GEOLOGY OF THE BORDER REGION BETWEEN COAHUILA AND ZACATECAS, MEXICO

R. VAN VLOTEN

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Para mi amigo J.J. Ojeda

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PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKSUNIVERSITEIT TE LEIDEN, OP GEZAG VAN DE RECTOR MAGNIFICUS Dr J. N. BAKHUIZEN VAN DEN BRINK, HOOGLERAAR IN DE FACULTEIT DER GODGELEERDHEID, TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP WOENSDAG 25 MEI 1955 TE 16 UUR

DOOR

ROGER VAN VLOTEN

GEBOREN TE LINDEN, NEW JERSEY, U.S.A., IN 1925

EDUARD IJDO N.V. — LEIDEN

Promotor: Prof. Dr L. U. de Sitter

To my parents and sister, in sincere gratitude
To Esther Barrera, my wife, who uncomplainingly weathered an inclement Dutch winter and thereby indirectly contributed much to the work on this thesis

Dit proefschrift verschijnt tevens als aflevering van de
Leidse Geologische Mededelingen, deel XIX, p. 111—166

CONTENTS.

ABSTRACT

The border region between Coahuila and Zacatecas is part of the mountainous country south of Parras in northeastern Mexico. It includes a thickness of about 2,600 meters of Jurassic and Cretaceous rocks that were deposited along the northern border of the Mexican geosyncline along the southern margin of the Coahuila Peninsula massif.

During early Tertiary time these sediments were compressed into folds parallel to the borders of the massif. The majority of the anticlines in the area mapped is overturned to the north.

After the compressive stage a tensional stage developed and a system of tensional faults was formed. Block faulting found place on a large scale.

A suggestion by DE SITTER that some longitudinal faults may be comparable to schistosity planes in microfolds is tested in the horizontal outcrop pattern of this area, and no indications are found which could contradict this hypothesis. It is suggested that this horizontal outcrop pattern should also vary with the relative competency of the rock formation.

The stratigraphic column is divided into formations. The Jurassic includes the Zuloaga limestone of Oxfordian age and the equivalent La Caja and La Casita formations of Kimmeridgian-Portlandian age. The Cretaceous from the base upward includes the Taraises formation of Lower Neocomian age, the Cupido limestone of upper Neocomian-lower Aptian age, the La Peña formation of upper Aptian-lower Albian age, the Aurora limestone of middle Albian age, the Indidura formation of upper Cenomanian-Turonian age, the Caracol formation of Coniacian age, and the Parras shale of Santonian age.

The La Caja formation contains a variable amount of phosphorites, the genesis of which is discussed. The conclusion is reached that there are indications that this deposit had a biochemical mode of origin rather than a purely chemical one as advocated by KAZAKOV.

SAMENVATTING

Het grensgebied tussen de staten Coahuila en Zacatecas is een gedeelte van het berglandschap ten Zuiden van Parras in het Noordoosten van Mexico. Het is opgebouwd uit een pakket met een dikte van ongeveer 2600 meter van Jura- en Krijtgesteenten, die zijn afgezet langs de noordelijke rand van de Mexikaanse geosynclinale en de zuidelijke grens van het massief van het Coahuila schiereiland.

In het vroeg Tertiair werden deze sedimenten samengeperst tot plooien, die parallel lagen aan de randen van het massief. De meerderheid van de anticlinalen in het gekarteerde gebied is overhangend naar het Noorden.

Na de periode van druk volgde een periode van rek en een systeem van tensionale breuken ontwikkelde zich. Slenkvorming vond plaats op grote schaal.

Een suggestie van DE SITTER, dat sommige strekkingsbreuken vergelijkbaar kunnen zijn met schistositeitsvlakken in micro-plooien is toegepast op het horizontale dagzoom-patroon in dit gebied en er werden geen aanwijzingen gevonden, die tegen deze hypothese ingaan. De veronderstelling wordt geopperd, dat dit horizontale dagzoom-patroon ook moet variëren met de relatieve competentheid van de gesteenten.

Het stratigrafische profiel wordt verdeeld in formaties. Tot de Jura-afzettingen rekent men de Zuloaga kalksteen van het Oxfordien en de equivalente La Caja en La Casita formaties van het Kimmeridgien-Portlandien. Het krijt wordt verdeeld, van oud naar jong, in de

Taraises formatie van het Onder Neocomien,
Cupido kalksteen van het Boven Neocomien-Onder Aptien,
La Peña formatie van het Boven Aptien-Onder Albien,
Aurora kalksteen van het Midden Albien,
Cuesta del Cura kalksteen van het Boven Albien-Onder Cenomanien,
Indidura formatie van het Boven Cenomanien-Turonien,
Caracol formatie van het Coniacien,
Parras schalie van het Santonien.

De La Caja formatie bevat een veranderlijke hoeveelheid fosforieten, waarvan de genese in een speciaal hoofdstuk wordt behandeld. Als conclusie wordt getrokken, dat er aanwijizngen zijn, dat deze afzetting een biochemische oorsprong heeft, eerder dan een zuiver chemische, zoals beschreven wordt door KAZAKOV.

United States Air Force

Fig. 1. View of Sierra del Gabán. San Francisco Fault in foreground. Sierra de San Francisco to the left. Constancia in the background. Looking northeast.

INTRODUCTION

> Hear a little further:
> And then I'll bring thee to the present business
> Which now's upon's; without the which, this story
> Were most impertinent.
>
> The Tempest

This thesis forms part of a series of investigations of the regional geology and phosphorite deposits of northern Mexico, made by the Instituto Nacional para la Investigación de Recursos Minerales of Mexico in collaboration with the United States Geological Survey.

LOCATION AND EXTENT OF AREA

The area under consideration straddles the border between the States of Coahuila and Zacatecas, from the old mining town of Melchor Ocampo (formerly San Pedro) to Rancho Manchuria. It is located between Saltillo and Torreón, to the south of Parras and to the north of Concepción del Oro. The surface area is about 4,000 square kilometers.

COMMUNICATIONS

Lines of communication are poor; there are no improved roads and the only railroad connection is at Melchor Ocampo, which lies at the end of a branch line of the Coahuila and Zacatecas Railroad. Once a week there is a train to Saltillo. The best road to Saltillo goes through Fraile and Agua Nueva. Gasoline can usually be bought in Melchor Ocampo and Garambullo, sometimes in Jalapa. A reserve tank is strongly recommended.

PREVIOUS INVESTIGATIONS

The area was not investigated previously, although IMLAY gave a brief description of the principal features (IMLAY 1938b, pp. 1672—1675). The same investigator mapped and described adjoining areas to the north (IMLAY 1936 and 1937) and the area around Melchor Ocampo (1938b), parts of which have been included, with his permission, in the present geologic map.

FIELD WORK

The field work was accomplished during the first half of 1954. Mapping was done directly on *Trimetrogon* photograps, sets of vertical and oblique aerial photographs taken by the United States Air Force in 1946, on a scale of approximately 1:40,000. Horizontal control was obtained with a few Geodetical Survey triangulation points and a few points of an official survey of the boundary between two haciendas in the area.

To make the map rectangular, parts of the adjacent areas, as mapped by IMLAY, have been included, with some modifications.

ACKNOWLEDGEMENTS

The office work on this thesis was done at the Geological Institute of the University of Leyden, The Netherlands. The Instituto Nacional para la Investigación de Recursos Minerales of Mexico provided a scholarship and gave other assistance to the writer.

Mr. CARL FRIES, Jr., chief of the Mexican branch office of the United States Geological Survey, always was ready to help with advice and the loan of equipment, such as vehicles for the field work, aerial photographs and instruments.

To Mr. CLEAVES L. ROGERS, geologist of the same office, I am indebted for his friendship and the many helpful suggestions he gave me.

I am grateful to Mrs. Dr. M. BRONGERSMA—SANDERS for criticism of the section on the phosphorites, valuable suggestions, and the kind permission to quote from a shortly to be published manuscript.

Messrs. W. F. TEGELAAR, J. HOOGENDOORN, and B. F. M. COLLET expertly produced respectively the map, the photographs and the sections and illustrations.

FEBRONIO CORTEZ, of Presa de San Javier, Coahuila, was an efficient field assistant.

TOPOGRAPHY

The area is situated in the northern part of the Mesa Central, a high plateau which stretches between the Sierra Madre Occidental and the Sierra Madre Oriental, with a slight inclination toward the north. It lies in a belt of mountain ranges and valleys that trend northwesterly. Relief in the area is moderate, except for the northwestern part of the area, where the relief is more pronounced and the terrain is rugged.

The mapped region contains six ranges, which are called, from north to south:

I — Sierra de San Francisco, with its eastward continuations: Sierra del Guaje, Sierra de la Taravilla, Sierra de San Jerónimo;
II — Sierra del Gabán;
III — Sierra Lorenzeña, Sierra del Socavón;
IV — Sierra del Toro;
V — Sierra de Trébol, Sierra Sombreretillo;
VI — Sierra Carpintero, Sierra Zuloaga.

Many of the ranges have no name, and then the name of one high point in the range has been extended to cover the whole.

In the north the region is bounded by the Barreal de Menchaca, in the west by the valley of Manchuria and the Bolsón de Cedros, in the east by the Bolsón de San Carlos. These are all great intermontane basins in the physiographic sense, trending generally northwesterly.

CLIMATE AND VEGETATION

The climate of the region is semi-arid, with a hot, rainy season during the summer. In winter the temperature in daytime is moderate but after sundown it drops sharply and light frosts are not uncommon. In winter precipitation is practically nil, in summer rainstorms are short and torrential.

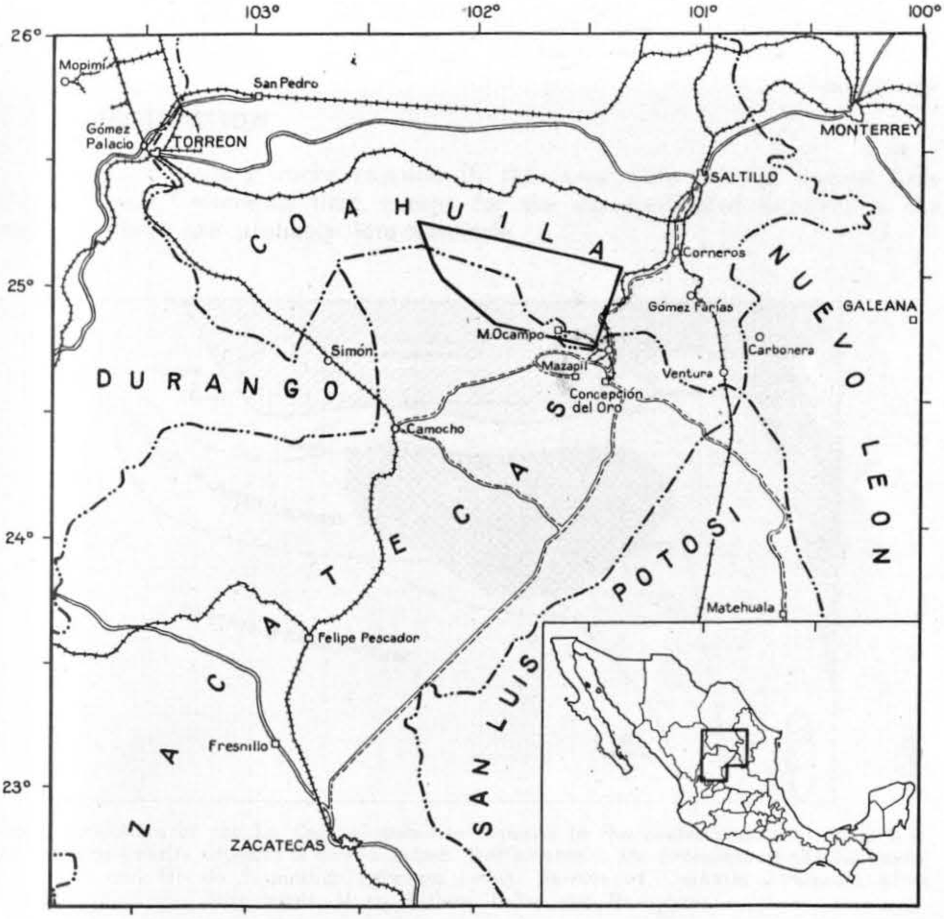


Fig. 2. Index map showing location of the area studied.

Annual rainfall amounts to about 500 mm. Most of the ranches depend for drinking water on small earth dams to catch the rainfall, but which dry up entirely when the rainy season starts late. A few of the ranches have wells with wind-driven pumps, but in some cases the water is fit for cattle only. Crops are watered directly from the sparse rainsqualls.

The vegetation is xerophytic; spiny brush and many kinds of cactus cover the large valleys and ranges. Any vehicle with four-wheel drive can get through almost anywhere.

CULTURE

The main industry is livestock raising. Most of the area is owned by a few land owners. Only around Melchor Ocampo there is some mining. The population keeps alive by gathering fiber from lechuguilla and palm for rope, and some farming of corn, wheat and beans. These crops frequently fail in dry years.

STRATIGRAPHY

> Had I been any god of power, I would
> Have sunk the sea within the earth, ...
> The Tempest

INTRODUCTION

The sedimentary rocks exposed in this area were formed during Late Jurassic and Cretaceous time, except for the unconsolidated deposits in the valleys, which are probably late Cenozoic.

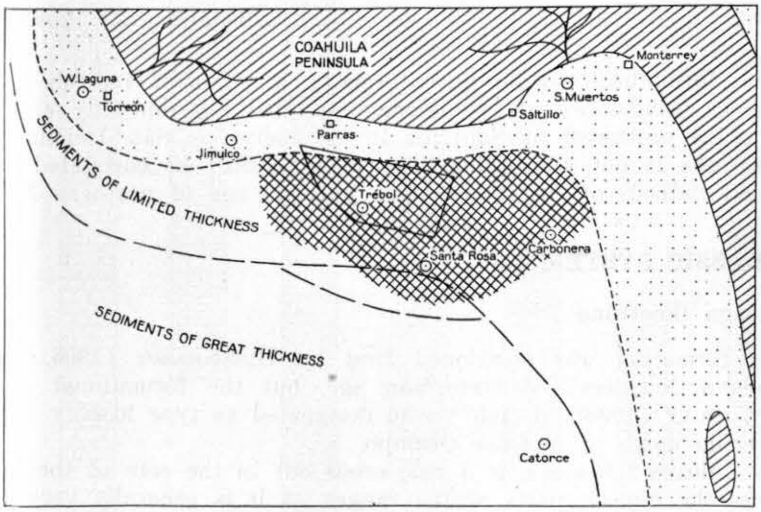


Fig. 3. Relation of the La Caja phosphorite deposits to the contemporaneous coast line. Area of phosphorite deposits is cross-hatched. Dotted area is the extension of the La Casita formation and Olvido formation (gypsum beds). Border of Coahuila Peninsula after Burckhardt, Muir, Kellum, Imlay and Humphrey.

The main part of the mountain ranges consists of Lower Cretaceous strata, the Upper Jurassic outcropping as a rule only in the cores of the anticlines. Upper Cretaceous rocks are found on the lower flanks of the mountain ranges and sometimes in the valleys.

In this thesis the system of formational division of the stratigraphic column, based on lithologic facies differences, has been adopted. The formations of this general region were named and described by RALPH W. IMLAY and other investigators of the University of Michigan.

