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EXPLORATION GEOPHYSICAL TECHNIQUES CARRIED OUT IN THE IXTLAN AND LOS NEGRITOS GEOTHERMAL AREAS, MEXICO

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RÉSUMÉ:

L'exploration géothermique dans deux régions le long de la Zone Néovolcanique du Mexique (Ixtlán et los Negritos dans l'État de Michoacán) en utilisant des méthodes géophysiques (prélèvements gravimétriques et magnétométrique suivis d'un prélèvement de réfraction) a donné d'excellents résultats en rapport de l'activité géothermique. Le modele structural obtenu par ces méthodes a éte corroboré apres, par le moyen desforages. L'utilisation des méthodes de réfraction, afin de résoudre les ambigüites des donnés gravimétriques et magnétometriques, sont conseillés pour l'exploration dans des conditions géologiques semblables.

SUMMARY:

Geothermal exploration in two areas along the neovolcanic belt in Mexico -Los Negritos and Ixtlán - (State of Michoacán) carried out by using conventional geophysical methods (gravity and magnetic surveysfollowed by a seismic refraction survey) has given excelent results, about structures with geothermal activity. The structural model obtained by these geophysical methods has been proven correct by holes drilled later. The use of refraction methods in order to resolve the ambigüities arising from gravity and magnetic data, is recommended in geothermal exploration under similar geological conditions.

INTRODUCTION

This article describes some of the geophysical results that led to the discovery of several structural features in connection to geothermics in the Ixtlán and los Negritos areas. The investigation was part of a detailed correlation between geological and geophysical studies carried out from 1968 to 1972 in the western part of the Trans-Mexican Volcanic Belt.

Resistivity, seismic, gravity and magnetic surveyings were undertaken across the area which is known to constitute the northern part of the Ixtlán graben separated from los Negritos area by the Sierra de Pajacuarán in the southwestward direction between Zamora City and Sahuayo City, on the vicinity of Ixtlán de los Hervores town and Villamar town in the State of Michoacán (Figure 1).

Due to the lack of enough energy through out the world, a variety of geophysical techniques have recently been applied in the search for, and delineation of geothermal areas. Some geothermal areas are defined as extensive volcanic occurrences within or - associated to volcanic belts, the upper surface of emplacement of which is likely shallow (0-3.5 km) in this sort of terranes.

The long range objective of the study was to attempt to perfect geophysical techniques to chart effectively and more efficiently the location and character of secondary structures and the thickness of rocks of Tertiary and Cenozoic age in a volcanic belt.

Finally the author wanted to find the optimum evaluation of physical property contrasts that are applicable in the interpretation of geological structures connected to geothermics in the Trans-Mexico Volcanic belt.

GEOLOGICAL SETTING

The Ixtlán de los Hervores-los Negritos geothermal area (Figure 1-A) is located in the northwest part of the State of Michoacán. It lies between the towns of el Salitre and Ixtlán in the northeast part and the towns of Pajacuarán and Villamar in the southwest part. There is a distance of 35 km in direction N 55° E from los Negritos area to Ixtlán area.

This geothermal area is an intermontane topographic depression in Michoacán in the Western Neovolcanic Belt province, which is known as a zone of Tectonic Trenches and Recent Vulcanism, (Alvarez, 1948 and Mooser, 1972). Most of the mountains surrounding the valleys are formed by volcanic flows. The predominant rocks are igneous effusive basalts ranging in age from Tertiary to Quaternary. In the studied areas they are overlapped by younger sediments such as lacustrine and alluvial deposits. According to González (1968), there were two enormous volcanic flows accompanied by small piroclastic deposits. They were produced by an activity which was in some extent explosive. The quiet recent period is characterized by gravel outwash, by the development of erosional land forms of pediments and terrace gravel, by deposition of alluvium, and by landslides. González and others (1968) mapped landslides debris composed of 300m long blocks of basalts. Large boulders of Tertiary rocks may also be observed in profiles I to III (Figure 1-B) at Ixtlán area. These boulders contained in alluvium indicate rock movement for a distance of 2.5 to 7.5 km from the nearest outcrops of these rocks. Also, there exist some fracture injection flows of hematized basalts varying in texture from subtraquitic to philotaxitic. From one volcanic flow to other there were some lacustrine environments which involved several tuffaceous and cineritic deposits. In general, these volcanic rocks present different degree of distribution along the zone; the major portion of the rocks is principally cineritic or debris material, but they are extremely complex. Minor amounts of evaporites, forming lenses or pods in the more abundant lacustrine deposits are also found. These lacustrine sediments show some beds with precipitates from steam and hot water under effusive form.

The area under study shows strong evidences of faulting systems. It is noticeable a conspicuous eastwest parallelism among several chain of volcanic mountains which coincides to the transcontinental trend of tectonic trenches extended from late Tertiary into the early Quaternary. Successive periods of tectonic activity in the late Quaternary times have been progressively freer from influence of old structure and have impressed their own pattern of deformation upon the older rocks.

The Tertiary tectonic history is not clearly known. The Mesozoic structures, although they must have had their influence in determining Tertiary structural pattern in the foreland region of the Pajacuarán zone, can not be related directly to the present structures in the area.

The Limón fault is one of the major structural features in Ixtlán area. The Quaternary rocks in the east are faulted against the late Tertiary rocks of the west. In as much as the early Quaternary rocks of the hanging wall are thrust over the rocks of Paleocene age; the age of the fault could be post-Paleocene.

According to González and others (1968), the fault trace extends northeastward in the form of an arc across the valley. Because the fault plane is not exposed anywhere in the area, the dip angle of the fault plane is not known. From modeling (Del Castillo et al, 1970) however, it was estimated that the fault plane dips to the southeast or northwest at an angle between 70° and 80° and implied that the fault was formed by a tectonic collapse. Other geologists concluded that the dip angle of the fault plane must be close to 90°, at least near the unknown trace. Also, the throw of the fault is unknown. However, it is estimated to be at least equal to the thickness of the sedimentary section at the base of the foothills of the Sierra de Pajacuarán.

Apparently, the structural pattern at los Negritos area is much more simpler than at Ixtlán area. Gómez (1969) assures that the structure at los Negritos is independent to the one at Ixtlán. Unfortunately, the seismic work (Del Castillo, 1971) and the drill hole program in los Negritos was executed later, and the information from drilling was only used here for correlationship.

From the above, the importance of tectonics in both areas is inferred. It is immaterial whether if we refer to the origin of trenches or to different volcanic phenomema (Bernea, 1972; Mooser, 1972). Both effects are responsible of geothermal manifestations at the surface. They formed structural conditions to make its presence possible. The surface evidences of geothermics in both areas is reflected clearly by the great number of fumaroles or geiseres and hot springs of various types. It is believed that the zone of endogene vapor is delineated by faulting systems whose evidences under ground are covered by alluvial and sedimentary material. Besides it is possible that the steam when invades sediments is trapped by its own volume in expansion. Then, salty precipitates seal the trap; otherwise, it flows due to the lack of equillibrium in pressure. (Sandoval, 1970).

Thus it was hoped that the combination of seismic refraction and gravity-magnetic data would indicate the geological structures under the valleys. In connection with the development of resources of energy through out the world, geophysical surveys have been recognized lately as an aid to discern structural patterns in the exploration phase.

GEOPHYSICAL SURVEY AND INTERPRETATION

Ten gravity-magnetic profiles, one and a half kilometer apart, with approximately two hundred and fifty meters spacing between stations were established across the valleys from north and south of the Sierra Pajacuarán. Later two northward and eastward trending seismic refraction profiles were established at Ixtlán area (Del Castillo et al 1970b; Del Castillo, 1971) and three northward at los Negritos area (Figures 1-B and 1-C). All profiles were reversed. The collected geophysical data are refered to a network of base stations established in the areas. This network was tied to station 1438 of the National Gravity Net in Zamora City, Michoacán. The total number of the gravity and magnetic stations occupied in the area (Del Castillo et al, 1970a) are 359 and 1506 respectively (Figures 1 to 3). The latter figures include stations locations of two regional control profiles; one of the regionals crossed all detailed profiles at Ixtlán and los Negritos.

The interpretation procedure followed in the gravity-magnetic work was essentially that of curve fitting by trial and error. A volcanic influence was assumed in the vicinity of each interpreted profile (Del Castillo et al, 1970a). Cominguez (1972) discussed the computed modelling in comparison of second vertical derivatives and continuation of fields for los Negritos area.

In the refraction data of Ixtlán area, Del Castillo et al (1970b and 1971) interpreted the higher velocities as repres entative of basaltic flows varying in texture or fractured, overlying and underlying bodies of alluvial and sedimentary lacustrine material. The anomalous feature of the curves could possibly be explained by a folding of the surface rocks or by a nearly vertical fault. The fault interpretation was preferred because of the observed change of gravity gradient and a magnetic polarity at this location (Figures 2 and 4). Thus, the interpretation of features of these curves is that they are manifestation of a nearly vertical fault acompanied by a strong seismic velocity contrast.

These facts confirm the aception of a graben. From the data, it was not possible to tell the exact amount of throw of the postulated faults; however, it was more than 150 m, as it is shown on Cross Section A-A' (Figure 4) on the basis of drill holes. The general structural pattern obtained by the refraction work at Ixtlán area was used on the polygon modelling to fit the gravity-magnetic data. Figure 2-B shows that the north-south magnetic trend in the northern part of the profiles is consistent along the area; however, the width of the rock-body producing anomaly may be variable along the N-S strike of the body; on the other hand the north east gravity nose (Figure 2-A) is too sharp and wide to be related to geological characteristics overlying older structures (Figure 4-A). This block was called Banco Ixtleco and plays an important role on the structural graben in the Ixtlán area. It should be noted that the total gravity relief due to the graben is about 5 mgal (-157 to -152). Although it is believed that the proposed structures are reasonable, it must be emphasized that instead of the few faults which are postulated, a series of smaller step faults will give similar results for the gravity and magnetic data. It is believed, however, that the total displacement along a fault block mountain often occurs by large movements along a relatively few major faults rather than the cumulative effect of small movements along many minor faults in the area (Figure 1-B). The indicated thickness of the valley fills for the largest density-susceptibility assumed constrast between the bedrock and the valley fill is about 200 or 350 m.

Of the faults shown on the west side of the valley the northward projection of the west fault at drill hole No. 2 coincides with hot springs, just off the map in Figure 1; and it is, therefore, suggested that these springs are possibly due to this fault. The eastward and westward extents of the graben and its relationship to the Tectonic Trenches are treated in another investigation (Mooser, 1972).

In los Negritos area (Figure 3-A) the Bouguer map shows a conspicuos flat along the gravity gradient of a 4 mgal per kilometer. The magnetic map shows dipolo rities in an E-W trend. On the basis of the gravity and magnetic expression, there is not many geologic bodies to choose which would produce such anomaly pattern. Therefore, the interpreted bodies had strong possibilities to match the residual anomalies obtained before (Del Castillo et al, 1970a). In recent seismic refraction surveying the gravity-magnetic interpretation fitted quite well (Del Castillo, 1971). The presented two cross sections (Figures 4-C and D) were built up from the combination of geophysical data and one drill hole log, trying to make use of the general quantitative interpretation given before.

The gravity and magnetic results together with resistivity data in the surrounding region (García, 1970), indicated that both valleys are a northeast-trending grabens, bounded north and south by two or more faults. Tertiary to Quaternary rocks, mostly fine texture and fractured basalts, out crop on either side of the valleys.

The drill hole program suggested that the seismic and gravity-magnetic results at Ixtlán and los Negritos areas gave additional features within a great graben in the valleys. The thickness of the Ixtlán valley fill was indicated to be at least 350 m by geophysical data and it was found to be at 380 m by the drill hole logs. Considering the geological-geophysical interpretation so arrived, 11 drill-holes were drilled during 1971-1973 along both areas with approximately 3 km spacing between them. Except along its west end in Ixtlán area, the N-S seismic profile and the drill holes were given essentially to coincide horizontally (within 0.5 km), with the gravity-magnetic profiles.

CONCLUSIONS

The geophysical information obtained, integrated with the geological information from the surveys and the logs, only have a slight modification in the locations of faults from those originally postulated prior to drill hole program in both areas. It is possible to make evident that the geophysical data provided information so that we could stamp physical properties which matched with a tilted broad banding of volcanic rocks. This banding includes the scoriaceous, fractured or sheared basalt and the sedimentary tufaceous material deposited in lacustrine environments. However, the assumed physical properties do not distinguish between the altered effusive rocks mineralizations or someone equivalent rock.

The experience on this investigation suggested an approach of making use of potential fields and their techniques controled by seismic refraction methods. This particular line of attack has provided good results. The contribution of geophysics to a better knowledge of the structures should certainly help to give a more complete understanding of the tectonics and history of the Neovolcanic belt and its relationship to endogene vapor in a trap.

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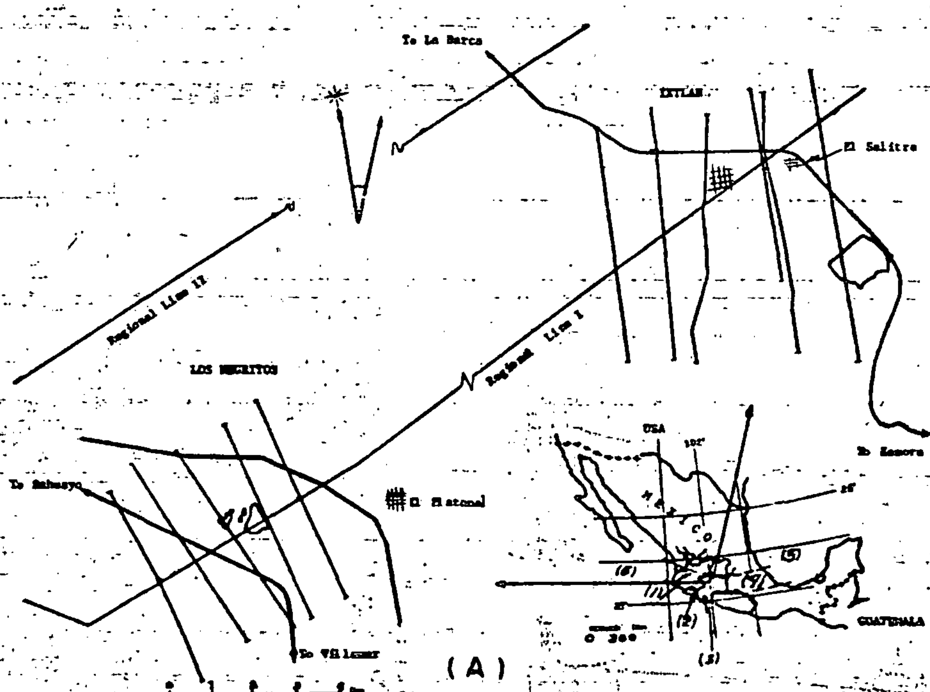


(A)

(1) State of Jalisco
État de Jalisco

(2) State of Colima
État de Colima

(3) State of Michoacan
État de Michoacan

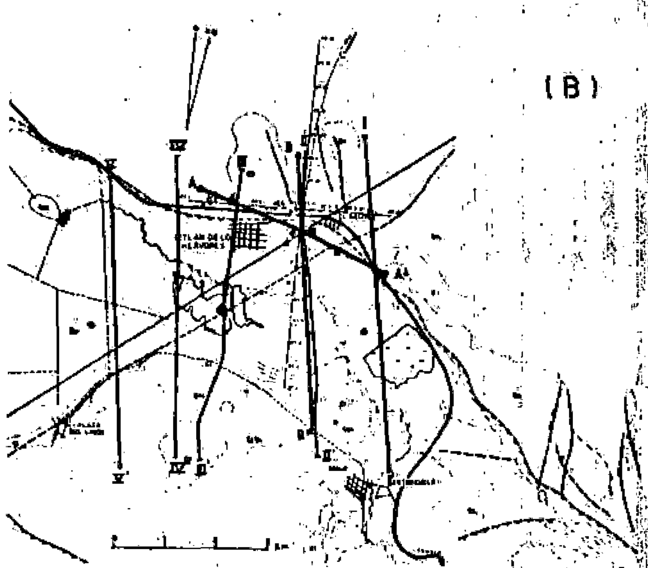
(4) Trans-Mexico Volcanic Belt
Zone Néovolcanique

(5) Gulf of Mexico
Gulfe du Mexique

(6) Pacific Ocean
Ocean Pacifique

FIG.1-A) LOCATION AND INDEX MAPS OF STUDIED AREAS

FIG.1-A) MAPPE INDEX ET DE LOCALIZATION DES RÉGIONS E'TUDIEES



Qb_c — Basalt (Quaternary)
Basalte (Quaternarire)

Qb_1 — Basalt (Early Quaternary)
Basalte (Base du Quaternaire)

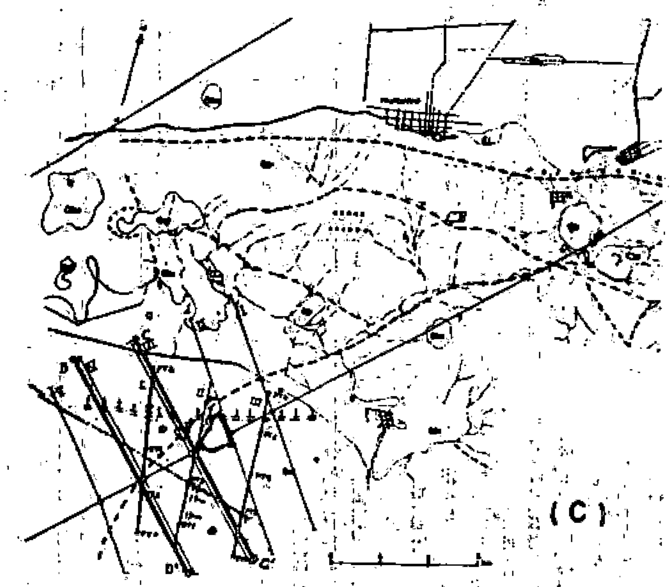
EL — Eluvial deposits
Eluvialle

Qal — Tuff, lacustrine sediments, and alluvial
Roche tufs, sedimentaire et alluviale

Mine
Mine

Lake
Lac

FIG. 1-B) GEOLOGICAL MAP OF THE IXTLAN AREA
FIG. 1-B) MAPPE GÉOLOGIQUE DE LA RÉGION D'IXTLAN



A—A' Cross Section
Coupe

II—II' Gravity and Magnetic profile
Ligne gravimétrique et magnétometrique

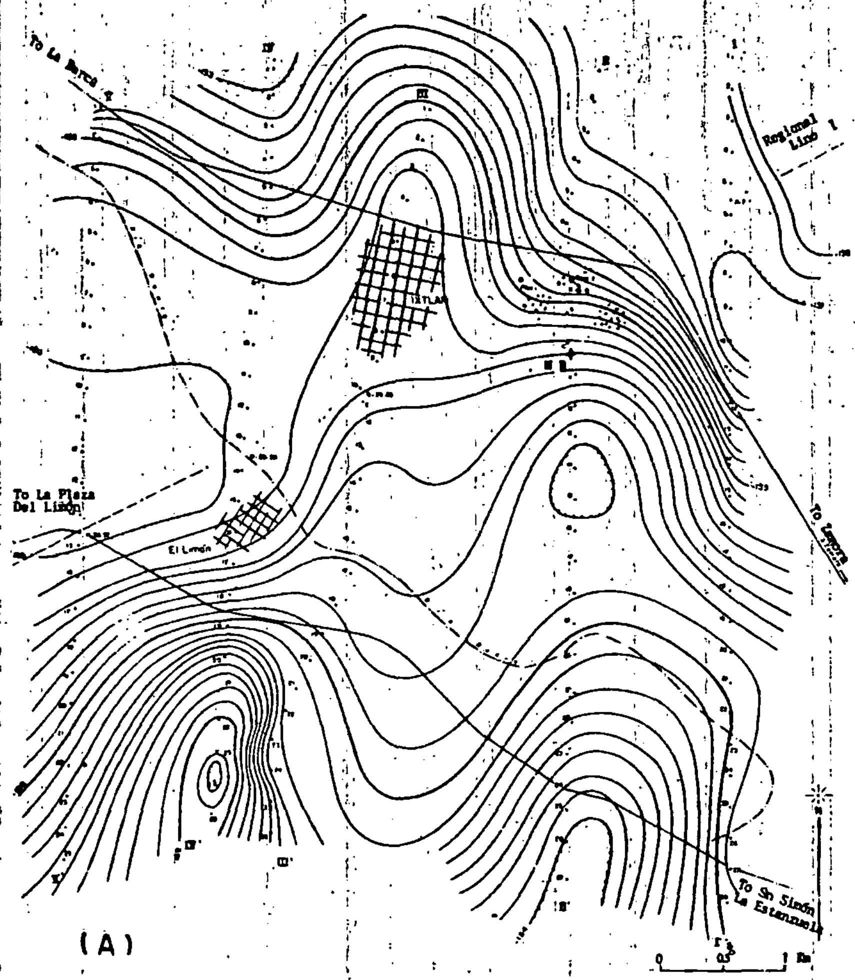
x—x PT4 Seismic refraction line showing shoot points
Ligne de refraction sismique (montre point - d'explosion)

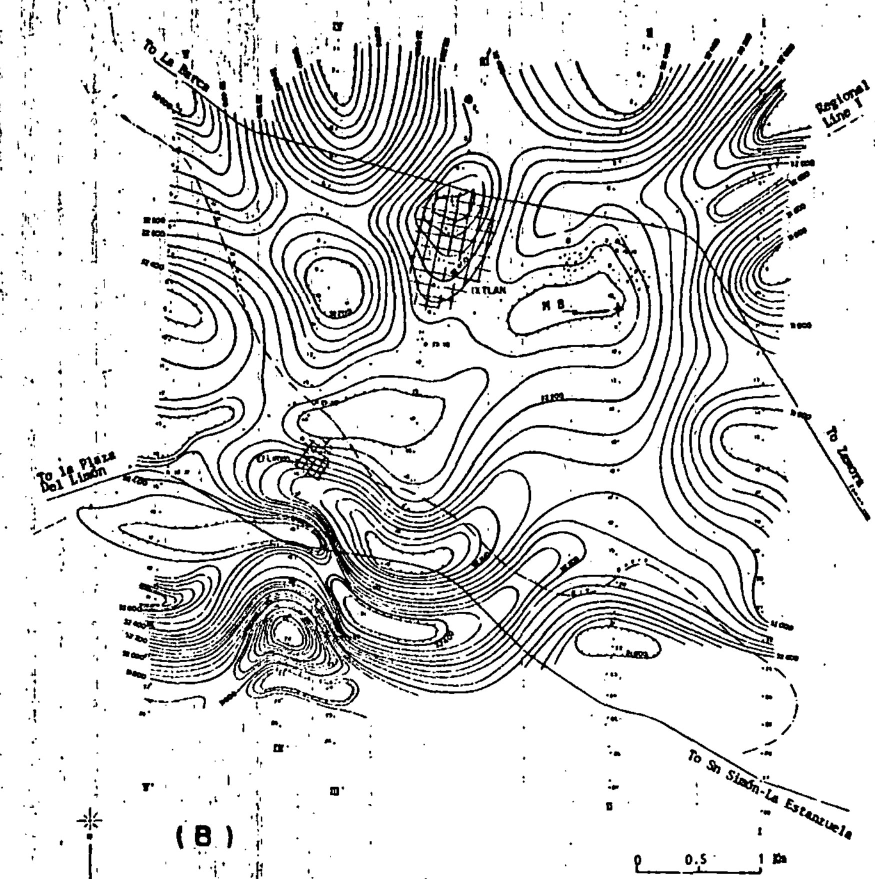
Drill hole
Forage

River
Riviere

Dam
Prise

FIG. 1-C) GEOLOGICAL MAP OF THE NEGRITOS AREA
FIG. 1-C) MAPPE GÉOLOGIQUE DE LA RÉGION DE LOS NEGRITOS





Gravity or magnetic high
Maximum gravimétrique ou magnétométrique

Gravity or magnetic low
Minimum gravimétrique ou magnétométrique

R-17 + Cross with regional line
Croisement avec la ligne régional

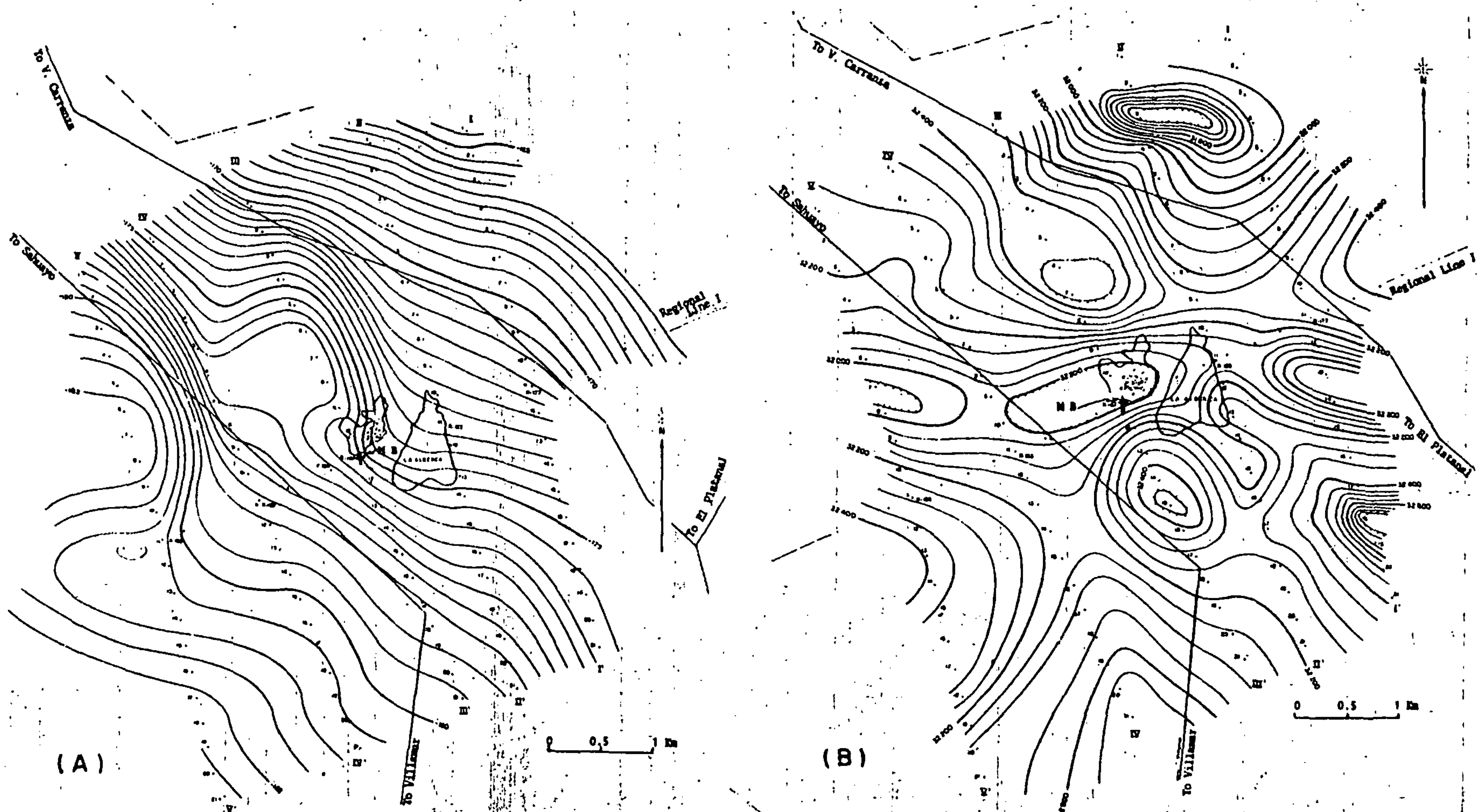
Geothermal manifestations
Manifestation géothermique

MB+ Master Base
Base Maîtresse

o5 Gravity or magnetic station
Station de lecture gravimétrique or magnétométrique

FIG. 2.- CONTOURING GEOPHYSICAL MAPS OF THE IXTLAN AREA. A) DETAILED GRAVITY MAP. B) DETAILED MAGNETIC VERTICAL INTENSITY MAP.

FIG.-2.- MAPPES GEOPHYSIQUES DE LA RÉGION D'IXTLÁN. A) MAPPE GRAVIMÉTRIQUE DETAILLE. B) MAPPE DE LA INTENSITE MAGNÉTIQUE VERTICALE DETAILLE.



Gravity or magnetic high
Maximum gravimétrique ou magnétométrique

Gravity or magnetic low
Minimum gravimétrique ou magnétométrique

R-7 Cross with regional line
Croisement avec la ligne régional

Geothermal manifestations
Manifestation géothermique

MB Master Base
Base Maitresse

Gravity or magnetic station
Station de lecture gravimétrique or magnétométrique

FIG.3.- CONTOURING GEOPHYSICAL MAPS OF LOS NEGRITOS AREA. A) DETAILED GRAVITY MAP. B) DETAILED MAGNETIC VERTICAL INTENSITY MAP.

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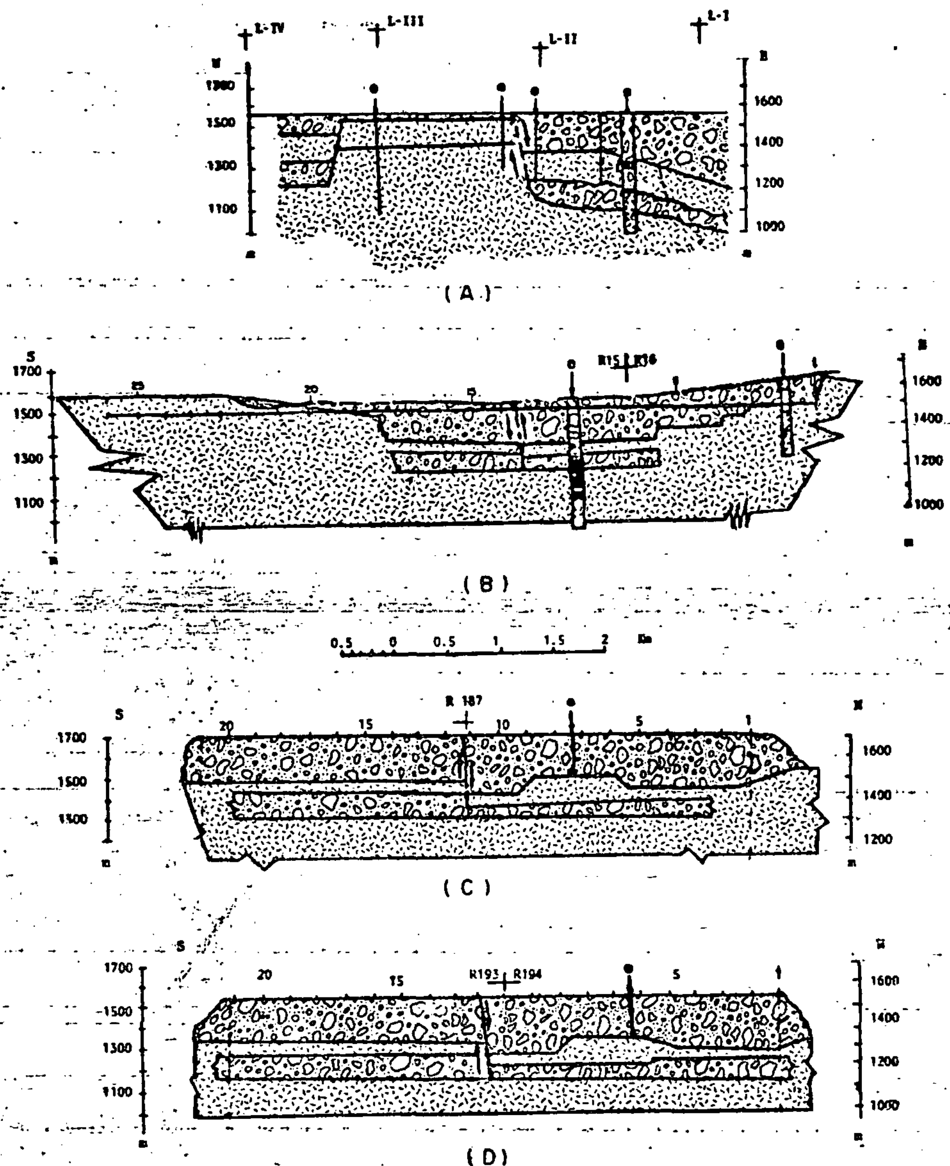

Drill hole extrapolated
Forage par extrapolation

Cross with regional line
Croisement avee la ligne régional

Gravity and magnetic station
Station de lecture gravimétrique, magnétométrique

Inferred fault from geophysical data
Faille par interpretation géophysique

Alluvial and sedimentary rocks
Roche alluviale et sédimentaire

Fractured basalt
Basalt fracture

FIG.4.-CROSS SECTIONS SHOWN IN FIGURE 1-B AND 1-C. (A) CROSS SECTION A-A' IXTLAN AREA (B) CROSS SECTION B-B' IXTLAN AREA (C) CROSS SECTION C-C' LOS NEGRITOS AREA (D) CROSS SECTION D-D' LOS NEGRITOS AREA.

