosphate. Although the calcareous phosphorite has an average thickness of 90 centimeters or more in the reserve areas, in some localities the thickness may fall a few centimeters under the minimum, and this might require the mine operator to take a small amount of wall rock. He would have to determine whether to take the hard phosphatic limestone underlying the phosphorite or the comparatively soft phosphatic siltstone overlying it. Possibly these materials could be included with the calcareous phosphorite without unduly diluting it.

The reserves data and the areas mentioned are given on the map in plate 2 (see also fig. 16). Area 1 is located in Cañón del Aire on the north flank of the range and is easily accessible by a broad trail from Mazapil which can be negotiated by trucks. The block ends on the west against a small graben structure containing Mazapil conglomerate, and on the east it ends at a dacite intrusive body.

Area 2 lies to the south of the large dacite intrusive body of Las Parroquias. It can be reached by a trail from Mazapil or by a trail from Valle de Santa Rosa, but most of the area is not easily accessible. The block ends against a segment of the dacite intrusive body on the west, and it is also cut out by the dacite on the east. Area 3 is a small block in the Puerto Blanco area, which is crossed by the trail leading from Santa Rosa to Mazapil. On the west it ends against the dacite of Las Parroquias, and it is limited on the east by low proportion of phosphate in the rocks. Area 4 occupies the upper part of Cañón de Los Mimbres and the lower part of Cañón de La Canela; it is easily accessible by the trails leading from Santa Gertrudis to Mazapil. It is limited on the west by low proportion of phosphate in the rocks and ends on the east against a dacite sill. Area 5 is the largest block, having a length of about 6.35 kilometers. It terminates on the west against a dacite sill and on the east against the fault bounding Valle de Santa Rosa, which is underlain by altered agglomerate(?). On the west it can be reached by the trail that follows Cañón de La Canela, and on the east it is easily reached from Valle de Santa Rosa or by the Chorreadero trail. The central part of the area, however, lies at a high altitude and is rather inaccessible.

POSSIBLE UTILIZATION OF PHOSPHATE ROCK

In the phosphate industry, phosphate rock is usually graded according to B. P. L. (bone phosphate of lime), the content of tricalcium phosphate ($Ca_3(PO_4)_2$). In the areas in the Sierra de Santa Rosa for which reserves have been estimated, the B. P. L. content of the phosphatic member averages about 35 percent, and the content of the calcareous phosphorite averages about 46 percent; whereas the grades of marketable phosphate rock in the United States range from 66 to 77 percent B. P. L. Some deposits, such as those of the soft unindurated Pliocene Bone Valley formation in Florida, are beneficiated to this grade by washing and flotation. As beneficiation or metallurgical tests have not been made of the hard phosphate rock of the Concepción del Oro district, it is not known whether the rock can be concentrated for the manufacture of superphosphate, but it seems unlikely that beneficiation will be feasible at low cost.

There would be no difficulty with a high iron and alumina content of the rock. Most phosphate rock is sold with a maximum of 3 or 4 percent of iron plus alumina, and analyses indicate that the Concepción del Oro rock generally averages well below 3 percent. Five samples of the calcareous phosphorite averaged only 1.28 percent, but a few samples of the cherty rocks composing the lower part of the phosphatic member averaged about 2.40 percent.

As fluorine is present in the Concepción del Oro rock in a proportion slightly greater than 10 percent of the P_2O_5 content, it might eventually be recoverable as a byproduct, particularly if it could be made into CaF_2. However, no commercial processes for the recovery of fluorine from this type of phosphorite have been put into practice as yet.

The Concepción del Oro deposits contain (p. 68) several minor metals. These metals form important elements of the phosphate fertilizers, for some are essential to plant growth.

Superphosphates are produced by treating the finely ground rock with sulfuric acid of 50 to 60 percent strength, which breaks down the calcium fluoride and carbonate and leaves a mixture of soluble phosphate and calcium sulfate. The process depends upon the following basic reaction

$$Ca_3(PO_4)_2+2H_2SO_4+6H_2O\rightarrow CaH_4(PO_4)_2+2H_2O+2(CaSO_4\,2H_2O)$$

As phosphate rock and sulfuric acid are bulky comparatively low value products that are expensive to ship, it is advantageous to have both available in the same area, or to have adequate means of cheap transportation for them. The Concepción del Oro deposits are in a fortunate location, for, with the installation of an acid plant, the smelter of the Mazapil Copper Co. in Concepción del Oro could produce 200 to 300 metric tons of sulfuric acid daily. This company is engaged in smelting sulfide ores, and large quantities of sulfur, which are present in the stack gases, are not being utilized.