The formations which occur in this area, with their average thicknesses, are:

	meters
Quaternary	
Alluvium	0—30
Upper Cretaceous	
Parras shale	1,000 +
Caracol formation	80 +
Indidura formation	180
Lower Cretaceous	
Cuesta del Cura limestone	209
Aurora limestone	60
La Peña formation	133
Cupido limestone	128
Taraises formation	153
Upper Jurassic	
La Caja formation	66
Zuloaga limestone	? 550
Total	2559 +

These formations overlie unconformably a series of redbeds consisting of siltstones, sandstones and conglomerates, that outcrop only a few kilometers to the southwest of Salitrillo in the Sierra de San Julián. The age of these rocks is not known but they may possibly be correlated with the widespread redbeds of probably Upper Jurassic age of northern Mexico.

JURASSIC SYSTEM

Zuloaga limestone

This formation was mentioned first by Burckhardt (1906, p. 4) as "Calcaires à Nerinées" of Oxfordian age, but the formational name was given by Imlay (1938b, p. 1657) who designated as type locality the Sierra Sombreretillo north of Melchor Ocampo.

The Zuloaga limestone as a rule crops out in the core of the anticlines and forms the highest parts of the ranges, as it is generally very resistant to erosion. In the Sierra Sombreretillo there is exposed a thickness of about 550 meters of the formation, while in the La Casita Uplift, just north of Garambullo, there is a thickness of about 580 meters exposed of the La Gloria formation (Imlay 1937, p. 600). The La Gloria formation is defined as the near-shore equivalent of the Zuloaga limestone. On the basis of the lithology these strata in the La Casita Uplift would probably be better named Zuloaga limestone. The limestones are predominant here, in contrast with the typical lithology of the La Gloria formation in the western Sierra de Parras, which consists of sandstones and shales.

The upper part of the formation consists of massive, dark-grey to black limestone, thick-bedded, weathering to grey and purplish red.

The limestone has the tendency to form karren. Locally there are concentrations of *Nerinea* shells, which are poorly preserved and which cannot be determined specifically. Stylolites are very common. Almost everywhere the rock is larded with calcite veinlets. Concentrations of coral fragments

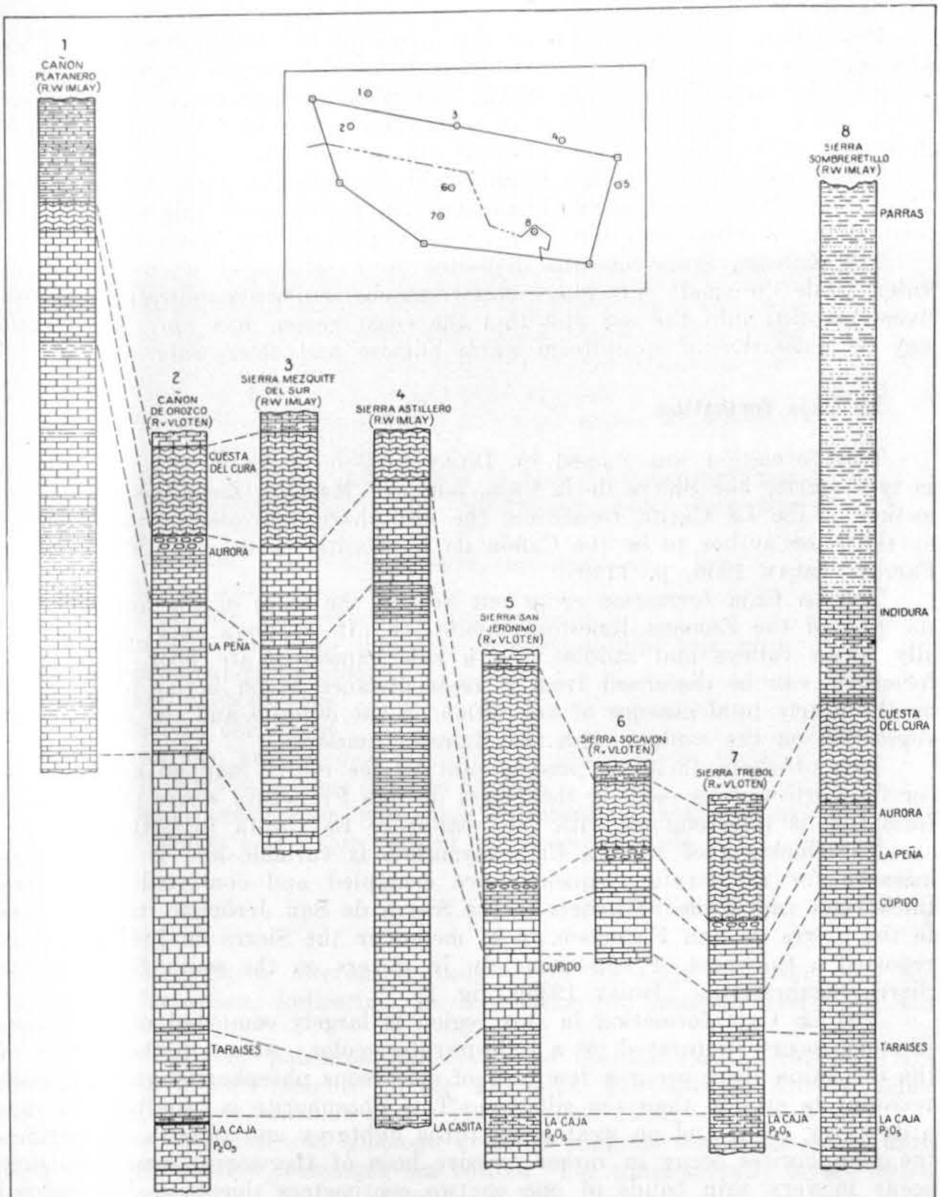


Fig. 4. Stratigraphic sections of the border region between Coahuila and Zacatecas, and their geographical location.
Scale 1 cm = 130 m.

occur in the Sierra de San Jerónimo, just south of San Jerónimo, and southeast of Manchuria.

The middle and lower parts of the formation are less massive and have intercalations of shaly beds. The color is light-grey to light-brown, weathering yellowish and reddish. Sometimes allochthonous fragments of corals are found. All through the formation one encounters irregular lentils and nodules of grey to black chert, which generally has a weathered appearance.

This formation is overlain conformably by the La Caja formation of Upper Oxfordian and Kimmeridgian age. On the basis of this stratigraphic position the Zuloaga limestone has been assigned to the Oxfordian.

The Zuloaga limestone was deposited in a structural basin in shallow water, while the small percentage of terrigenous sediments indicates that few rivers emptied into the sea and that the coast region was low. The corals may be indicative of a uniform warm climate and clear water.

La Caja formation

This formation was named by IMLAY (1938b, p. 1659), who designated as type section the Sierra de la Caja, north of Mazapil, Zacatecas. The type section of the La Casita formation, the near-shore equivalent, was indicated by the same author to be the Cañón de La Casita, in the Middle Sierra de Parras (IMLAY 1936, p. 1110).

The La Caja formation crops out around the cores of the anticlines, at the foot of the Zuloaga limestone mountains. It weathers easily and generally forms valleys and saddles. As a rule exposures are poor. Often the formation can be discerned from a great distance or on aerial photographs by the nearly total absence of vegetation on the outcrop and the often dense vegetation on the contact with the Zuloaga limestone.

This off-shore facies is predominant in the entire mapped area, except for the northwestern part, in the Sierra de San Francisco, where the La Caja formation is intertongued with the near-shore La Casita formation.

The thickness of the La Caja formation is variable and is difficult to measure for the strata frequently are crumpled and contorted. Measured thicknesses vary from 58 meters in the Sierra de San Jerónimo, to 97 meters in the Sierra de San Francisco, to 41 meters in the Sierra de Trébol. IMLAY reported a thickness of approximately 75 meters on the south flank of the Sierra Sombreretillo (IMLAY 1938b, fig. 2).

The La Caja formation in this region is largely composed of calcareous siltstone, poorly indurated, of a light-purplish color. About in the middle of the formation there occur a few beds of calcareous phosphorite which is more resistant to erosion than the siltstone. This phosphorite is usually hard, has a darkgrey color, and on weathering turns lightgrey and pinkish. Sometimes the phosphorites occur in rather massive beds of flagstones, sometimes they occur in very thin bands of one or two centimeters thickness, intercalated with bands of siltstone. In the lower part of the formation a bed is found of a highly fossiliferous, fetid limestone, containing principally *Glochiceras fialar* (Oppel). Concretionary grey limestone boulders are occasionally found, usually of from 20 to 100 centimeters diameter, mostly in the lower part of the formation.

The La Casita formation is characterized by dark-grey to black carbonaceous shales, some thin beds of yellow limestone and some thin beds of calcareous, fine-grained yellow sandstone. The upper six meters consists of thin-bedded to shaly, greyish-yellow sandstone (Imlay 1936, p. 1110). In the Sierra de San Francisco this formation is found intertongued with the La Caja formation. A complete section measured in the overturned beds in the Cañón de Orozco near Valle de Hermanos, from top to bottom, is as follows:

Section in Cañón de Orozco (El Salto), north flank San Francisco Anticline.

Unit		Meters
12	Siltstone, calcareous	20.00
11	Limestone, argillaceous, beds of 10 to 20 cm, blue, weathers in flakes. Highly fossiliferous, mainly ammonites. Interbedded with thin beds of siltstone. Some limestone concretions in lower beds, and pyrite crystals	18.00
10	Shales, black, carbonaceous, and coal seams interbedded with lightblue siltstone (fig. 5)	5.30
9	Siltstone, purplish, with bands of blue phosphoritic limestone, thickness one to two centimeters. Some limestone concretions	6.30
8	Phosphorite, calcareous, massive, darkgrey	1.25
7	Siltstone, calcareous, lightblue	3.50
6	Phosphorite, calcareous, massive, darkgrey	0.20
5	Siltstone, with some limestone concretions and thin phosphorite bands, fossiliferous	9.30
4	Shale, carbonaceous	1.50
3	Siltstone, calcareous	11.60
2	Limestone, argillaceous, fossiliferous, (*Glochiceras fialar*), shell fragments, some gypsum crystals	1.80
1	Siltstone, calcareous, with some limestone concretions. At the bottom a few thin beds of carbonaceous shale	18.00
	TOTAL	96.75

This section shows alternating beds of the La Caja formation and the La Casita formation, indicating an alternation of lagoonal and open sea conditions.

On the basis of paleontological evidence the La Casita and La Caja formations have been assigned to the Tithonian, Portlandian, Kimmeridgian and possibly upper Oxfordian stages (Burckhardt 1930, tables 4, 5, 6).

The paleontological and lithologic evidence suggests that these strata were deposited on a shallow, subsiding sea bottom. The conglomeratic layers which are often encountered in the phosphorite beds, indicate that the wave base sometimes reached these beds. The absence of clastics, even in the La Casita formation within the map area would show that few rivers emptied into the sea. However, the carbonaceous shales formed of plant remains indicate that the climate was not always arid, and that lagoonal conditions existed sometimes. This would probably require the postulation of emergent off-shore bars, which in turn might explain the variations in the thickness of the La Caja formation.

CRETACEOUS SYSTEM

Taraises formation

This formation was named by IMLAY (1936, p. 1111), who designated the Cañón Taraises in the Sierra de Parras as the type section.

The outcrops of the Taraises formation are coextensive with the underlying Zuloaga limestone and La Caja formation, and with the overlying Cupido limestone. The contact with the La Caja formation is rather sharp, but with the Cupido limestone it is gradual.

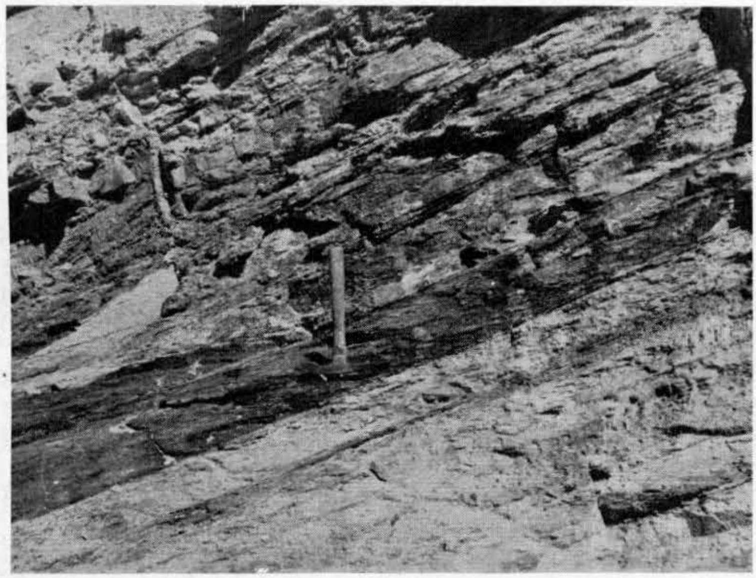


Fig. 5. Coal bed in overturned La Casita formation, El Salto, Cañón de Orozco, Sierra de San Francisco. Note the almost horizontal flow cleavage.

The thickness of the Taraises formation was measured in the Sierra de Jerónimo to be 154 meters, and in the Sierra Trébol 152 meters. In the Sierra Sombreretillo the thickness is 141 meters, while in the Sierra Astillero, north of Garambullo, it is about 82 meters (IMLAY 1938b, fig. 2).

The Taraisses formation consists of medium-bedded, dense, dark-grey to blue limestone, weathering to a light-blue color. In the lower part of the formation occur a few dark-grey to black limestone beds which look very much like upper Zuloaga limestone. Toward the middle calcareous siltstone beds predominate so that topographic saddles and valleys develop. Throughout the formation thin beds of light-blue chert occur. Pyrite crystals are disseminated through the rock. The fossils, mostly ammonites, though some belemnites are encountered, are characteristically flattened along the bedding plane, possibly because of tectonical compression.

Fossil evidence suggests that these strata are of Valanginian and lower Hauterivian age. Fossils of the Berriasian have not been found (IMLAY 1938a,

p. 550) in the Sierra de Parras and in the Concepción del Oro region, and possibly there was a temporary lowering of the sea level in that stage, causing a diastem.

The Taraises formation was probably deposited in an infraneritic environment, as the preponderance of ammonites and the lithology indicate. The pyrite nodules may be indicative of a stagnant environment where hydrogen sulphide is produced.

Cupido limestone

The Cupido limestone type section is the Cañon Mimbre in the Sierra de Parras, north of Garambullo (IMLAY 1937, p. 606).

This formation, which is very resistant to erosion, forms the highest parts of some of the mountain ranges, next to the Zuloaga limestone. Outcrops are generally good. The measured thickness is 136 meters in the Sierra de San Jerónimo, and 69 meters in the Sierra Trébol. In the Sierra Sombraratillo the thickness was measured as about 260 meters, and in the Sierra Astillero near Garambullo as about 495 meters (IMLAY 1938b, fig. 2).

The Cupido limestone is a medium- to thick-bedded, massive, dark-blue limestone with a reddish tint on a fresh surface, and weathering with the same colors. There are some nodules and lenses of pink chert which weather yellowish brown. Stylolites are characteristic of the formation, and pyrite nodules are found throughout.

The lack of any identifiable fossils makes it impossible to date this formation on paleontologic evidence, but because of its stratigraphic position it has been assigned to upper Hauterivian, Barremian, and possibly lower Aptian.

The depositional environment was probably infraneritic, with occasionally restricted currents causing stagnant waters.

La Pena formation

The type section is on the north flank of the Sierra de Taraises, northwest of our region (IMLAY 1936, p. 1119).

The La Peña formation is much less resistant to erosion than the underlying Cupido limestone and generally forms valleys and saddles. Good outcrops are rare.

The thickness of this formation varies from 268 meters in the Cañon de Orozco, 108 meters in the Sierra del Socavón, 92 meters in the Sierra Trébol, to 76 meters in the Sierra San Jerónimo. In the Sierra Sombreretillo a thickness was measured of about 80 meters, and in the Sierra Astillero near Garambullo 390 meters (IMLAY 1938b, fig. 2). This indicates that there is a large decrease in thickness southward from the Coahuila Peninsula.