FIG.4.-COUPES DES FIGURES 1-B ET 1-C (A) COUPE A-A' DE LA RÉGION D'IXTLAN (B) COUPE B-B' DE LA RÉGION D'IXTLÁN (C) COUPE C-C' DE LA RÉGION DE LOS NEGRITOS (D) COUPE D-D' DE LA RÉGION DE LOS NEGRITOS.

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The Limón fault is one of the major structural features in Ixtlán area. The Quaternary rocks in the east are faulted against the late Tertiary rocks of the west. In as much as the early Quaternary rocks of the hanging wall are thrust over the rocks of Paleocene age; the age of the fault could be post-Paleocene.

According to González and others (1968), the fault trace extends northeastward in the form of an arc across the valley. Because the fault plane is not exposed anywhere in the area, the dip angle of the fault plane is not known. From modeling (Del Castillo et al, 1970) however, it was estimated that the fault plane dips to the southeast or northwest at an angle between 70° and 80° and implied that the fault was formed by a tectonic collapse. Other geologists concluded that the dip angle of the fault plane must be close to 90°; at least near the unknown trace. Also, the throw of the fault is unknown. However, it is estimated to be at least equal to the thickness of the sedimentary section at the base of the foothills of the Sierra de Pajacuarán.

Apparently, the structural pattern at los Negritos area is much more simpler than at Ixtlán area. Gómez (1969) assures that the structure at los Negritos is indêpendent to the one at Ixtlán. Unfortunately, the seismic work (Del Castillo, 1971) and the drill hole program in los Negritos was executed later, and the information from drilling was only used here for correlationship.

From the above, the importance of tectonics in both areas is inferred. It is immaterial whether if we refer to the origin of trenches or to different volcanic phenomema (Bernea, 1972; Mooser, 1972). Both effects are responsible of geothermal manifestations at the surface. They formed structural conditions to make its presence possible. The surface evidences of geothermics in both areas is reflected clearly by the great - number of fumaroles or geiseres and hot springs of various types. It is believed that the zone of endogene vapor is delineated by faulting systems whose evidences under - ground are covered by alluvial and sedimentary material. Besides it is possible that - the steam when invades sediments is trapped by its own volume in expansion. Then, salty precipitates seal the trap; otherwise, it flows due to the lack of equillibrium in pressure. (Sandoval, 1970).

Thus it was hoped that the combination of seismic refraction and gravity-magnetic data would indicate the geological structures under the valleys. In connection - with the development of resources of energy through out the world, geophysical surveys have been recognized lately as an aid to discern structural patterns in the exploration phase.

GEOPHYSICAL SURVEY AND INTERPRETATION

Ten gravity-magnetic profiles, one and a half kilometer apart, with approximately two hundred and fifty meters spacing between stations were established across the valleys from north and south of the Sierra Pajacuarán. Later two northward and eastward trending seismic refraction profiles were established at Ixtlán area (Del Castillo et al 1970b; Del Castillo, 1971) and three northward at los Negritos area (Figures 1-B and 1-C). All profiles were reversed. The collected geophysical data are refered to a network of base stations established in the areas. This network was tied to station 1438 of the National Gravity Net in Zamora City, Michoacán. The total number of the gravity and magnetic stations occupied in the area (Del Castillo et al, 1970a) are 359 and 1506 respectively (Figures 1 to 3). The latter figures include stations locations of two regional control profiles; one of the regionals crossed all detailed profiles at Ixtlán - and los Negritos.

The interpretation procedure followed in the gravity-magnetic work was essentially that of curve fitting by trial and error. A volcanic influence was assumed in the - vicinity of each interpreted profile (Del Castillo et al, 1970a). Cominguez (1972)discussed the computed modelling in comparison of second vertical derivatives and continuation of fields for los Negritos area.

In the refraction data of Ixtlán area, Del Castillo et al(1970b and 1971) interpreted the higher velocities as repres entative of basaltic flows varying in texture or fractured, overlying and underlying bodies of alluvial and sedimentary lacustrine material. The anomalous feature of the curves could possibly be explained by a folding of the surface rocks or by a nearly vertical fault. The fault interpretation was prefered because of the observed change of gravity gradient and a magnetic polarity at this location (Figures 2 and 4). Thus, the interpretation of features of these curves is that they are manifestation of a nearly vertical fault acompanied by a strong seismic velocity contrast.

These facts confirm the aception of a graben. From the data, it was not possible to tell the exact amount of throw of the postulated faults; however, it was more than 150 m, as it is shown on Cross Section A-A' (Figure 4) on the basis of drill holes. The general structural pattern obtained by the refraction work at Ixtlán area was used on the polygon modelling to fit the gravity-magnetic data. Figure 2-B shows that the north-south magnetic trend in the northern part of the profiles is consistent along the area; however, the width of the rock-body producing anomaly may be variable along the N-S strike of the body; on the other hand the north east gravity nose (Figure 2-A) is too sharp and wide to be related to geological characteristics overlying older structures (Figure 4-A). This block was called Banco Ixtleco and plays an important role on the structural graben in the Ixtlán area. It should be noted that the total gravity relief due to the graben is about 5 mgal (-157 to -152). Although it is believed that the proposed structures are reasonable, it must be emphasized that instead of the few faults which are postulated, a series of smaller step faults will give similar results for the gravity and magnetic data. It is believed, however, that the total displacement along a fault block mountain often occurs by large movements along a relatively few major faults rather than the cumulative effect of small movements along many minor faults in the area (Figure 1-B). The indicated thickness of the valley fills for the largest density-susceptibility assumed constrast between the bedrock and the valley fill is about 200 or 350 m.

Of the faults shown on the west side of the valley the northward projection of the west fault at drill hole No. 2 coincides with hot springs, just off the map in Figure 1; and it is, therefore, suggested that these springs are possibly due to this fault. The eastward and westward extents of the graben and its relationship to the Tectonic Trenches are treated in another investigation (Mooser, 1972).

In los Negritos area (Figure 3-A) the Bouguer map shows a conspicuos flat along the gravity gradient of a 4 mgal per kilometer. The magnetic map shows dipolarities in an E-W trend. On the basis of the gravity and magnetic expression, there is not many geologic bodies to choose which would produce such anomaly pattern. Therefore, the interpreted bodies had strong possibilities to match the residual anomalies obtained before (Del Castillo et al, 1970a). In recent seismic refraction surveying the gravity-magnetic interpretation fitted quite well (Del Castillo, 1971). The presented two cross sections (Figures 4-C and D) were built up from the combination of geophysical data and one drill hole log, trying to make use of the general quantitative interpretation given before.

The gravity and magnetic results together with resistivity data in the surrounding region (García, 1970), indicated that both valleys are a northeast-trending grabens, bounded north and south by two or more faults. Tertiary to Quaternary rocks, mostly fine texture and fractured basalts, out crop on either side of the valleys.

The drill hole program suggested that the seismic and gravity-magnetic results at Ixtlán and los Negritos areas gave additional features within a great graben in the valleys. The thickness of the Ixtlán valley fill was indicated to be at least 350 m by geophysical data and it was found to be at 380 m by the drill hole logs. Considering the geological-geophysical interpretation so arrived, 11 drill-holes were drilled during 1971-1973 along both areas with approximately 3 km spacing between them. Except along its west end in Ixtlán area, the N-S seismic profile and the drill holes were given essentially to coincide horizontally (within 0.5 km) with the gravity-magnetic profiles.

CONCLUSIONS

The geophysical information obtained, integrated with the geological information from the surveys and the logs, only have a slight modification in the locations of faults from those originally postulated prior to drill hole program in both areas. It is possible to make evident that the geophysical data provided information so that we could stamp physical properties which matched with a tilted broad banding of volcanic rocks. This banding includes the scoriaceous, fractured or sheared basalt and the sedimentary tufaceous material deposited in lacustrine environments. However, the assumed physical properties do not distinguish between the altered effusive rocks mineralizations or someone equivalent rock.

The experience on this investigation suggested an approach of making use of potential fields and their techniques controled by seismic refraction methods. This particular line of attack has provided good results. The contribution of geophysics to a better knowledge of the structures should certainly help to give a more complete understanding of the tectonics and history of the Neovolcanic belt and its relationship to endogene vapor in a trap.

Acknowledgements.- The interpretation was conducted by the Departamento de Exploración at the Instituto de Geofísica of the Universidad Nacional Autónoma de México, under contract and in cooperation with the Comisión Federal de Electricidad. Appreciation is given to Departamento de Recursos Geotérmicos at the CFE for permission to present this revision of data. Many thanks to J.H. Sandoval, M.A. Calderón and M. Rivas T. for helping to construct cross sections and drawings.

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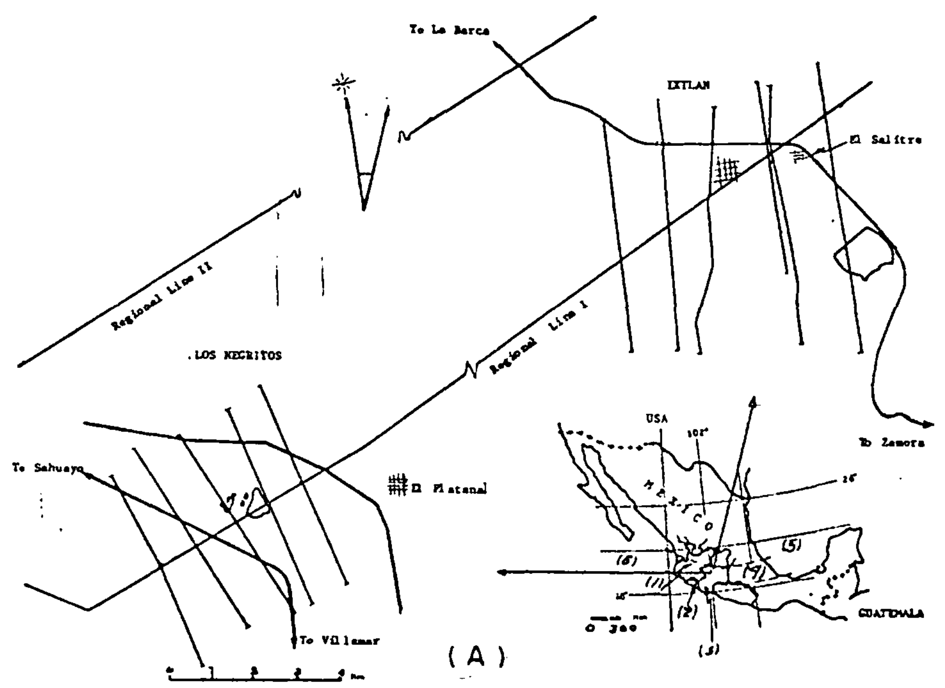


(A)

(1) State of Jalisco
État de Jalisco

(2) State of Colima
État de Colima

(3) State of Michoacan
État de Michoacan

(4) Trans-Mexico Volcanic Belt
Zone Néovolcanique

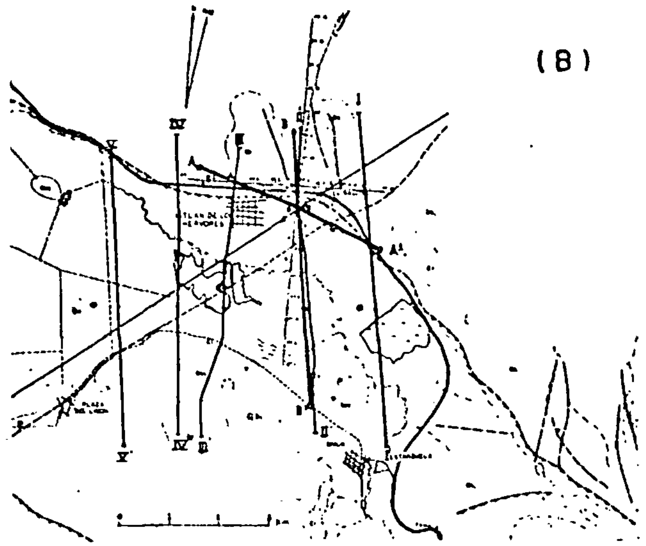
(5) Gulf of Mexico
Gulfe du Mexique

(6) Pacific Ocean
Ocean Pacifique

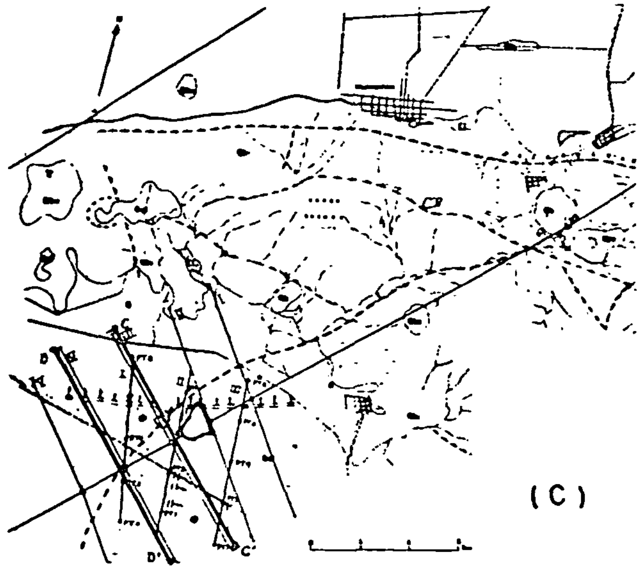
FIG.1-A) LOCATION AND INDEX MAPS OF STUDIED AREAS

FIG.1-A) MAPPE INDEX ET DE LOCALIZATION DES RÉGIONS E'TUDIEES

(B)



(C)



Qb$_c$ — Basalt (Quaternary)
Basalte (Quaternarire)

Qb$_1$ — Basalt (Early Quaternary)
Basalte (Base du Quaternaire)

EL — Eluvial deposits
Eluvialle

Qal — Tuff, lacustrine sediments,and alluvial
Roche tufs, sedimentaire et alluviale

Mine
Mine

Lake
Lac

A — A' Cross Section
Coupe

II — II' Gravity and Magnetic profile
Ligne gravimétrique et magnétometrique

x — x PT4 Seismic refraction line showing shoot points
Ligne de refraction sismique (montre point d'explosion)

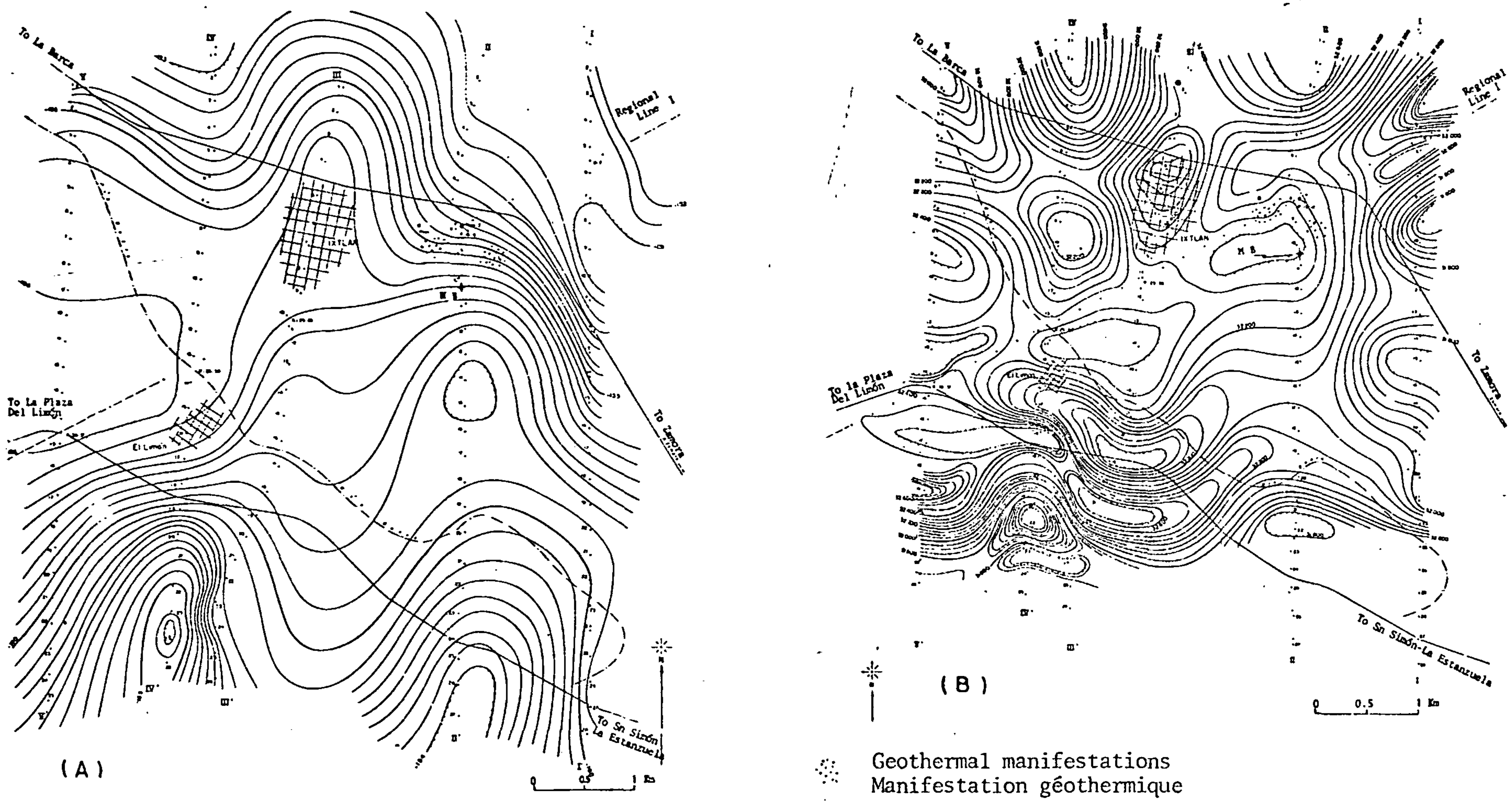
Drill hole
Forage

River
Riviere

Dam
Prise

FIG.1-B) GEOLOGICAL MAP OF THE IXTLAN AREA
FIG.1-B) MAPPE GÉOLOGIQUE DE LA RÉGION D'IXTLAN

FIG.1-C) GEOLOGICAL MAP OF THE NEGRITOS AREA
FIG.1-C) MAPPE GÉOLOGIQUE DE LA RÉGION DE LOS NEGRITOS



Gravity or magnetic high
Maximum gravimétrique ou magnétométrique

Gravity or magnetic low
Minimum gravimétrique ou magnétométrique

Cross with regional line
Croisement avec la ligne régional

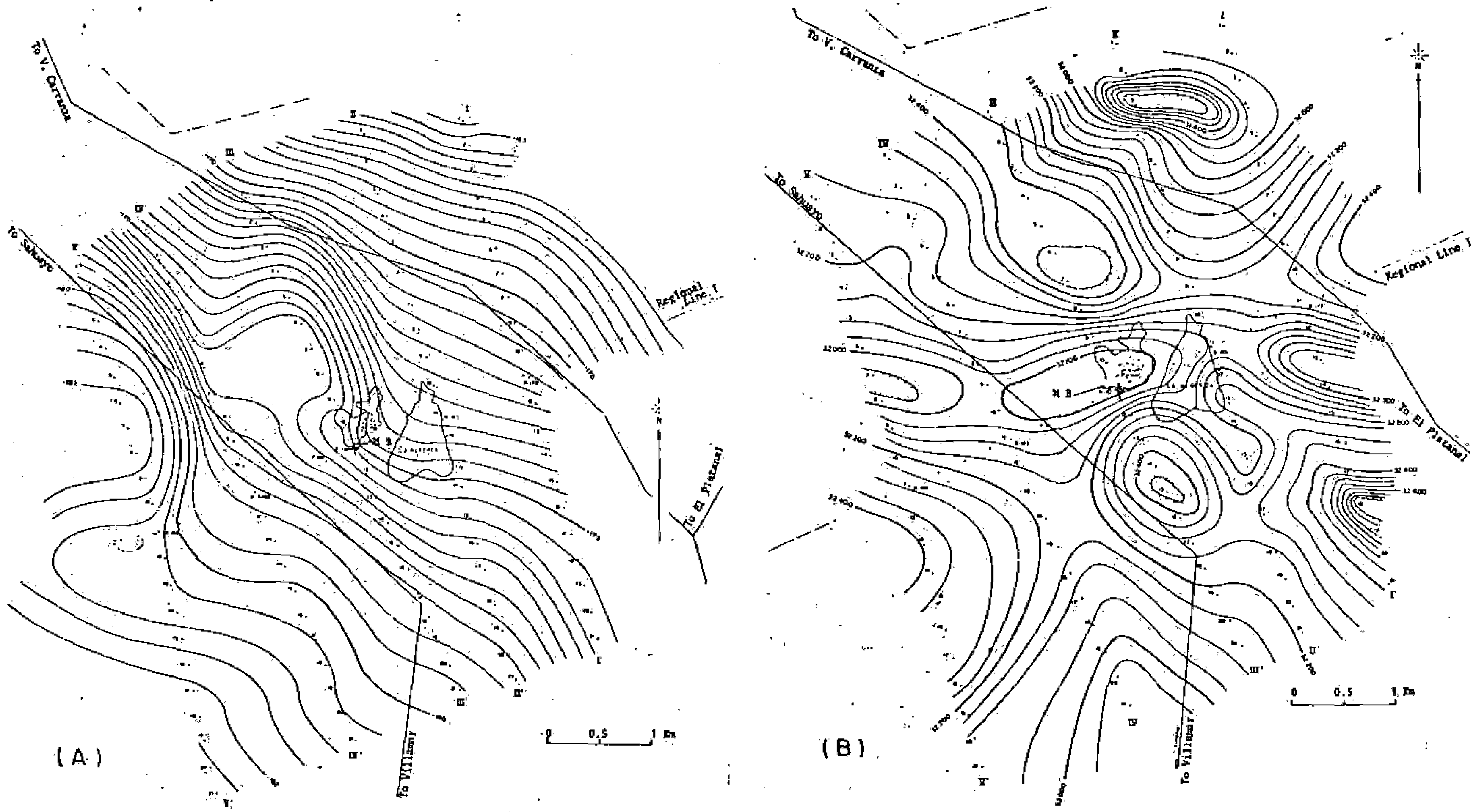
Geothermal manifestations
Manifestation géothermique

Master Base
Base Maîtresse

Gravity or magnetic station
Station de lecture gravimétrique or magnétométrique

FIG. 2.- CONTOURING GEOPHYSICAL MAPS OF THE IXTLAN AREA. A) DETAILED GRAVITY MAP. B) DETAILED MAGNETIC VERTICAL INTENSITY MAP.

FIG.-2.- MAPPES GEOPHYSIQUES DE LA RÉGION D'IXTLÁN. A) MAPPE GRAVIMÉTRIQUE DETAILLE. B) MAPPE DE LA INTENSITE MAGNÉTIQUE VERTICALE DETAILLE.



Gravity or magnetic high
Maximum gravimétrique ou magnétométrique

Gravity or magnetic low
Minimum gravimétrique ou magnétométrique

R-7 Cross with regional line
Croisement avec la ligne régional

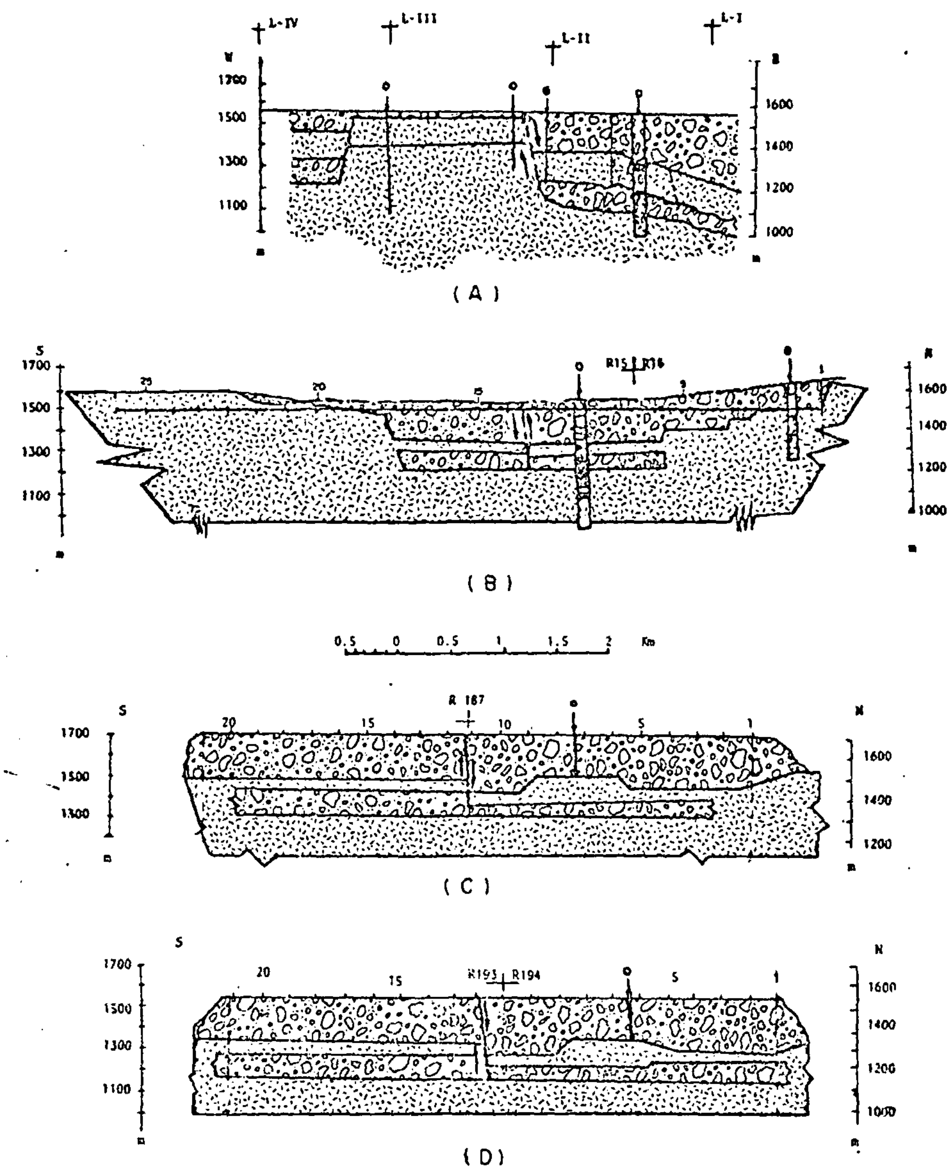
Geothermal manifestations
Manifestation géothermique

MB Master Base
Base Maitresse

Gravity or magnetic station
Station de lecture gravimétrique or magnétométrique

FIG.3.- CONTOURING GEOPHYSICAL MAPS OF LOS NEGRITOS AREA. A) DETAILED GRAVITY MAP. B) DETAILED MAGNETIC VERTICAL INTENSITY MAP.

FIG.3.- MAPPES GÉOPHYSIQUES DE LA RÉGION DE LOS NEGRITOS. A) MAPPE GRAVIMETRIQUE DETAILLE. B) MAPPE DE LA INTENSITE MAGNÉTIQUE VERTICALE DETAILLE.



• Drill hole extrapolated
Forage par extrapolation

Inferred fault from geophysical data
Faille par interpretation géophysique

R-7 + Cross with regional line
Croisement avee la ligne régional

Alluvial and sedimentary rocks
Roche alluviale et sédimentaire

15 Gravity and magnetic station
Station de lecture gravimétrique, magnétométrique

Fractured basalt
Basalt fracture´

FIG.4.-CROSS SECTIONS SHOWN IN FIGURE 1-B AND 1-C. (A) CROSS SECTION A-A' IXTLAN AREA (B) CROSS SECTION B-B' IXTLAN AREA (C) CROSS SECTION C-C' LOS NEGRITOS AREA (D) CROSS SECTION D-D' LOS NEGRITOS AREA.

FIG.4.-COUPES DES FIGURES 1-B ET 1-C (A) COUPE A-A' DE LA RÉGION D'IXTLAN (B) COUPE B-B' DE LA RÉGION D'IXTLÁN (C) COUPE C-C' DE LA RÉGION DE LOS NEGRITOS (D) COUPE D-D' DE LA RÉGION DE LOS NEGRITOS.

AREA. A) DETAILED GRAVITY MAP. B) DETAILED MAGNETIC VERTICAL INTENSITY MAP.

INTENSITE MAGNETIQUE VERTICALE DETAILLE.

Joe Joint CFE/DOE mtg. Geochemistry

3/89 5-85151 5 hs

STRATIGRAPHY OF THE LOS AZUFRES GEOTHERMAL RESERVOIR

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ABSTRACT

The reservoir at Los Azufres is developed primarily in lava flows, breccias, and tuffaceous deposits of the Mil Cumbres andesites. Chemical analyses of samples from five wells drilled in the northern part of the field has led to the recognition of four distinct volcanic sequences within the upper 2500 m of the reservoir. These sequences can be correlated across the field.

The upper three sequences consist dominantly of andesite with minor interbedded basaltic andesite and dacite. These sequences can be differentiated on the basis of their rare-earth element, MgO, TiO_2, and P_2O_5 contents. The deepest volcanic sequence encountered in the wells is composed mainly of basaltic andesite interbedded with minor andesite.

RESUMEN

El yacimiento de Los Azufres es desarollado principalmente en flujos de lava, brechoides y depósitos tobáceos de las Andecitas Mil Cumbres. Analysis químicos de muestras de cinco pozos perforados en la parte norte del campo, ha dado a reconocer cuatro secuencias volcánicas distintas dentro de los 2500 m superiores del yacimiento. Estás secuencias pueden ser correladas atravez del campo.

Las tres secuencias superiores consisten mayormente de andesitas con menores intercalaciones de andesita basáltica y dacita. Estás secuencias se pueden diferenciar basado en sus contenidos de elementos tierras raras, MgO, TiO_2, y P_2O_5. La secuencia volcánica mas profunda encontrada en los pozos es compuesta mayormente de andesita basáltica intercalada con andesita menor.

INTRODUCTION

Los Azufres, located 80 km east of Morelia, Michoacan is one of several high-temperature geothermal fields occurring along the northern margin of the Neovolcanic Belt of central Mexico and the only one that is currently generating electricity (Fig. 1). Since detailed investigation of the geothermal system began in 1975, 57 wells have been drilled to depths of up to 3.5 km. These wells have encountered temperatures near 300°C in fractured volcanic rocks of Tertiary age. The field currently supports a 50 Mw power plant and six 5 Mw wellhead generators.

In contrast to the geothermal systems at Los Humeros and La Primavera, which are both associated with calderas, Los Azufres is associated with young silicic domes emplaced into highly faulted Neogene andesites. The complex geometry of the andesite flows and the lack of lithologically distinctive horizons has so far hindered development of a detailed stratigraphic and structural model of the thermal system. In this paper we first describe the chemistry of the volcanic rocks encountered in five wells drilled in the northern part of the field. These data are then used to define the stratigraphy in the upper 2500 m of the reservoir.

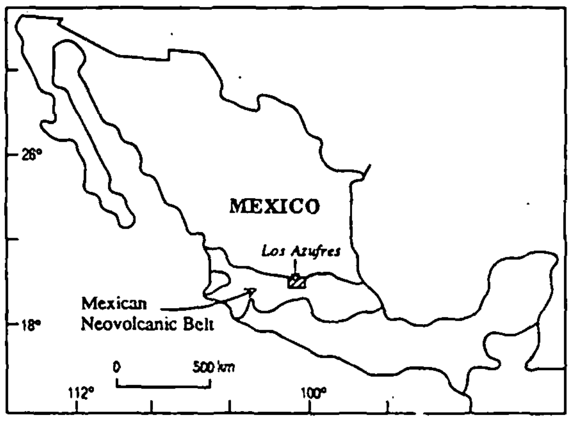

Fig. 1. Location map of the Los Azufres geothermal system.