If the Concepción del Oro rock cannot be beneficiated for the manufacture of superphosphate by the sulfuric-acid process, it might be beneficiated for the manufacture of elemental phosphorus by electric-furnace methods. Rock used in this process in the United States contains about 24 percent P_2O_5 or 52 percent B. P. L. Although crude phosphoric acid and triple superphosphate for fertilizer can be produced more economically by the sulfuric-acid process, electric-furnace methods have some advantages in the manufacture of pure phosphoric acid and chemical-grade phosphate salts (Waggaman and Bell, 1950). The success of an electric-furnace operation is, of course, dependent upon the development of cheap electric power. Although there is obviously no possibility of developing hydroelectric power in the Concepción del Oro district, it might be feasible to install a thermoelectric plant. Such a plant might be run with coal from the coalfields of Coahuila, which would require a rail haul of 400 to 450 kilometers, or possibly it could be operated by natural gas, which is available in the city of Saltillo, Coahuila, 125 kilometers to the northeast of Concepción del Oro.

If the Concepción del Oro rock can be used in no other way, it might be pulverized and applied as a fertilizer in the raw state. An increasing quantity of phosphate rock is being used in this manner, and approximately 10 percent of the present world production is being used for direct application to the soil. The phosphorus in rock phosphate is less easily available to plant life than that contained in superphosphates, but if used in a suitable crop system and in a long-range soil-building program, it might benefit some types of soils, particularly acid soils low in content of iron, and, of course, phosphate. It is mainly the presence of CaF_2 that limits the availability of phosphorus in rock phosphate. If the material could be defluorinated, its value would be considerably greater.

Several greenhouse experiments have been made with pulverized calcareous phosphorite from the Concepción del Oro district, and the results are presented in table 8. The rock was crushed to the size of

TABLE 8.—*Results of greenhouse experiments testing the effects of Concepción del Oro phosphate on yields of wheat*

Treatment	Weight of first harvest (grams)	Weight of second harvest (grams)	Total weight of first and second harvests (grams)	Average number of plants harvested
Soil number 1, pH 7.4				
Control experiment; no material added	0.24	7.4	7.6	15
Superphosphate added at rate of 500 kg per hectare	.26	8.9	9.1	14
Florida phosphate rock added at rate of 1 ton per hectare	.18	7.8	7.9	14
Florida phosphate rock added at rate of 2 tons per hectare	.13	8.0	8.1	15
Florida phosphate rock added at rate of 4 tons per hectare	.12	9.4	9.5	15
Concepción del Oro phosphate rock added at rate of 1 ton per hectare	.18	8.1	8.2	14
Concepción del Oro phosphate rock added at rate of 2 tons per hectare	.19	7.6	7.7	14
Concepción del Oro phosphate rock added at rate of 4 tons per hectare	.18	7.6	7.7	14
Soil number 2, pH 5.5. Old red soil formed on volcanic rocks				
Control experiment; no material added	0.15	4.0	4.1	14
Superphosphate added at rate of 500 kg per hectare	.27	9.1	9.3	15
Florida phosphate rock added at rate of 1 ton per hectare	.21	8.4	8.6	14
Florida phosphate rock added at rate of 2 tons per hectare	.30	10.1	10.4	15
Florida phosphate rock added at rate of 4 tons per hectare	.29	10.3	10.5	14
Concepción del Oro phosphate rock added at rate of 1 ton per hectare	.23	5.6	5.8	15
Concepción del Oro phosphate rock added at rate of 2 tons per hectare	.22	7.5	7.7	16
Concepción del Oro phosphate rock added at rate of 4 tons per hectare	.22	6.4	6.6	15

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—100 mesh and applied directly to the soils, without beneficiation or treatment of any kind. To show the relative value of the Concepción del Oro rock, simultaneous experiments were conducted with a standard superphosphate, with Florida pebble phosphate, and with soils to which no fertilizing material had been added. The Concepción del Oro rock produced a substantial increase in wheat yields, although it was less effective than the other materials used. The Florida rock that was used contained about 50 percent more phosphate.

PHOSPHATE INDUSTRY IN MEXICO

Although Mexico has a rapidly growing fertilizer industry, the production is still insufficient to meet the nation's needs. Large-scale production of superphosphates is contingent upon the discovery of an adequate source of raw material within the country. The present industry depends in part upon the Nuevo León deposits, which are small, scattered, and rather variable in grade, and in part upon phosphate rock imported from the United States. The fertilizers being produced are costly and are, in general, beyond the reach of the small independent farmer.