The lower part of the formation is a medium-bedded massive, fine-grained, dark-grey limestone, weathering yellow, with thin lenses of weathered chert. The limestone contains rather abundant pyrite crystals. Toward the top of the lower half thin-bedded, argillaceous, dark-grey limestones come in, with beds of light-grey to light-brown calcareous siltstone. The limestones weather yellowish to greenish. There are some beds of light-blue chert. In the middle of the formation the siltstones are predominant, causing the formation of topographic depressions.

The upper part of the formation consists of thin-bedded, laminated, dark-grey limestones with alternating soft, buff-colored siltstones. Fossils were not encountered within the mapped area, but a very rich fauna of ammonites, molluscs, brachiopods and echinoids was found between Saltillo and Monterrey by W. E. Humphrey (1949). This formation has been assigned to the lower Albian and the Aptian stages on the fossil evidence.

The La Peña formation is a bathyal deposit of lime oozes, locally stagnant, with some clay and mud being deposited by rivers draining far-away highlands.

Aurora limestone

The Aurora limestone was first described by Burrows (1910, p. 96) in the Sierra de La Aldea along the Río Conchos in northeastern Chihuahua. This formation is much thinner in the mapped area than in the Sierra de Parras where it is one of the main mountain-building formations.

It consists of alternations of massive, thick- to medium-bedded grey limestone, which weathers yellowish, and dark-grey limestone, finely laminated with dark grains and some extremely thin chert beds. At the top of the formation there is always a dense conglomeratic limestone, thick-bedded, with pebbles of the underlying Aurora beds, varying in size from one to ten centimeters diameter, and with larger boulders at the bottom. This conglomerate is especially well developed at the entrance to the Cañon de Orozco (figs. 6 and 7). No mention is made of this conglomerate in the publications on the surrounding regions, although the writer found this facies in all exposures of the contact between the Aurora and the overlying Cuesta del Cura limestone within the area. In the Sierra de Parras by far the greater part of the formation consists of a reef facies (Imlay 1937, p. 613) and the Aurora limestone in our region represents the bathyal equivalent. The formation could be traced down to the Sierra Sombreretillo, where Imlay included it in the Cuesta del Cura, although suggesting that it might represent the equivalent of the Aurora reef facies.

On the basis of its stratigraphic position the Aurora limestone is probably of middle Albian age.

Cuesta del Cura limestone

The Cuesta del Cura limestone was defined by Imlay (1936, p. 1125) and the type section is near the city of Parras, Coahuila.

This formation crops out usually at the foot of the ranges in the mapped area. It is generally resistant to erosion and forms low hills. The thickness of this formation is very variable and measuring it is complicated by the characteristic tight folding of the beds. It ranges from 389 meters in the Sierra de San Jerónimo to 120 meters in the Sierra del Socavón.

The formation consists of a characteristic alternation of medium-bedded, dense, dark-grey limestone with thin-beds of soft argillaceous siltstone and short, thick lenses of black chert. This chert causes a typical wavy bedding, which is found throughout the formation, and at all localities in northern Mexico where Cuesta del Cura beds have been identified (fig. 8). In the limestone occasional thinly laminated argillaceous bands occur. Fossils are

Fig. 6. Overturned massive conglomerate beds of Aurora limestone, Cañón de Orozco, Sierra de San Francisco. Man in circle for scale.

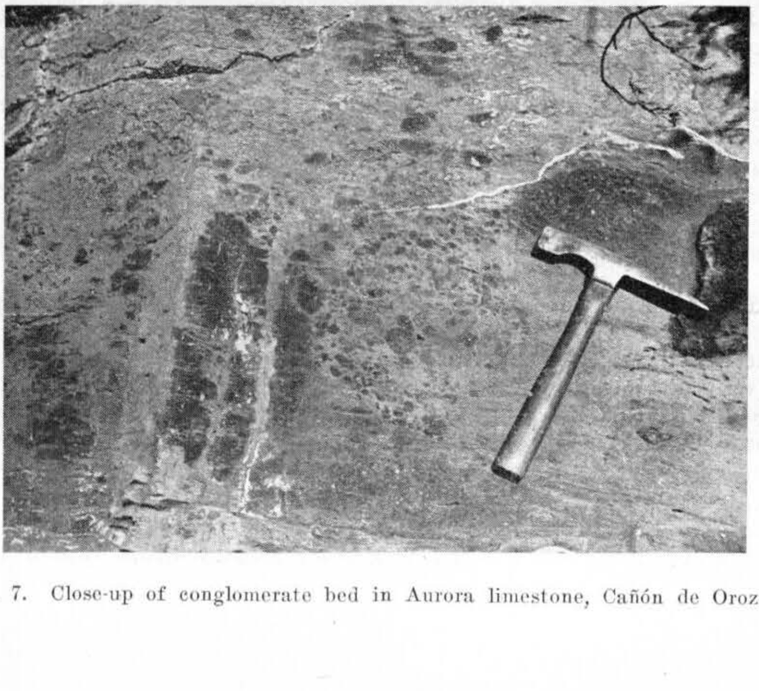


Fig. 7. Close-up of conglomerate bed in Aurora limestone, Cañón de Orozco.

rare except for some poorly preserved small uncoiled ammonites in the limestone beds near the top of the formation.

Because of its stratigraphic position the Cuesta del Cura limestone has been assigned to the upper Albian stage. Possibly the highest beds represent the lower Cenomanian. This formation is very persistent in the Mexican geosyncline.

Deposition took place in bathyal waters with frequent influxes of argillaceous mud from the continent.

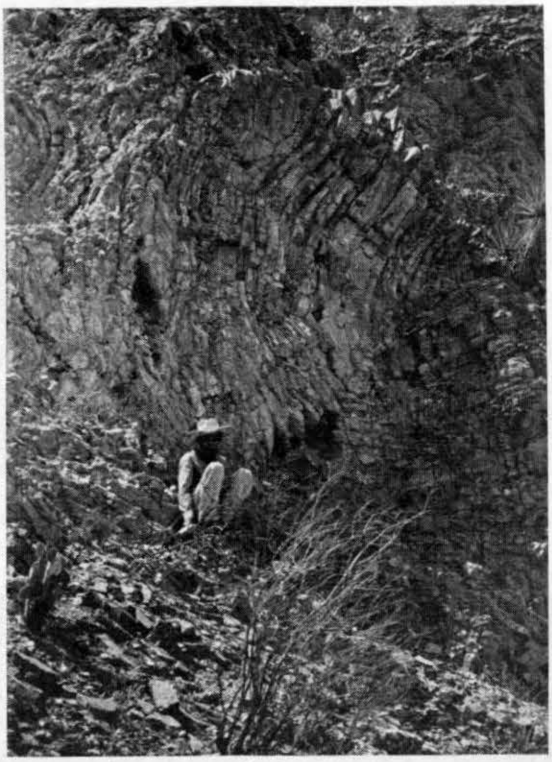


Fig. 8. Crumpled beds of Cuesta del Cura limestone, overlying the Indidura formation. Cerro Calvario, Sierra de San Francisco.

Indidura formation

The Indidura type section was described by W. A. Kelly at the Sierra de Santa Ana in the region of Las Delicias, Coahuila (Kelly 1936, p. 1028—1029).

The exposures of the Indidura formation in our region are rather poor and generally covered with alluvium. Best outcrops are along the north base of both the Sierra de San Francisco and the Sierra del Gabán (figs. 9, 10, 11).

The thickness of the formation in the Cerro del Calvario is estimated roughly to be some 400 meters, but exact measurements cannot be made because of crumpling of the soft shales, and some thrusting. The formation, as far as it crops out here, consists of poorly indurated purple shales at the bottom, while higher up sandy limestones and lenses occur, which weather to a bright orange and brown (fig. 14). These sandy beds show ripple marks and contain a few *Inoceramus* sp. Cross-bedding was also observed.

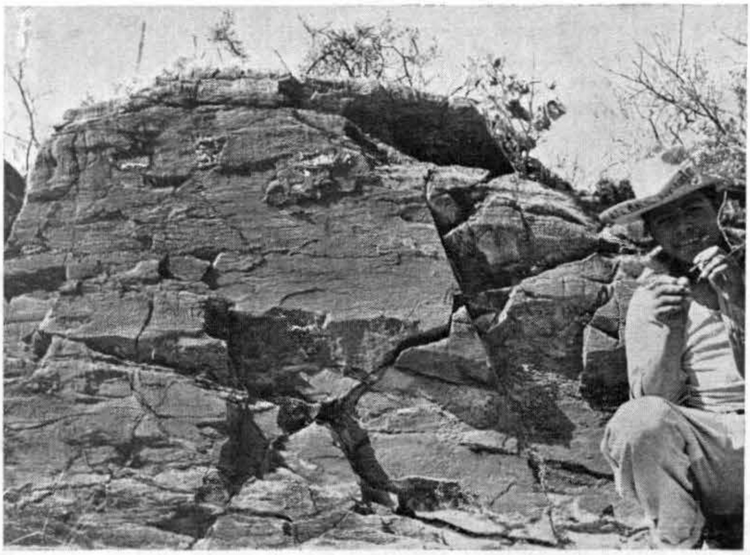


Fig. 9. Bedding surface of a vertical bed of sandy limestone, Indidura formation. Note lapiés in upper left corner. North limb of Gabán Anticline, Cañón del Mimbre.

Higher up in the formation occurs a massive, thick bed of black limestone. This limestone does not crop out at Cerro del Calvario, but was found on the north flank of Sierra del Guaje and to the northwest of Sierra Sombreretillo. This limestone is very resistant. In the Cañon del Mimbre, on the south flank of the San Francisco Anticline the fossil skeleton of a fish fin was found, just above the contact with the Cuesta del Cura limestone.

On the basis of stratigraphic position and the occurrence of *Inoceramus*, this formation probably belongs to the upper Cenomanian and the Turonian. The lithology indicates that these strata were deposited in a rather shallow sea, and that occasionally fine clastics were furnished from the continent.

Caracol formation

The Caracol formation was described by Imlay (1937, p. 616) in the Sierra San Angel, just north of Sabanilla.

Outcrops of the Caracol are found in the large synclinal valleys of the area, where they have not been faulted down by the large longitudinal faults. The best exposures are between Lavaderos and Tapón de los Angeles, and in the valley of Melchor Ocampo. Imlay reports a thickness of more than 1,000 meters here. (Imlay 1938b, p. 1666). In the type section the thickness is 282 meters. The formation consists of alternations of calcareous shales

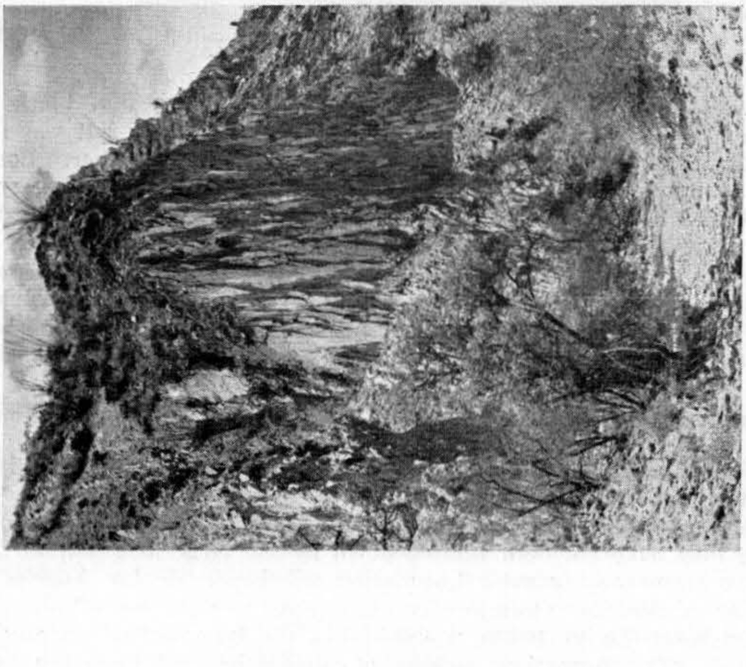


Fig. 10. Overturned beds of Indidura formation in Lorenzeña Anticline, Cañón Salsipuedes.

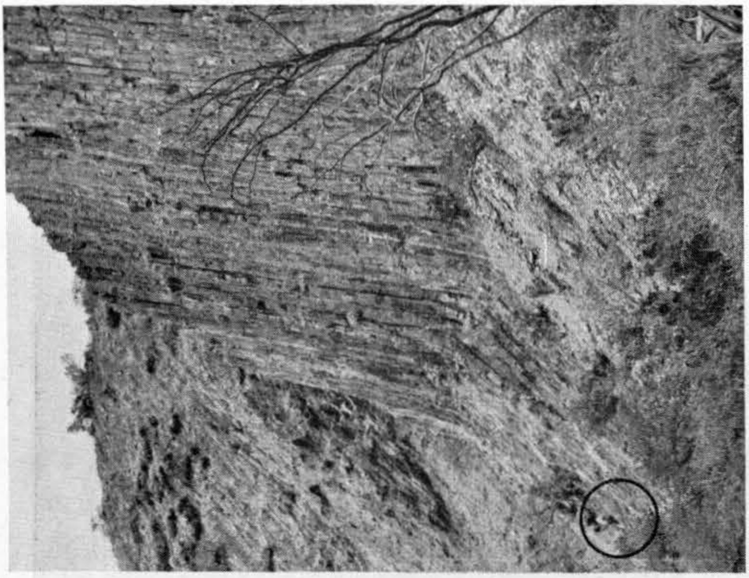


Fig. 11. Same beds as of fig. 10, from the other side. Man in circle for scale.

which weather yellowish, and some massive, calcareous, sandy beds. Although these sandy beds were described originally as tuffs, ROGERS states that they contain no material that is demonstrably volcanic in origin, and they are more accurately described as "calcareous, arkosic sandstones, perhaps approaching graywacke in composition" (ROGERS *et al.* 1955). These sandy beds are rather homogeneous in composition and are generally hard. The color ranges from grey to olive-green and brownish. It weathers to reddish brown and chocolate-brown. Fossils were not found in this formation in the present area but according to IMLAY (1944, p. 1160) the Caracol formation is probably of Coniacian age and its lower beds correlate with the upper beds of the Indidura formation in the Sierra de Parras.

These strata were probably deposited rapidly in shallow water from clastics that derived from an emergent land mass.

Parras shale

This formation, which was first described by IMLAY at the Lomas de San Pablo near the city of Parras (IMLAY 1936, p. 1132), crops out near Melchor Ocampo, where the same author reports a thickness of about 600 meters. The Parras shale also crops out to the south of the Sierra de San Jerónimo, but contacts are covered with alluvium.

This formation is made up of black carbonaceous and calcareous fissile shales, and occasional thin beds of fine-grained dark-grey sandstone. Judging from its stratigraphic position it probably represents the Santonian stage.

The Parras shale must have been deposited in shallow waters with restricted currents and with occasional influxes of clastics from an emergent land mass. The Parras shale is the youngest Cretaceous formation found in the mapped area.

QUATERNARY SYSTEM

Alluvium

All the intramontane valleys have a cover of alluvium that ranges from gravel to sand and clay. The hills south of the Sierra del Guaje are covered with a mantle of gravel, of Upper Jurassic and Lower Cretaceous rocks, which looks like a lake deposit. In the cañon where the road crosses the Sierra de San Jerónimo, west of tne ranch of this name, the rest of a gravel terrace deposit are found some 100 meters above the level of the cañon floor. It is not known whether these deposits represent the Tertiary of the Quaternary System.