REGIONAL GEOLOGY OF THE LOS AZUFRES AREA

The prevolcanic basement beneath Los Azufres consists of metamorphic and sedimentary rocks that range in age from late Mesozoic to Tertiary. Early Cretaceous sandstones, shales, and intercalated volcanic rocks that have been metamorphosed to the greenshist facies are exposed to the south and east of Los Azufres near Aporo, Senguio, Tuxpan, and Zitacuaro (Comacho, 1979). In the Pat-

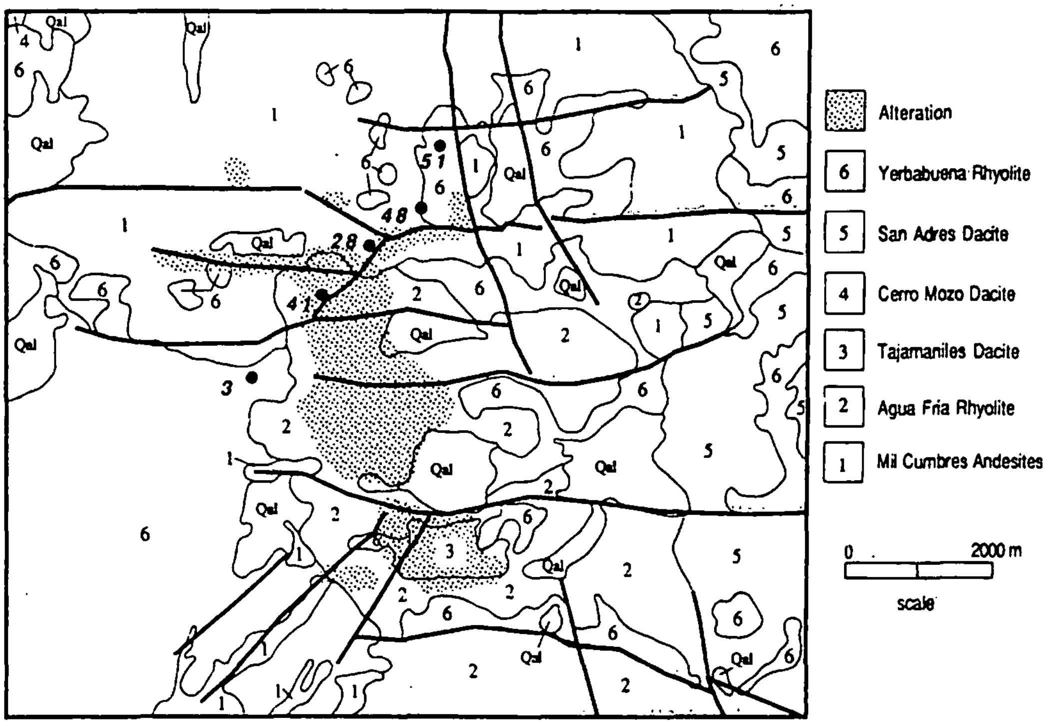

Fig. 2. Geologic map of the Los Azufres thermal area. The locations of the wells included in this investigation are shown by the large dots.

ambaro anticline, located 35 km southwest of Los Azufres, the metamorphic rocks are overlain by sedimentary deposits that consist of a lower sequence of flysch facies sandstones and mudstones/siltsones and an upper sequence of mollasse facies deposits. The lower sequence of marine deposits has been assigned to the late Cretaceous. The upper deposits are thought to be correlative with the iron-rich arenaceous conglomerates of the Paleocene-Oligocene Balsas Group.

The sedimentary basement is covered by a thick, dominantly andesitic suite of flows, breccicas, and tuffs. Deposition of this lithologically diverse volcanic suite, known as the Mil Cumbres andesites, may have begun as early as Oligocene or Miocene time. Lava flows from the upper part of the volcanic section exposed near Querendaro have yielded K-Ar ages of 18 and 13.5 my (Table 1; Demant et al. 1975). Similar lavas from a depth of 2700 m in well Az-20 have a K-Ar age of 10.2 my (Dobson and Mahood, 1985). Andesitic volcanism continued at least until 1.03 my ago with the eruption of flows exposed north of Zacatonal (Dobson and Mahood, 1985). The distribution of the Mil Cumbres andesites at Los Azufres is shown in Figure 2.

Volcanic activity at Los Azufres changed from dominantly andesitic to silicic approximately 1 my ago (Table 1; Dobson and Mahood, 1985). Silicic volcanism began with the eruption of the Tejamaniles dacites and Agua Fria rhyolites and rhyodacites in the central part of the geothermal field between 1.03 and 0.8 my ago (Fig. 2). The Agua Fria rhyolites are overlain, on the eastern margin of the thermal system, by flows and domes of the San Andres dacites. These flows range from dacite to rhyodacite in composition. One of the flows of the San Andres dacites has yielded a K-Ar age of 0.3 my. The Cerro Mozo dacite dome, located in the northwest corner of Figure 2 may be

TABLE 1
Summary of K-Ar dates for the Los Azufres region

Locality	Age (m.y.)	Source
Mil Cumbres Andesites		
Querendaro Michoacan	18	2
19°39':100°57'	13.8 ± 0.7	2
19°46'23":100°41'10" (2700 m)	10.2 ± 0.6	4
19°49'04":100°39'29"	5.92 ± 0.14	5
unknown drill hole	5.9 ± 0.4	4
19°46'47":100°40'00" (900 m)	5.0 ± 0.4	4
19°45'23":100°41'10" (720-1000 m)	3.1 ± 0.2	4
19°50'31":100°39'32"	1.36 ± 0.06	5
19°49'48":100°38'11"	1.03 ± 0.20	1
Agua Fria Rhyolites		
unknown	1.2 ± 0.4	4
19°46'21":100°30'26"	1.03 ± 0.02	1
19°48'34":100°38'50"	0.90 ± 0.03	5
19°48'46":100°40'22"	0.84 ± 0.02	1
Tejamaniles Dacites		
19°47'09":100°29'52"	1.08 ± 0.025	5
19°46'58":100°39'46"	0.93 ± 0.04	1
San Andres Dacites		
19°46'38":00°37'30"	0.33 ± 0.07	1
Yerbabuena Rhyolites		
19°45'32":100°42'52"	0.30 ± 0.07	1
19°47'41":100°42'27"	0.15 ± 0.05	1
19°48'05":100°43'15"	0.14 ± 0.02	1
19°47'39":100°41'14"	0.13 ± 0.01	5

1. Dobson and Mahod, 1985
2. Comacho, 1979
3. Demant et al., 1975
4. Aumento and Guiterrez, 1980
5. This study

contemporaneous with this volcanic episode. The youngest phase of silicic activity is represented by the Yerbabuena rhyolites and rhyodacites. This eruptive cycle produced five domes that were emplaced on the western margin of the field between 0.14 and 0.3 my ago. Dobson and Mahood (1985) have suggested that a shallow magma body which produced the Yerbabuena rhyolite domes may provide the heat that supports the present geothermal system.

Pleistocene cinder cones that partially ring the thermal system represent the youngest episode of volcanic activity in the Los Azufres region (Dobson and Mahood, 1985). A diabase dike, thought to be related to this basaltic volcanism was encountered at a depth of 600 m in well Az-7 (Gutierrez and Aumento, 1982).

The structural and volcanic setting of the Los Azufres region is intimately related to the evolution of the Neovolcanic Belt of Mexico. On a regional scale, Cenozoic activity within this trend reflects the interactions of the Cocos, North American, and Caribbean plates. In the central and eastern parts of the Neovolcanic Belt, movement of the plates has given rise to fracture systems oriented N60E and N7W. Similar fault orientations have been mapped at Los Azufres (Fig. 2). It is apparent from this geologic map that no simple age relationship exists between the different fault sets. The distribution of hot springs, fumaroles, and altered ground indicates that both north- and east-trending faults are open and that they play an important role in controlling fluid movement. Stratigraphic relationships discussed below imply that some of the movement on the east-trending faults was contemporaneous with emplacement of the Mil Cumbres andesites.

CHARACTERISTICS OF THE RESERVOIR ROCKS

The reservoir at Los Azufres is developed primarily in fractured lava flows of the Mil Cumbres andesites. Petrographically, these flows range from olivine basalt to hornblende andesite and dacite, with andesites being the most common (Gutierrez and Aumento, 1982; Viggiano, 1987). The primary mineral assemblages in the more mafic volcanics consist of plagioclase, clinopyroxene, iron-titanium oxides, and olivine. The more silicic rocks are characterized by variable proportions of plagioclase, ortho and clinopyroxene, hornblende, iron-titanium oxides, biotite, and zircon. Primary quartz is present in the dacites.

The Mil Cumbres andesites are overlain by the Agua Fria rhyolites in the central and southern portions of the geothermal field. The rhyolites typically range from a few tens of meters to three hundred meters thick although wells drilled into the vent areas have encountered as much as 1100 m of silicic rocks. The Agua Fria rhyolites are characterized by 5 to 15 percent phenocrysts of quartz, plagioclase, and sanidine (Dobson and Mahood, 1982; Viggiano, 1987).

Hydrothermal alteration related to the geothermal system has converted the glassy matrix and primary mineral assemblages of the volcanic rocks to mixtures of clays, chlorite, micas, calcite, iron oxides, quartz, and epidote (Cathelineau et al. 1982; Viggiano, 1987). However, even in the intensely altered rocks, the primary textures and the relative proportions of ferromagnesium minerals to feldspar and quartz can frequently be determined. From petrographic relationships, Gutierrez and Aumento (1982) were able to distinguish four major volcanic sequences within the Mil Cumbres andesites which they considered to be of field wide extent. However, with the exception of the upper sequence of "felted andesites", it was generally not possible to accurately locate the boundaries of these volcanic sequences or to correlate flows even between closely spaced wells.

CHEMISTRY AND CHEMICAL SUBDIVISION OF THE MIL CUMBRES ANDESITES

Chemical fingerprinting of aphyric lava flows lacking distinctive mineralogical characteristics has proven to be a useful method for correlating flow packets on a regional scale (Mangan et al., 1986). In the present investigation, the compositions of 36 samples from five wells were determined and statistically evaluated. The statistical procedure used here was initially tested on samples from wells Az-51 and 48 because the two wells are deep and located near each other. The objective of this initial study was to determine the range of compositions displayed by volcanic rocks of the Mil Cumbres andesites and to determine if the rocks could be grouped into chemically related sequences of regional extent. Wells Az-28, 41, and 3 were subsequently added to extend the initial correlations to the southwest.

Chemical analyses were performed on representative samples of each of the major lithologic units found in the wells by CFE geologists (unpublished CFE lithologic logs). The sample intervals ranged from 6 to 12 m depending on the quantity of material that was available, and the extent of hydrothermal alteration present in the samples. Efforts were made to select samples that displayed the least amount of alteration. Each sample was analyzed for its major, minor and trace element contents by inductively coupled argon plasma (ICP) spectrometry, and wet chemical techniques at the University of Utah Research Institute. The rare-earth element (REE) contents of the samples were determined by instrumental neutron activation analysis (INNA) at Portland State University by Dr. M. Beeson.

The results of the chemical analyses are summarized in Table 2. Because of the large amount of chemical data, cluster analysis was used to determine the number of distinct chemical groups that are present in the sample population. This technique provides a direct method of grouping samples together based on the similarity of their chemical compositions. Cluster analysis algorithms differ in the criteria they use to determine the similarity between individual samples and groups. The algorithm that was used in this study was the weighted pair-group average clustering algorithm for distance similarity given by Davis (1973). The cluster analysis was performed on the major element contents of the samples calculated on an anhydrous basis.

The results of the cluster analysis are summarized in Table 2 and illustrated graphically in Figure 3. Eighty one of the 86 samples could be assigned to one of nine major chemical groups (Groups A-D and G-K; Table 2). The rocks range in composition from basaltic andesite to dacite with andesites being dominant. The basaltic andesites (Groups H and I) have silica contents that range from 53.2 to 54.6 weight percent. The low silica basaltic andesites of Group H can be distinguished from the slightly more siliceous flows of Group I by higher concentrations of Al_2O_3, and Zr and lower contents of MgO and Cr.

The andesites have silica contents that range from 56.9 to 62.5 weight percent. Figure 4 shows that the andesites can be distinguished from each other and from the basaltic andesites and dacites on the basis of small but significant variations in their SiO_2 and MgO contents. Groups A, B, and G can be separated by their MgO contents and from groups C, D, and J by lower SiO_2 concentrations.

Only five samples could not be assigned to the nine major chemical groups or correlated with each other. Samples E and F differ from the majority of the andesites in their Al_2O_3 and MgO

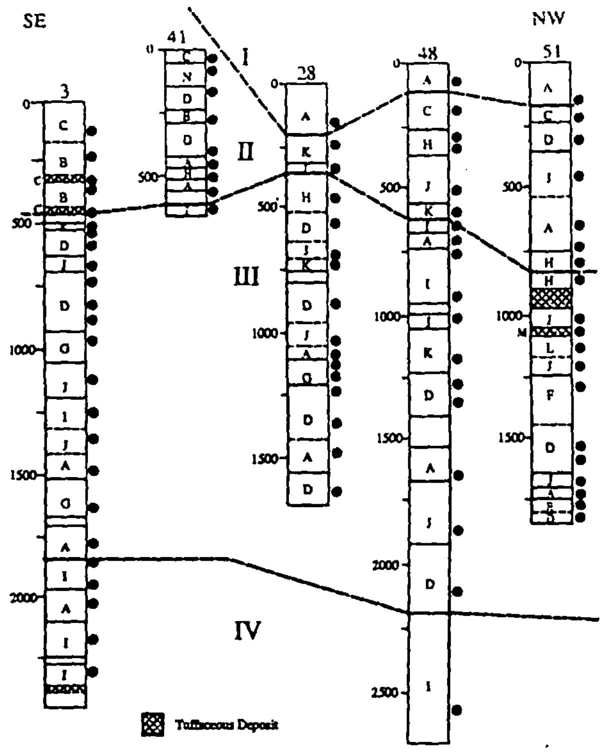

Fig. 3. Chemical stratigraphy of the Mil Cumbres andesites in the northern part of the reservoir. The chemical groups labeled A through N correspond to those listed in Table 2. Solid contacts between chemical groups were taken from unpublished Comision Federal de Electricidad logs. The dashed contacts are based on the chemical data. Volcanic sequences of field-wide extent are delineated by Roman numerals.

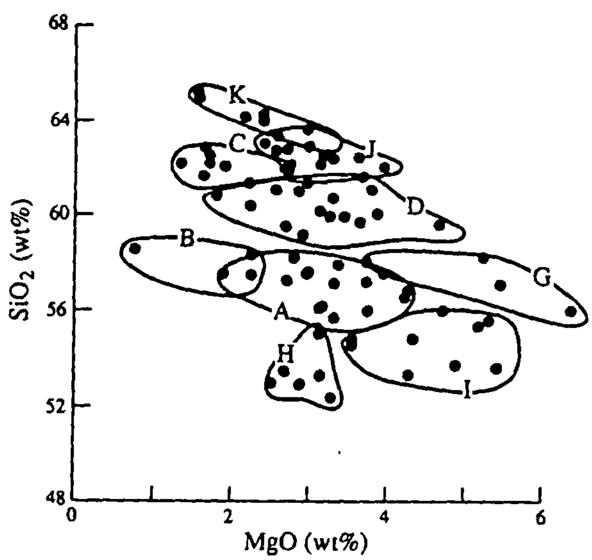

Fig. 4. MgO-SiO_2 variation diagram showing compositional fields defined by the nine major chemical groups given in Table 2.

TABLE 2

Average compositions[1] of chemical groups of the Mil Cumbres andesites

Chemical Group	A		B		C		D		E	F	G
SiO2	56.91	(0.73)	57.99	(0.50)	62.29	(0.39)	60.51	(0.78)	58.47	60.09	57.25
TiO2	1.26	(0.28)	1.58	(0.07)	1.15	(0.12)	0.95	(0.18)	0.90	0.96	1.00
Al2O3	18.14	(0.50)	18.06	(0.73)	17.83	(0.70)	17.39	(0.60)	17.28	14.80	16.41
Fe2O3	7.15	(0.95)	8.14	(0.47)	6.21	(0.54)	5.79	(0.65)	5.63	6.90	6.46
Na2O	3.73	(0.36)	4.21	(0.56)	3.72	(0.63)	3.67	(0.54)	5.66	3.52	3.08
K2O	1.36	(0.50)	2.20	(0.47)	2.22	(0.33)	1.73	(0.49)	2.18	2.02	2.08
CaO	7.46	(0.68)	5.54	(0.39)	4.87	(0.35)	6.44	(0.53)	4.23	6.28	7.11
MgO	3.35	(0.59)	1.81	(0.72)	1.73	(0.17)	3.15	(0.64)	3.73	5.42	5.19
P2O5	0.32	(0.10)	0.53	(0.07)	0.29	(0.03)	0.24	(0.05)	0.25	0.35	0.32
MnO	0.12	(0.02)	0.13	(0.01)	0.08	(0.02)	0.10	(0.01)	0.09	0.09	0.11
Sr	564	(108)	630	(79)	429	(71)	623	(171)	677	506	634
Ba	454	(89)	760	(54)	647	(112)	493	(77)	510	550	475
Zr	149	(58)	215	(25)	232	(32)	115	(44)	65	130	93
Co	32	(7)	30	(2)	39	(22)	27	(5)	33	29	28
Cr	59	(32)	64	(81)	48	(59)	66	(38)	130	150	127
La	17.6	(4.5)	27.4	(5.6)	22.7	(0.3)	16.1	(2.8)	17.9	16.6	17.4
Sm	4.83	(0.97)	7.17	(1.26)	5.55	(0.92)	4.32	(0.79)	4.97	4.6	4.69
Sc	16.89	(1.98)	13.57	(2.34)	13.39	(1.36)	13.85	(1.92)	13.61	14.59	15.73
Ta	0.8	(0.6)	1.4	(0.1)	0.8	(0.5)	0.3	(0.5)	0.9	0.8	0.3
Cs	1.02	(1.00)	0.76	(0.56)	1.00	(0.61)	1.67	(2.25)	1.11	1.63	0.95
Hf	4.3	(0.7)	4.9	(0.2)	5.2	(0.3)	4.3	(0.9)	4.4	3.3	4.5
Ce	37	(9)	54	(9)	46	(3)	35	(6)	42	36	37
Nd	7	(10)	34	(11)	5	(12)	4	(9)	0	28	12
Eu	1.33	(0.22)	1.84	(0.21)	1.38	(0.35)	1.12	(0.17)	1.21	1.23	1.32
Tb	0.57	(0.11)	0.66	(0.12)	0.98	(0.73)	0.56	(0.19)	0.48	0.47	0.48
Yb	1.2	(1.3)	0.9	(1.3)	2.6	(4.2)	0.8	(1.2)	0.0	0.0	1.5
Lu	0.38	(0.10)	0.30	(0.02)	0.44	(0.32)	0.24	(0.10)	0.34	0.42	0.22
No.	15		3		6		19		1	1	4

TABLE 2 cont.

Chemical Group	G		H		I		J		K	L	M	N
SiO2	(0.89)	53.22	(0.84)	54.57	(0.93)	62.54	(0.51)	64.28	(0.67)	66.00	58.42	79.74
TiO2	(0.02)	1.82	(0.11)	1.48	(0.37)	0.84	(0.08)	0.82	(0.08)	0.97	0.67	0.10
Al2O3	(0.18)	19.56	(0.74)	17.12	(0.77)	16.61	(0.64)	16.49	(0.56)	13.78	13.09	18.12
Fe2O3	(0.41)	9.14	(0.42)	8.68	(0.82)	5.23	(0.49)	5.02	(0.71)	4.77	4.54	0.42
Na2O	(0.32)	4.06	(0.50)	3.45	(0.32)	3.59	(0.40)	3.40	(0.27)	3.15	2.15	0.22
K2O	(0.30)	1.36	(0.18)	1.28	(0.32)	2.04	(0.66)	2.01	(0.35)	1.95	1.22	0.86
CaO	(0.24)	7.26	(0.91)	8.35	(0.45)	5.60	(0.60)	4.57	(0.20)	5.63	17.04	0.59
MgO	(0.93)	3.00	(0.26)	4.59	(0.66)	3.04	(0.41)	2.29	(0.55)	1.60	2.52	0.10
P2O5	(0.03)	0.48	(0.14)	0.40	(0.09)	0.20	(0.02)	0.19	(0.04)	0.16	0.17	0.04
MnO	(0.01)	0.13	(0.02)	0.14	(0.02)	0.09	(0.01)	0.08	(0.01)	0.07	0.12	0.01
Sr	(115)	561	(108)	582	(43)	579	(198)	428	(44)	418	395	545
Ba	(43)	473	(84)	442	(97)	515	(69)	542	(125)	410	290	770
Zr	(28)	180	(58)	115	(25)	123	(33)	122	(46)	110	85	226
Co	(5)	33	(4)	31	(5)	28	(4)	24	(3)		17	68
Cr	(30)	76	(48)	132	(70)	93	(55)	62	(27)		120	3
La	(1.3)	19.5	(5.2)	18.9	(4.6)	17.5	(2.9)	16.5	(3.7)		13.6	22.6
Sm	(0.25)	5.78	(1.02)	5.29	(0.94)	4.48	(0.49)	4.39	(0.30)		3.76	5.32
Sc	(0.60)	19.26	(2.83)	19.56	(1.46)	12.85	(1.17)	12.38	(0.92)		10.1	11.33
Ta	(0.6)	0.9	(0.7)	0.3	(0.5)	0.5	(0.6)	0.6	(0.5)		0.9	1.2
Cs	(0.20)	1.12	(2.04)	1.05	(1.22)	1.68	(1.53)	1.67	(0.89)		6.50	0.42
Hf	(0.4)	4.9	(0.8)	4.8	(0.8)	4.5	(0.6)	4.9	(0.8)		4.2	5.4
Ce	(3)	45	(11)	42	(9)	37	(5)	37	(4)		30	42
Nd	(12)	13	(14)	16	(12)	0	(0)	0	(0)		0	0
Eu	(0.07)	1.63	(0.23)	1.47	(0.22)	1.04	(0.06)	1.04	(0.07)		0.88	1.24
Tb	(0.10)	0.60	(0.07)	0.55	(0.09)	0.62	(0.09)	0.69	(0.10)		0.65	0.64
Yb	(1.6)	0.9	(1.1)	2.1	(1.4)	1.5	(1.1)	1.8	(0.8)		1.3	0.0
Lu	(0.14)	0.46	(0.12)	0.45	(0.08)	0.28	(0.07)	0.29	(0.03)		0.00	0.47
No.	6		9		13		6		1	1	1	1

1 Calculated on an anhydrous basis. Major and minor oxides in weight percent; trace and REE in ppm. Values in parentheses are standard deviations.

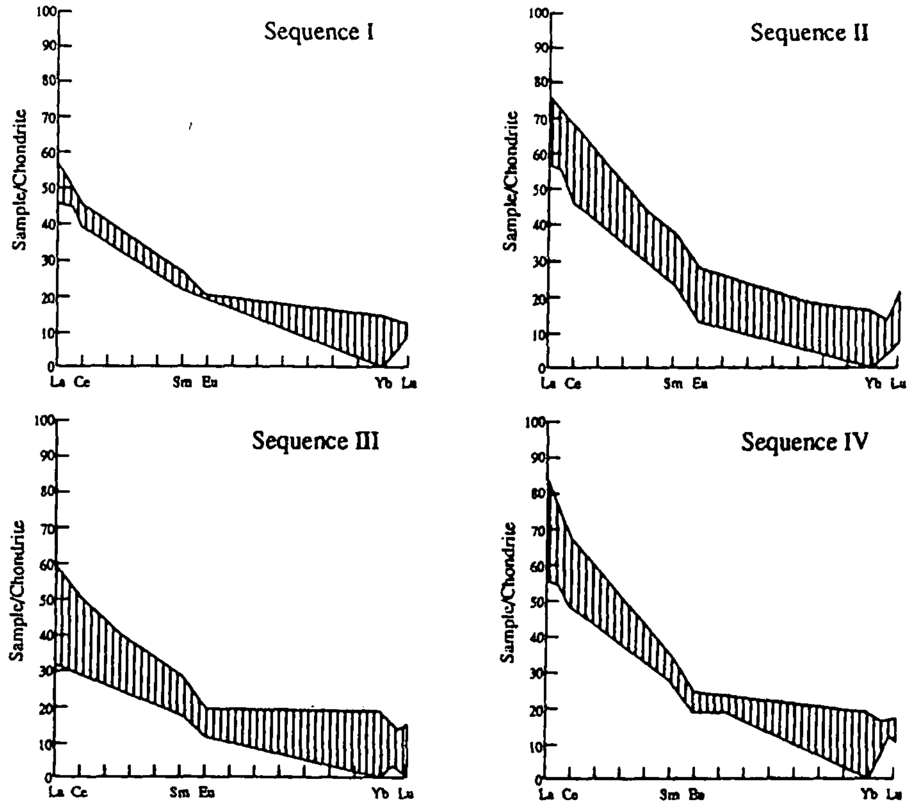

Fig. 5. Range of REE contents for each of the four volcanic sequences normalized to the chondrite values of Nakamura (1974).

concentrations. Sample L is a dacite with a relatively low Al_2O_3 content compared to Group K and dacites of the San Andres dacite (Dobson and Mahood, 1985). Samples M and N are hydrothermally altered. Sample M was taken from a tuffaceous deposit encountered in well Az-51. The high concentration of CaO in this sample is due to the abundance of calcite. Sample N appears to be silicified, as indicated by relative enrichments in SiO_2 and Al_2O_3 and depletions in the other major and minor elements.

Comparison of the major, minor, and rare-earth element (REE) chemistries of the individual samples demonstrates that they can be further grouped in four volcanic sequences of regional significance. The distribution of these sequences with respect to depth is shown in Figure 3. With the exception of a few outlying points, rocks of volcanic sequences I and III are distinguished from those of sequences II and IV by lower La_n and Ce_n (Fig. 5), higher MgO, and lower P_2O_5 and TiO_2 (Fig. 6).

The differences in the chemistries of volcanic sequences II and III are also apparent from a comparison of their alkali-lime indices. Analyses of volcanic rocks of sequence II define a calc-alkalic suite with an alkali-lime index of 59.5. In contrast, the rocks of sequence III define a calcic suite with an alkali-lime index of 63.5.

STRATIGRAPHY OF THE MIL CUMBRES ANDESITES

The results of the cluster analyses shows that despite the relatively small number of chemical groups, many of the individual flow packets are laterally discontinuous and are repeated at irregular intervals within the Mil Cumbres andesites. Consequently, only a few of the individual flow packets within each of the

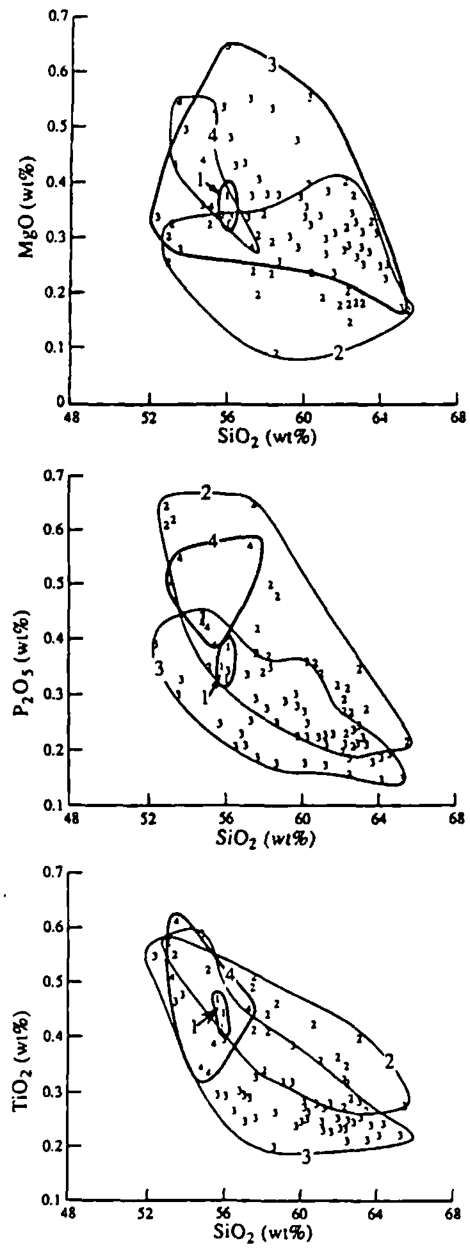

Fig. 6. Variations in MgO, P_2O_5 and TiO_2 with respect to SiO_2 of volcanic sequences I through IV.

major volcanic sequences could be correlated between the wells.

The flows of volcanic sequence I consist entirely of chemical group A. This flow packet reaches a maximum thickness of 200 m in well Az-28 but is only slightly thinner in well Az-51. The absence of unit I in wells Az-3 and 41 suggests that chemical group A was erupted from a vent located in the eastern part of the field. The volcanic sequences underlying sequence I are compositionally heterogenous. Sequence II is composed of rocks ranging in composition from basaltic andesite to dacite. In the eastern part of the field, chemical group J is present at similar depths in wells Az-28, 48, and 51. This high silica andesite reaches a thickness of about 200 m in the eastern wells, but thins to less than 50 m in well Az-28 and is absent in the southwestern wells studied. These relationships suggest that the flows in group J were erupted from a vent in the eastern part of the field. In contrast, the lower part of sequence II in well Az-3 consists mainly of flows belonging to chemical group B. These rocks correspond to the felted andesites of Gutierrez and Aumento (1982). As shown by Gutierrez and Aumento (1982), the rapid thinning of this unit to the east and south suggests that it was derived from an eruptive center located beneath the Yerbabuena rhyolites. Sequence II is capped by a high silica andesite (chemical group C) that appears to be of regional extent. Although this flow packet is thickest in well Az-3, no systematic thinning is evident from our data. Thus, the eruptive center may have been located to the northwest of the section line containing the wells we have studied.

Sequence II is underlain by 1500 m of andesite interbedded with minor dacite (chemical group K) and basaltic andesite (chemical group I). Sequence III is distinguished from the other volcanic sequences by the occurrence of thick flow packets of andesite corresponding to chemical group D. In addition, sequence III lacks flows of groups B and C which characterize sequence II.

The oldest of the four volcanic sequences consists dominantly of basaltic andesites (chemical group I). In well Az-3, these rocks are intercalated with andesites of group A and minor tuffaceous deposits. This volcanic sequence has a minimum thickness of 500 m in well Az-3.

No sedimentary or pyroclastic deposits of field wide extent were found during this investigation. Tuffaceous deposits are prominent near the base of volcanic sequence II in well Az-3 and in the upper part of volcanic sequence III in well Az-51. The deposits in the upper part of well Az-3 are similar in composition to andesites of chemical group C. However, flows of this chemical group have not been found in the underlying volcanic sequences. Thus the tuffaceous deposits may be part of pyroclastic deposits formed prior to eruption of the andesite flows.

As noted above, the tuffaceous deposit sampled at a depth of 1056 m in well Az-51 has been hydrothermally altered. Comparison of the P_2O_5/TiO_2 ratio of this sample with the underlying flows indicates that it is similar to group J. Thus, the fragments in group M could have been derived from the underlying rocks.

The stratigraphic section shown in Figure 3 crosses several east-trending faults. In the eastern part of the section containing wells Az-51, 48, and 28, the base of volcanic sequence II is progressively downdropped to the northeast across these normal faults. In addition, there is a thickening of sequence II in a northeast direction. These relationships suggest that movement along the faults between wells Az-48 and 51 may have been contemporaneous with the deposition of the andesites.

CONCLUSIONS

Eighty-six flows and tuffaceous deposits of the Mil Cumbres andesites have been chemically analyzed in order to establish the stratigraphy of the upper 2500 m of the reservoir at Los Azufres. Nine major chemical groups, ranging from basaltic andesite through andesite and dacite, were distinguished on the basis of their major element chemistries. Although most of the chemical groups are repeated at irregular intervals throughout the volcanic section, a few have limited lateral and vertical distributions. These observations suggest that several different eruptive centers were active during emplacement of the Mil Cumbres andesites.

Although the majority of the individual flow packets have limited distributions, systematic variations in their chemistries, particularly with respect to La, Ce, MgO, TiO_2, and P_2O_5, have allowed us to group them into four volcanic sequences which can be correlated across the field. The uppermost sequence (sequence I) is found only in the eastern half of the field. This sequence consists entirely of andesite flows with intermediate SiO_2 contents. Volcanic sequences II and III consist dominantly of andesite although minor dacite and basaltic andesites are also present. The oldest sequence encountered in the drill holes is composed mainly of basaltic andesite with minor interbedded andesite.

Flows of the Mil Cumbres andesites have been disrupted by east-trending faults that control much of the present surficial alteration. An northeastward thickening of volcanic sequence II suggests that some of these faults were active during deposition of the andesite flows. The greatest offsets are found at the base of this sequence.

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Progress Report on Recent Developments of Geothermal Energy and Volcanology in Mexico *

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Introduction

While volcanism in Mexico has remained quiescent during the past two years, the interest awakened by Geothermics has led to extensive exploration of the thermal springs in Mexico's volcanic areas, accompanied by geochemical analysis of their waters (3). Drilling in the geothermal field of Pathé, Hidalgo, has continued and, since early 1964, new drilling has been undertaken in the geothermal field of Cerro Prieto, near the northern end of the Gulf of Baja California. Parallel with these activities, photogeological mapping at a scale of 1 : 100,000 has been carried out in the central Mexican volcanic region between the Pico de Orizaba volcano near the Gulf coast and the city of Tepic on the Pacific.

The Pathé Geothermal Field

This field, lying in a highly fractured area occupied by Middle Tertiary volcanic rocks, has been producing wet steam from several drill holes at depths varying from 200 m to 500 m. The pilot plant, with installed capacity of 2 MW, has been producing electricity steadily since 1956. In view of the fact that the formations drilled are characterized by low permeability, new drilling has been proposed to reach Cretaceous limestone formations lying below the volcanics at a probable depth of 1000 m to 1500 m. From these, a larger production of steam is expected. Well No. 7 has reached, as of July 1964, a depth of 1100 m. The temperatures registered reach 175° C.