The fertilizer needs of Mexico have been demonstrated by a number of experimental programs, although further experimental work is desirable. For example, the Oficina de Estudios Especiales of the Secretaría de Agricultura y Ganadería conducted a series of field tests during 1945 in the States of Puebla, Tlaxcala, México, Morelos, Querétaro, Guanajuato, and Jalisco, which showed that 22 percent of the soils being tested were seriously deficient in phosphorus. These soils gave an average increase in corn yields of 1,026 kilograms per hectare when superphosphate was added at the rate of 250 kilograms (or 40 kilograms of P_2O_5) per hectare. Some of these soils were deficient in nitrogen as well as phosphorus, but it was found that the addition of nitrogen in the form of ammonium sulfate, without the simultaneous application of phosphate, was ineffective.

In 1953, the mining of phosphate rock in Mexico was limited to three small fields in the State of Nuevo León. The northernmost field is in the Sierra de Sabinas, a few kilometers to the northwest of Sabinas Hidalgo, and contains two mines operated by Fertilizantes de Mexico, S. A. This company also owns the two small mines that make up the Ayancual district, about 60 kilometers east of Monterrey. The production from these fields, amounting to 4,000 or 5,000 metric tons annually, was shipped to the company's fertilizer plant in El Vergel, Durango, which is a few kilometers to the northwest of Torreón. Superphosphate is produced, using acid obtained from the Mexican Zinc Co. plant in Nueva Rosita, Coahuila.

The rock in the Sabinas and Ayancual fields occurs in relatively small scattered deposits, which are irregular in form and consist of two distinct lithologic types. The predominant material is a reddish or brownish-red earthy laminated rock, which occurs as cave deposits and was apparently derived from accumulations of bat guano (Peréz Martínez and Wiggin, 1953). Below this material, fractures in the limestone bedrock are filled with a hard to brittle white to yellowish or buff rock, which is commonly banded and is clearly secondary in origin. This rock is much richer than the earthy material, and the two are mixed in varying proportions by the company, so as to maintain a relatively uniform end product. A mineralogical study of the deposits has revealed that they are composed mainly of beta tricalcium phosphate and should probably be classed as martinite (Cady, Hill, Miller, and Magness, 1952). Only a very small proportion of apatite is present.

The third phosphate field, which was developed in 1952, lies near the village of Dulces Nombres in the southeastern part of the State of Nuevo León, only a few kilometers west of the border with Tamaulipas. The field is on the eastern slope of the Sierra Madre Oriental and lies at an altitude of about 2,300 meters. Several small mining companies and individuals were exploiting these deposits, which are small scattered pockets occupying cavities and fractures in the limestone bedrock. The pockets are generally tabular, but they may be irregular in shape. The deposits consist mainly of hard, banded, buff to light-brown material having a maximum grade of 80 percent tricalcium phosphate and less than 0.75 percent fluorine. The authors visited the field and sent a sample of the material to W. L. Hill of the Agricultural Research Service, United States Department of Agriculture, who referred it to J. G. Cady for mineralogical examination by X-ray spectrometer and petrographic microscope. Hill[9] reported that the rock is largely apatite rather than beta tricalcium phosphate, as the authors had thought. The material may have had an origin similar to that of the Sabinas and Ayancual deposits, although the caves in which the deposits formed have been completely eroded. Some layers contain accumulations of bones, which presumably are bat remains.

In 1953, production in the field was at the rate of 200 to 300 metric tons a week. The rock was being shipped to two principal markets: a part was exported to the United States for the manufacture of animal feeds, and most of the rest was shipped to Beick Felix y Compañía in Mexico City for the manufacture of superphosphate. This company was buying phosphate rock at the rate of about 3,300 metric tons annually and was treating this material with acid obtained from its own plant. The rock has a grade ranging from 45 to 75 percent tricalcium phosphate.

[9] Written communication.