TERTIARY INTRUSIVE ROCKS

In the border region between Coahuila and Zacatecas only two separate plutons were found, both too small to map on the scale employed. One pluton lies at the western end of the Sierra Carpintero, and the other on a hill called Cerro Colorado near San Jerónimo. Both possibly represent apophyses of underlying larger plutons.

The intrusive in the Sierra Carpintero has a diameter of some 20 meters and seems to be more or less round in outcrop. It is intruded in the Aurora limestone in the south flank of the Zuloaga Anticline. The intrusive rock is a leucocratic diorite with plagioclase phenocrysts and some smaller mafic minerals in a fine-grained groundmass.

The pluton in the Cerro Colorado (Sp.: Red Hill) crops out in a number of small patches and is possibly genetically related to a large fault which runs parallel to the San Jerónimo Anticline, along its north flank, and a transverse fault which may run southwest along the straight cañon which cuts the Sierra de San Jerónimo at this point. The intrusion lies in rocks of the Caracol formation, near the contact with the Indidura formation. The enclosing sedimentary rocks have been slightly altered and as a result are more resistant, causing the preservation of this small hill. The intrusive rock again is a leucocratic diorite with plagioclase phenocrysts, some mafic minerals, and very little quartz. It is quite similar in appearance to the rock found in the Sierra Carpintero.

ORIGIN OF THE PHOSPHORITES

General Remarks. — The origin of the phosphorite deposits, besides being of scientific interest, is also of economic importance, because knowledge of the conditions of deposition may help to predict the localization of similar deposits and to estimate the extension.

For the purpose of studying the conditions of deposition, two kinds of existing deposits may be studied. One kind is the submarine deposit *in statu nascendi*, the other is the ancient deposit, at present on dry land. The submarine kind has of course the obvious drawback of inaccessability, but the great advantage that most of the factors which may have a bearing on the problem, can be studied at first hand; such factors may include depth below sea level, distance from the shore line, topography of the bottom, composition and temperature of the sea water, prevailing currents and winds, climate and erosion of the continent, biogenic influence, configuration of the shore line, etc. Most of these factors cannot be studied in ancient deposits, at least until more refined methods of investigation are found.

On the other hand, the ancient, emerged kind of deposit is the only kind that has economical interest, and here the advantage is that it is generally more accessible, and that the development in time, such as gradual transgressions or regressions, can be studied in their relation to the phosphorite deposit.

As yet our knowledge of the sea bottom and its sediments is extremely limited, but already from many parts phosphatic sediments have been reported. Phosphate nodules have been dredged up, for instance, from the following areas (CAYEUX 1934):

1. — off the coast of southern California;
2. — off the coast of Chile;
3. — off the east coast of Japan;
4. — off the east coast of Australia;
5. — off the coast of the Argentine;
6. — off the east coast of the United States, between the Straits of Florida and Cape Hatteras;
7. — on the slope of Agulhas Bank, near Cape Town.

Recent deposits of phosphorite

1. — The deposits off the southern California coast were fully described

by DIETZ, EMERY and SHEPARD (1942) and some of the following notes were taken from their paper.

The results of the dredging showed that phosphatic material is found over the entire submarine "continental borderland" without any notable preference, except for the relatively flat shelf-zone of up to 120 meters depth, where the concentration is definitely lower. Beyond this shelf phosphorites were found on the top and sides of banks, on steep escarpments, on walls of submarine cañons. All of the localities where phosphorite is found are essentially nondepositional environments (*op. cit.*, p. 829). Glauconite grains are found associated with the phosphorite in some areas. The material of phosphorite is abundant in hauls made in the outer portions of the 150-mile wide continental borderland, but was not found in the few samples beyond the continental slope. The shoalest sample of phosphorite was dredged from 240 feet (73 meters) and the deepest from about 8,400 feet (2,940 meters). Foraminiferal tests are rather abundant, and closely associated with the phosphate pellets.

The area where the phosphorites were dredged lies off a slightly concave coast. The prevailing ocean current is the cold California Current, which runs along the California coast, from north to south, with a width of some 700 kilometers (SVERDRUP *et al.* 1946, p. 724).

In spring and early summer the prevailing wind is north-northwesterly; this causes the light surface water to be blown away from the coast, at a certain angle to the wind direction, because of the Coriolus force. To compensate for the disequilibrium which develops, the colder, dense, relatively deep water is drawn to the surface. GUNTHER (1936) has shown that this upwelling water comes from depths not exceeding 200 to 300 meters, and that the average depth of origin is 130 meters. In summer the rainfall is very scarce.

The nodules dredged up off the coast of southern California have a concentric structure of layers of fluorapatite alternated with layers of manganese oxide. These lapses in fluorapatite deposition might be related to seasonal changes in wind direction. In fall and winter there is no upwelling along the coast, because the then prevailing wind does not blow the surface water away from the coast.

2. — The phosphorite nodules encountered by the scientists on the expedition of the *Challenger* (MURREY and RENARD 1891) off the coast of Chile, lie in a region which in many regards is similar to the environment off the coast of southern California.

Here the main feature is the Peru Current, running along the coast line of Chile and Peru, bringing cold water from the Antarctic region toward the Equator. The prevailing winds are southerly and south-southeast, causing upwelling of cold water from moderate depths. Here again upwelling is an intermittent process, greatly influenced by local winds.

The coast region has an extremely dry climate.

3. — Off the east coast of Japan, where phosphatic nodules were found by the *Challenger* expedition, the cold water of the Oyashio runs south from the Bering Sea and meets the waters of the Kuroshio coming from the opposite direction. This encounter of the two currents causes numerous eddies, just north of 35° N. (SVERDRUP *et al.* 1946, p. 721).

4. — The oceanic currents off the east coast of Australia are too little known to be able to draw any conclusions, but it seems that at least part of the year cold water from the south runs along the coast. The winds are rather variable, but sometimes westerly to northwesterly winds occur which might cause upwelling of phosphate-rich water.

5. — Along the coast of the Argentine, between the Falkland Islands and the mouth of the Plata River the Falkland Current is operative, bringing cold water from the Antarctic region northward up to about 30° S., where it meets the warm Brazil Current streaming southward.

6. — About the coast of southern Florida it was pointed out by BRONGERSMA (1948, p. 23, quoting DIETRICH 1937) that occasionally it is possible for relatively deep water to reach the surface. This is the kinetic effect of the great speed with which the Florida Current runs along the coast. At Cape Hatteras this current leaves the continental slope (SVERDRUP *et al.* 1946, p. 672).

7. — The phosphate nodule deposit on the slope of Agulhas Bank was described by CAYEUX (1934). The scientist came to the conclusion that the deposit represents two generations. The older generation would have been uplifted several hundred meters. In his long discussion, however, he makes no mention of the prominent ocean currents around the Cape of Good Hope, except for the fact that there seems to be a rather strong submarine erosion.

There are several oceanic currents flowing near the South African coast. The South Atlantic Current diverges here to form the Benguela Current and to flow into the Indian Ocean. This South Atlantic Current carries cold water. From the Indian Ocean comes a relatively warm current, the Agulhas Stream, which also diverges, a minor part flowing into the Benguela Current, the major part returning to the Indian Ocean. As a result of these divergences and various currents, numerous eddies develop, resulting in a highly complicated system of surface currents, which probably is subjected to considerable variations during the year and variations from one year to another (SVERDRUP, *et al.* 1946, p. 696).

CAYEUX found glauconite grains intimately associated with the phosphorites, in addition to benthic and pelagic foraminifera.

Conclusions

From these summary descriptions of widely scattered occurrences of phosphatic nodules we may, if we assume that the environmental conditions have not changed since their deposition, draw the following tentative conclusions:

a) phosphatic nodules are found along the continental borderland and have never been reported from the abyssal sea bottom;

b) in most of the regions where phosphorites are found volcanism is absent;

c) the depth at which phosphorite nodules have been found ranges from 73 meters to about 2940 meters in the case of southern California; on the Agulhas Bank the range is from 88 meters to 1024 meters;

d) the surface on which the nodules are found is essentially nondepositional;

e) phosphate nodule occurrences are limited to areas where strong currents are operative;

f) upwelling of cold water or eddies are often associated with the deposits;
g) in such areas the climate is usually arid;
h) some of the phosphatic nodules show a concentric lamellar structure;
i) although fossil remains are found occasionally with the deposits, in most cases they are only of secondary importance;
j) the phosphate nodules are often black;
k) glauconite grains are often associated with phosphate nodules;
l) in some places foraminifera were found with the phosphorites;
m) the environment of the deposits does not show the characteristics of stagnant conditions or low oxygen content.

It is rather a striking circumstance that in the vicinity of several of these phosphate localities periodical mass mortality of animals has been reported (BRONGERSMA 1948, figs. 2 and 3; more data are given in BRONGERSMA 1955).

It seems that in most cases this mass mortality is caused by an explosive growth of certain species of dinoflagellates, which turns the water red or brown. When this growth is sufficiently dense, other organisms poisoned and litter the beach and the sea floor. We will return to this subject later on.

Ancient deposits of phosphorite

Phosphate deposits are known in many parts of the world, and from many different epochs. We will only discuss shortly a few deposits that have some characteristics in common with the recent deposits.

When we look at the characteristics of the phosphorite deposits of northern Mexico, we note the following features.

The deposits lie not very far from the contemporaneous shoreline of the Coahuila Peninsula and are situated in an embayment formed by this peninsula, between the near-shore clastic deposits and the thicker beds farther south, as in Catorce (fig. 3).

In the phosphatic La Caja formation no sediments were found which could be said to be of volcanic origin and it is therefore unlikely that volcanic products had any influence on the genesis of the phosphorites.

The deposits were probably laid down in rather shallow water, as is indicated by the following characteristics. The phosphorites consist of pellets or oolites, which are thought to be indicators of a shallow-water environment. The pellets are frequently joined together to form conglomeratic pebbles, also indicating wave action. Several pieces of fossil phosphatized wood were found by ROGERS in the Concepción del Oro region (ROGERS *et al.*). Fragments of ribs and part of a skull of a reptile were found embedded in phosphorite in the area of Carbonera, Nuevo León, by the author. This reptile is probably herbivorous. At the same locality the surface of one of the phosphorite beds shows oscillation ripple marks (VAN VLOTEN, 1953). According to ROGERS *et al.* the presence of fossil wood and reptile bones at a distance of a hundred kilometers from the shore of the mainland can be explained by assuming that a row of islands existed in this neighbourhood.

The fauna which existed here at this time includes pelecypods and cap-shaped gastropods, that would indicate an environment of shallow, agitated marine waters and a firm substratum (R. W. IMLAY in ROGERS *et al.*). Some of the phosphatic beds contain a large fauna of minute gastropods and pelecypods, with an abundance of tiny, immature forms (ROGERS *et al.*). To the present author this would suggest that suddenly the environment became such that life was impossible for these forms; some catastrophe seems to be indicated.

All the phosphatic beds are dark-grey to black in color and have a fetid odor. They contain a variable amount of silica, in the form of chert. Occasionally pellets show a concentric lamellar structure, caused evidently by changes in the physico-chemical environment.

The contemporaneous sediments that were deposited on the border of the Coahuila Peninsula include gypsiferous beds and coal beds.

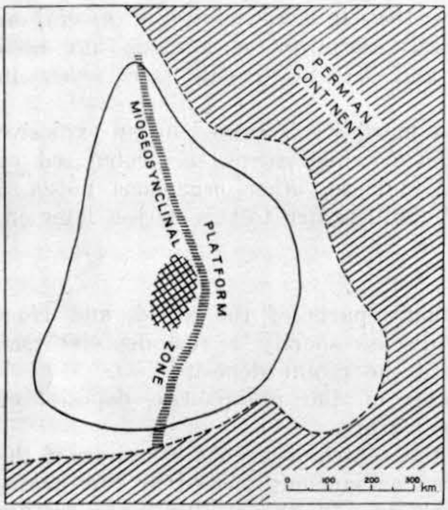


Fig. 12. Sketch map of phosphorite deposits of Phosphoria formation, western United States. Solid line encloses area of phosphatic rocks; area of highest concentration is cross-hatched. Adapted from MCKELVEY *et al.* (1953).

Another occurrence of phosphorite which has been well studied, is the Phosphoria formation of the western United States.

These Permian phosphorites were laid down near the contemporaneous continental slope (fig. 12). The area represents a basin, shelving to the west, north and east, according to MCKELVEY *et al.* (1953, p. 58). Shelving to the west is suggested by westward intertonguing with a thin redbed. MANSFIELD (1927, p. 185) thinks that a connection with the north is suggested by faunal affinities with Alaskan rocks.

The depth at which these phosphorites were formed, lies between 200 and 1,000 meters or more, according to MCKELVEY *et al.* They base this opinion on the even, fine lamination of the rocks, the absence of ripple or scour marks and the near-absence of cross-bedding and the association of the phosphorite with fine-grained clastics and carbonaceous matter. In our opinion this might also suggest tranquil atmospherical conditions and rather shallow water.

The contemporaneous sediments toward the east are conglomerate and traces of glauconite, and still further east redbeds, consisting of even-bedded sandy siltstone, calcareous siltstone and evaporites. The combination of redbeds and evaporites suggests dry and warm climatic conditions. The scarcity of clastic material might also indicate an arid climate or a continent of low relief.

With the phosphorites an abundance of organic matter is found, which, according to TRASK (1939), is produced chiefly by phytoplankton. Further associations are chert and glauconite. MCKELVEY stresses the geographic association of beds of chert and beds of phosphorite. He states that perhaps the most likely possibility is that the chert is the product of the luxuriant growth of plankton supported by the phosphate-rich water.

During the Permian System there was some volcanic activity to the west, and MANSFIELD (1940) has suggested that fluorine of volcanic origin may have influenced the genesis of fluorapatite deposits. But as KAZAKOV (1950) has pointed out, no special source of fluorine is needed to account for the fluorine content of the phosphatic rocks as the amount of fluorine in sea water now is much greater than the amount of phosphate.

The Senonian phosphatic chalk deposits of Taplow in southeast England were studied by WILLCOX (1953), who came to the conclusion that a trough was present which provided a tranquil environment for the accumulation and impregnation of phosphatic material. It is suggested that gyratory eddy currents produced this trough. The water was warm and shallow and an absence of clastics is noted. There is an extraordinary abundance of fragments of the skeletons of fishes, and phosphate-impregnated foraminifera. The final conclusion is that the main factor of origin is a rich planktonic growth, maintained by phosphate-rich upwelling waters.

The phosphate deposits of French North Africa have been studied intensively by French scientists. SALVAN (1952) gives a good resume of the results in Morocco and the following notes were taken from his paper.

The following characteristics of the phosphate beds were encountered:

1. — the intensity of the phosphate genesis is very variable, both in time and in localization;
2. — they do not correspond to a major transgression;
3. — the thickness of the whole series is abnormally thin for the amount of time it represents, which implies that the area was subjected to strong currents and that the sedimentation was very much reduced;
4. — the sea was shallow and agitated, which is indicated by the occurrence of calcareous algae;
5. — only pellets are found, never nodules;
6. — the pellets have a certain maximum size;
7. — the pellets often have inclusions of clastic quartz but never of bone remnants; the conclusion is drawn that they could not have formed from organic elements;
8. — the abundance of the microflora and the microfauna indicates the existence of a dense plankton population;
9. — the extreme abundance of large sharks indicate a shallow environment but with wide communications to the open ocean;
10. — the invertebrates are rarely found in the beds with high phosphate content;
11. — alle the molluscs encountered in the phosphate beds indicate a rather shallow depth and agitated waters, but are contra-indicative of fresh-water deposits.