* Paper delivered at the IAV Summer Meeting, scientific session of July 23, 1964.

The Cerro Prieto Geothermal Field

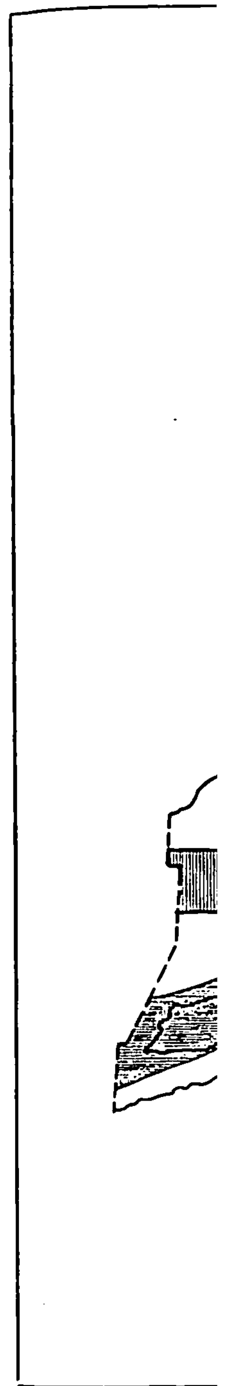
As of July 1964, two new wells have been sunk into this fiel contained in a 2 × 5 km thermal area rich in steam blowholes, mu volcanoes and hot springs. Well No. M-3 (2), drilled into the broa graben area and close to what is believed to be the San Jacinto branc of the San Andreas fault system, reached a depth of 2532 m, where th formation changed abruptly from Quaternary river sands to Creta ceous granitic basement rock. The production of a water/steam mixture was obtained from a depth of 600 m to 900 m at a rate of 20 tons/hour. Wellhead pressures of 18 atmospheres were recorded, an temperatures ranged as high as 210° C. Chemical analysis reveals tha the water obtained is high in sodium and potassium chlorides (sodium 5000 ppm and potassium, 1100 ppm).

Mapping

The photogeological survey of the Central Mexican volcani belt (5) revealed the presence of several volcano-tectonic structures Fracturing and faulting very often are induced by the movement o shallow magmatic bodies. As a whole it seems that the entire volcani area extending across the Republic from West to East between Paral lels 21 and 19 N, is largely produced by a rising convection current (6 in the mantle, which may extend as far East as the Isthmus an Guatemala. The counterpart to such a rising convection current i seen in the Acapulco Trench, where low thermal flow and intensiv seismic activity strengthen the assumption that the same convectio current enters its sinking phase here (10).

Proposals for a Nuclear Power Program

The dissemination of knowledge of the possibilities of containe nuclear explosion has given rise to two interesting proposals withi Volcanology and its applied science, Geothermics. A proposal wa presented to use nuclear devices in areas where large bodies of ho rock exist at shallow depths of 1000 m to 2000 m. The explosion would shatter these impermeable bodies and permit the developmen of a geothermal field by simply injecting water into the rubble-fille cavity, transforming it instantly into dry steam which would flow



out of other wells (7). The same idea was presented independently by G. C. Kennedy at the III Ploughshare Symposium held last April at the University of California.

Another proposal was recently presented for the use of nuclear devices to stop volcanic eruptions in their initial phase. It is argued that by placing two nuclear charges strategically, deep under a nascent volcano such as Paricutín in 1943, close to the vent or the feeding dyke, and detonating them successively, the eruption in the chimney would be interrupted and, most probably, the shattering of the vent would result in a permanent seal (9). The estimated cost of such an operation, involving two drill holes to a maximum depth of 1,000 m and two one-megaton charges, would not exceed U.S. $ 4,000,000, according to U.S. Atomic Energy Commission figures. Such a technique might also be used with success to stop further devastation of the San José area by the Irazú volcano in Costa Rica.

Geothermal Provinces

The crust in the Mexican Republic, apparently of considerable thickness (40 km and more in Durango) has undergone intense fracturing in Cenozoic time. This fracturing has allowed the rise of magmas and the formation of wide volcanic areas. In the absence of direct measurements, but using fracturing, volcanism and thermal spring distribution, an attempt was made to define seven geothermal provinces thought to represent zones of high heat flow (6). The influence of the San Andreas fault system seems to be apparent in much of the fracturing throughout the whole Mexican west coast (8).

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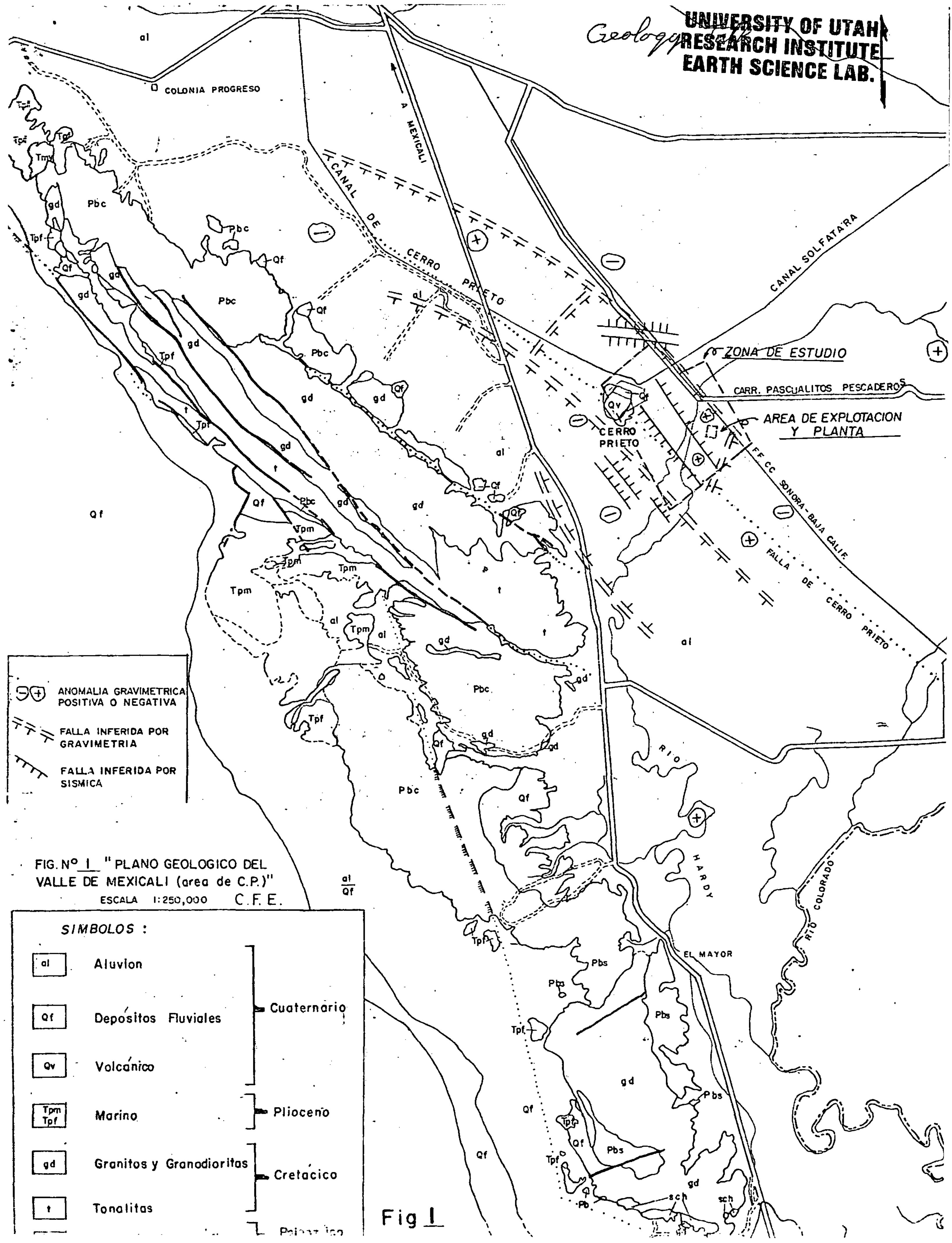
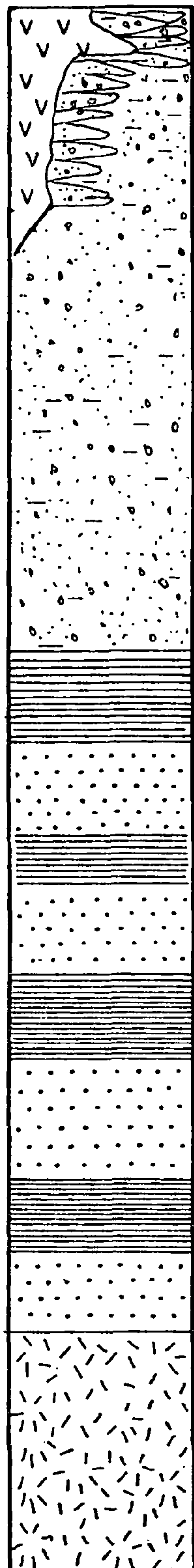


FIG. Nº 1 "PLANO GEOLOGICO DEL VALLE DE MEXICALI (area de C.P.)"
ESCALA 1:250,000 C.F.E.

Fig 1

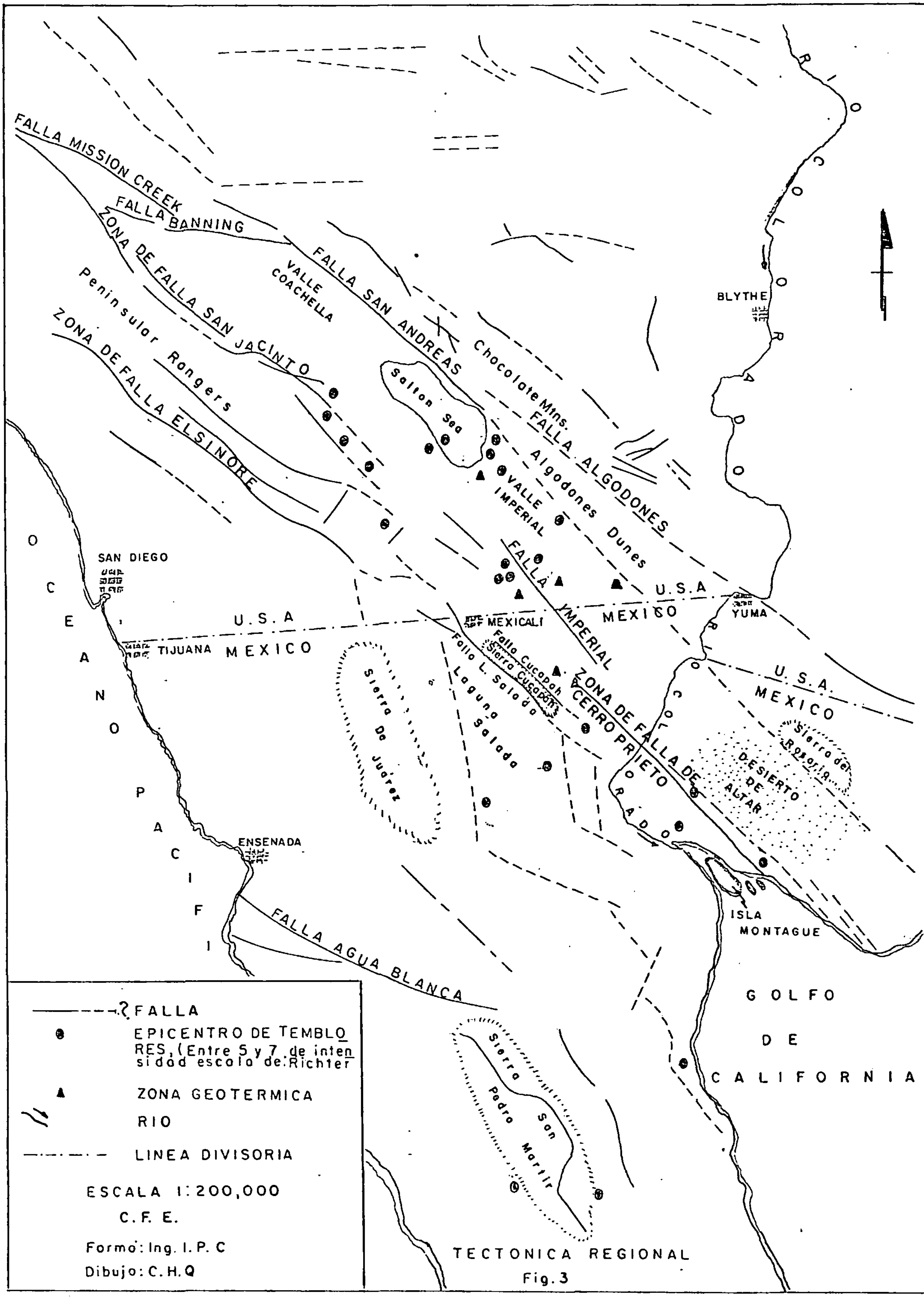


ABANICOS ALUVIALES DE CUCAPAH DE ORIGEN GRANITICO Y METASEDIMENTARIO	RECIENTE		CENOZOICA
ROCAS RIODACITICAS	PLIO PLEISTOCENO	CUATERNARIO	
DEPOSITOS NO CONSOLIDADOS CONSTITUIDOS POR ARCILLAS, ARENAS Y GRAVAS; CON ESPESORES DE 600 A 2 500 m.			
DISCORDANCIA, CAMBIO DE FACIES ? O CONTACTO POR METAMORFISMO.			
LUTITAS DE COLOR CAFE CLARO CAMBIANDO A PROFUNDIDAD A COLORES GRIS CLARO Y GRIS OSCURO, INTERESTRATIFICADAS CON ARENISCAS DE COLOR GRIS CLARO, CONSTITUIDAS DE FRAGMENTOS DE CUARZO Y FELDESPATOS CEMENTADOS INDISTINTAMENTE CON CARBONATOS Y SILICE. SU ESPESOR ES DE 2 000 m. APROXM.	TERCIARIO	NO DIFERENCIADO	
ROCAS IGNEAS Y METAMORFICAS CONSTITUIDAS POR GRANITO, GRANODIORITAS, GNEISSES Y ESQUISTOS.	CRETACICO SUPERIOR		MESOZOICA

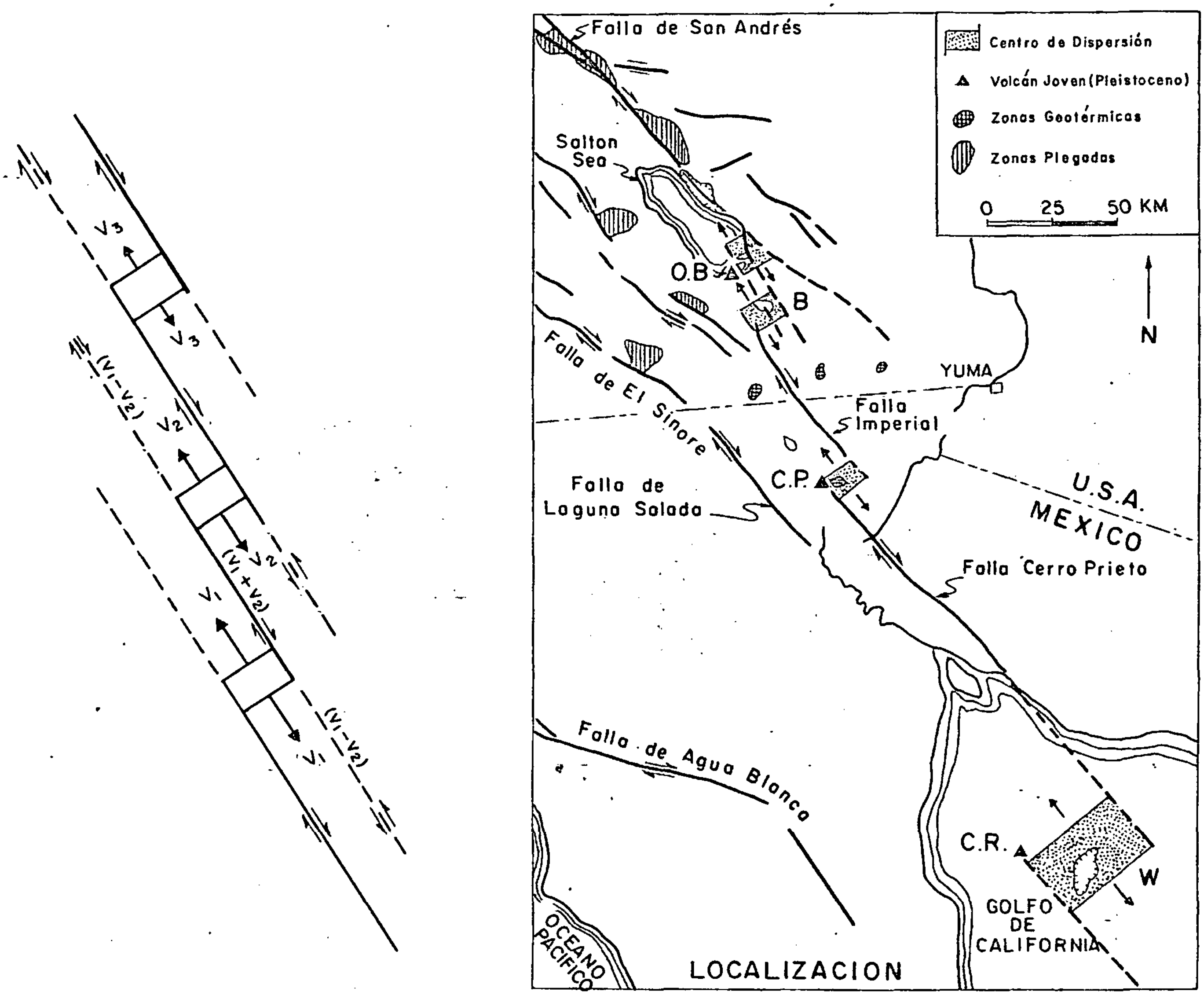
"COLUMNA ESTRATIGRAFICA GENERALIZADA DEL AREA DE CERRO PRIETO"

FIG. 2

C.F.E.



TECTONICA REGIONAL
Fig. 3



A

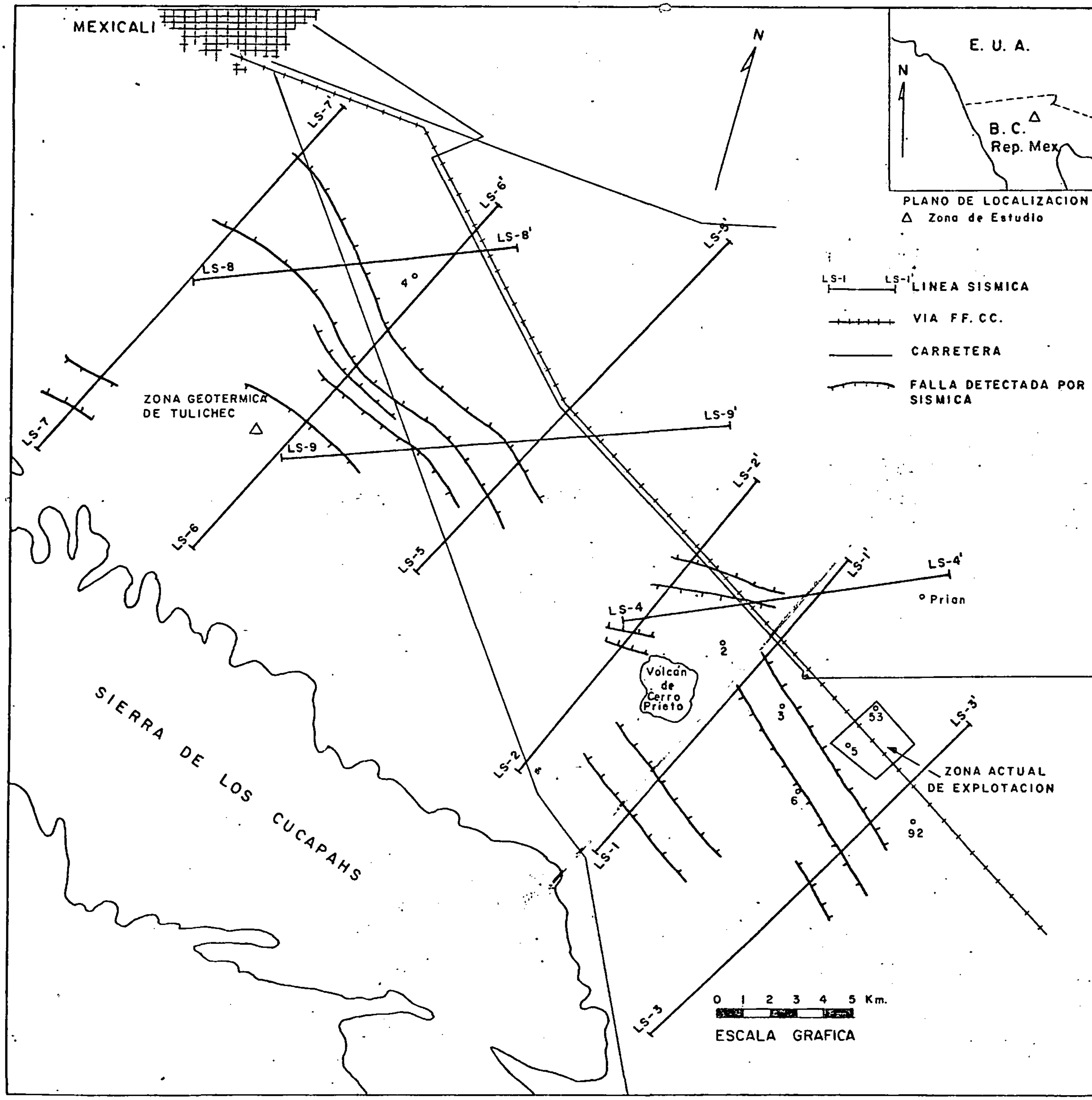
B

A.— Modelo de Fallas transformes y Centros de Dispersión propuesto por Lomnitz, W. Elders y otros (1972)

B.— Localización de ellas en los Valles Imperial y Mexicali.

FIG. 4

C.F.E

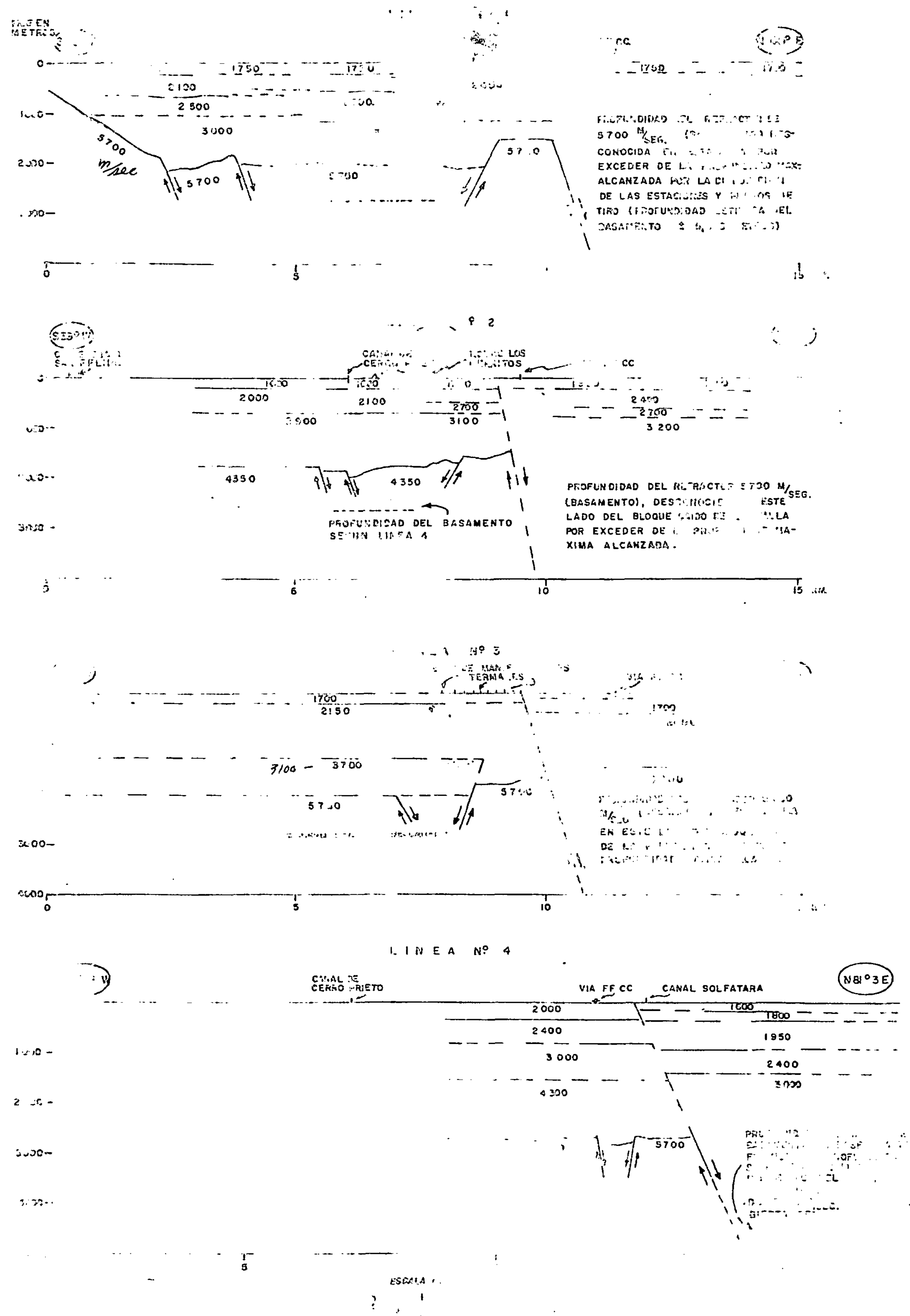


PLANO DE LOCALIZACION
DE LINEAS SISMICAS DE
REFRACCION.

C.F.E
FORMO: Ing. I. P. C.
D I B : C.H.Q.

Fig. 5

1962 seismic lines



METROS
1750
2100
2 500
3000
5700
m/sec
5 700
2000
PROFUNDIDAD DEL REFRACTOR
CONOCIDA
EXCEDER DE
ALCANZADA POR LA
DE LAS ESTACIONES Y
TIRO (PROFUNDIDAD
BASAMENTO
0
5
15
2 2
CANAL
2000
2100
3100
2700
2 400
2 700
3 200
4350
4 350
PROFUNDIDAD DEL REFRACTOR 5700 M/SEG.
(BASAMENTO), DESCONOCIDA
ESTE
LADO DEL BLOQUE
POR EXCEDER DE
XIMA ALCANZADA.
PROFUNDIDAD DEL BASAMENTO
SEGUN LINEA 4
3000
6
10
15 KM
Nº 3
TERMALES
1700
2150
3700
5700
3000
4000
0
5
10
L I N E A Nº 4
CANAL DE
CERRO PRIETO
VIA FF CC
CANAL SOLFATARA
N81°3E
2000
1600
1800
2400
1950
3 000
2 400
3 000
4 300
5700
5
ESCALA

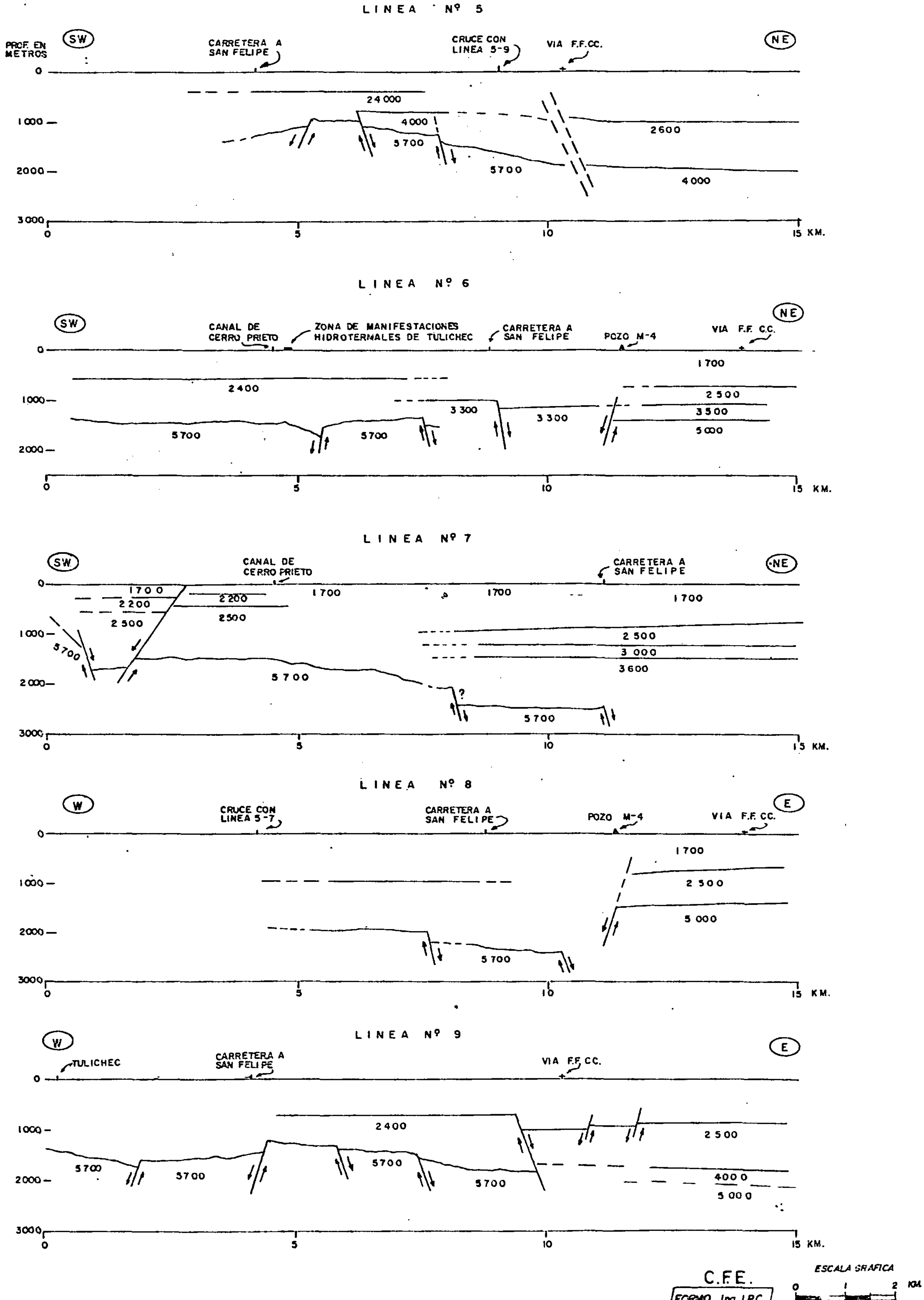
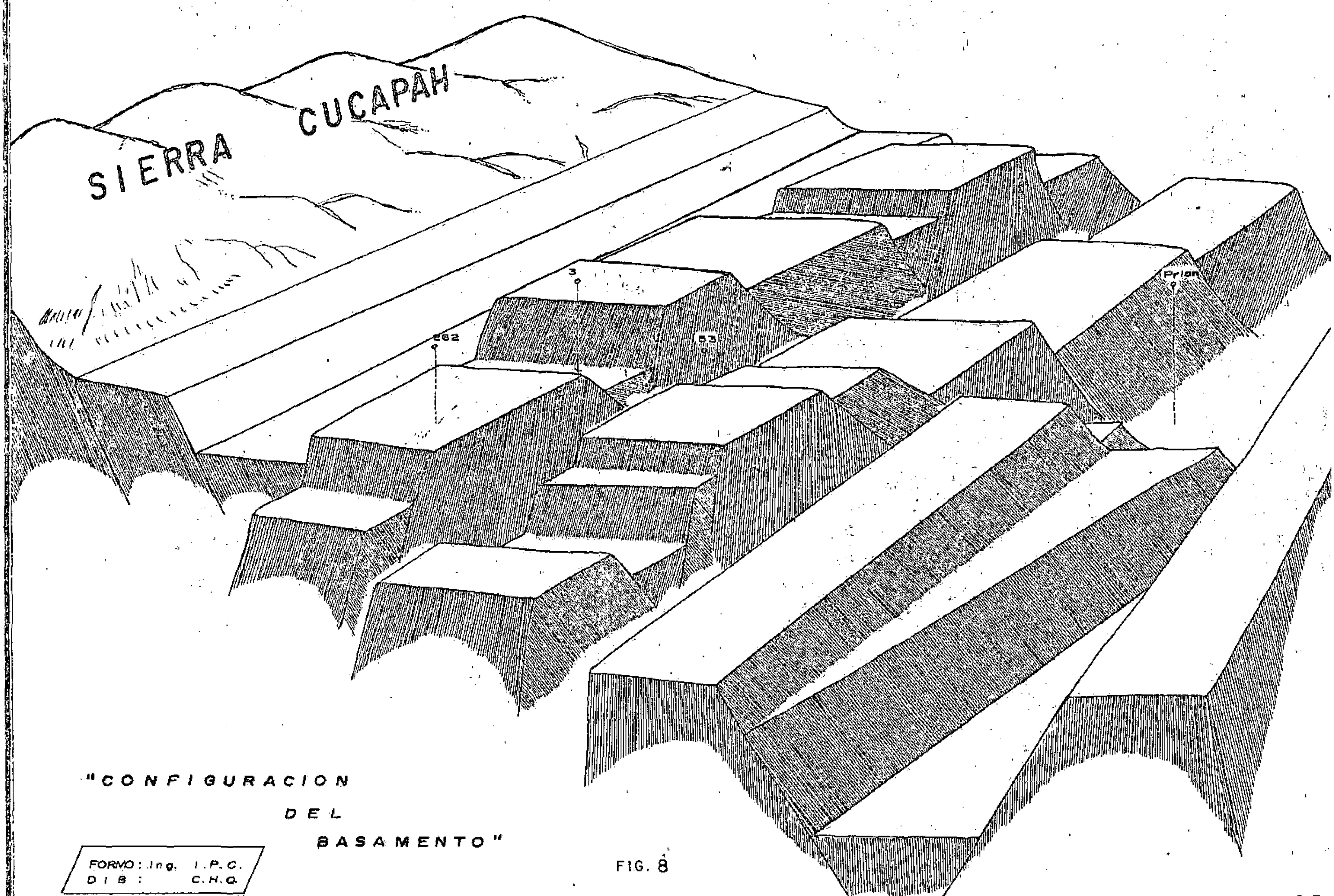

LINEA Nº 5
PROF. EN METROS
SW
NE
CARRETERA A SAN FELIPE
CRUCE CON LINEA 5-9
VIA F.F.CC.
24 000
4000
5700
2600
5700
4000
LINEA Nº 6
CANAL DE CERRO PRIETO
ZONA DE MANIFESTACIONES HIDROTERMALES DE TULICHEC
CARRETERA A SAN FELIPE
POZO M-4
VIA F.F. CC.
1700
2400
3300
3300
2500
3500
5000
5700
5700
LINEA Nº 7
CANAL DE CERRO PRIETO
CARRETERA A SAN FELIPE
1700
2200
2500
5700
LINEA Nº 8
W
E
CRUCE CON LINEA 5-7
CARRETERA A SAN FELIPE
POZO M-4
VIA F.F. CC.
1700
2500
5000
5700
LINEA Nº 9
TULICHEC
CARRETERA A SAN FELIPE
VIA F.F CC.
2400
2500
5700
4000
5000
KM.
C.F.E.
FORMO Ing I.P.C.
DIB C.H.Q.
ESCALA GRAFICA

Fig. 7



"CONFIGURACION DEL BASAMENTO"

FIG. 8

FORMO: Ing. I.P.C.
DIB: C.H.Q.