Guanos y Fertilizantes de México, S. A., which receives support from the Nacional Financiera of the Mexican Government, is the leading fertilizer manufacturer in the country. The following data regarding its production of superphosphates were obtained with the kind assistance of Dr. Alfonso Romero, in charge of company research. The company operates a modern plant in the city of San Luis Potosí, which between July 1, 1953 and June 30, 1954 produced 36,519 metric tons of superphosphate. The raw material, imported from Florida, is pebble phosphate with a minimum grade of 70 percent tricalcium phosphate and less than 4 percent iron and alumina. It is treated with sulfuric acid obtained from the American Smelting and Refining Co. plant situated in the same city. In October 1953, the company began operating a new plant at Cuautitlán on the outskirts of Mexico City. By June 30, 1954, this plant had produced a total of 28,204 metric tons of superphosphate. The raw material is Florida pebble phosphate, and the sulfuric acid is produced in the same plant. The company also operates a small plant in Guadalajara, Jalisco; production amounts to several thousand tons annually of fertilizers derived from bird guano, obtained from small islands close to the west coast of Baja California. Total production of superphosphates in metric tons by Guanos y Fertilizantes de México, S. A. during the last five fiscal years is summarized as follows

1950	13, 335
1951	12, 604
1952	28, 589
1953	53, 963
1954	64, 723

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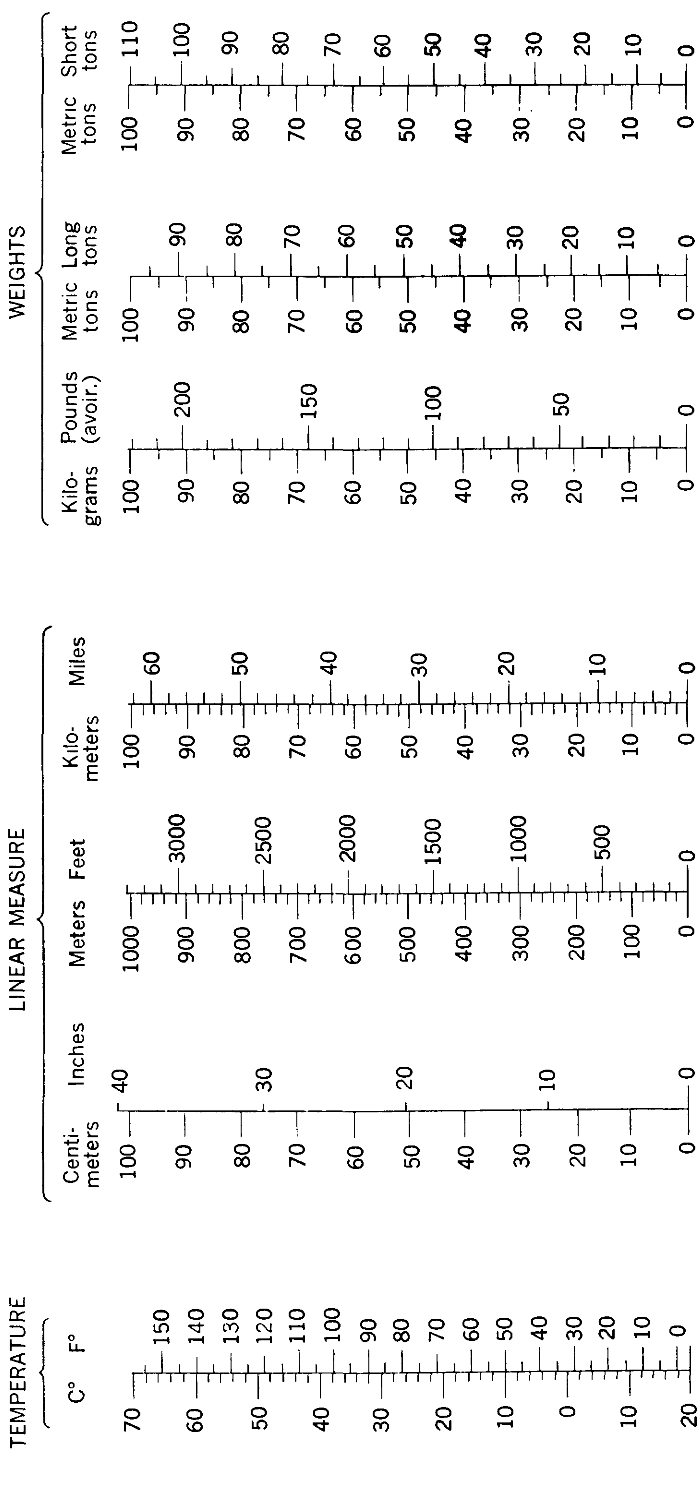
METRIC EQUIVALENTS



1 cm. = 0.3937 inch
1 inch = 2.5400 cm.

1 meter = 3.2808 ft.
1 ft. = 0.3048 meter
1 sq. meter = 1.20 sq. yd.
1 hectare = 2.47 acres
1 cu. meter = 1.31 cu. yd.

1 km. = 0.6214 mile
1 mile = 1.6093 km.

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

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