SALVAN proposes as a working hypothesis that the phosphate might originate from submarine eruptive rocks which are sufficiently abundant to furnish large quantities of phosphate to the sea water which then, after welling up from the sea floor, could be deposited on the continental shelf as a chemical precipitate.

The abundance of fish remains in the Moroccan deposits is explained as only being the result of good conservational conditions in the phosphatic sandy bottom.

VISSE (1949), among numerous other studies of the phosphates of Morocco, investigated the phosphatic pellets with inclusions of detrital quartz and came to the conclusion that they must have formed as a result of transportation from a "milieu générateur" to a "milieu d'accumulation". VISSE reaches this conclusion after describing an experiment with the pellets: "... un lot de pseudoolithes ... fut soumis à une agitation mécanique en milieu liquide." After a certain time the pellets are reduced in size, and some of the abraded phosphate goes into suspension in the water.

To the writer it is not quite clear why this must have been produced by transportation of the pellets and not by simple agitation of shallow water, as in the experiment.

The results of the investigations of the Moroccan deposits are quite similar to the characteristics of the deposits of northern Mexico and other deposits.

It is possible to continue in this manner the discussion of ancient phosphate deposits, but this would lead us too far and become monotonous. It is evident that in many cases the characteristics of recent deposits, as we listed them, are paralleled in ancient deposits.

Genesis

Several hypotheses have been advanced to explain the genesis of phosphate deposits.

The volcanic-fluorine hypothesis of MANSFIELD has been mentioned briefly already. The absence of any volcanism in most cases and the argument that ordinary sea water when constantly replenished contains more than sufficient fluorine for the formation of fluorapatite, seem to make this hypothesis rather unlikely.

An inorganic-precipitation hypothesis was advanced by the Russian scientist KAZAKOV (1937). He suggests that phosphate is chemically precipitated between depths of 50 and 200 meters, where the pH of ascending cold waters rises as their temperature increases and the partial pressure of CO_2 decreases. He emphasizes thas phosphate cannot be precipitated either in the zone of photosynthesis, where available phosphorus is assimilated by phytoplankton, or at depths below 200 meters, where the high CO_2 content prevents conditions of supersaturation.

A point which is not explained by KAZAKOV is that phosphate nodules have been found at depths much below his 200 meter limit, as for instance on the Agulhas Bank and off southern California.

Another point which weakens in our opinion the hypothesis of KAZAKOV is that the upwelling cold currents are not warmed very much below the zone of photosynthesis.

MCKELVEY *et al.* (1953) accept KAZAKOV's hypothesis in the case of the Phosphoria formation, although with a few modifications. They think that the phosphorites were probably deposited at depths of 200 to 1,000 meters. This opinion is based on the facts mentioned earlier. But at this greater depth it is more difficult yet to see why the cold ascending waters should rise in temperature.

KAZAKOV seems to base his theory on the assumption that waters from the very bottom of the ocean well up onto the continental platforms (see table at end of KAZAKOV's 1937 paper, and various other statements through the text). This is not in accord with the findings of GUNTHER (1936) mentioned earlier, that upwelling water originates from depths not below 200 meters.

The third theory which was advanced to explain the formation of phosphorites is the classical biolith hypothesis.

KAZAKOV stated that phosphates could not be precipitated in the euphotic layers of the water, because here the phytoplankton would absorb any phosphorus which might be brought up by ascending currents. According to the biolith theory it is exactly this process which produces the phosphorites. The organisms which absorbed the phosphorus sink to the bottom and slowly disintegrate, and the phosphates are resorbed into the bottom water and possibly precipitated into concretions, if the concentration of phosphates gets high enough. In parts of these hypertrophic areas where the amount of oxygen used by the disintegrating plankton is greater than the supply per time unit, anaerobic conditions may occur. This may explain why phosphorites are associated sometimes with H_2S and carbonaceous matter. At least temporarily conditions would exist, which have always been ascribed in geological literature to "restricted basins", but which can equally well exist in the open sea, as was shown by BRONGERSMA (1951). The conclusion by GALLIHER (1935) that glauconite is a product of such a "restricted" environment, seems to be contradicted by DIETZ *et al.* (1942, p. 832) who state that the areas where glauconite sands were found are "among the most oxidizing environments of the sea floor."

McKELVEY and his associates, although they subscribe to the hypothesis of KAZAKOV, give various arguments in favor of a biologic origin of the Phosphoria formation, and rather seem to be in favor of a combination of both theories.

In the case of the deposits of northern Mexico it seems that all the characteristic features can be explained by the biolith theory, although many points can be equally well explained by KAZAKOV's hypothesis. The reason is that both theories have much in common. Both assume the existence of upwelling, phosphate-rich waters, near a continental borderland. But while KAZAKOV specifically limits the genesis of phosphorites to the depths below the zone of photosynthesis, the biolith theory is mainly concerned with this very zone. But it should be mentioned here that it is of course quite possible for dead organisms to sink below the zone of photosynthesis and reach a deeper bottom as long as the physico-chemical conditions are such that complete resorption does not occur. This is possibly what happens in the waters off southern California and on the Agulhas Bank, where the phosphorites are found below the euphotic zone. In this respect it is important to remember that upwelling waters are produced by an off-shore current in the upper layers, which may carry the dead phytoplankton into deeper waters, much as fine clastics.

The KAZAKOV hypothesis takes no account of the coquina beds or the beds with immature fossils which are sometimes found in phosphatic strata. On the other hand the biolith theory can account for this with the mass mortality which occurs occasionally in areas of great plankton production.

Neither does the KAZAKOV hypothesis account for the frequent content of hydrogen sulphide or the carbonaceous constituents of the deposits.

In the opinion of the writer the conditions of very shallow water which the phosphatic beds of northern Mexico suggest, preclude the possibility of a purely chemical origin of these deposits.

STRUCTURE

GENERAL FEATURES

The main structural unit in this region is the Coahuila Peninsula of Mesozoic time (fig. 3). This southward extension of the Ouachita-Marathon trend of the folded Paleozoic geosyncline of eastern North America may have been rejuvenated during late Triassic or early Jurassic time (HUMPHREY 1949, p. 111). It served as a buttressing element during the folding of the Mesozoic sediments of the Mexican geosyncline by the Laramide movements. During upper Jurassic and lower Cretaceous time there appear to have taken place numerous minor movements of the Coahuila Peninsula, which occasionally furnished coarse clastics to the sediments laid down in the geosyncline. The peninsula was probably submerged by late Aptian time, but it continued to act as a relatively high and stable mass.

During late Cretaceous or Eocene time the sediments of the Mexican geosyncline were deformed into folds more or less parallel to the shoreline of the upper Jurassic landmasses. These long, parallel folds constitute the present Sierra Madre Oriental of northern and eastern Mexico. When followed from south to north, the folds bend around sharply to the west, near Monterrey, continue via Saltillo to Torreón, and then bend again toward the north (fig. 3). It is in the east—west component of the Sierra Madre Oriental that the present area is situated.

FOLDS

Six anticlinal folds were mapped; the most northerly fold consists of four anticlines, the next three folds of one anticline each, the fifth fold of two anticlines, and the most southerly fold of only one anticline.

All the anticlines are cut off on the west side by faulting, although the Trébol Anticline plunges just before reaching the fault. On the east side the Taravilla Anticline plunges into the Bolsón de San Carlos, but the San Jerónimo Anticline, which lies *en échelon* to the Taravilla Anticline, continues to the east as the Sierra de La Punta. The Sierra de La Presita is faulted down on the east side, and so are the Sombreretillo Anticline and probably the Zuloaga Anticline.

Thus only one anticline continues outside the area mapped.

The anticlines are all asymmetrical, mostly overturned toward the north. Two of the anticlines, the Toro and the Trébol Anticline, present a remarkable double curve in their outcrop pattern. In both cases the eastern part of the anticline seems to have been moved to the northwest relative to the western part of the anticline. Significantly, the structure in the Toro Anticline also lies north-northwest of the corresponding structure in the Trébol Anticline, and is even repeated in the north limb of the Sierra Carpintero. In the opinion of the author these curves might be interpreted as giant drag-

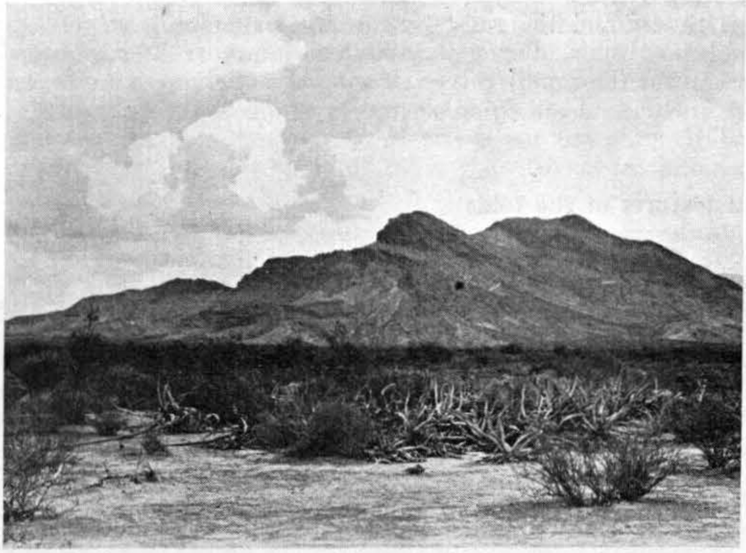


Fig. 13. Cerro Calvario, showing dip of overturned strata on north flank of San Francisco Anticline. Looking east.

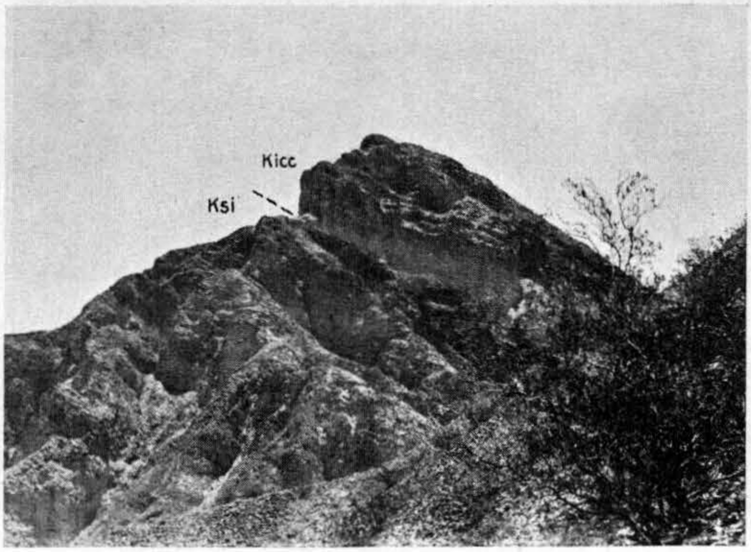


Fig. 14. Indidura formation (Ksi) overlain by Cuesta del Cura limestone (Kicc) on Cerro Calvario.

folds, resulting from a couple, produced by the prevalent forces from the west or southwest and the resistance or friction offered by the buttress of the Coahuila Peninsula, during the Laramide orogeny. It may be mentioned here that a somewhat similar type of curved anticline was observed in the Sierra de Jimulco, about 80 kilometers west of the present area (KELLUM 1932, fig. 5).

Local features of the folds

San Francisco Anticline

This anticline, the most northerly of the area, plunges east to the south of La Constancia. This easterly end of the anticline is approximately symmetrical, but near the line of section A—B the anticline becomes increasingly asymmetrical, and then overturned (fig. 17, 18, 19). At the extreme west end it even becomes recumbent (fig. 13, 14). At the Cañon de Orozco the beds are overturned with a dip of about 25° to the south, but in the "bridge" between the Sierra Atajo and the Sierra de San Francisco proper, beds of Cuesta del Cura limestone lie horizontal and overturned. In the Sierra Atajo the Cuesta del Cura beds even dip north, forming part of the inverted limb of the San Francisco Anticline. Further outcrops to the north are obliterated by valley fill, but the aerial photographs show a rather indistinct line of slight elevations to the north of and parallel with the Sierra Atajo, which may represent part of the arch-bend of the recumbent anticline.

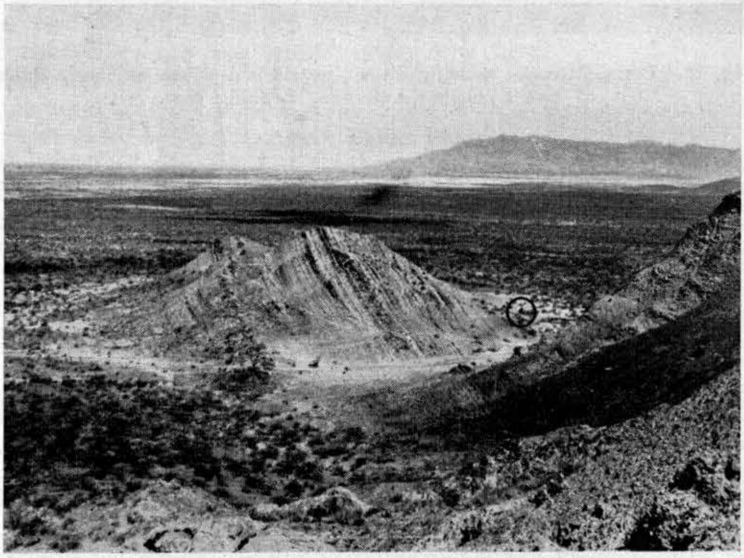


Fig. 15. View from Cerro Calvario toward the northwest. In the middle distance on the right the end of the Sierra Atajo. In the far distance the Sierra Capadero (IMLAY 1936). Indidura formation in foreground. Jeep in circle for scale.

The Cerro Calvario is a good exposure of the overturned Cuesta del Cura limestone overlying the Indidura beds. That there has been some interformational thrusting is indicated by the attitude of the Cuesta del Cura, which is crumpled into secondary folds at the contact with the Indidura (fig. 8). The thrust plane or one of the thrust planes is shown in fig. 16.

To the west the San Francisco Anticline is cut off abruptly by a large fault, trending north-northwest (fig. 15). The Cañon del Mimbre, to the south of the San Francisco Anticline, is a wide synclinal valley, underlain by Caracol beds and possibly some beds of Parras shale. The outcrop pattern of the anticline shows a similar obliquely crossing "dragfold" as the Trébol-Toro structure.

Fig. 16. Thrust plane of Cuesta del Cura limestone, above, over Indidura beds, below.

Sabanilla Anticline

Just southeast of La Constancia lies a small range that probably is a remnant of the south limb of the Sabanilla Anticline, which continues further east as the Sierra Guitarra (Imlay 1937). It consists of lower Cretaceous rocks, overturned toward the south, dipping 60° north. Part of the north flank lies due east of La Constancia. There has evidently been some faulting in this area, but it is difficult to find any evidence other than the sudden disappearance of the strata along the strike.