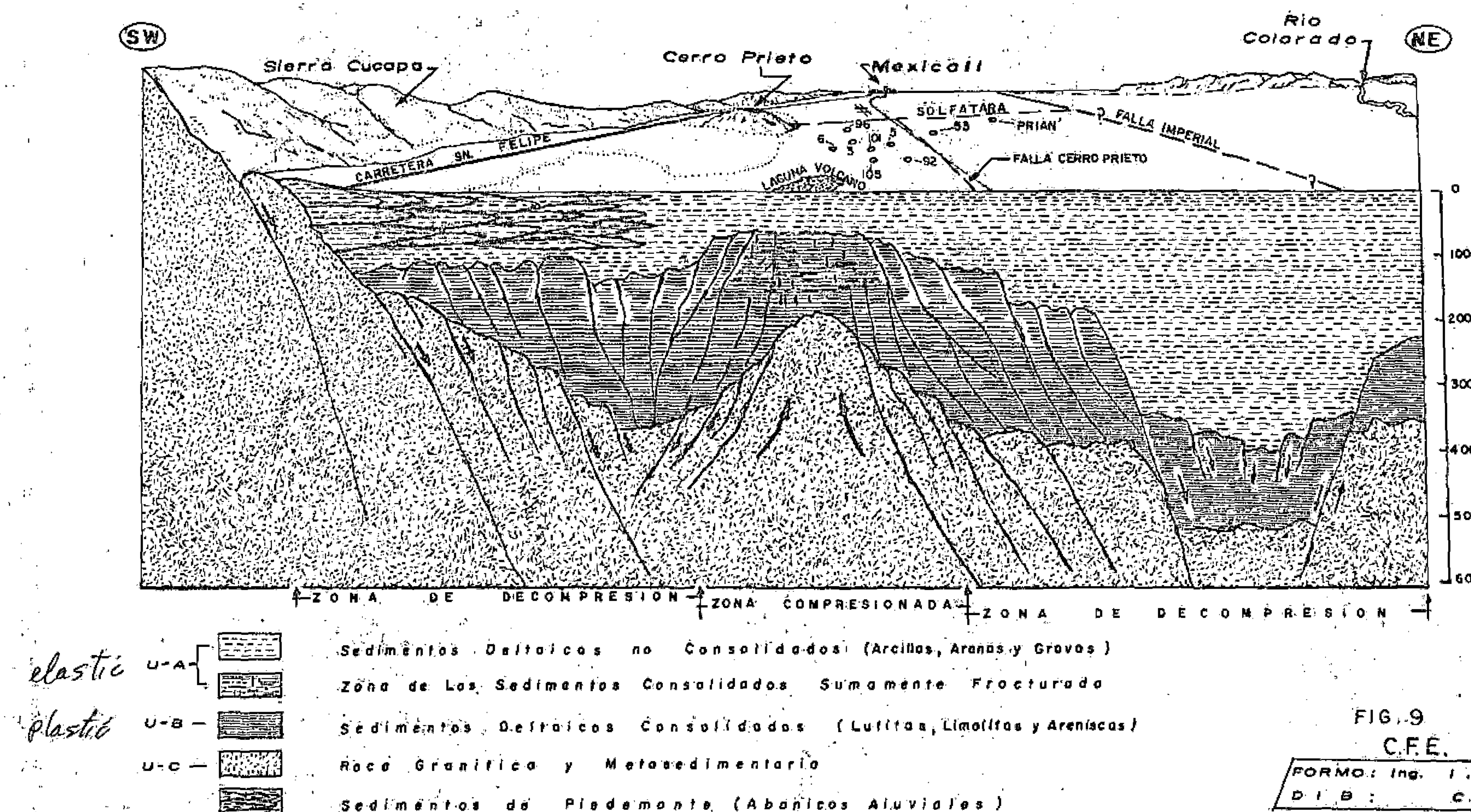
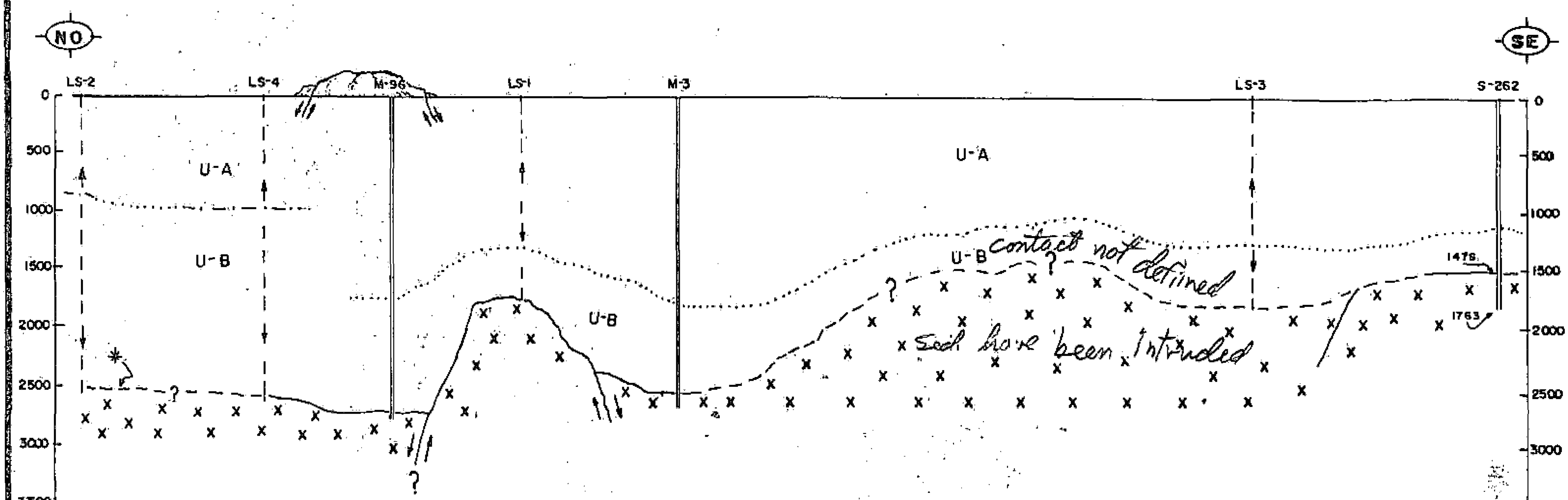


FIG. 9
C.F.E.

FORMO: Ing. I. P. C.
DIB: C. H. Q. A.
JUL/1978



LS- PUNTO DE LA LINEA SISMICA DE REFRACCION DONDE SE DETECTO EL BASAMENTO

········ CONTACTO GEOLOGICO ENTRE LAS UNIDADES A y B INDEFINIDO, TANTO POR SISMICA COMO POR PERFORACIONES

CONTACTO GEOLOGICO, DEFINIDO POR SISMICA

✳ CONTACTO PROYECTADO, SEGUN LINEA SISMICA 4

x x x BASAMENTO

FALLAS SUPERFICIALES EN LOS LADOS SE y NO DEL VOLCAN DE CERRO PRIETO

0 500 1000 m.

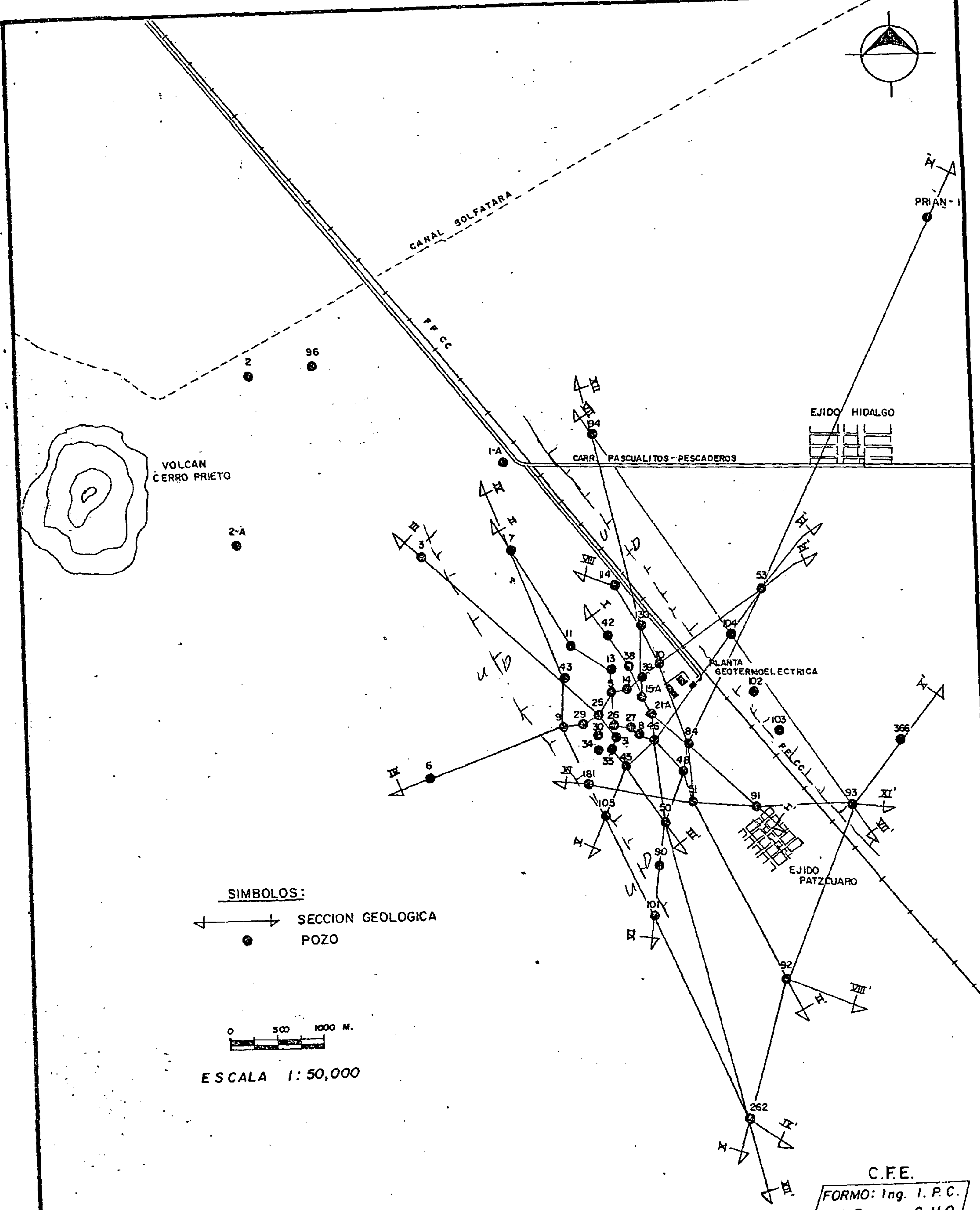
ESCALA 1 50,000

Fig. 10

FORMO : Ing. I.P.C.
DIBUJO : C.H.Q.A.

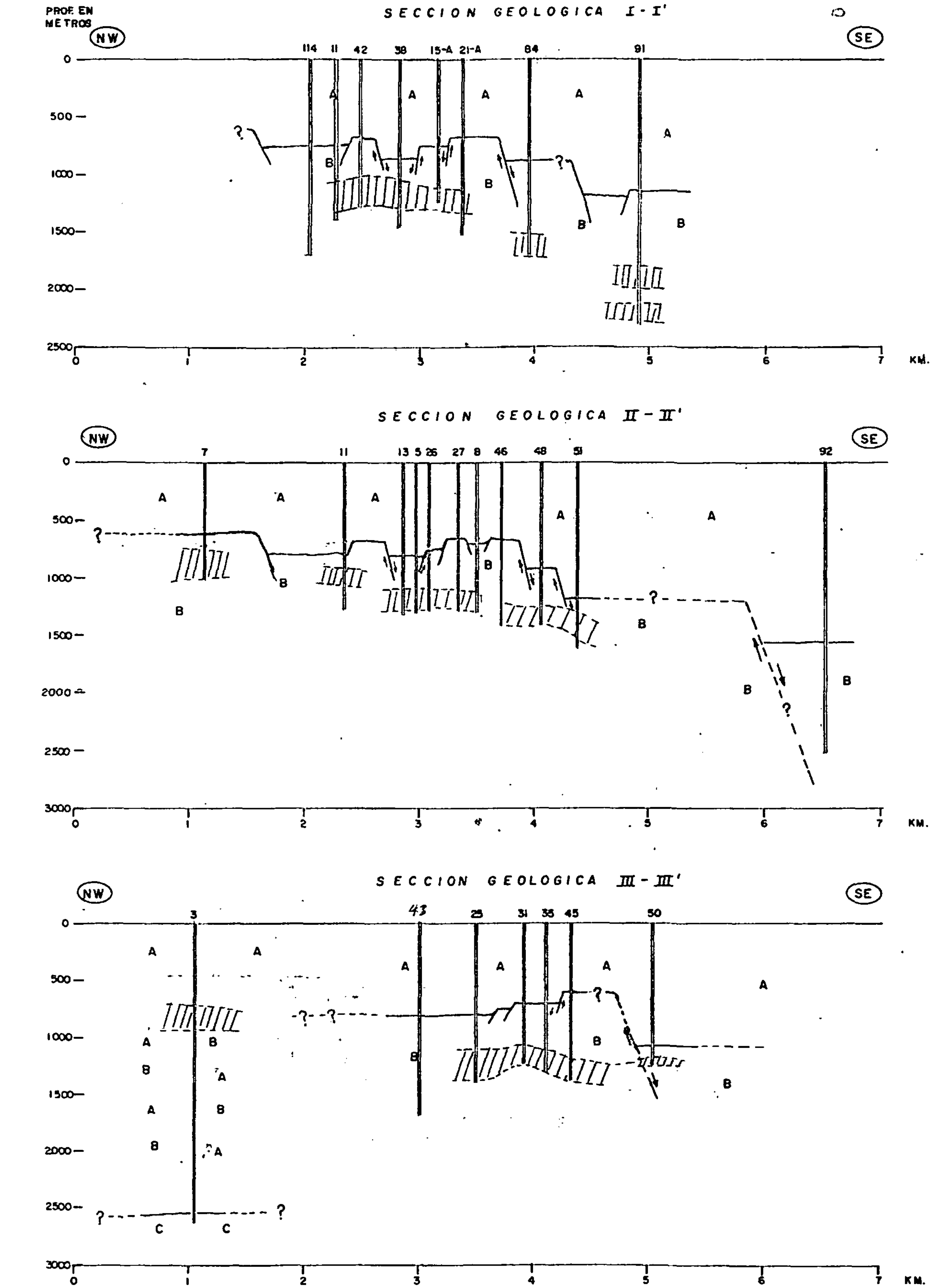
CONFIGURACION DEL BASAMENTO EN BASE A LA SISMICA DE REFRACCION Y POZOS

C.F.E.



CANAL SOLFATARA
FF CC
VOLCAN CERRO PRIETO
EJIDO HIDALGO
CARR. PASCUALITOS - PESCADEROS
PRIAN - I
PLANTA GEOTERMOELECTRICA
EJIDO PATZCUARO
SIMBOLOS:
SECCION GEOLOGICA
POZO
0 500 1000 M.
ESCALA 1: 50,000
C.F.E.
FORMO: Ing. I. P. C.
D I B: C. H. Q.

Fig. 11



SIMBOLOS

CONTACTO GEOLOGICO DEFINIDO

-?- - - CONTACTO GEOLOGICO INDEFINIDO

[A] SEDIMENTOS DELTAICOS NO CONSOLIDADOS (ARCILLAS, ARENAS Y GRAVAS)

[B] SEDIMENTOS DELTAICOS CONSOLIDADOS (LIMOLITAS, LUTITAS Y ARENISCAS)

[C] BASAMENTO (GRANITO DE BIOTITA)

FALLA

ZONA PRODUCTORA DE VAPOR

ESCALA GRAFICA

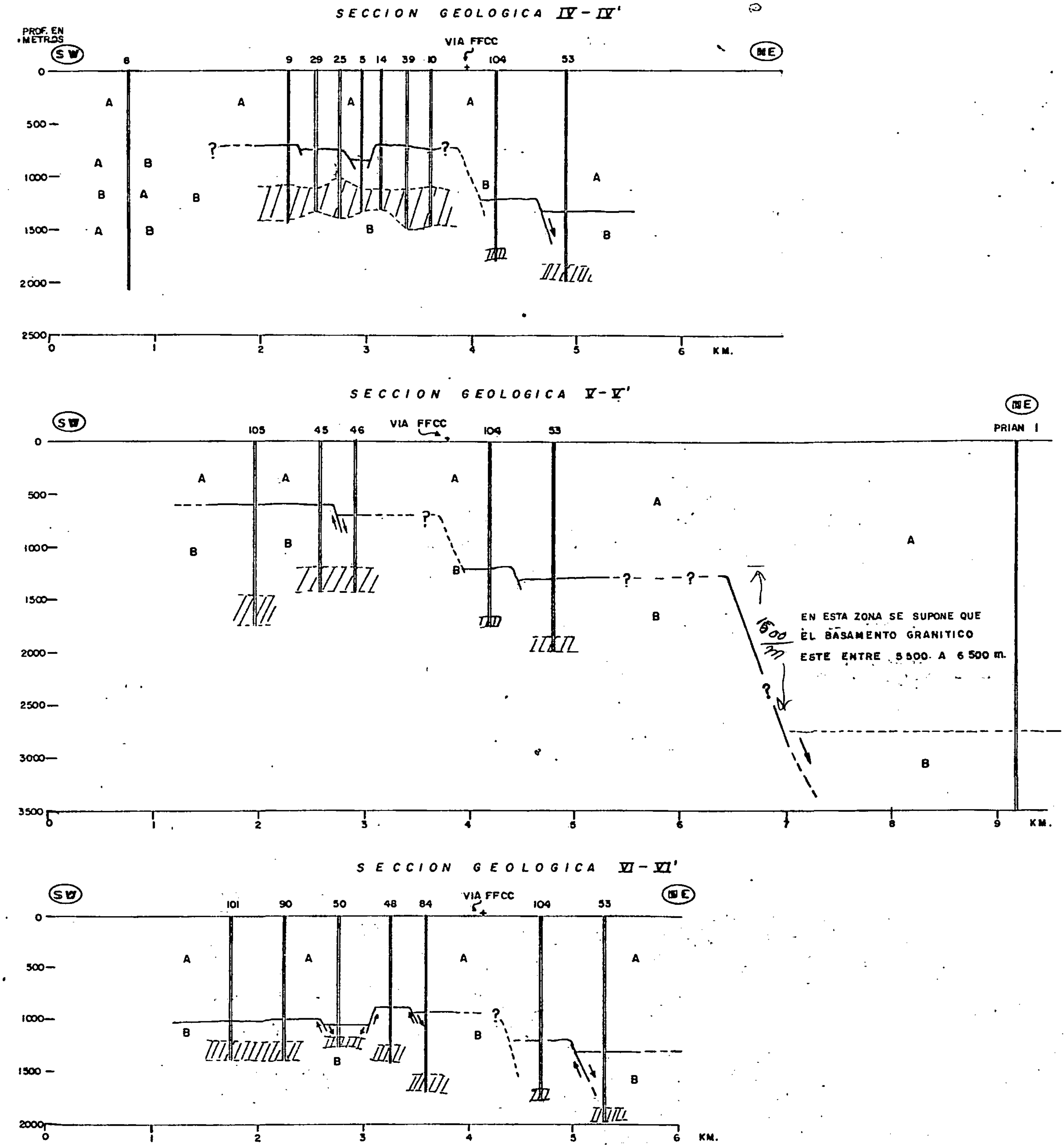
0 500 1000 m.

1 : 50,000

FIG. 12.

FORMO	Ing. I.P.C.
DIB	C.H.Q.

C.F.E.



SIMBOLOS

CONTACTO GEOLOGICO DEFINIDO

--?-- CONTACTO GEOLOGICO INDEFINIDO

A — SEDIMENTOS DELTAICOS NO CONSOLIDADOS (ARCILLAS, ARENAS Y GRAVAS)

B — SEDIMENTOS DELTAICOS CONSOLIDADOS (LIMOLITAS, LUTITAS Y ARENISCAS)

FALLA

ZONA PRODUCTORA DE VAPOR

ESCALA GRAFICA

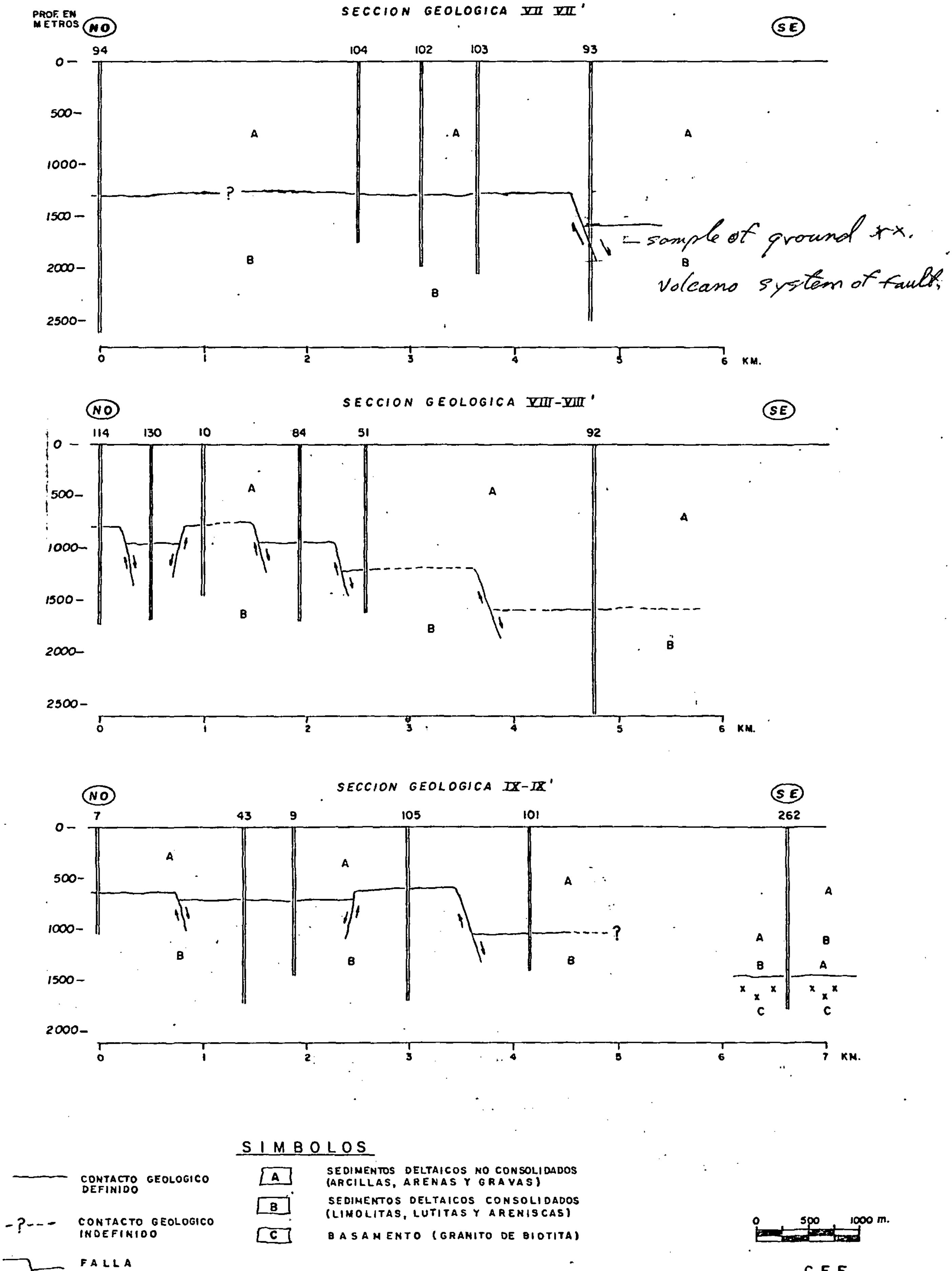
0 500 1000 m.

1 : 50,000

C.F.E.

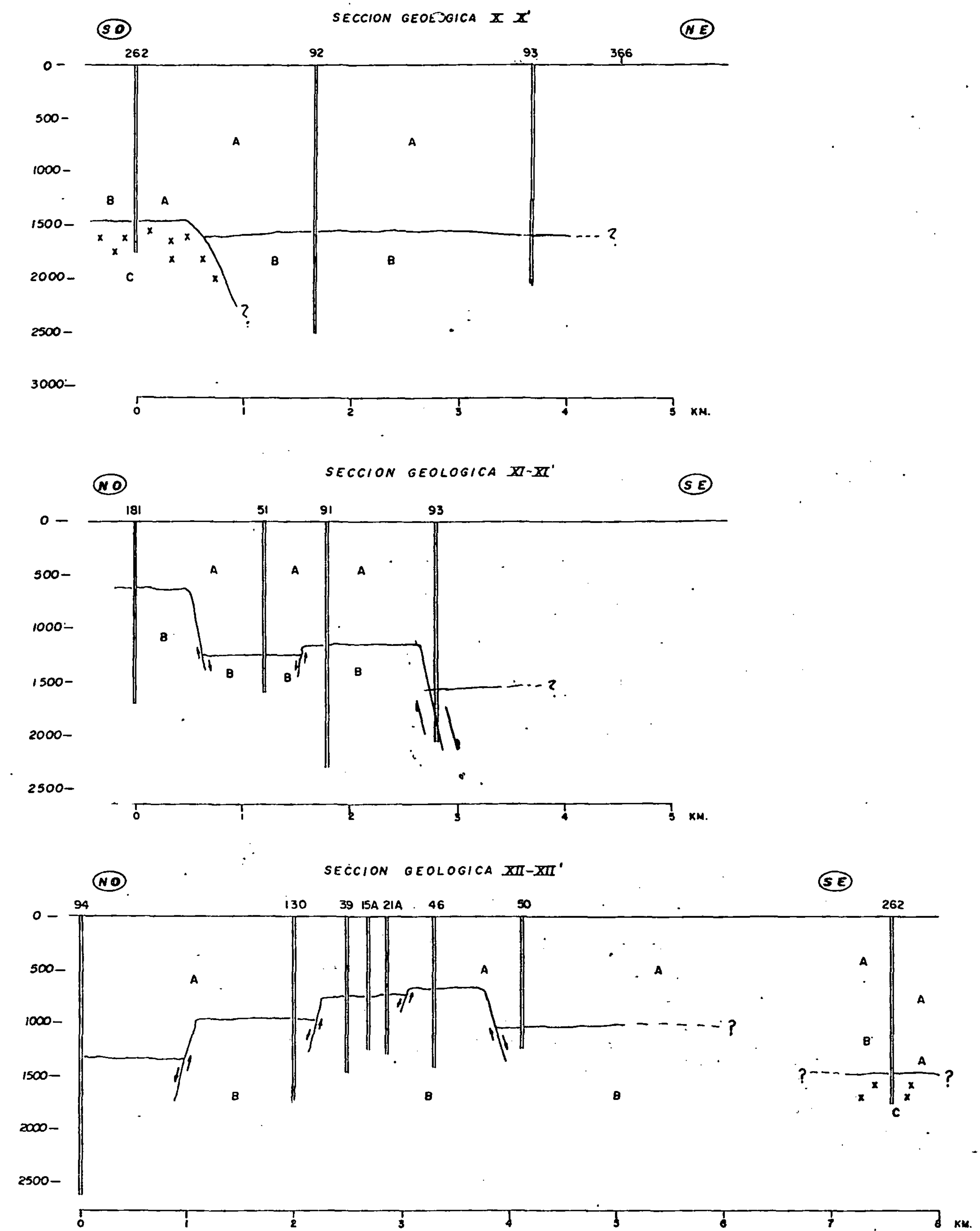
FORMO	Ing. I.P.C.
D I B	C.H.Q.

FIG. 13



C.F.E
FORMO: Ing. I.P.C.
DIB.: C.H.Q.

FIG. 14



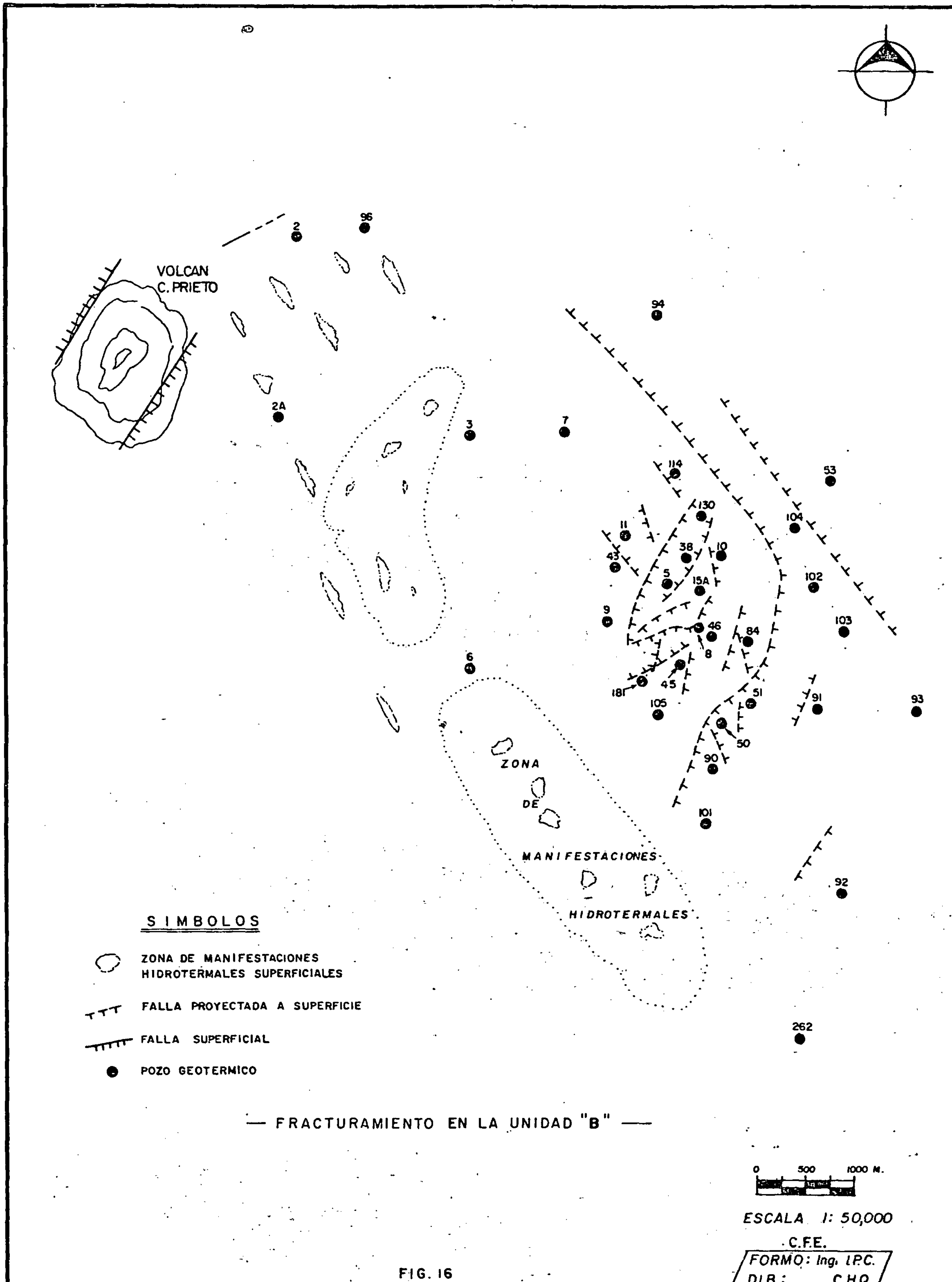
SIMBOLOS

——	CONTACTO GEOLOGICO DEFINIDO
-?---	CONTACTO GEOLOGICO INDEFINIDO
(falla)	FALLA
A	SEDIMENTOS DELTAICOS NO CONSOLIDADOS (ARCILLAS, ARENAS Y GRAVAS)
B	SEDIMENTOS DELTAICOS CONSOLIDADOS (LIMOLITAS, LUTITAS Y ARENISCAS)
C	BASAMENTO (GRANITO DE BIOTITA)

0 500 1000 m.