Guaje Anticline

The Guaje Anticline, which is oriented somewhat differently from the other anticlines, runs from southeast of La Constancia to Lavaderos, where it disappears into the plain south of Sabanilla, although there is no evidence

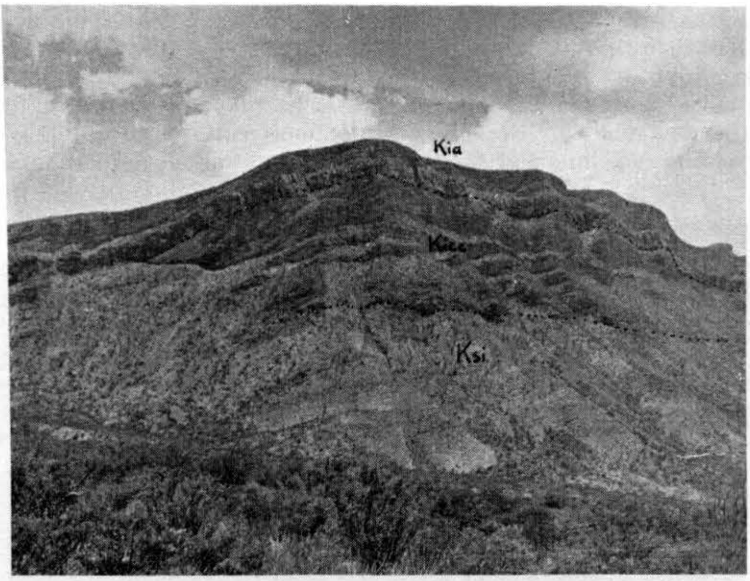


Fig. 17. Overturned Cretaceous beds on the north limb of San Francisco Anticline, near Valle de Hermanos. Kia, Aurora limestone; Kicc, Cuesta del Cura limestone; Ksi, Indidura formation.

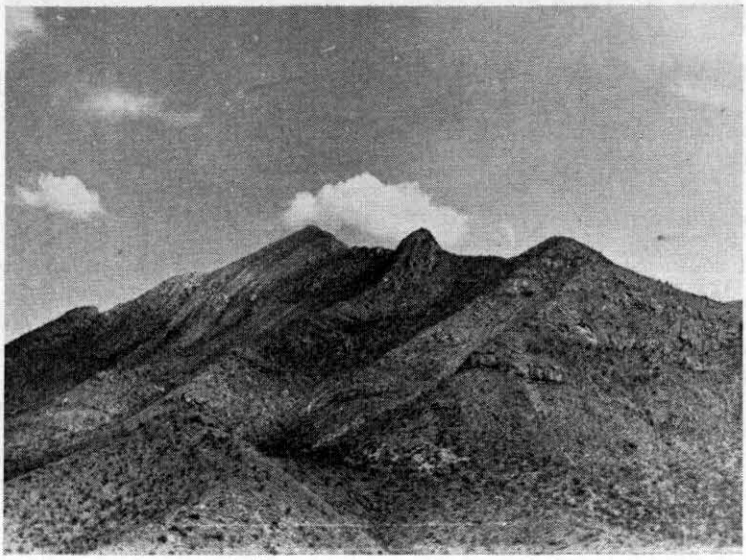


Fig. 18. San Francisco Anticline near Cañón de Orozco. Overturned beds below.

that it plunges here. There is a possibility that the fault which is found at Palos Altos continues to the west and has faulted down the east part of the Guaje Anticline. On the north limb the Indidura beds stand on end or dip steeply south, while on the south flank the beds of Caracol and Parras dip less steeply south. Therefore this anticline is slightly overturned toward the north. Nowhere do rocks older than Cuesta del Cura crop out, so the anticlinal fold was never very high. The south limb is mostly covered with loose gravel, which must have preserved the rather soft beds of the underlying Caracol formation and Parras shale.

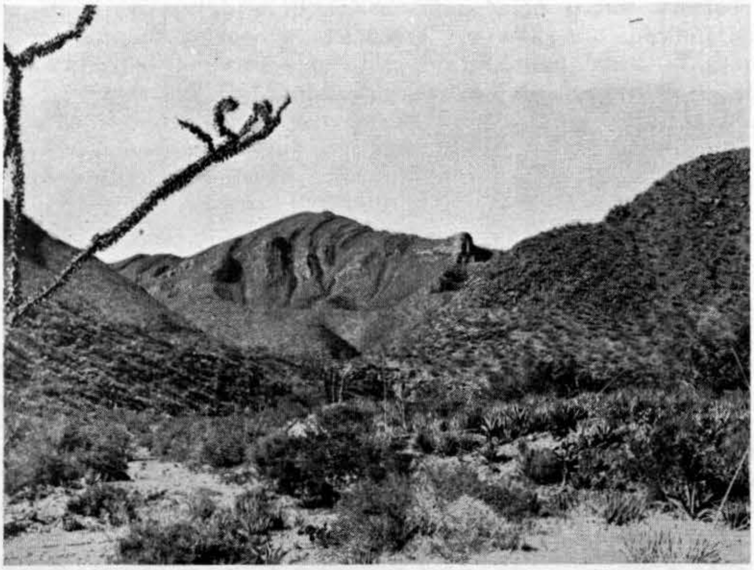


Fig. 19. North limb of San Francisco Anticline, seen from Barreal de Menchaca, near San Francisco.

Taravilla Anticline

The Taravilla Anticline runs from Lavaderos almost to Jalapa. It is slightly convex toward the north and the axial plane dips mostly south. The larger part of the anticline has been eroded down to a series of low hills, and only in two places are there rather high elevations; on the south limb, near Tapón de los Angeles, and on the north limb in the Sierra de la Taravilla (fig. 20). A large section of the north limb has been faulted down, and near Palos Altos Upper Jurassic rocks crop out at the border of the large plain south of Sabanilla. The Sierra de la Taravilla consists mostly of Lower Cretaceous rocks. A wide cañon runs south-southeast from Palos Altos, and a narrow, steep-walled cañon runs toward Tapón de los Angeles parallel to it. Between Herradura and Jalapa the anticline plunges beneath the Bolsón de San Carlos.

San Jerónimo Anticline

The San Jerónimo Anticline plunges westward in the vicinity of Herradura (fig. 20) just north of and *en échelon* with the Taravilla Anticline. From here to San Jerónimo only Cretaceous rocks crop out and only from southeast of San Jerónimo on do the Upper Jurassic rocks crop out. The San Jerónimo Anticline therefore presents a double plunge, first at San Jerónimo the Zuloaga limestone, the La Caja formation and the Taraises formation plunge out of sight, while the Cupido limestone continues to crop out up to a point about ten kilometers further west. Then the rest of the anticline plunges beneath the surface. To the east the San Jerónimo Anticline continues outside the area mapped, where it forms the Sierra de La Punta.

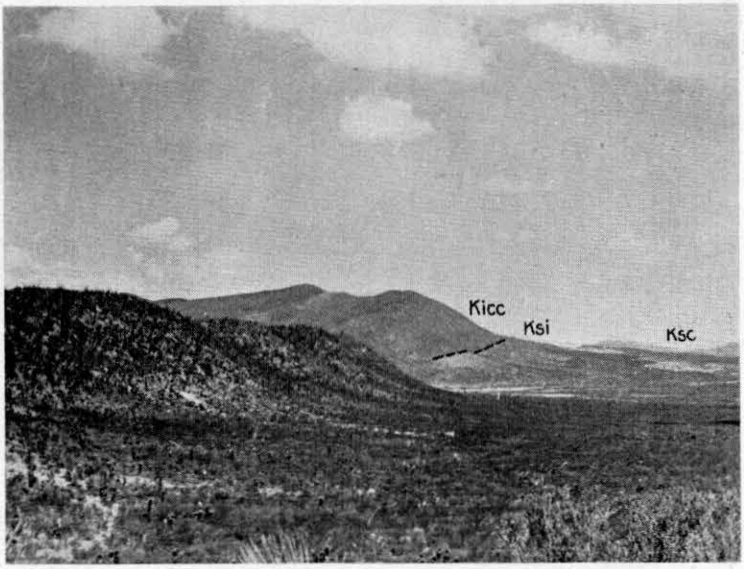


Fig. 20. View of overturned beds of Taravilla Anticline, from the nose of the San Jerónimo Anticline. Herradura at cañon in middle distance. Kicc, Cuesta del Cura limestone; Ksi, Indidura formation; Ksc, Caracol formation.

Within the borders of our area, the anticline is cut by three large cañons. The most westerly, the Cañón de San Cayetano, widens considerably on the south limb, and probably some block-faulting has taken place here. The cañon near Cerro Colorado probably was formed along the fault plane of a transverse fault. The third cañon lies south of San Jerónimo.

The western end of the anticline is more or less symmetrical, but from Cerro Colorado eastward the San Jerónimo Anticline is overturned to the north, with dips of about 70° south. The south limb dips about 50° south. To the east of San Jerónimo the formations above the La Peña formation have been faulted down.

Gabán Anticline

The second fold forms the Gabán Anticline, which in many respects is similar to the San Francisco Anticline (fig. 1). Like the latter it plunges eastward to the south of La Constancia, and is truncated on the west side by the large San Francisco Fault. However, the anticline continues as a low anticlinal ridge eastward as far as La Cruz. This ridge consists mainly of Cuesta del Cura limestone and represents only the north limb of the anticline. The south limb has been faulted down.

Dips on this anticline are rather moderate, except on the north flank, where the Cuesta del Cura beds are sharply overturned. At the northwest corner of the Sierra del Gabán the sandy limestone beds of the Indidura formation stand on end (fig. 9). Near Manchuria a few isolated hills of Zuloaga limestone, overturned to the north, represent the continuation of the Gabán Anticline on the west side of a down-faulted block. The southwest corner of the Sierra del Gabán has been cut off by a smaller, partly longitudinal fault. The anticline is cut by at least two transverse faults, one of which also cuts the San Francisco Anticline, while the more westerly cuts also the Lorenzeña Anticline.

Lorenzeña Anticline

This anticline forms the Sierra Lorenzeña and the Sierra del Socavón. It is overturned toward the north along most of its length, and is slightly concave toward the south, northeast of Salitrillo.

The northern limb of the Lorenzeña Anticline continues westward as far as Cerro Calera, where it disappears. The south limb, on the other hand, is cut off already near Salitrillo by the Salitrillo Fault, which curves around here to continue westward as a longitudinal fault. In general this anticline is more strongly eroded than the rugged ranges to the north, and parts have been eroded down to the level of the valleys. South of La Cruz the Lorenzeña Anticline disappears under a wide basin, except for part of the north limb, which continues to close to La Presita, where the rest of the anticline emerges again as the Sierra de La Presita. This wide basin without outcrops is probably a down-faulted block or graben. At La Presita the Lorenzeña Anticline is finally truncated by a large fault running north-northwesterly.

Near Laguna Seca the north limb of the anticline is cut by a transverse fault which dips 80° west (fig. 24) and is the continuation of a fault in the Sierra del Gabán. The cañon which has been eroded along the fault, exhibits generally very steep walls, and is therefore called Cañón Salsipuedes (Sp. "get out if you can").

In the center of the anticline in the Sierra del Socavón a large cave was discovered, reputedly of some 40 meters diameter, when a tunnel was driven from the north side, several years ago. It is presumably a solution chamber formed in the squeezed and shattered Zuloaga limestone beds near the axial plane.

Toro Anticline

This anticline is structurally rather low, and only Cretaceous rocks crop out in it. The south limb of the western half of the anticline has been faulted down, and does not appear at the surface. As the beds at the extreme western end show no sign of forming a plunging nose, it must be assumed that the anticline is truncated by the Salitrillo Fault here. From north of Trébol eastwards both anticlinal limbs crop out, and northeast of Compostela the anticline plunges in the direction of the Sierra de La Presita. At this eastern end the anticline is slightly convex toward the south. An interesting feature, the S-curve in the strike of the beds, has been discussed already.

Trébol Anticline

In the Trébol Anticline the Upper Jurassic rocks form the highest ridges, with the Lower Cretaceous rocks on both sides at lower elevations. The anticline is approximately symmetrical from Tajitos to north of San José. It starts to plunge toward the west but before the beds of the Cupido limestone and the younger formations can form the nose of the anticline they are cut off by the Salitrillo Fault (fig. 21). North of San José the strike of the strata exhibits the double curve which was also noted in the Toro Anticline. From a point south of Trébol to Compostela only the north limb of the Trébol Anticline crops out; the south limb has been faulted down below the surface of the large valley which is found here (fig. 22). South of Trébol the strata are overturned and dip steeply south. Near Trébol a transverse fault is found, and further east the anticline is traversed by various cañons that possibly follow planes of fracture, although no positive evidence was found in the field.

North of Compostela the Sierra de Trébol is truncated obliquely by a fault running slightly north of east. Straddling this fracture the landowners have constructed an earth dam for a water reservoir, but the project has not been a success.

Zuloaga Anticline

The Zuloaga Anticline is formed by the Sierra Carpintero and the Sierra Zuloaga. The latter has been described adequately by IMLAY (1938b) together with the Sierra Sombreretillo, so we will limit the discussion to the western half of the anticline, the Sierra Carpintero. At the Bolsón de Cedros the Zuloaga Anticline is truncated by the Salitrillo Fault. Although the Sierra Carpintero reaches considerable elevations, no rocks older than the Cupido limestone crop out.

Towards the east the anticline shows a slight structural depression, before it goes over into the Sierra Zuloaga. The curve in the outcrop pattern near the section-line E—F is probably caused by a downward flexure on the west side or possibly faulting.

FAULTS

The fracture pattern in the border region between Coahuila and Zacatecas consists of a number of very large transverse faults, a few large longitudinal faults, and two sets of smaller transverse faults.

The large transverse faults have a general northwest trend. They are large structural elements and continue far beyond the scope of the present area. The large basins bounding our area to the west and east are partly the results of these faults.

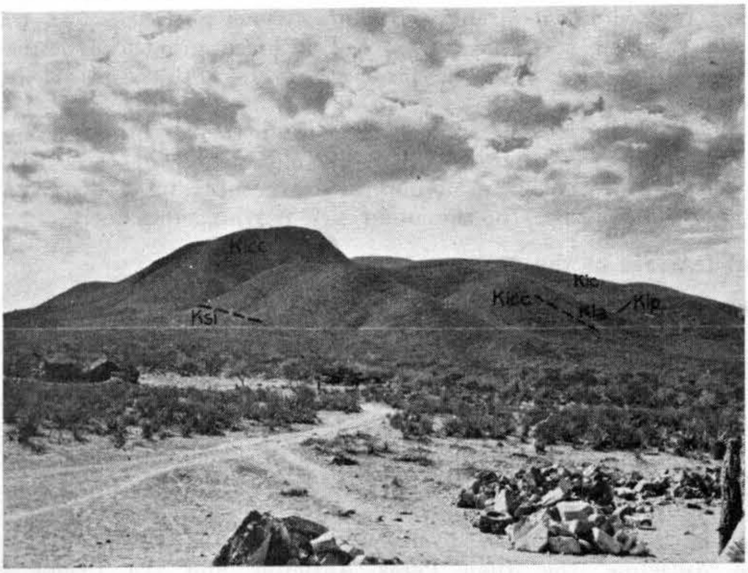


Fig. 21. View of plunging Trébol Anticline from Tajitos. Kic, Cupido limestone; Kip, La Peña formation; Kia, Aurora limestone; Kicc, Cuesta del Cura limestone; Ksi, Indidura formation.

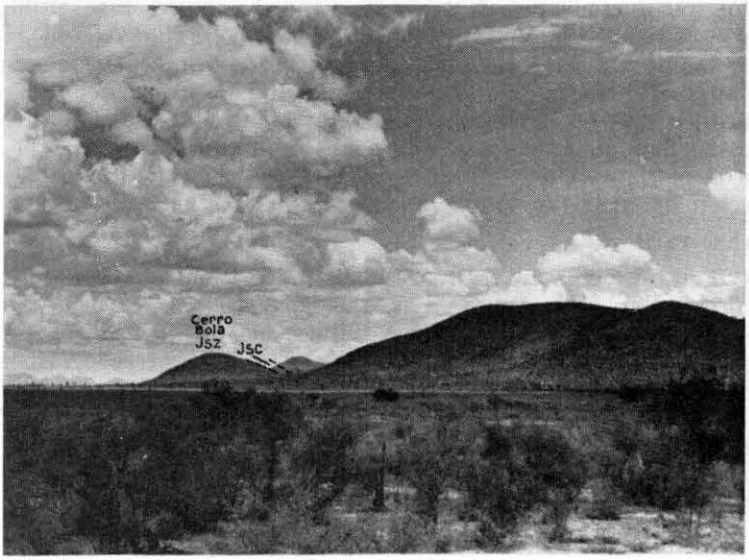


Fig. 22. View of Sierra de Trébol from near Compostela, westwards. South flank of Trébol Anticline is faulted down. Jsz, Zuloaga limestone; Jsc, La Caja formation.

Very prominent in the area are a number of large longitudinal faults which have faulted down sizable parts of various anticlines. In the center of the area mapped they have produced a large graben structure. Some of these faults go over into the large transverse faults, as at the Sierra Sombreretillo.

The smaller transverse faults mainly find their expression in various cañons which cross the ranges. Movements along most of these faults seem to have been minor. We can divide these fractures into two sets, one set trending north-northwesterly, the other set north-northeasterly.

Local features of the faults

Large transverse faults

A prominent feature of the region is the size of the transverse faults. Although these faults in past publications have been overlooked or ignored, it seems to the writer that they are of sufficient significance to be described.

For instance the Sombreretillo Fault in the eastern half of the area mapped, continues southeast for a distance of about 50 kilometers in the Concepción del Oro district (ROGERS *et al.*), and truncates the majority of the anticlines there. On the west side, the San Francisco Fault continues for some 20 kilometers toward the Puerto de La Peña, truncating the Capadero Anticline, the Juan Pérez Anticline and the Prieta Anticline (IMLAY 1936), and possibly continuing yet further along the south flank of the Sierra de La Peña. None of the anticlines mentioned shows any signs of plunging westward, and the disappearance of these anticlines along such a straight line could hardly be explained plausibly by simple erosion of these resistant rocks.

San Francisco Fault

Within the boundaries of the area mapped this fracture truncates the San Francisco Anticline and the Gabán Anticline. The vertical movement along this fault must have been considerable, because in the large plain north of Manchuria no outcrops at all are found of the resistant Lower Cretaceous rocks. As there are no outcrops of the fault plane, it is not known in which direction and how much the San Francisco Fault dips; therefore the symbols on the geologic map (Plate 1) are hypothetical. The most plausible assumption seems to be that the San Francisco Fault is a normal fault.

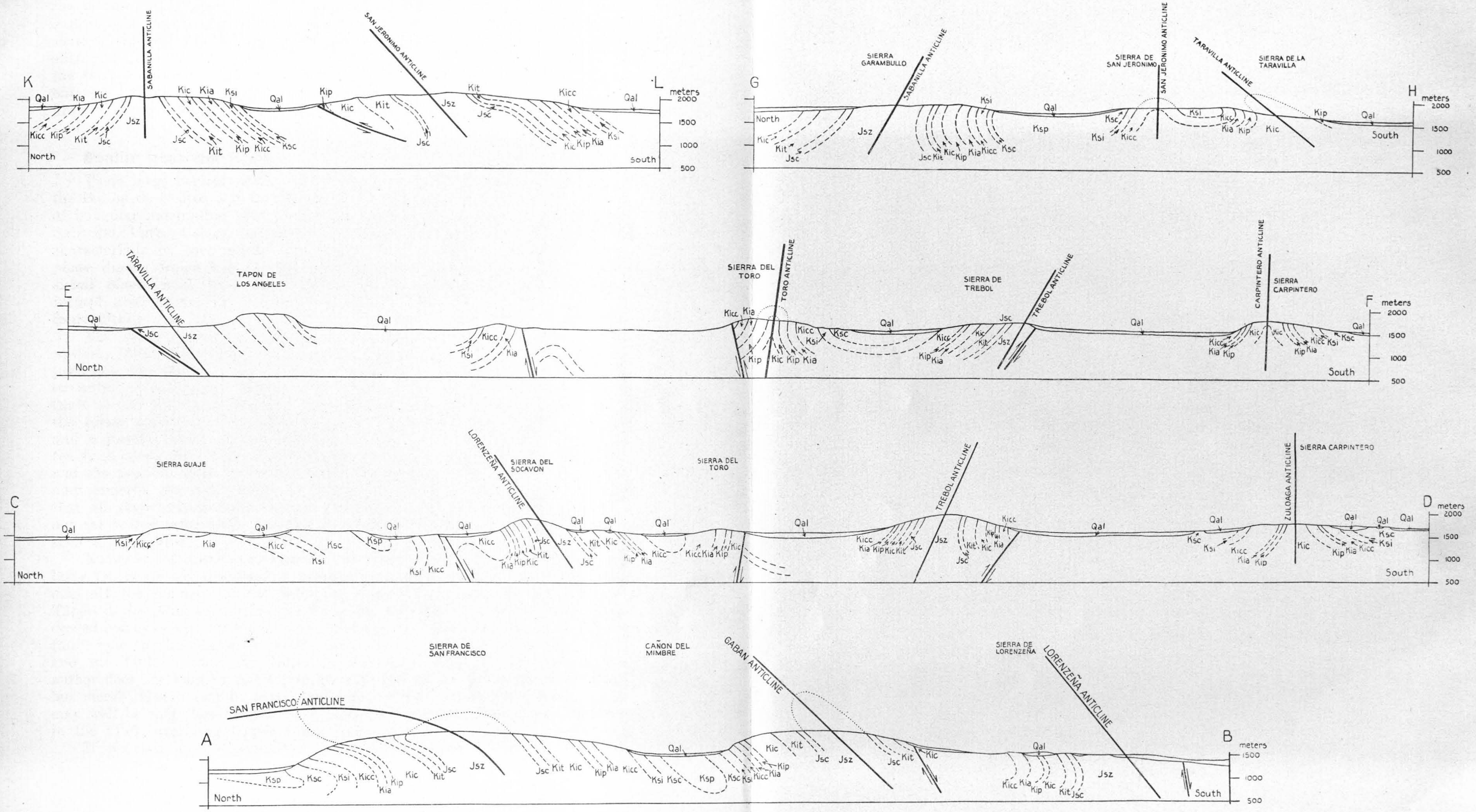
Salitrillo Fault

This fault, which may really be the continuation of the San Francisco Fault, can be divided into two parts, the northern part is longitudinal, the southern part transverse. The latter part truncates the Sierra Carpintero near Matamoros, part of the nose of the plunging Trébol Anticline, and probably the Toro Anticline. The longitudinal part faults down the south limb of the Lorenzeña Anticline from Salitrillo to Cerro Calera. Nowhere does this fault actually crop out, but the evidence for its existence is clear in the truncated anticlines. This fault may be the same as the fault which seems to cut off the western plunge of the Sierra de Santa Rosa in the Concepción del Oro district, about 50 kilometers south of the Sierra Carpintero.

Sombreretillo Fault

This fault is the continuation of a very large fault which borders the Bolsón de San Carlos in the Concepción del Oro district (ROGERS *et al.*).

PLATE 1



Structural sections. Scale 1: 100,000

It curves around the Sierra Sombreretillo near Jalapa and may continue to the north near La Presita. It terminates the Sierra Zuloaga at the extreme eastern end of the area mapped, and the nose of the Sombreretillo Anticline south of Jalapa. Then it curves westward to continue as a longitudinal fault slicing off the northern limb of the same anticline. Then a continuation of the fault abruptly truncates the Sierra de La Presita. Here again no actual outcrops of the fault plane are found, because one side of the fault has always moved down and the erosion of the rocks of the other side masks the fault outcrop effectively with talus.

Smaller transverse faults

These large normal faults have formed the great block-faulted plains as the Bolsón de Cedros and the Bolsón de San Carlos. The remarkable pattern of irregular indentation that is observed in these faults, as for instance near Salitrillo, Cerro Calera, southwest of Jalapa, and south of La Presita, is characteristic of the pattern of tensional faults. After the compressional phase during which the Jurassic and Cretaceous rocks were folded, a tensional phase must have taken place, in which these great faults were formed, and during which parts of the folded strata subsided into structural fault blocks.

The large normal faults show a marked tendency to follow a northwesterly trend. The smaller transverse faults, which show less displacement, predominantly follow a trend which runs either slightly north of northwest or north of northeast. Examples of faults with the latter trend are the fault in the Cañón Salsipuedes near Laguna Seca; the fault along which the cañon southwest of El Quemado runs; the fault just south of Trébol, and a possible fault just east of line of section E—F in the same range; the fault along the Cañón de San Cayetano, in the Sierra de San Jerónimo, and the possible fault to the south of Cerro Colorado; and the fault which may underlie the cañon south of San Jerónimo. The writer is not certain that all these cañons were formed along faults, but merely wants to point out the rather remarkable parallelism which is found in all these cases over such a large area.

Examples of north-northwesterly trending faults are, in addition to the large faults already discussed: a possible fault south of La Constancia, which cuts off the remnant of the Sabanilla Anticline; a cañon to the north of Tapón de los Angeles, cutting the Taravilla Anticline; a possible fault in the eroded valley south of Palos Altos, through the same anticline; a possible fault zone in the Sierra de Trébol just west of the line of section E—F; and two faults mapped by IMLAY in the Sierra Zuloaga. Here again the author does not want to assert that all these cañons are the result of faulting, but merely that a certain parallelism may be observed in these features. It may well be that these cañons were eroded at a higher level along fractures in the thick, overlying Upper Cretaceous strata.

If we look at the movement along some of these faults, as far as it can be observed, we note that in both faults in the Sierra del Gabán the movement probably was relatively down on the west side; the width of outcrop of the Zuloaga limestone is considerably less on the west side than on the east side of the faults. A similar feature is observed about one kilometer to the west, in the Sierra del Gabán, probably also caused by faulting. In the case of the fault which continues to the Cañón Salsipuedes, the dip was measured as 80° to the west (fig. 24). In the transverse fault of the Sierra de Trébol the same relative movement can be noticed; the west side of the fault has dropped down in comparison with the east side and the outcrop of the overturned north limb has moved north relative to the outcrop of the north limb on the east side of the fault. The transverse fault southwest of Melchor Ocampo again shows an outcrop of Zuloaga limestone narrower on the west side than on the east side, signifying that the western side was dropped in relation to the east side. Thus in these four or five cases where the results of vertical movements could be observed, in each case the west side is the down-thrown side.

Longitudinal Faults

A rather large number of longitudinal faults is found in the area mapped. Good outcrops are scarce and the attitude of the faults has to be inferred in most cases. Many of the synclinal valleys seem to be bounded by longitudinal faults running along the foot of the anticlinal ranges or sometimes faulting down slices of the limbs. In the center of the area, west of the Sierra de La Presita, a graben has been produced by these longitudinal fractures, in which part of the Lorenzeña Anticline has been faulted down below the surface. A well drilled for water (!) to a depth of 370 meters near the center of this structure traversed conglomerates but did not reach Cretaceous sediments.

This conglomerate has also been reported from similar graben structures in the Concepción del Oro district by ROGERS and his associates, who named it the Mazapil conglomerate of Tertiary age, possibly to be correlated with the Guanajuato red conglomerate of Late Eocene or Early Oligocene age.

The down-faulting must have occurred before or contemporaneously with the deposition of the conglomerate.

West of La Cruz another longitudinal fracture is found, which faults down the south limb of the narrow extension of the Gabán Anticline. It is possible that the south side of the valley that was produced here, was overthrust somewhat by the overturned Lorenzeña Anticline.

The southwest corner of the Sierra del Gabán, as was mentioned before, was truncated by a partly longitudinal fracture.

Two additional faults were encountered in the south flank of the Sierra del Toro and in the south flank of the Sierra de Trébol. In the former the entire south limb of the anticline has been faulted down from the western end to a point near Trébol. In the Sierra de Trébol the south limb of the eastern part has been faulted down and only a section of the south limb of the middle part crops out. In the eastern half of the anticline the Upper Jurassic Zuloaga limestone crops out directly at the border of the large valley of Compostela. This fault continues beyond Compostela. Every few years or more frequently readjustments find place along the fault plane, as is indicated by the surface cracks (fig. 23), which open periodically just north of Compostela. These cracks run exactly in the direction of the fault, and the inhabitants of Compostela report that occasionally earthquakes are felt and thunder is heard "from a blue sky".

A fracture which may be related to the Trébol Fault runs obliquely across the strike to the north of Compostela. This fault also has occasional movements and causes surface cracks near the extreme east end of the Sierra de Trébol. A well for water was sunk along one of these surface cracks

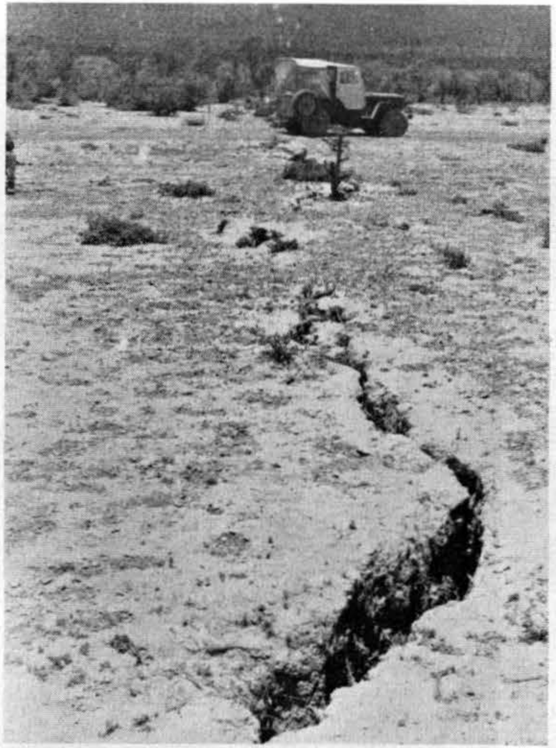


Fig. 23. Surface cracks above Trébol Fault, near Compostela. Looking east.

Fig. 24. View of transverse normal fault in Cañón Salsipuedes, Sierra Lorenzeña. Looking south.

Fig. 25. Small fold in Indidura formation, illustrating the variation in angle between cleavage and anticlinal axis, in rocks of different competency. A, rock of high competency, the angle is about 50°; B, rock of moderate competency, the angle is about 18°; C, rock of low competency, the angle is zero to negative.

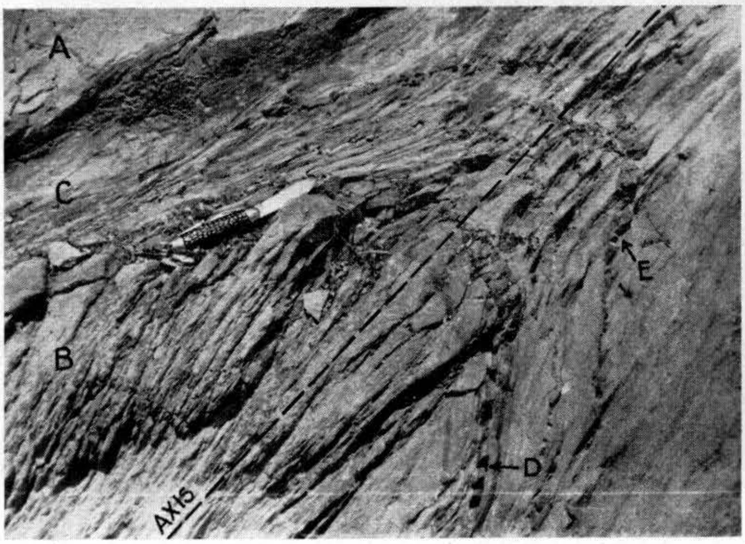


Fig. 26. Close-up of fold of fig. 25. A, B, and C are the same beds, D and E, very thin competent beds; the angle between the cleavage and the axis is about 40°.

down to a depth of 87 meters but the cracks continued deeper, evidently to the bedrock. No water was found.