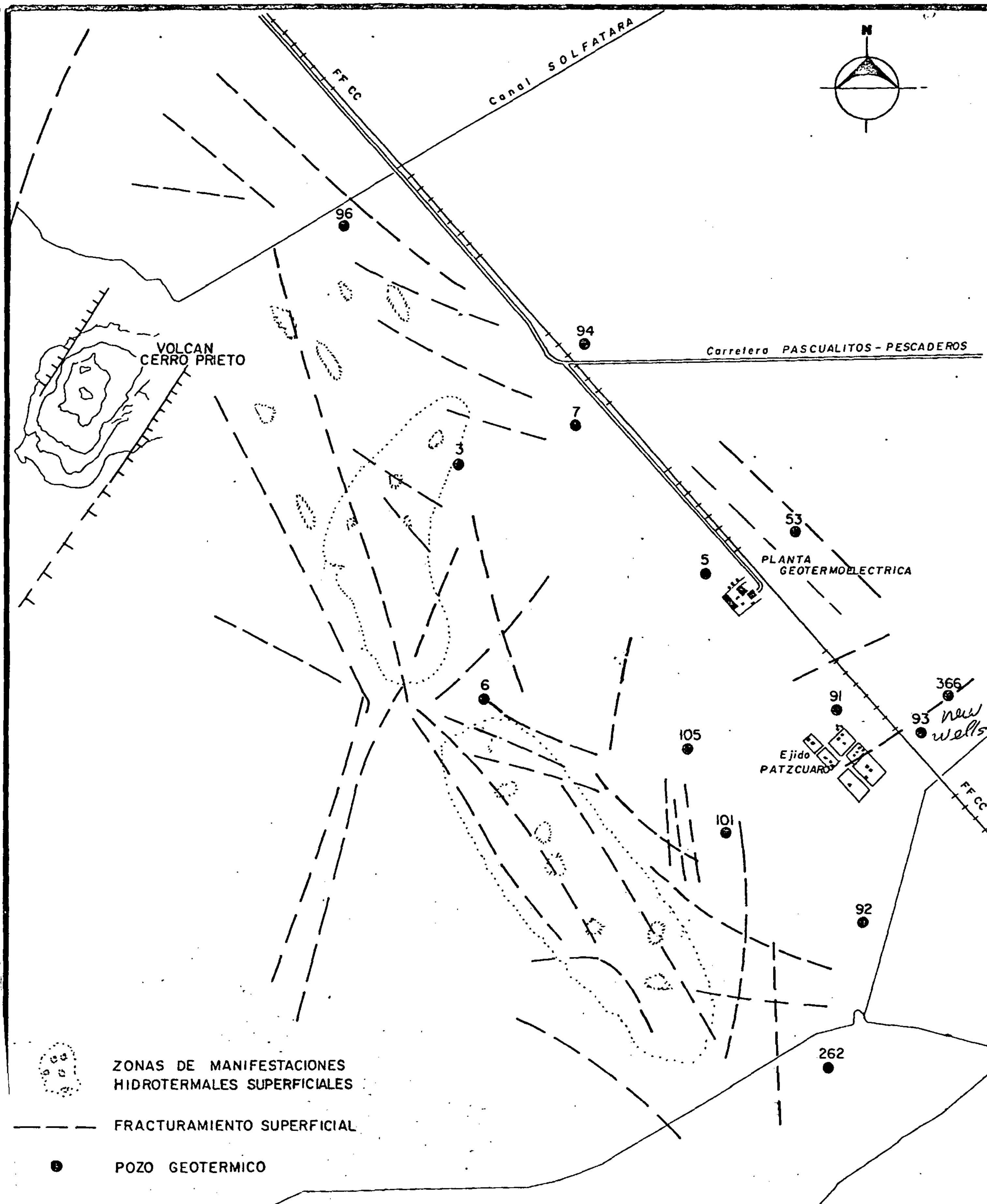
FIG. 15

C.F.E.
FORMO: Ing. I.P.C.
DIB.: C.H.Q.



— FRACTURAMIENTO EN LA UNIDAD "B" —

FIG. 16



— FRACTURAMIENTO SUPERFICIAL EN BASE A FOTOGRAFIAS AEREAS —

ESCALA : 1: 50,000

FIG. 17

Interpreto: Ing. I. P. C
Dibujo: C.H.Q

C.F.E.

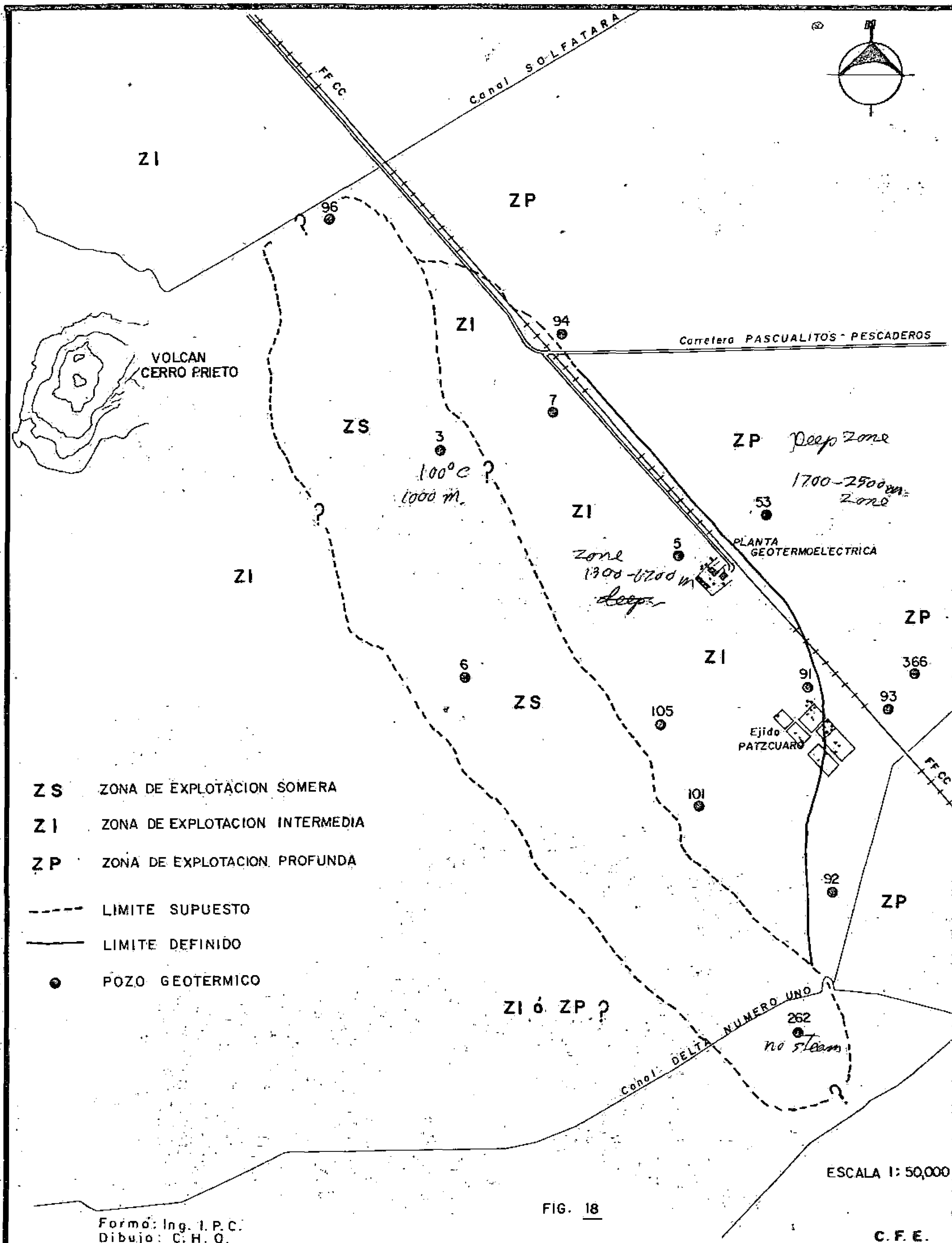

Canal SOLFATARA
FF CC
ZI
ZP
96
94
Carretera PASCUALITOS - PESCADEROS
VOLCAN CERRO PRIETO
ZS
3
100°C
1000 m.
7
ZP Deep zone
1700-2500 m. zone
53
ZI
5
PLANTA GEOTERMOELECTRICA
zone 1300-1700 m deep
ZP
ZI
366
91
93
6
ZS
105
Ejido PATZCUARO
FF CC
101
92
ZP
ZS ZONA DE EXPLOTACION SOMERA
ZI ZONA DE EXPLOTACION INTERMEDIA
ZP ZONA DE EXPLOTACION PROFUNDA
LIMITE SUPUESTO
LIMITE DEFINIDO
POZO GEOTERMICO
ZI ó ZP ?
Canal DELTA NUMERO UNO
262
no steam
ESCALA 1: 50,000
Formo: Ing. I. P. C.
Dibujo: C. H. Q.
C. F. E.

FIG. 18

LATE CENOZOIC BOLSON INTEGRATION IN THE CHIHUAHUA TECTONIC BELT

by
William S. Strain
University of Texas at El Paso

Laramide folding followed by early Cenozoic uplift, volcanic activity, and block faulting formed a series of basins and ranges in northern Chihuahua, northwestern Coahuila, and adjoining areas in Texas and New Mexico (Index Map), (DeFord, 1969, p. 65). A similar succession of events produced a sequence of bolsons extending from the northern border of this area northward into New Mexico and Colorado.

The bolsons in the Chihuahua Tectonic Belt (fig. 1) began filling early in their history. Some are not yet filled, but others have completely filled, buried small mountains, and overflowed their borders so that the basin floors have coalesced with those of adjacent basins. In many of the connected basins, the drainage systems have become integrated.

The basin fill is partly lava flows, pyroclastic debris, and fluvial deposits. Some silt and clay in the fluvial deposits originated in the surrounding mountains, but much of it came from distant sources. The Sierra Madre Occidental was the source of much of the fine-grained sediment, but some of it was brought in by the "upper" Rio Grande from its drainage basin in New Mexico and Colorado. Fine sediment reached every part of the basins, but in most, coarser materials are limited to the alluvial fan areas of their margins or to the courses of axial streams (Burrows, 1910, p. 102).

At times of adequate rainfall ephemeral lakes formed in the bolsons as they do today in those which have not yet filled (Baker, 1927, p. 38). Because of fluctuating water levels, clay and silt which settled in the standing water interfingered with coarser terrigenous particles around the margins of the basins, resulting in characteristic facies changes extending from the borders to the centers of the basins. In some basins evaporites interbedded with the fine-grained deposits indicate almost, if not complete dessication from time to time. Further evidence of this is the remains of burrowing animals found in the paleosols of the basin floors.

Environment of deposition was similar in the various basins. Where erosion has exposed basin fill, volcanic rocks, conglomerate, sandstone, red and brown claystone, and siltstone are the dominant rock types. The central areas of the bolsons contain similar facies of fine-grained material which suggests that the deposits formed in the same type of climate and physical environment.

In elongate bolsons or where two or more basins adjoined, a stream often occupied the axis of the depressions and either terminated in ponded water at

BOLSONS IN CHIHUAHUA TECTONIC BELT

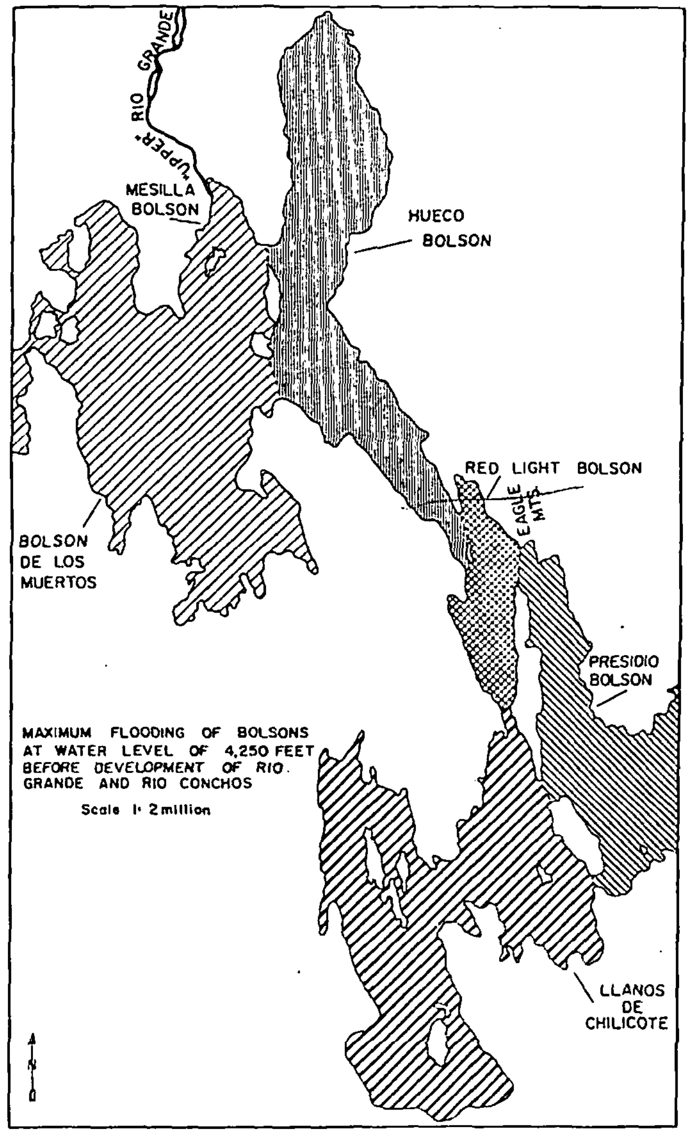
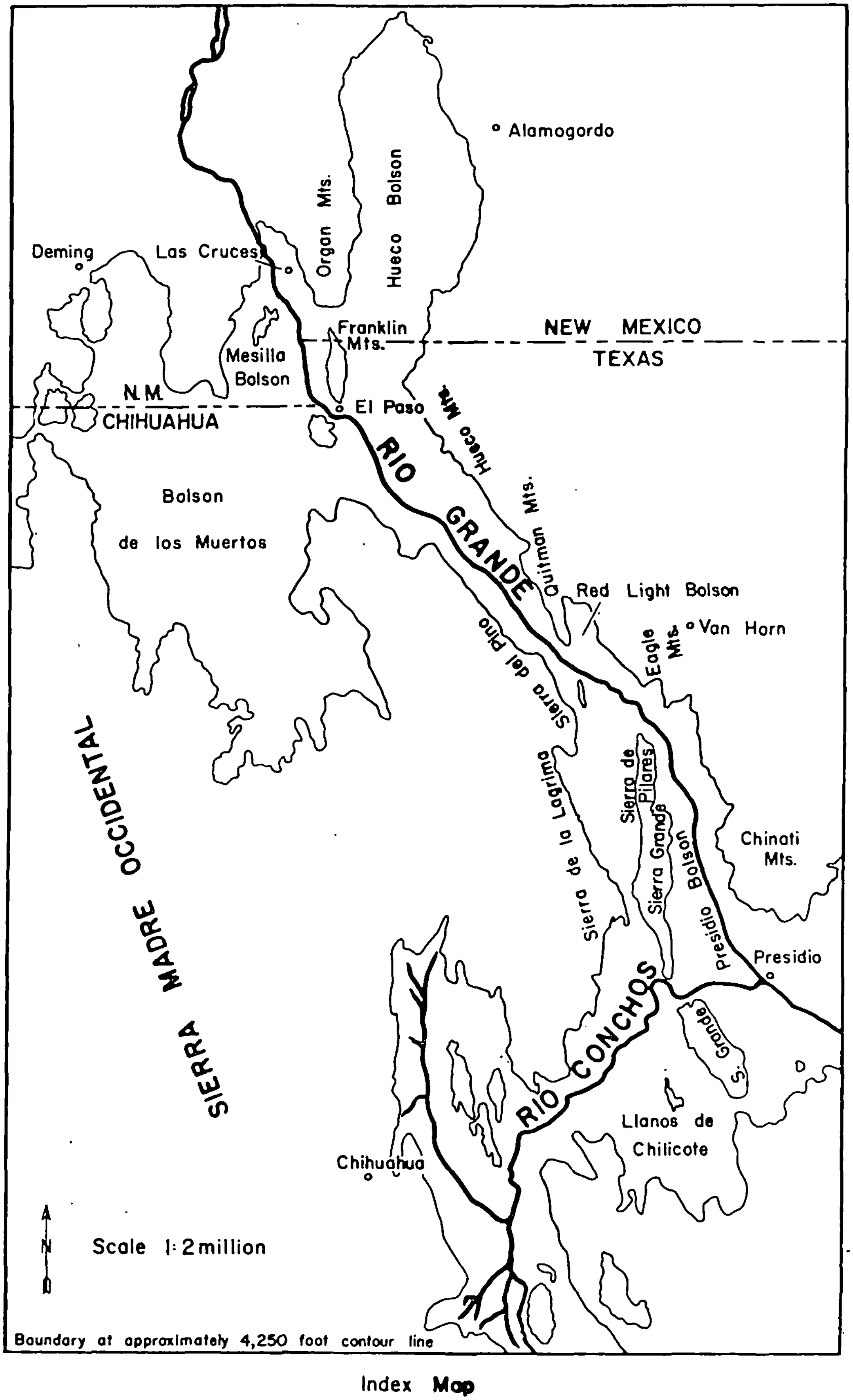


Figure 1

the lowest point of a single bolson or integrated the drainage systems of two or more basins. As drainage from the headwaters of the developing stream successively filled topographically lower basins, lake levels rose until outlets were found at structurally low places (King, 1935, p. 260). The bedrock at these places formed a temporary base level for the developing master stream system. As basins filled independently and reduced their capacity to hold water, relatively

BOLSONS IN CHIHUAHUA TECTONIC BELT



Index Map

small amounts of water spilling from basin to basin during floods would spread widely to inundate numerous bolsons.

The flooding of the bolsons in Chihuahua and in the Big Bend region of Texas (fig. 1) resulted from water shed mostly from the Sierra Madre Occidental. The Rio Conchos drains about 250 miles of the Sierra Madre Occidental along its eastern slope (Burrows, 1909, p. 87). Most of the water which filled the bolsons in Chihuahua and spread eastward through the Big Bend area originated from that source. The drainage into the Chihuahua bolsons certainly began early in the Cenozoic Era, but entrenchment of the channel in older basin fill may not have taken place until the first pluvial climate of the Pleistocene when the annual rainfall was probably larger than the present-day 20 to 40 inches (Gill, et al., 1970, p. 17). Some water may have come from the "upper" Rio Grande during exceptionally large floods (Baker, 1927, p. 38; Lee, 1906, p. 22). In this way an outlet formed through the Sierra del Carmen on the eastern side of the Chihuahua Tectonic Belt and established the Rio Conchos as a consequent stream from the Sierra Madre Occidental through the Big Bend.

The through-flowing stream was not established until the lakes were finally drained by removal of rock barriers which impounded water in the basins (King and Adkins, 1946, p. 293; Dietrich, 1965, p. 164). The course of the river through Chihuahua and the Big Bend was largely fortuitous and depended on favorably located structurally low places where it could cut through the mountain ranges. The river is then consequent to or superimposed upon most of the structural features which it crosses (King, 1935, p. 261; Maxwell, et al., 1967, p. 22), and not antecedent as Udden (1907, p. 15) believed.

After passing through the canyons of the Big Bend, the river continued to the Gulf of Mexico. This may have occurred as the result of eastward tilting of the region as suggested by Baker (1927, p. 56), or possibly by being captured by the "lower" Rio Grande as it lengthened its course headward toward the Big Bend (King, 1935, p. 259). Although most geologists who have studied the region agree in general on this sequence of events in basin intergration, Burrows (1910, p. 89) thought faulting produced the passages through bedrock to form the stream channel connecting the basins.

I believe that at the time of the formation of the Rio Conchos-"lower" Rio Grande system (fig. 2), there was no river connecting the Presidio Bolson with the Red Light, the Hueco, and the Mesilla bolsons. Later the Rio Grande course from near Presidio to west of El Paso developed by headward erosion from the Presidio Bolson or by overflow of Lake Cabeza de Vaca into the Red Light Bolson and then the Presidio Bolson or by a combination of the two.

In earliest Pleistocene or before, water entering the Mesilla Bolson at Las Cruces was impounded in the Mesilla, the Hueco, and the Bolson de los Muertos to form Lake Cabeza de Vaca (fig. 3) (Strain, 1966, p. 10; Lee, 1906, p. 21; Bryan, 1938, p. 198).

The three bolsons held the entire volume of the river flow and served as an evaporation basin except at times of extreme flooding (Kottlowski, 1958, p. 48). At

BOLSONS IN CHIHUAHUA TECTONIC BELT

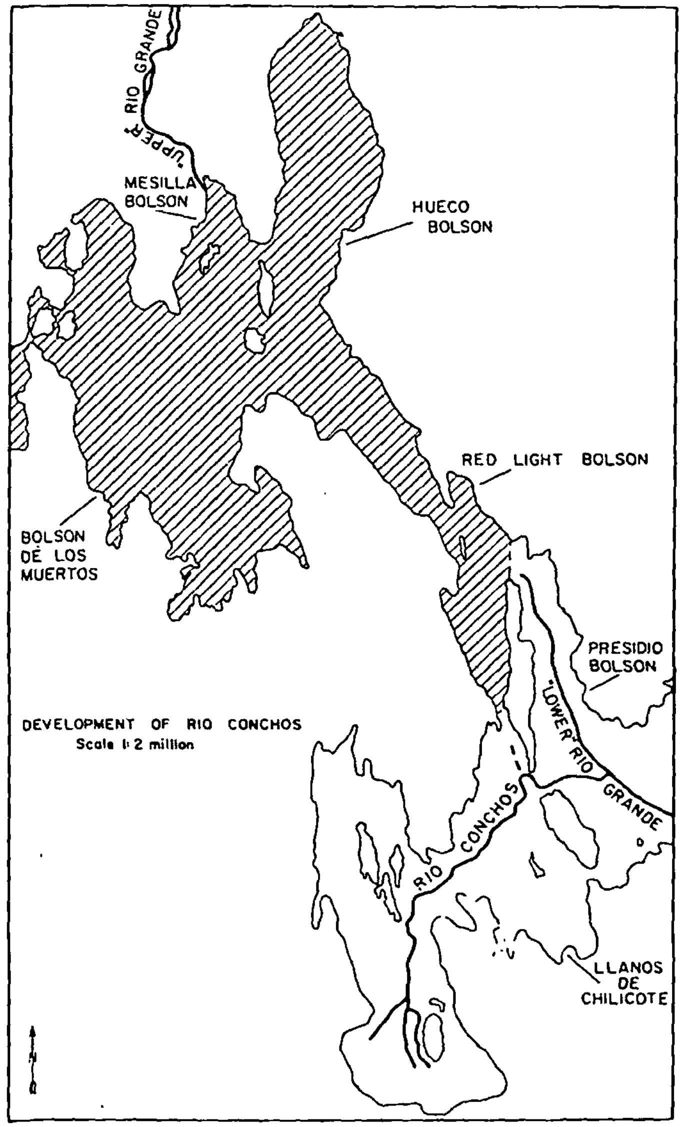


Figure 2

maximum high-water stages the lake level probably rose to an elevation of at least 4250 feet. This elevation is the hypothetical boundary used to outline the bolsons on the accompanying figures. Overflow into bolsons to the south and east may have expanded Lake Cabeza de Vaca as far south as Bolson de Mapimi near Torreon, Mexico, and eastward into the Big Bend region of Texas (Baker, 1927, p. 38; Bryan, 1938, p. 138). The lake thus formed would have been comparable in size to Lake Superior whose surface area is 31,820 square miles. Lake Cabeza de Vaca normally had a surface area of about 16,500 square miles which is approximately three-fourths the size of Pleistocene Lake Bonneville. No evidence of the water levels is recognized. Levels probably fluctuated so rapidly that characteristic shore features did not form, or if they did they have been destroyed by subsequent erosion.

Lake Cabeza de Vaca did not overflow frequently until the holding capacity of the Mesilla, the Hueco, and the Bolson de los Muertos was reduced by filling of the basins with fine sediment brought mostly from New Mexico and Colorado by the "upper" Rio Grande (fig. 2). Late in early Pleistocene aggradation in the lake basins had reduced their holding capacity to such an

BOLSONS IN CHIHUAHUA TECTONIC BELT

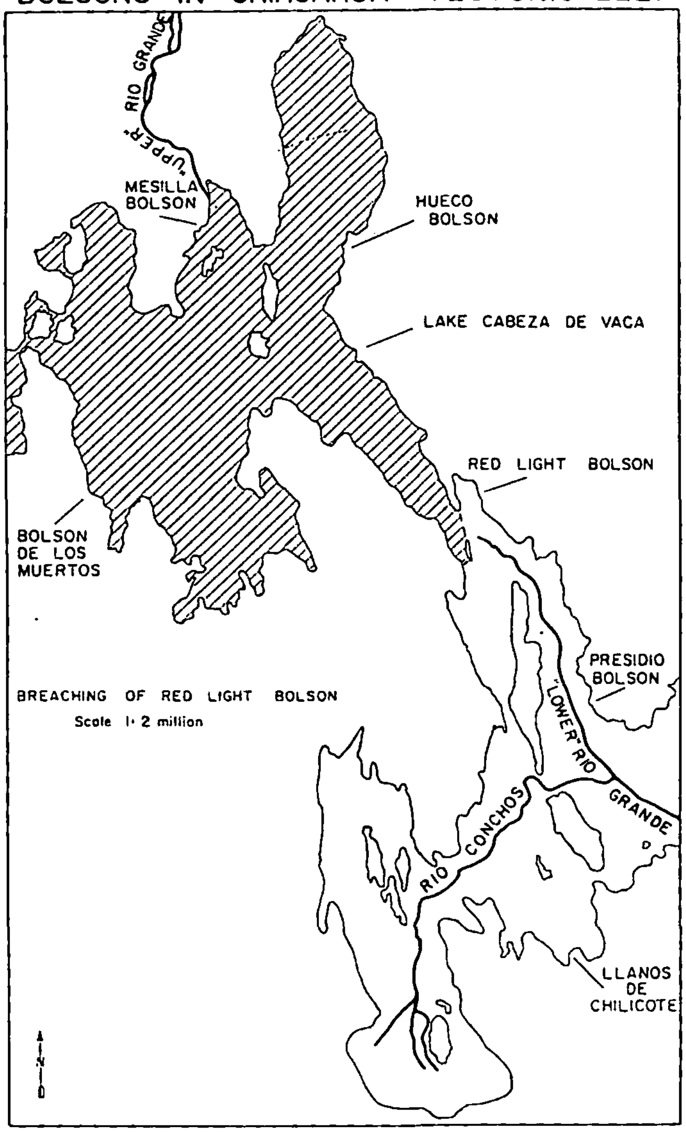


Figure 3

extent that the normal volume of the river was sufficient to overflow the lowest barrier impounding the water and develop an outlet to the bolsons to the southeast. The water first spilled over the barrier between the Quitman Mountains and the Sierra del Pino and into the Red Light Bolson. It probably then spread southward in the valley west of the Sierra de Pilares-Sierra Grande range and joined the Rio Conchos near where it crosses Sierra Grande west of Ojinaga and Presidio (fig. 2).

Akersten (197, p. 20) believed there was a stream in the Red Light Bolson which flowed southward into Mexico prior to the breaching of the barrier between it and the Hueco Bolson. It would have been the stream valley through which the spillover from the Hueco Bolson could have flowed southward to the Rio Conchos. This flow to the Rio Conchos could have continued until the barrier between the Presidio and the Red Light bolsons was removed. It is possible that when water was flowing southward in the Red Light Bolson there was a tributary of the Rio Conchos working northwestward in the Presidio Bolson (fig. 2). This tributary later breached the barrier between the bolsons and diverted the water from the Red Light into the Presidio (fig. 3). Strength is lent to this view by Dickerson (1966, p. 82) who suggested that a stream developed in the Presidio Bolson before there was a connection between it and the Red Light Bolson.

It is possible, however, that instead of water flowing southward to the Rio Conchos from the Red Light Bolson, it spilled eastward into the Presidio Bolson south of the Eagle Mountains where it then entered the Rio Conchos.

Either of the above sequences of events could have connected the Presidio, the Red Light, the Hueco, and Mesilla bolsons, provided a connection between the "upper" Rio Grande near Las Cruces, New Mexico and the "lower" Rio Grande at Presidio and created a through-flowing stream from Colorado to the Gulf of Mexico (fig. 5).