At least two fractures were encountered along the north flank of the most northerly fold, on the north limb of the Taravilla Anticline and the north limb of the San Jerónimo Anticline. The first fault slices off all the formations above the Zuloaga limestone (although a few remnants of the La Caja formation were found on the slope south of Palos Altos) of the western half of the anticline, but the fault must curve around to the north before reaching the Sierra Taravilla. The fracture along the base of the Sierra de San Jerónimo cuts off only the strata above the La Peña formation.

In an interesting paper De Sitter (1954) suggests that the schistosity planes of microfolds might be represented by fault or crush zone in large folds.

If this is true, we might apply the knowledge of the attitude in three dimensions of schistosity planes in small folds to regional structures as mapped in our present area.

In general it can be observed that cleavage planes (or schistosity planes) form a certain angle with the axial plane of an anticline. This angle seems to be dependent on the relative competency of the beds. In more competent beds the cleavage planes tend to diverge from the axial plane in the direction of the anticlinal apex, while in relatively incompetent beds these planes tend to be parallel with or even to converge to the axial plane in the same direction (fig. 25, 26). In the first case some authors use the term fracture cleavage, while in the last case the term flow cleavage or slaty cleavage is used.

When this attitude is studied in its three-dimensional implications, we obtain the concept of longitudinal fractures which in competent limestones dip toward the anticlinal axial plane and curve away from a plunging anticline, while in incompetent shales these longitudinal fractures are either parallel with the axial plane or dip away from the latter; in an anticlinal plunge they would then converge to the nose.

According to this hypothesis, in our area where predominantly limestones are found, longitudinal faults should be found which exhibit the characteristics of fracture cleavage. As dips have not been observed on longitudinal faults, we can only note the attitude in the horizontal plane; the curving-away of the fault when the anticline plunges. This phenomenon is observed in various cases: on the south limb of the Gabán Anticline, plunging eastwards; on the south flank of the Trébol Anticline, plunging westwards; (?) on the north flank of the Taravilla Anticline, plunging westwards; on the north limb of the San Jerónimo Anticline, plunging westwards; (?) on the north limb of the Sombreretillo Anticline, plunging westwards. The only remaining longitudinal faults are two fractures related to graben structures, and the fault which continues westward along the strike of the Toro Anticline that does not show any evidence of plunging. Not one case was found in which a longitudinal fracture runs into the nose of a plunging anticline.

Although this evidence is rather inconclusive, based as it is on only a two-dimensional view, still we may draw the conclusion that in many cases there is a parallelism between longitudinal faults and fracture cleavage planes. It would be interesting to note whether in folds in incompetent beds the similarity between the flow cleavage and the pattern of longitudinal faults also holds.

GEOLOGIC HISTORY

> . . . What seest thou else
> In the dark backward and abysm of time?
> The Tempest

The red beds which do not crop out in the area mapped, but underlie the Upper Jurassic rocks, and are found in extensive outcrops to the west of the present area, must have been deposited during a period of great aridity. That these arid conditions must have been widespread, is attested by the fact that these red beds are found in many sections of Mexico and the Gulf region of the United States.

The great variability in thickness of these red beds in northeastern Mexico is attributed to a period of folding and subsequent erosion in late Callovian or early Oxfordian time.

During late Jurassic time the first stage in the formation of the Mexican geosyncline started along the margin of the Coahuila Peninsula. This positive area furnished the sediments for the Jurassic and Lower Cretaceous rocks found in this region. Upper Cretaceous sediments were furnished by a western continent, as the Coahuila Peninsula was submerged by this time.

In late Oxfordian time marine transgression began and the Zuloaga limestone was deposited over the folded and partly eroded redbeds, in a shallow, epicontinental sea. The climate probably was warm, and the relative absence of clastics might indicate that few rivers emptied into the sea.

During Kimmeridgian and Portlandian time the sediments became more clastic, possibly reflecting changes in climate. The characteristic variability in thickness of these sediments may have been caused by deposition on an uneven surface, where the sea bottom was characterized by a series of gentle swales and ridges, as was suggested by Rogers *et al.* Occasional emergence of ridges to form small islands may explain the reptile remains that were found in these sediments in many parts. On the other hand the presence of the phosphorites in these rocks would suggest that there was free passage for upwelling waters. Analogy with recent phosphorite deposits suggests that the climate was arid (Brongersma 1948), and that therefore clastic deposition was reduced, and that, although the sea was shallow, quiet conditions prevailed during times of phosphorite deposition.

No unconformity can be noticed between the Upper Jurassic and the Lower Cretaceous sediments,. but Imlay (1944) reported an absence of Berriasian fossils in the Sierra de Parras, and it is possible that a diastem is present.

During Lower Cretaceous time predominantly non-clastics sediments were deposited in a moderately deep sea. In middle Albian time a large amount of coarse clastics was poured into the sea, possibly through a sudden uplift of a continental area or a change in climate.

During upper Albian and lower Cenomanian time the widespread Cuesta del Cura limestone was deposited, indicating that similar conditions persisted over large areas of northern Mexico. The limestone was probably formed in the bathyal sea, but occasionally fine clastics were deposited. At the beginning of the Upper Cretaceous the sedimentation became increasingly more clastic, and deposition took place in shallower waters. The Parras shale of Santonian age consists of black and brown shales and lenses of sandstones which must have derived from a rising, western continent.

With the Laramide orogeny, starting probably in late Cretaceous time and continuing into the Late Eocene, the Jurassic and Cretaceous sediments were compressed into long, narrow folds, parallel to the margin of the Coahuila Peninsula, by compressive forces directed from the west or southwest. Overturning and some thrusting was predominantly to the north, although anticlines overturned to the south are also encountered. Rogers and his associates report that toward the end of the orogeny the anticlinal structures were invaded by large masses of granodiorite in the district of Concepción del Oro, but in the border region between Coahuila and Zacatecas these plutons are either absent or did not reach high enough levels to crop out at the present surface.

After the compressive phase had ended, a phase began in which tensional stresses were predominant. The resulting normal faults produced graben structures and various large down-faulted blocks. If it is true that the longitudinal faults were formed by compressional forces as representing schistosity planes in microfolds, then these would be anterior to the tensional fractures.

If the conglomerate which was encountered when drilling a well in the graben structure south of La Cruz can be correlated with the late Eocene or early Oligocene Guanajuato red conglomerate, then the time of formation of this graben structure may be presumed to be Eocene or early Oligocene.

Since the Laramide orogeny the geosynclinal belt has remained above sea level, and the present topography is the result of subaerial erosion during the Tertiary and the Quaternary.

GEOMORPHOLOGY

The land forms as they are encountered in the area of the border region between Coahuila and Zacatecas show the typical results of the arid geomorphic cycle. The morphology of the area presents a sub-mature topography. The anticlinal mountains have been eroded already for a large part and the synclinal valleys have been filled with the products of weathering of rocks at higher levels. The erosion is being accomplished by chemical weathering, mechanical weathering, wind, and streams.

STREAMS

Streams are all intermittent in this region. Only violent and concentrated rainstorms can cause the flowing of surface water. When the precipitation remains below a certain minimum within a given period the water is absorbed into the dry soil and streams cannot form. Only if a sufficient quantity falls within a short time it is impossible for the soil cover to absorb it rapidly enough and the water runs off in great sheetfloods.

When this happens on the mountainside the flood is soon channeled into consequent arroyos, which follow the dip of the anticlinal mountains.

The soft Upper Cretaceous sediments that must once have covered the folds were soon removed from the anticlines, and the streams began cutting into the more resistent Lower Cretaceous rocks, covering meanwhile the synclinal valleys with debris.

The cores of the anticlines are in most cases constituted by the resistent Upper Jurassic Zuloaga limestone and the overlying soft siltstone of the La Caja formation. When the consequent streams reached the Zuloaga limestone, they must almost always have been deflected into subsequent valleys because of the differential erosion of these dissimilar rocks. This is very clear when the aerial photographs of the region are studied (fig. 1).

The most conspicuous feature of the anticlinal mountains of this region is the deep subsequent valley development on the outcrops of the softer strata of the La Caja formation and in a lesser degree, of the relatively soft La Peña formation. This is at variance with what von Engeln (1942, p. 407) states for desert areas, namely that subsequent streams get little opportunity for development.

As long as these intermittent streams rush down through the steep-walled valleys in the mountain ranges, they are strongly degrading currents, carrying along great loads of debris which has accumulated through the dry periods from chemical and mechanical erosion of the solid rock. But almost as soon as the stream reaches the foot of the mountain range, it changes in character and becomes largely aggrading. Beautiful examples of such degrading streams are found all through the area (fig. 1).

In the border region between Coahuila and Zacatecas the fan deposits at the foot of the mountain ranges are well developed, and adjacent fans have almost everywhere coalesced to form bajadas, which slope down gently to the large intermontane valleys and basins (fig. 1, right foreground). The bajadas which surround practically all the anticlinal remnants, have left these almost isolated as inselberge.

The surface of the bajadas is often channeled by arroyos and washes through which the flood-flows pass. The depth of these channels depends mostly on the local gradient. Usually the deepest arroyos are found near the mountain front.

VALLEYS

The valleys in this region can be divided into two groups; synclinal valleys and block-faulted basins.

Synclinal valleys

The valleys of this group generally are elongate in the direction of the regional strike. In the narrower ones, such as the Cañón del Mimbre between the Sierra del Gabán and the Sierra de San Francisco, the bajadas from these mountain ranges overlap to such a degree that the level of the valley lies considerably above that of the valleys on the outside flanks of the mountain ranges (fig. 1).

The same happens in the narrow valley of Melchor Ocampo. These are extreme cases, but in general it can be said that the synclinal valleys have a higher level than the block-faulted basins, and therefore they are contributaries to the latter.

The floor in the center of these valleys is generally flat and waters coming down after an occasional rainstorm have too wide a path to do any channeling. Usually these shallow floods leave some silt behind. Playas do not develop here as the water does not become stationary and is always drained off by the bolsons. Only in one wide longitudinal valley, the Barreal de Menchaca, does a sedimentation type develop reminiscent of a playa deposit (fig. 1, middle distance, beyond the Sierra de San Francisco). But even here the gradient is too great and the playa deposits are soon dissected by arroyos.

Badlands topography is developed on a small scale just east of La Barranca. The old bajada level is being attacked by erosion because a lower base level has been established downstream. The difference between the two levels amounts to about two meters, and the transition is rather abrupt, along an approximately circular bench, concave on the downslope or west side.

Block-faulted basins

The block-faulted basins form the bolsons where the streams converge. They lie on a lower level than the synclinal valleys, which may have been caused by tectonic processes or because the bajadas have more ample room to spread out. The Bolsón de Cedros and the valley of Manchuria may, when particularly heavy rains occur, ultimately drain into the Laguna de Viesca, toward the northwest. The Bolsón de San Carlos, on the other hand, has no exterior drainage and the water that flows into it must evaporate or seep into the subsurface. In accordance with this, the central part of the bolson, east from Jalapa, is a playa with a silt bottom. This playa extends well beyond the limits of the map area, and is an ideal driving surface, when dry.

LAKE DEPOSITS

As has been mentioned shortly under the section on stratigraphy, lake deposits were encountered in the center of the area, covering a large part of the Sierra del Guaje, and remnants were found of a lake terrace on the hillside near Cerro Colorado in the Sierra de San Jerónimo.

These gravels indicate that the climate must have been considerably more humid than it is now, so that lakes could form. Although it is difficult to assign a definite age to these deposits, it would seem that they must be rather young, as such gravels, only slightly cemented, could not have withstood the erosional forces for very long times in such an exposed position.

COMPARISON WITH THE JURA MOUNTAINS

When comparing the border region between Coahuila and Zacatecas with the Jura Mountains, we note various geomorphological similarities, in spite of the different climatic conditions that are found in these two regions at present.

Of course the first characteristic of these regions is the correspondence between relief and structure; each mountain is an anticline, almost every valley a syncline. In both regions a thick cover of relatively soft beds was eroded after the orogeny and in general the drainage was made consequent on the more resistant beds which were laid bare. The major longitudinal consequents flow down the synclinal throughs and are joined by secondary lateral consequents descending the flanks of the anticlines (VON ENGELN, 1942, p. 316).

Further similarities can be found in the narrow water gaps which cut through the ranges, and the cluses in the Jura, although the genesis of these cañons may be different.

Finally we may note a possible correspondence between the wide cañon on the south flank of the San Jerónimo Anticline to the south of San Jerónimo, and the larger lateral consequents (ruz) of the Jura which have started eroding the anticlines with secondary subsequent streams.

Although the Jura is still in the stage of youth of the fluvial cycle and our region is in the submature stage of the arid geomorphic cycle, we may say that the present area is the "arid equivalent" of the Jura Mountains.

CONCLUSIONS

1. — The structure of the Sierra de San Francisco (Atajo Anticline of Imlay) was revised and has been shown to consist of a recumbent anticline.

2. — The structure of the Sierra de Trébol, which originally was described as the remnant of the south limb of a southward-overturned anticline, has been shown to consist of the north limb of a symmetrical anticline whose south limb has been faulted down by a longitudinal fault.

3. — The existence is pointed out of a few very large northwest-trending block faults, of up to 80 kilometers length, which have not been mentioned earlier in the literature.

4. — The outcrop pattern of the longitudinal faults in the area mapped does not contradict the suggestion of de Sitter that the schistosity planes of microfolds may be represented by fault or crush zones in large folds.

5. — The remarkable outcrop pattern of a double curve, in three adjacent anticlines, has been tentatively interpreted as giant drag folding, possibly resulting from a couple produced by the orogenic forces from the west or southwest and the friction caused by the almost parallel Coahuila Peninsula buttress.

6. — The Aurora limestone of middle Albian age, characterized by reef deposits in the Sierra de Parras, was found to continue as a medium-bedded, fine-grained limestone over the entire area and does not wedge out to the south as was originally thought.

7. — A massive, ill-sorted conglomerate bed was encountered at the contact between the Aurora limestone and the overlying Cuesta del Cura limestone. This conglomerate thins out towards the south, but does not vanish completely.

8. — The conclusion is reached that in the genesis of the phosphorites of northern Mexico the biologic factor was probably of more importance than the purely chemical precipitation of phosphates.

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> It is the quality o'the climate.
>
> The Tempest

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R. VAN VLOTEN werd 30 Juli 1925 te Linden, New Jersey, U. S. A., geboren. Hij genoot zijn middelbare schoolopleiding aan het Lyceum te Baarn. Begon in 1944 zijn geologische studie onder leiding van Prof. Dr L. M. R. RUTTEN te Utrecht, welke werd onderbroken door de oorlogsomstandigheden en voortgezet in 1945—1946. Studeerde van begin 1947 aan de Columbia Universiteit te New York, waar B. S.- en M. A. graad behaald werden onder leiding van Prof. Dr W. H. BUCHER. Sinds 1950 werkzaam te Mexico aan het Instituto Nacional para la Investigación de Recursos Minerales. Beëindigde zijn dissertatiewerkzaamheden aan de Rijksuniversiteit te Leiden in de cursus 1954—1955.

Instituto de Recursos Minerales
Abraham González No. 3-401
México 1, D. F.

PLATE 2. Leidse Geologische Mededelingen, deel XIX

GEOLOGIC MAP OF THE BORDER REGION BETWEEN COAHUILA AND ZACATECAS MEXICO

by

ROGER VAN VLOTEN

Scale 1 : 100.000

Credit and relative accuracy

Map is based on *Trimetrogon* photographs, Mexican geodetic survey points, and local boundary surveys.

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