BOLSONS IN CHIHUAHUA TECTONIC BELT

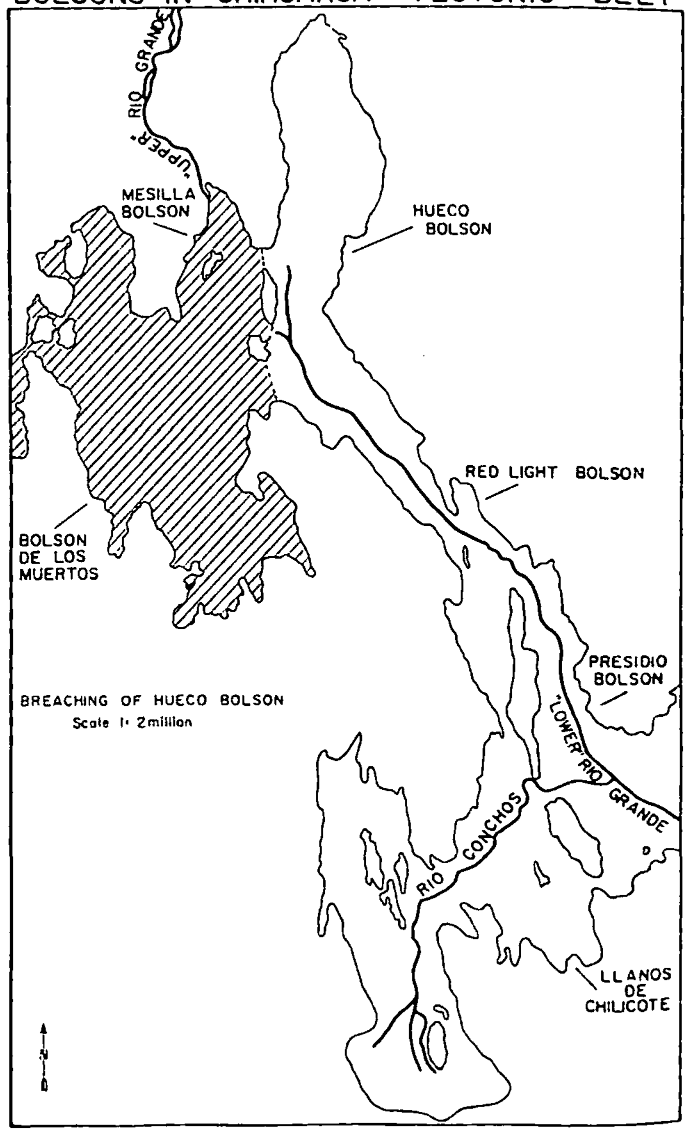


Figure 4

Although basin integration by bolson overflow would explain the development of the Rio Grande between Presidio, Texas and Las Cruces, New Mexico, an alternate view of the process would just as satisfactorily explain basin integration. This hypothesis suggests that the same result would have been accomplished by headward erosion of a tributary stream of the Rio

BOLSONS IN CHIHUAHUA TECTONIC BELT

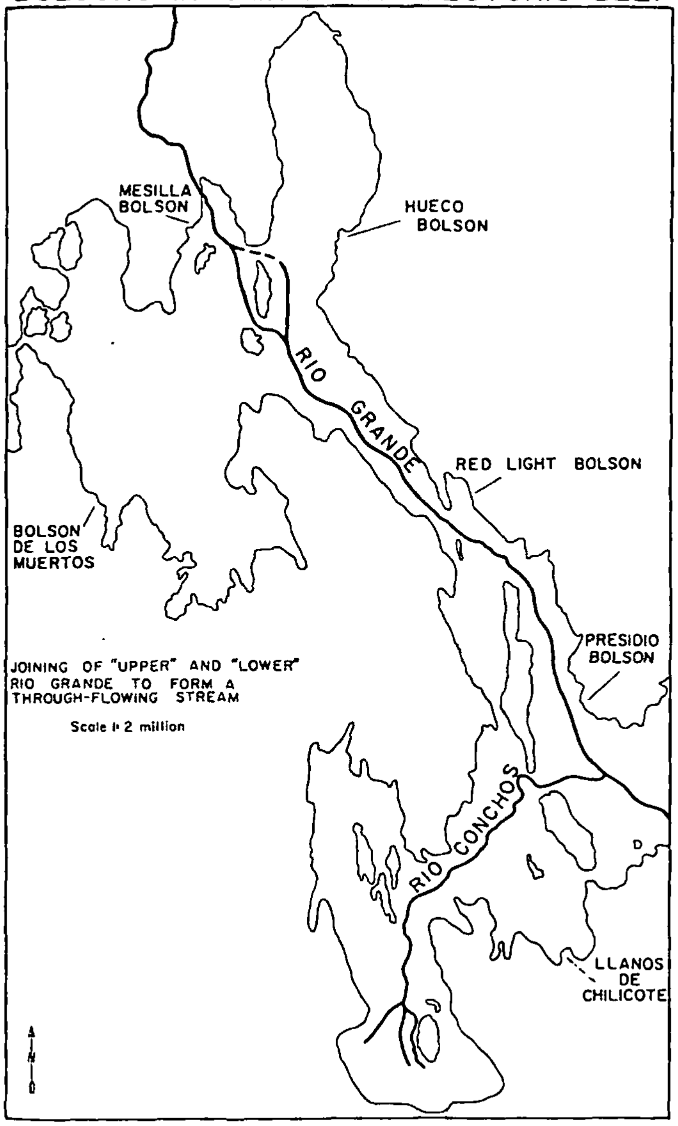


Figure 5

Conchos working northwestward from near Presidio (fig. 2) through the Presidio, Red Light (fig. 3), Hueco (fig. 4), and Mesilla (fig. 5) bolsons where it intersected the "upper" Rio Grande and diverted its water through the new channel to Presidio (fig. 5).

The river probably first flowed through Fillmore Pass between the Franklin and Organ mountains (fig. 5). Stream channel gravel is found there and it is at the highest level of the basin fill where only the first stream to form after Lake Cabeza de Vaca was drained could have deposited it. At a later time the stream through the pass was abandoned when a tributary working headward cut a channel between the Franklin and the Juarez mountains. It then lengthened its course headward along the western side of the Franklin Mountains to intersect the main stream near Las Cruces and divert the river through the course which it maintains today (fig. 5).

Regardless of method, the formation of the river channel between Presidio and Las Cruces established the Gulf of Mexico as a new base level for that part of the river system from Presidio to the headwaters of the Rio Grande. Rock barriers between the bolsons acted as temporary base levels for each bolson, but with the new permanent base level the river quickly entrenched itself in the poorly consolidated basin fill of the various newly breached bolsons.

Because of the ease with which the river could cut unindurated deposits, it is logical to assume that cutting of the channel in the Red Light, Hueco, and Mesilla bolsons took much less time than for the Rio Conchos to cut its channel through the mountains of Chihuahua. If this hypothesis is correct it strengthens the assumption that the Rio Conchos-Rio Grande system is older than the stream between Presidio and Las Cruces (Bryan, 1938, p. 108; Strain, 1966, p. 11).

The time at which through drainage of the Rio Grande became effective can be estimated by the use of vertebrate fossils. Strain (1966, p. 19) has shown that the Fort Hancock Formation (fig. 7) which is genetically related to intermittent Lake Cabeza de Vaca contains vertebrate fossils of Blancan Mammalian Age (Hibbard, et al., 1965, p. 513) (fig. 6). Blancan faunas lived in North America from latest Pliocene to middle Kansan Age of the Pleistocene. The fauna described by Strain can be assigned to the Pleistocene part of the Blancan. The rodents and the large tortoises suggest a semi-arid climate which would most likely indicate a late Nebraskan or an Aftonian age for the lacustrine deposits and their contained fauna.

Vertebrate fossils are also found in the Camp Rice Formation (fig. 7) (Strain, 1966, p. 19) which is in part sand and gravel laid down by the Rio Grande as it began its initial entrenchment in the older lacustrine strata. In the Hueco Bolson "Pearlette" Volcanic Ash is interbedded with the fluvial deposits. The fossils indicate a probable middle Kansan age for the lower part of the Camp Rice and the "Pearlette" Ash establishes a late Kansan age for the middle part of the formation. The upper part of the Camp Rice contains Mammuthus, Smilodon, and Equus (Equus) which indicate that it can be no older than late Kansan because these animals did not arrive in North America before that time.

They belong to the Irvingtonian Mammalian Fauna (Hibbard, et al., 1965, p. 513) whose geologic range is from about middle Kansan to Illinoian. The upper part of the Camp Rice which is also the top of the Santa Fe Group (Hawley, et al., 1969, p. 59) marks the highest terraces in the Hueco and Mesilla bolsons. These were the last deposits to be laid down by the Rio Grande before the initial entrenchment of the present valley.

Vertebrate fossils then indicate that a through-flowing stream probably first developed between the Presidio area and the Las Cruces area some time in early or middle Kansan. This event was possibly related to an increased flow of the "upper" Rio Grande as a result of runoff from glaciation in the southern Rocky Mountains.

In summary, I suggest that the Rio Conchos developed as a through-flowing stream to the Gulf of Mexico by early Pleistocene time. Later the Presidio, Red Light, Hueco, and Mesilla bolsons were integrated. This connected the "upper" Rio Grande near Las Cruces with the "lower" Rio Grande-Rio Conchos system and formed a through-flowing Rio Grande from Colorado to the Gulf of Mexico. Vertebrate fossils indicate this event probably took place in early Kansan time.

AGE		N.A. MAMMALIAN AGES	INDEX FOSSILS
PLEISTOCENE	Wisconsin	Rancholabrean	Bison
	Sangamon		
	Illinoian		
	Yarmouth	Irvingtonian	Equus (Equus) Mammuthus
	Kansan		
	Aftonian	Blancan	Nannippus Plesippus
	Nebraskan		
PLIOCENE			

Figure 6

DIAGRAMATIC SECTION OF BOLSON FILL IN HUECO BOLSON

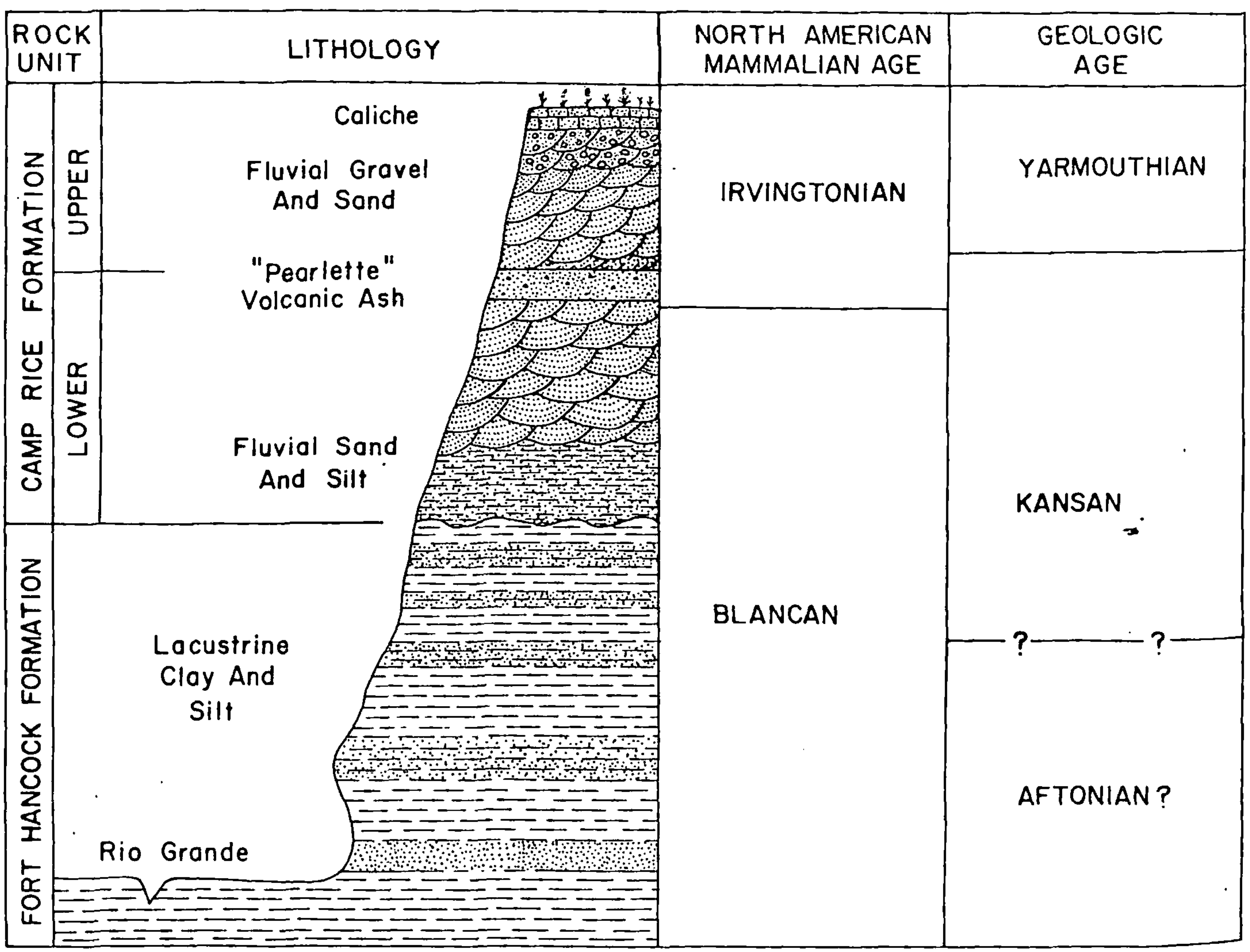


FIGURE 7

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STRUCTURAL EVOLUTION OF THE EASTERN CHIHUAHUA TECTONIC BELT

John C. Gries and Walter T. Haenggi

The Chihuahua Trough, a narrow, northwest-southeast trending negative feature is flanked by the Aldama and Diablo Platforms. The Chihuahua Tectonic Belt is the area of complexly deformed sediments which had accumulated in the trough during Late Jurassic and Cretaceous. A zone of recurrent faulting along the western margin of the Diablo Platform marks the eastern limit of the Chihuhua Tectonic Belt. This zone of faulting separates the thick, complexly deformed rocks of the basin from the predominately block-faulted platform rocks to the east and north of the basin.

In relation to present geography, the eastern limit of this deformed belt lies immediately east of the eastern flanks of the various sierras extending from La Mula, Chihuahua to Sierra Blanca, Texas referred to here as the La Mula - Sierra Blanca Range. This paper will be restricted to examining this range in detail.

PRE-LARAMIDE DEFORMATION

The sparse evidence for Pre-Laramide deformation in the La Mula-Sierra Blanca Range comes mostly from data outside the folded belt. Wiley (1970) reviewed the considerable evidence of Precambrian deformation in the Van Horn-Sierra Blanca area of Trans- Pecos Texas. A possible indication of the complexities of the early tectonic history of the Chihuahua Tectonic Belt is inferred from this closest exposure of Precambrian rocks.

The evidence for Paleozoic depositional basins in this area is examined in detail in other papers of this symposium. With the data available it is evident that by Late Paleozoic a major zone of crustal weakness had developed along the western edge of the Diablo Platform bounding the ancestral Chihuahua trough.

Along what was to become the northern edge of the Mesozoic Chihuahua trough a major crustal disruption - the Texas lineament - existed. Numerous workers have studied the nature and significance of this structural discontinuity. Albritton and Smith (1957) and Muehlberger and Wiley (this symposium) presented excellent reviews of the history of thought concerning this feature.

The Tertiary Rim Rock fault along the western margin of the Diablo Platform has been traced from Presidio to the Van Horn Mountains by the surface mapping of C. L. Baker (1935) and numerous University of Texas students. Wiley (1970) has traced the fault from the Van Horn Mountains to Eagle Flat near Sierra Blanca by gravity measurement. DeFord (1969) suggested that the Rim Rock fault is a "master" fault [illegible] southeastward from the Texas lineament. North of Eagle Flat where the west edge of the Diablo Platform coincides with the Texas lineament, Late Paleozoic movement is probably related to similar movement on the Rim Rock fault.

In Early Mesozoic the north and east boundaries of the Chihuahua trough paralleled the earlier zones of recurrent uplift and faulting. The south end of the trough was restricted by reefs or other means from the marine sea farther south in Mexico. It is possible that the restriction was the result of a southwestward extension of the Ouachita structural zone. The resultant restricted marine environment was the site of thick evaporite deposition. Evaporite exposures indicate that the eastern limit of evaporite deposition in the trough is approximately coincident with the west flanks of the La Mula-Sierra Blanca Range (Haenggi and Gries, 1970, p. 58). All evaporite outcrops and subsurface data seem to be diapiric areas so that the "normal" evaporite thickness is unknown. Ramírez and Acevedo (1957, p. 663-667) reported that Petroleos Mexicanos Cuchillo Parado No. 1 drilled 7,636 feet of evaporite and associated rock near Cuchillo Parado on what we believe to be a diapiric anticline. Of this thickness 80 percent was salt, 5 percent gypsum, 1 percent anhydrite, and 14 percent claystone and limestone. All surface exposures consist of gypsum with a minor content of anhydrite and debris from younger rock units. No fossils have been found in the evaporites. The thick evaporites below the Navarrete and Las Vigas Formations, where no Navarrete has been recognized have been assigned a Late Jurassic and-or Neocomian age (Haenggi, 1966, p. 142-150; Humphrey, 1964, p. 38-41). It is possible that lower evaporites may have been deposited in the Paleozoic.

Various structural features, which were active during the Laramide but diverge from Laramide structural trends, have been suggested as being related to pre-Mesozoic structure. Northwest lineaments on aerial and satellite photographs; the flexure in the La Mula-Sierra Blanca Range near the Río Conchos; and the La Parra, La Chiva, Cipress, and "Jim Brake" faults (fig. 1 and 2), all have been suggested as examples of the pre-Mesozoic trends (DeFord, 1969, p. 64; Haenggi, 1966, p. 301; Haenggi and Gries, 1970, p. 65).

LARAMIDE DEFORMATION

Origin of the La Mula-Sierra Blanca Range

Structures related to the deformation that involved Upper Cretaceous and Early Eocene rocks, but not the

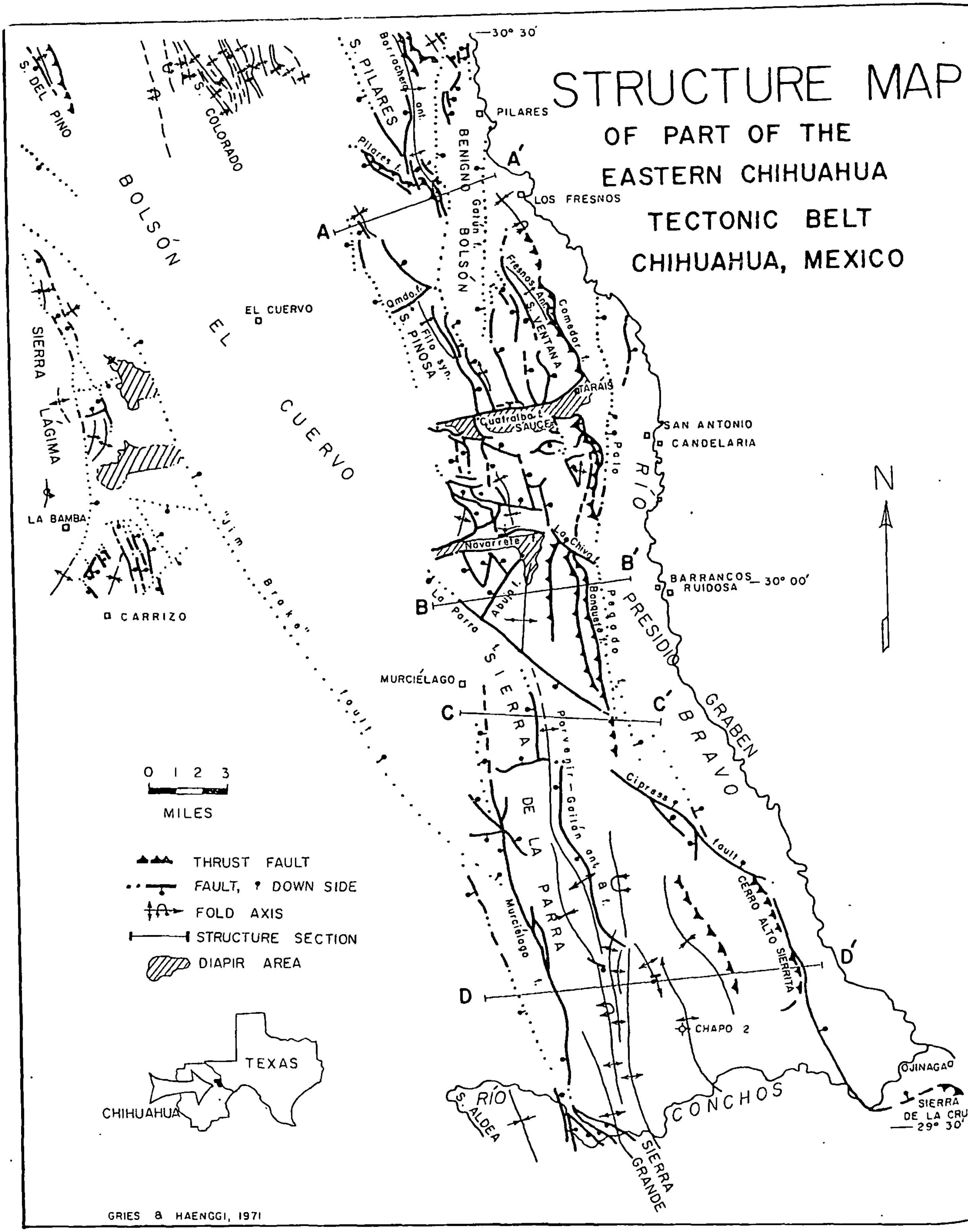


Figure 1. Structure map of part of the eastern Chihuahua Tectonic Belt.

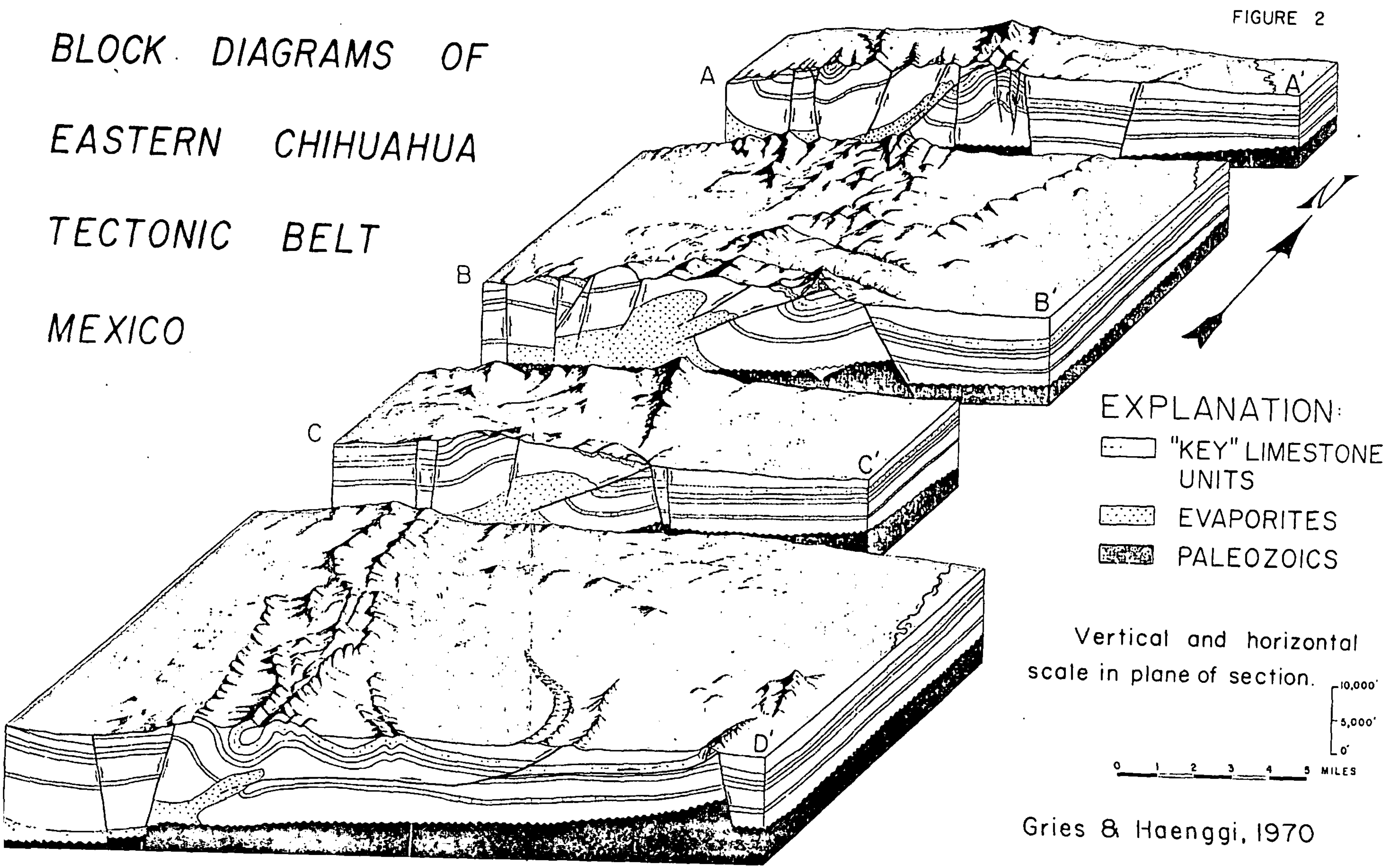


Figure 2. Block diagrams of part of the eastern Chihuahua Tectonic Belt.

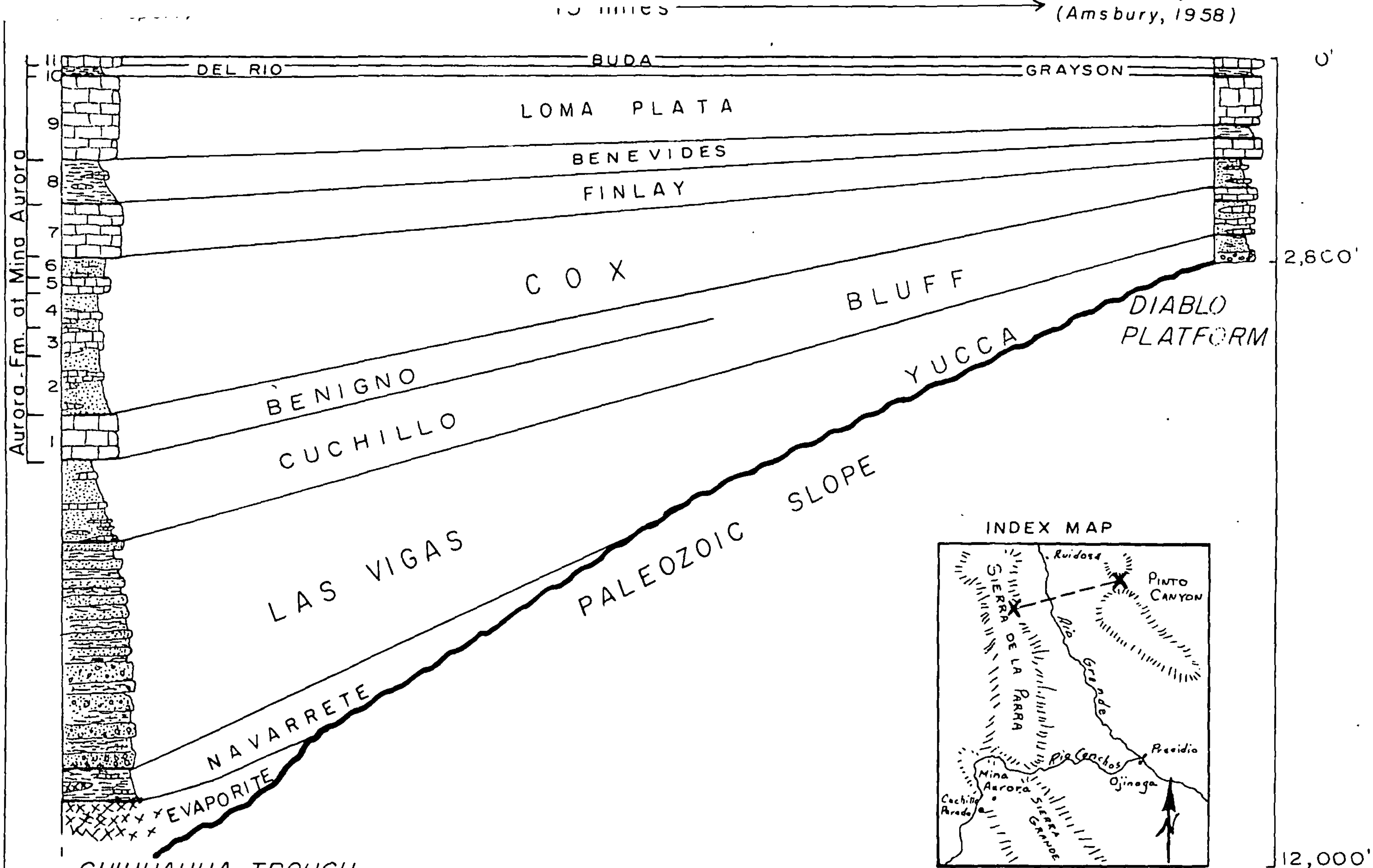


Figure 3. Comparison of Lower Cretaceous rock in the Chihuhua Trough at El Banquete and on the Diablo Platform at Pinto Canyon.

Regional data are used to determine the ages of most structures interpreted as Laramide.

Up to 18,000 feet of siliciclastic and carbonate sediments were deposited on top of the evaporites in the subsiding basin. In the 15 miles from Pinto Canyon to El Banquete in the Sierra de la Parra the depositional thickness of Lower Cretaceous rocks ranges from 2,800 feet to 12,500 feet (fig. 3).

Well data from the intervening Presidio graben may show an even sharper boundary between platform and shelf. This boundary was almost certainly in part a zone of faulting. Haenggi's (1966, p. 168) lithosomal isopachous maps of Loma Plata Limestone suggest an arching or tilting of the basin edges away from the basin center. If the fault zone along the platform edge allowed the basin edge to subside, the thick succession of Cretaceous rocks overlaying an evaporite layer would tend to move down "dip" toward the basin margin. The evaporite would serve as a décollement zone allowing the overlying rock to glide eastward on the evaporite. Haenggi (1966, p. 289) suggested that regional compression formed "ancestral" folds in the Paleozoic basement. Evaporite flowage toward the crests of these features amplified these folds in the overlying Cretaceous rocks. The formation of an amplified ancestral fold near the eastern limit of the evaporite basin coupled with eastward gliding of the overlying rock on the evaporite would produce a large overturned fold approximately coincident with the limit of the evaporite basin (fig. 4). Continued evaporite flowage and eastward gliding would eventually shear the fold and form thrust faults along the eastern margin of the folds.

The same resultant structures could be formed by regional extension. Extension would allow tilting of the Paleozoic basement by downdropping the basin margin along the platform edge fault zone. Eastward gliding of the post-evaporite sedimentary rock would take place to the eastern limit of the evaporite basin. At this limit, folds with cores of evaporite would form and tend to overturn eastward. Shearing and thrustfaulting would take place as in the hypothesis of compression.

Few data are available to favor one hypothesis over the other. One possible clue is the series of small thrust faults east of the main thrust faults near the limit of evaporite deposition. The Devils Ridge thrust fault near Sierra Blanca (Underwood, 1962); Dieciocho fault in the Rim Rock Country (Twiss, 1959); and the Cerro Alto and Sierrita thrust faults of this report represent relatively small thrusts related to the major thrusts to the Chihuahua Tectonic belt, but they are not known to be directly associated with evaporite. Cerro Alto thrust fault is about 10 miles east of the supposed eastern limit of the evaporite basin . Other thrust faults are similar distances from the postulated basin margin faults. This requires low-angle, bedding-plane faulting

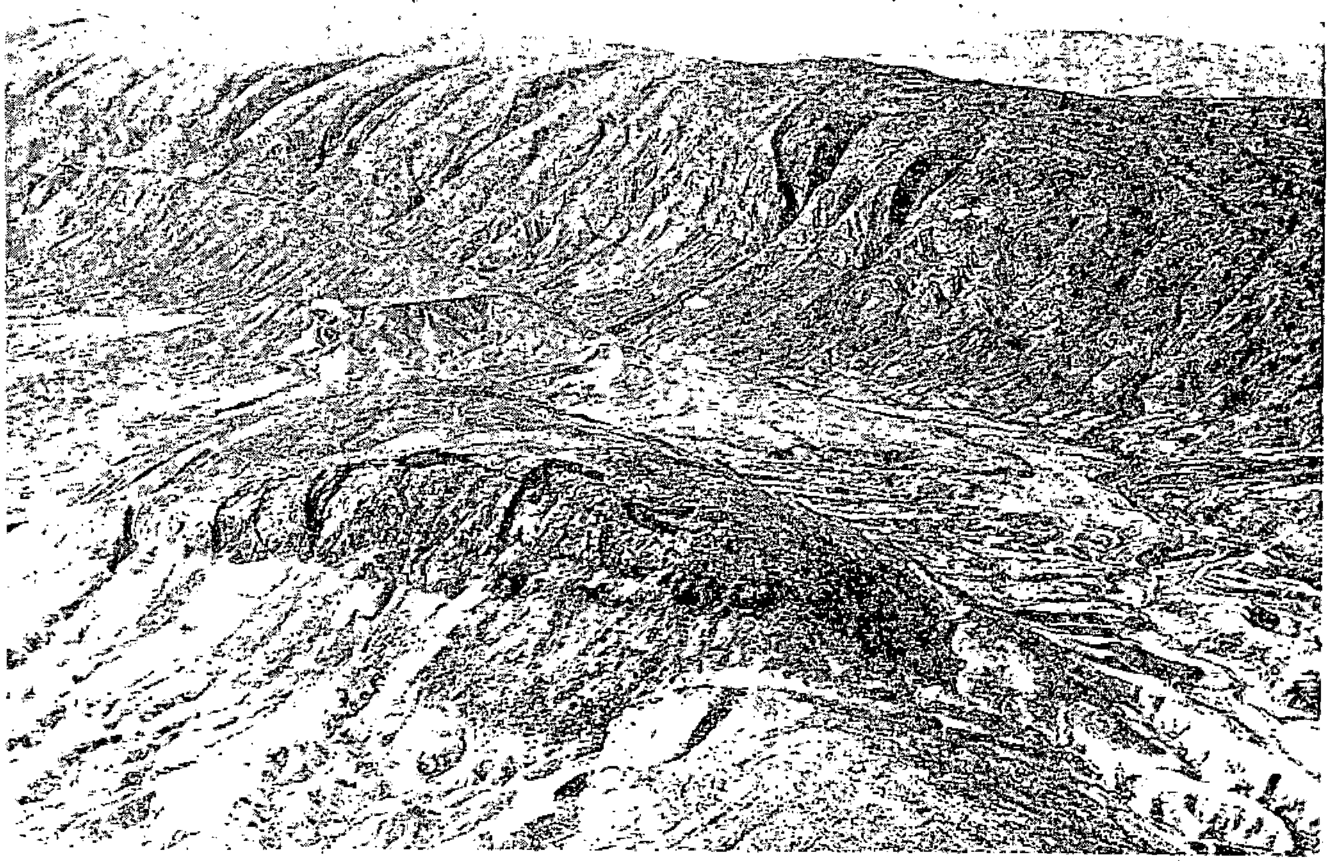


Figure 4. Aerial view of the Sierra Grande anticline. View is south from over the cañon the Rio Conchos cut through the range. The "kink" fold in the foreground is related to the change in strike of the La Mula-Sierra Blanca Range at this point. Massive limestone is the Loma Plata.

east of the evaporite basin.

As seen in figure 5, folding in the Paleozoic basement raises the evaporite rocks prior to the development of the thrust faults. Therefore, the initial zone of faulting is also higher where the basement is folded than where it is not. The higher fault plane may steepen and break to the surface a short distance in front of the main sheared anticline. Consequently, the lower plate would be little affected by the faulting.

The lower fault plane associated with an unfolded basement would tend to produce low angle, bedding-plane faults, disrupting more of the lower plate. This analysis would favor a relatively unfolded Paleozoic basement to produce the small "foreland" thrust faults.

North of the La Parra fault in both the Sierra de la Parra and El Cuervo areas the shortening of the Cretaceous strata is accomplished by major thrust faults, multiple imbricate thrust faults, and small-amplitude complex folding such as seen in the El Banquete area (fig. 6). South of the La Parra fault, the shortening is accomplished by large disharmonic folds of amplitudes up to 10,000 feet. North of the La Parra fault the differential displacement between structural blocks is absorbed by tear faulting such as the La Chiva and Cuatralbo faults. South of the La Parra fault these differences are adjusted by complex folding as seen near the south end of Porvenir-Gaitán anticline (fig. 7).

Origin of Crestal Normal Faults

In the La Mula-Sierra Blanca Range several large anticlines have a normal fault near the fold crest and parallel to it. The Fresno and Borrachera anticlines of El Cuervo area (Haenggi, 1966, pl. 1) and the La Parra, Porvenir-Gaitán, and Sierra Grande anticlines (Gries, 1970, pl. 1) all have crestal normal faults down to the west. Both the Murciélago fault on the Sierra Grande anticline and the Porvenir-Gaitán fault on that anticline displace Oligocene ignimbrite and tuff. The Murciélago fault has a total stratigraphic throw of 6,000 feet of which 1,200 feet represents post-ignimbrite displacement.

One hypothesis is that these faults and others associated with them were formed by evaporite flowage from the west limb into the crest of the fold (fig. 8). The Murciélago fault is 3 ½ miles east of the east limb of the evaporite core of the Cuchillo Parado anticline. It is possible that as the fold developed evaporite from its west limb flowed into the Cuchillo Parado anticline (fig. 8).

The initial movement on these normal faults was Laramide as the large diapiric anticlines overturned to the east and thrust faults developed. Faulted Oligocene volcanic rocks indicate either slow continuous movement of the evaporites after Laramide defor-

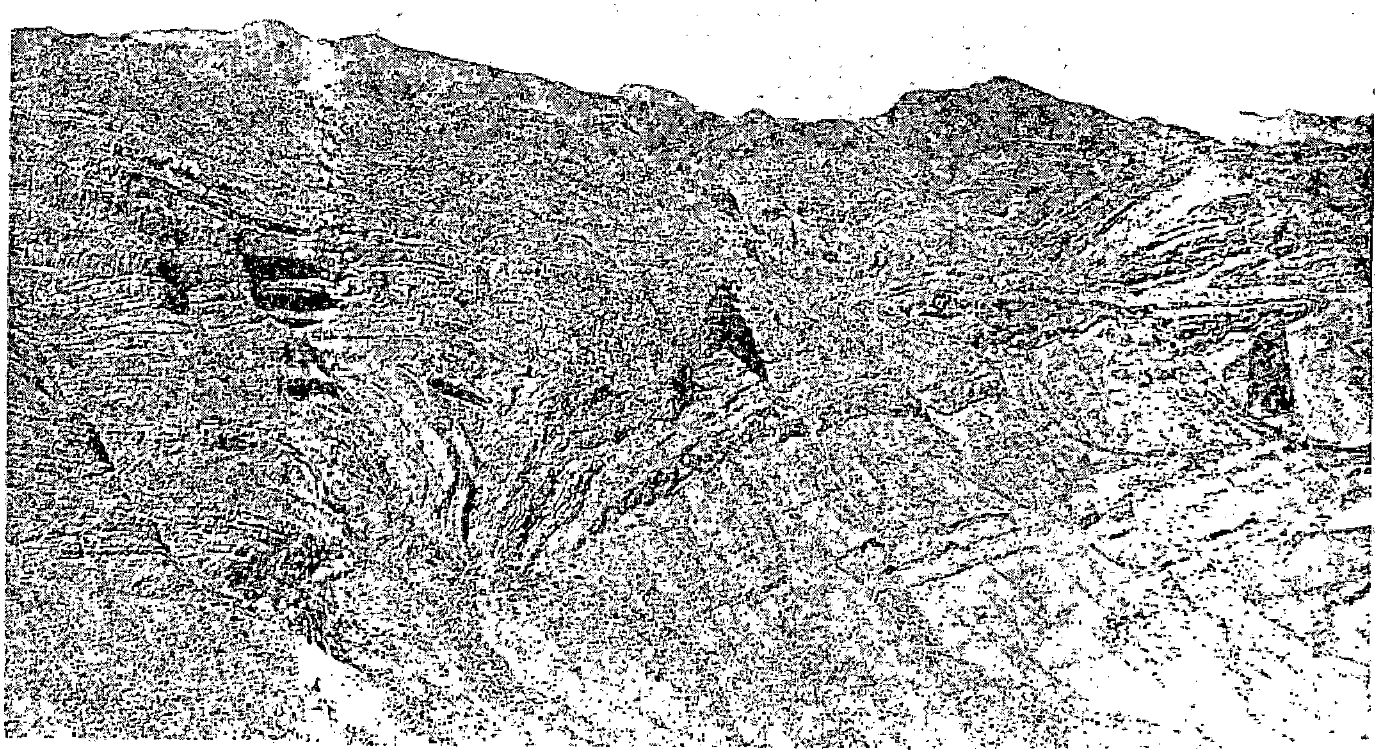


Figure 6. Aerial view of the complexly folded Finlay Limestone in the upper plate of the Banquete thrust fault. Cañon de las Villistas is seen at the south end of El Banquete at the

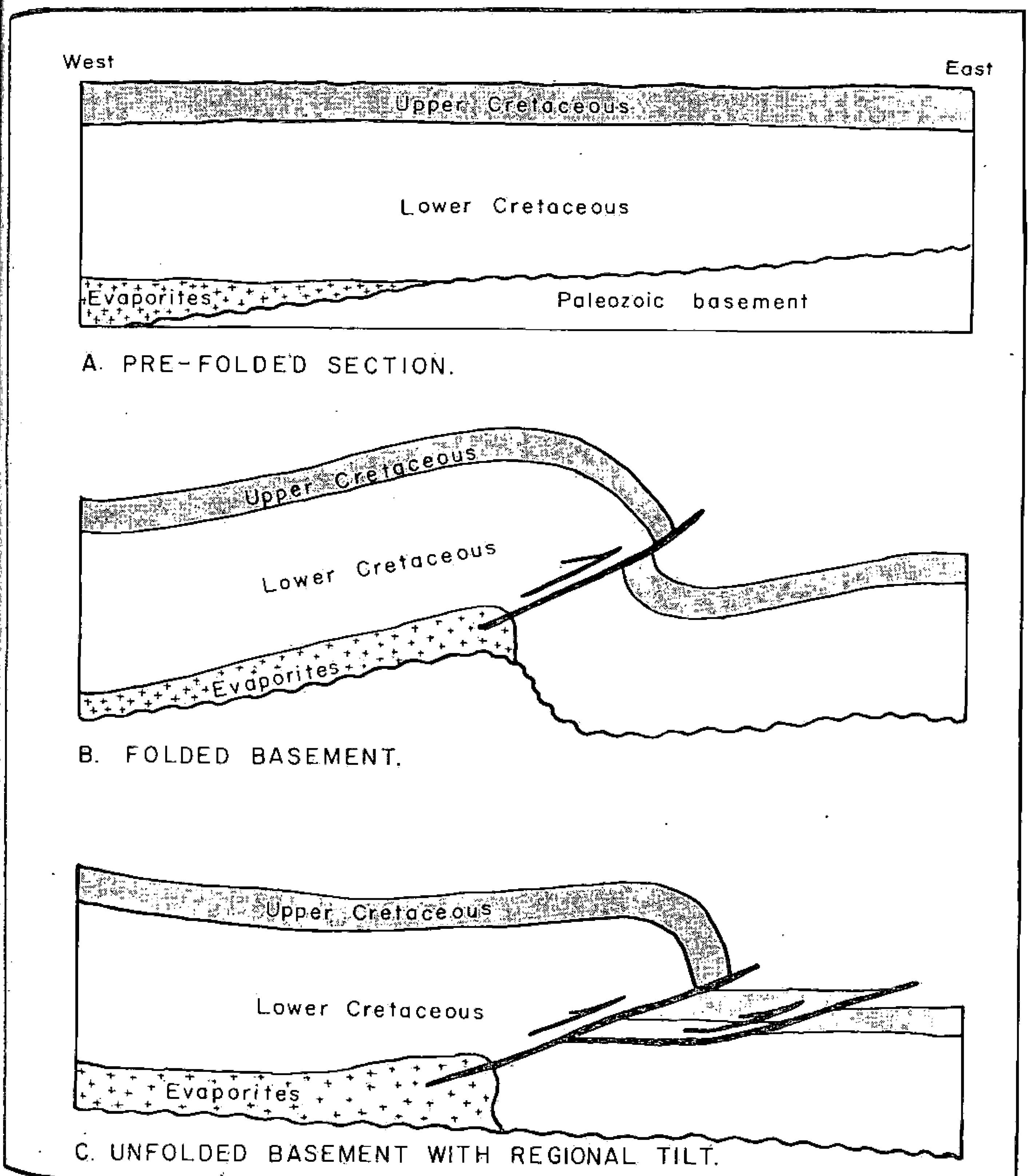


Figure 5. Diagrammatic comparison of the effects of folded vs. unfolded Paleozoic basement and the position of thrusts with respect to strata in the lower plate.

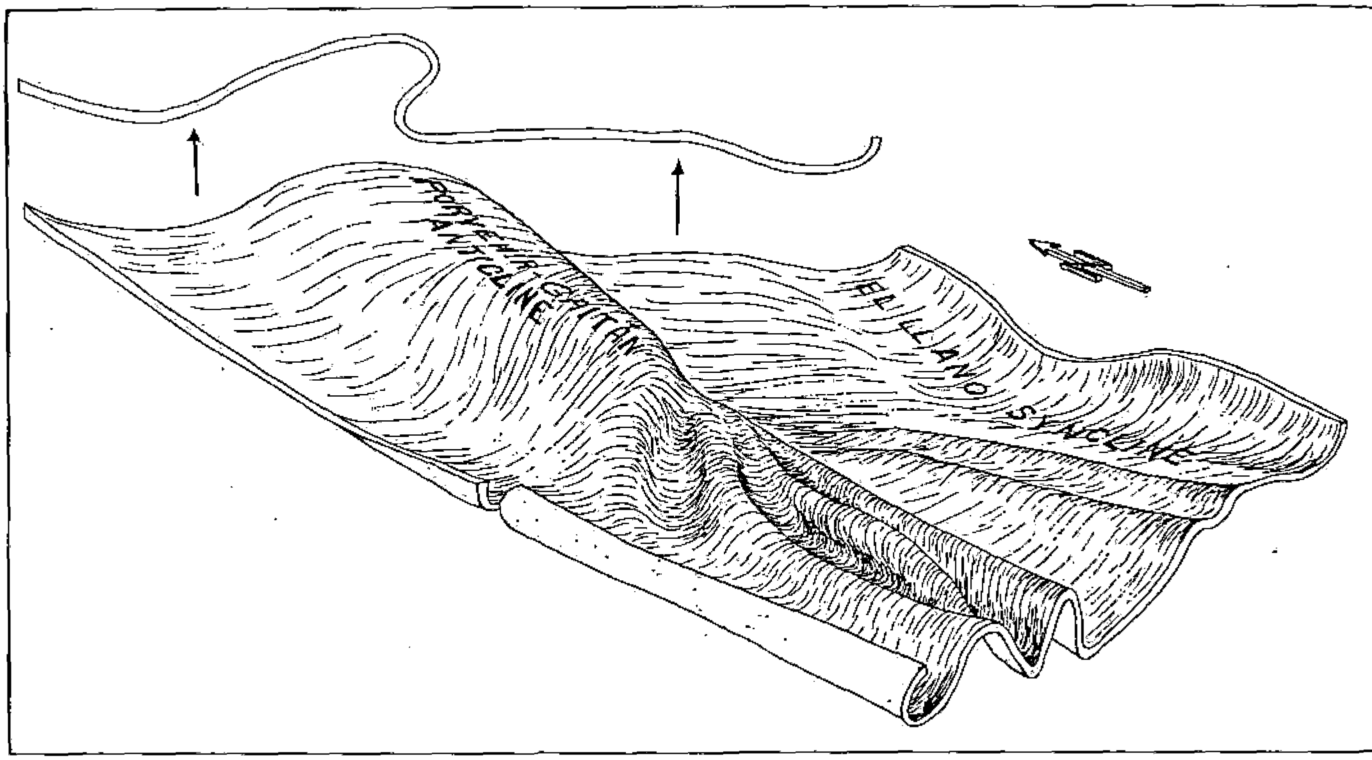
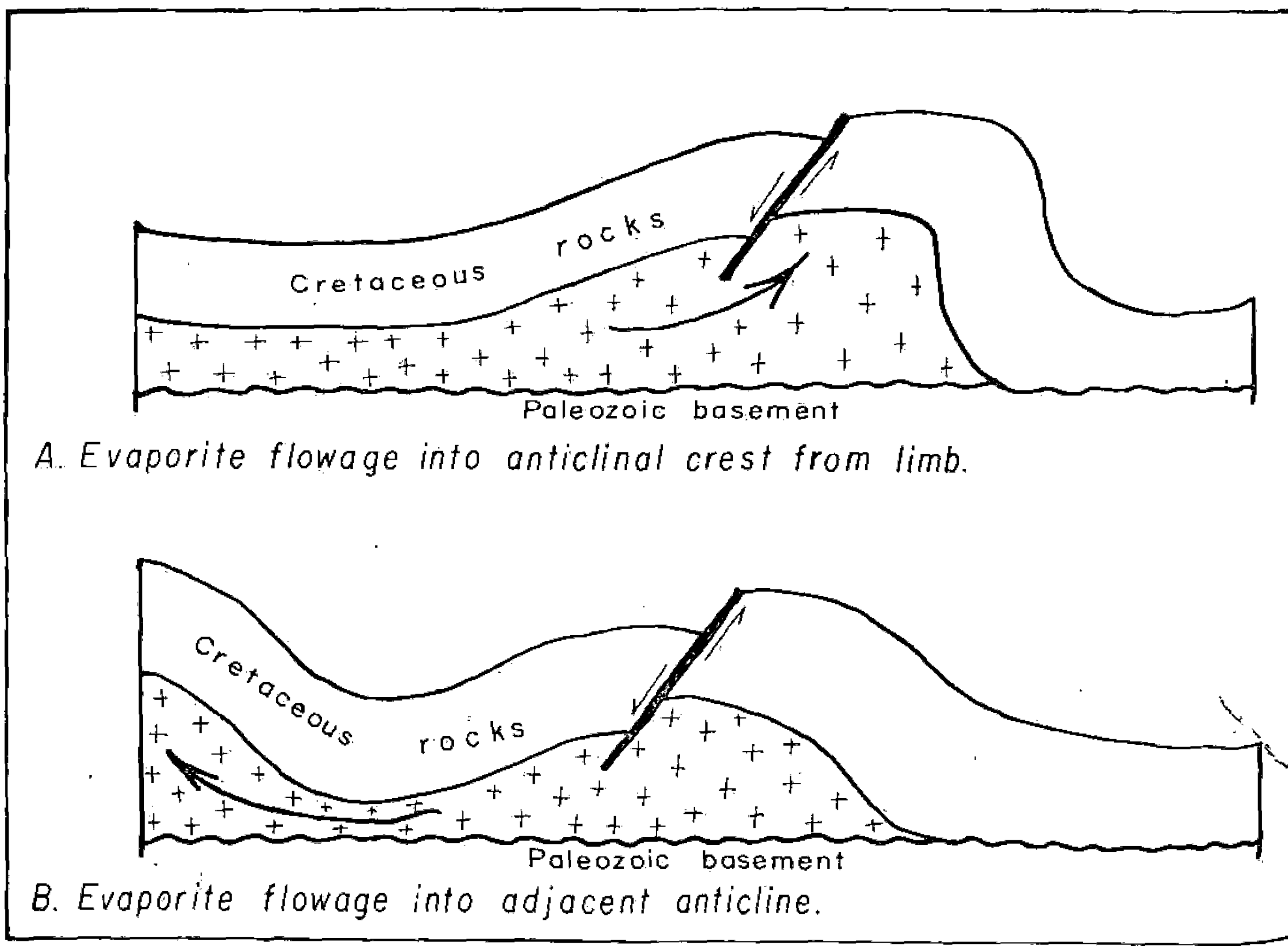


Figure 7. Schematic diagram illustrating changes in fold shapes immediately north of cross-section D-D' (fig.1) at the south end of Porvenir-Gaitan anticline.



mation or a reactivation of the Laramide faults in post-Oligocene and therefore a part of regional Cenozoic block faulting.

The Murciélago fault can also be explained as a normal fault affecting Tertiary, Mesozoic, Paleozoic, and pre-Paleozoic rocks. Significantly the major activity along the fault was pre-Tertiary volcanic rock which is older than most of the block faulting superimposed on Laramide structure in Trans-Pecos Texas. Hence, the fault appears to have originated during or prior to Laramide deformation. Possibly it is a rejuvenated Paleozoic feature associated with the "Jim Brake" fault. The latter fault is inferred from the west flank of the Sierra de la Parra to the east flank of the Sierra Lágrima across the south end of Bolsón El Cuervo and has a similar trend to the La Parra, Cipress, and La Chiva faults, all of which may have had their origins during Paleozoic time. Prominent jointing near the inferred intersection of the "Jim Brake" and Murciélago faults fits the northwest trend of the postulated Paleozoic structures and does not fit Laramide structures well. If this speculation is correct, the Murciélago fault indicates a change in trend of pre-Laramide structure in the vicinity of the Sierra de la Parra. All of these structures have experienced rejuvenation during Laramide deformation and-or Tertiary uplift.

Origin of Bolsón El Cuervo

Two basic and mutually exclusive hypotheses concern the structure of the Bolsón El Cuervo located immediately west of the La Mula-Sierra Blanca Range (fig. 9): 1. Structure beneath fill is basically a large anticline, which trends north and probably plunges north toward the Sierras del Alambre and Colorado and also plunges southward toward the Rio Conchos cañon. 2. The bolson is a graben with boundary faults west of Cerro El Moro and east of isolated outcrops of the Lagrima Formation west of El Cuervo. Both interpretations are consistent with gravity data.

Arguments supporting the anticlinal interpretations are:

1. It is possible to interpret structure between the central Sierra Pilares and the Sierra de la Cieneguilla without invoking normal faults of large displacement.

2. Along the west front of the Sierra Pinosa midway between the Cuatralbo and Navarrete transverse structures the Las Vigas Formation crops out in the mountains, adjacent to the bolson, and dips eastward and there are no traces of normal faults of large displacement along the boundary between the bolson and the mountains. Presumably the structure along the mountain front is the east limb of an anticlinal feature, and older formations than the Las Vigas crop out beneath bolson fill. The anticlinal structure of the southwestern part of the Sierra Pinosa may be part of the postulated anticline or may be a secondary fold on the flank of the postulated anticline. The structure of the bolson can be interpreted to be basically due to folding.

3. South of Bolsón El Cuervo the Cuchillo Parado anticline has been breached by erosion and a long intermontane valley has formed along it. The Sierra de [illegible] east flank of an anticline, and evaporites are present below a thin veneer of alluvium in the axial valley (Pérez, 1950, p. 107; Salas, 1955, p. 100-101; Ramírez and Acevedo, 1957, p. 663-667). Geographically the Cuchillo Parado anticline occupies the same position with respect to the La Mula-Sierra Blanca Range as does Bolsón El Cuervo. Sipperly (1967, pl. 1) has mapped the overturned anticline shown west of the Sierra Colorado northward along the west flank of the Sierra del Alambre for a distance of about 12 miles from 30°30' N latitude. This structure continues northward, beneath bolson fill, and is the same anticline that has the southern Quitman mountains as its east flank. Most of the basic structural elements of the Chihuahua Tectonic Belt trend north for long distances; e.g., La Mula-Sierra Blanca Range; "Trendology" places the Cuchillo Parado anticline, Bolsón El Cuervo, and the "Sierra del Alambre-Quitman anticline along the same structural-geographical trend.

A compromise between the anticlinal and graben hypotheses for Bolson El Cuervo is indicated by the Murciélago fault. Basement faulting, under salt, could cause diapiric folding and secondary faulting in rocks overlying the evaporites. The relatively minor thrust faulting at Cerro El Moro (fig. 9) could be an expression of such a process. In areas where evaporites are thin, as postulated along the Murciélago fault, the basement faulting could have broke through to overlying sediments.

Origin of the La Parra and Cipress Faults

The following conclusions can be reasonably drawn from field studies of the La Parra and Cipress faults:

1. No post-Laramide movement can be demonstrated on the La Parra fault because an Oligocene (?) trachyte dike crosses the fault without apparent displacement.

2. Only post-Oligocene movement with throw down to the north can be demonstrated on the Cipress fault.

3. That the alignment of both faults (N. 40°-50° W.) along the same general lineament diverges from Laramide structural trends must be more than coincidental.

4. Movement older that the definitely established periods of faulting on each fault can not be ruled out.

5. Gravity measurements fail to establish faults along the projections of their trends east of the Rio Bravo.

6. Fold axes in the thrust plates north of the La Parra trend due north; fold axes in the thrust plate south of the La Parra trend N. 15° W.

7. The axial traces of the La Parra anticline on the north side of the fault and the Porvenir-Gaitán anticline on the south side are nearly aligned with each other.

We propose the following sequence of events in the development of the La Parra and Cipress Faults to satisfy the above relations:

1. A pre-Mesozoic fault or structural weakness formed parallel to the present faults.

2. The La Parra fault formed as a normal fault down to the south just before or contemporaneously with the initial thrust development. The fault extended from the southeast end of Bolsón El Cuervo, to just north of [illegible]

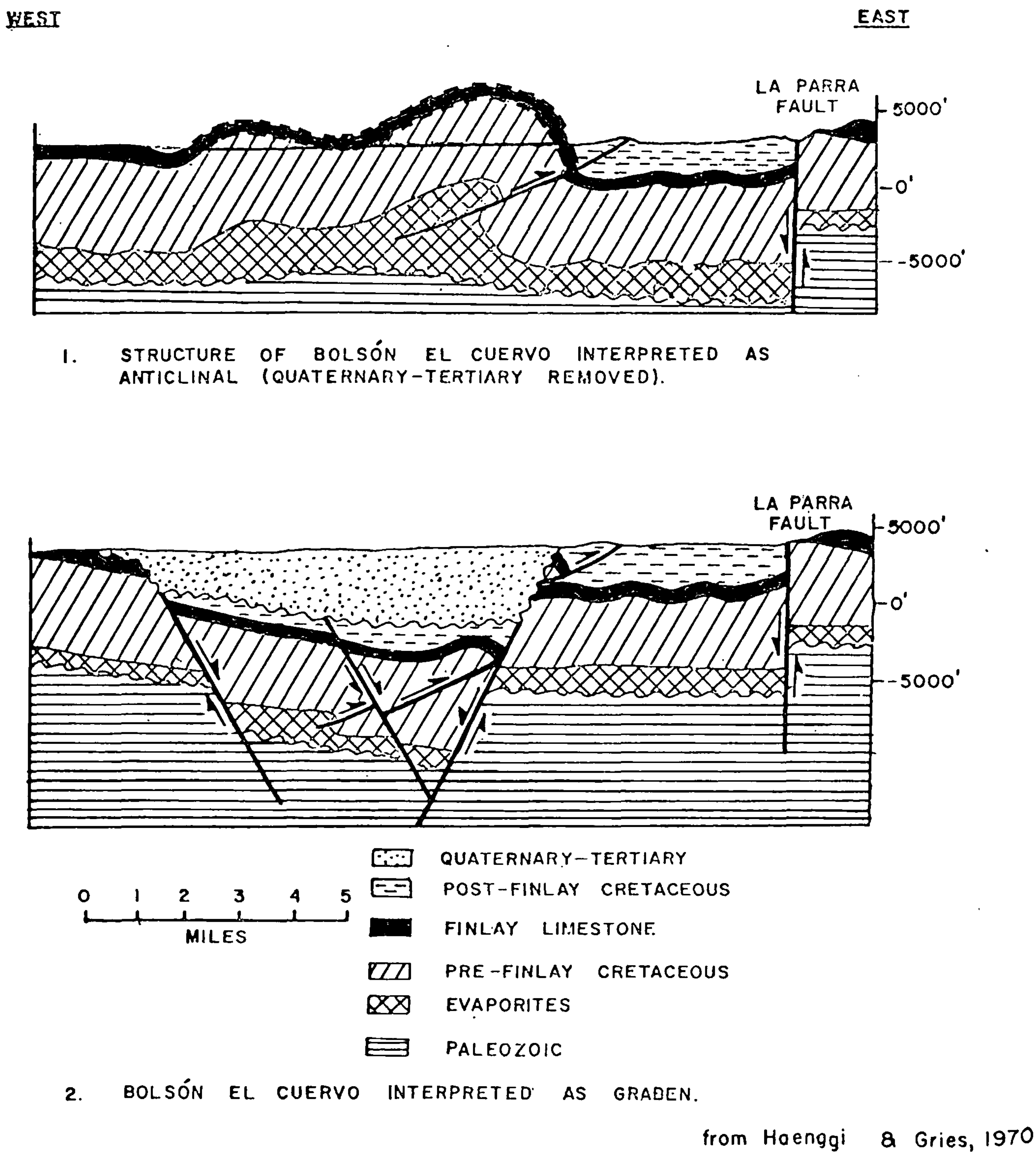


Figure 9. Alternate interpretations for structure of Bolson El Cuervo. Sections are at 30° 00' latitude.

faults) was about the same on both sides of the La Parra fault. Therefore no major stirke-slip faults or tear faults developed along the La Parra fault. Throw on the La Parra fault was 500 to 1000 feet down to the South.

The La Parra faulting could not have taken place after the initial thrusting or the upper-plate fold axes north and south of the La Parra trend would be parrallel instead of diverging 15 degrees from each other. Minor drag features developed along the easternmost La Parra fault where the minor folds butt against each other from each side of the fault. Minor tear features may have also developed at the north end of the small Cerro Alto thrust fault. The axes of the La Parra anticline and Porvenir-Gaitán anticline remain essentially in line; there is no major strike-slip component on the La Parra fault.

3. Evaporite flowage continued into the La Parra anticline, while surrounding areas foundered because of outflow of evaporite that formed the Abuja fault (fig. 10).

4. Continued evaporite flow induced a trap-door uplift of the part of the La Parra anticline that is bounded on the northwest by the Abuja fault and on the southwest by the La Parra fault. The hinge of the trap door is a north-south line on the east limb of the anticline. Thus maxium throw on both the Abuja and La Parra faults was near the intersection of the two faults; the throw decreased eastward on both faults.

5. Strata on the steep east limb of the anticline slide by gravity eastward and formed the Villista thrust fault.

6. Tertiary normal faults intersected part of the old fault as the Presidio graben developed. Thus the Cipress fault formed as the line-of-least-resistance during this later period of faulting.

An andesite intrusion crops out on the downthrown side of the La Parra fault near its northwest limit and two intrustions crop out on the upthrown side of the Cipress fault which has the same strike as the La Parra fault. This alignment of intrusion may have its origin in a zone of weakness in the crust that developed prior to or perhaps during Laramide deformation.

Deformation in vicinity of Arroyo Cuatralbo

The most probable explanation for the origin of the structure along Arroyo Cuatralbo fault is that it originated as a tear fault during thrust faulting along the Comedor fault. Faulting along the tear probably did not affect Paleozoic "basement" rocks below the evaporite décollement zone.

The hypothesis of strike-slip displacement along the Cuatralbo fault assumes that the syncline adjacent to the Cuatralbo fault near the center of the transverse structure) is a drag fold along a left-lateral strike-slip fault. Relative to the north side of the Cuatralbo fault the estimated eastward displacement of the south side is 2,000 to 3,000 feet. This is the probable order of magnitude of the difference in eastward displacement of segments of the Comedor fault north and south of the Cautralbo fault. According to the tear-fault

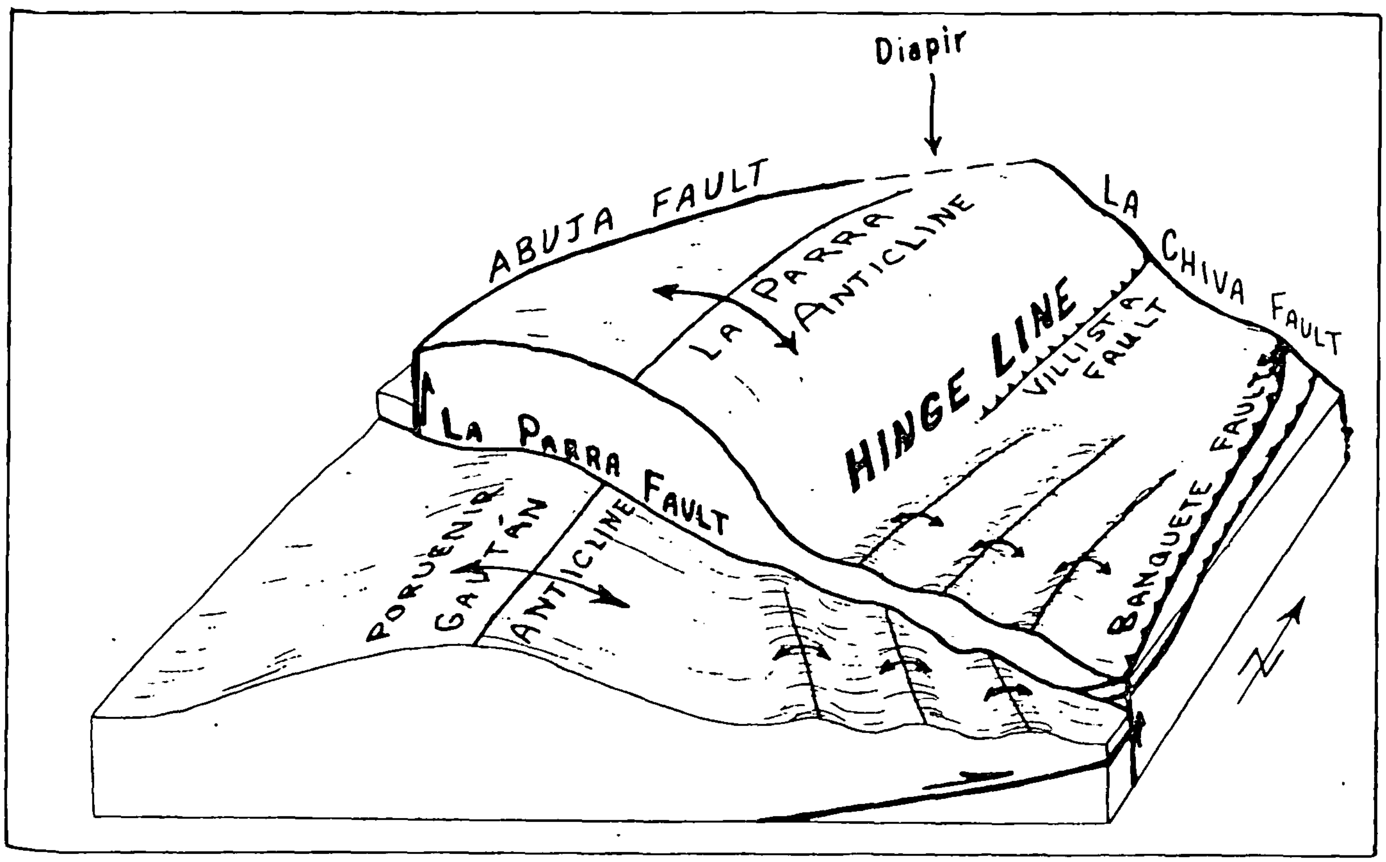


Figure 10. Schematic diagram showing diapiric uplift of the La Parra anticline between

hypothesis, the diapirs along the Cuatralbo structure west of El Sauce originated in cores of drag anticlines adjacent to the drag syncline (fig. 11).

The diapir at Tarais is in the area where the trace of Cuatralbo fault, if projected eastward, would intersect the trace of the Comedor thrust fault. Presumably this diapir was injected along the Comedor fault pushing the hanging wall block up, away from the footwall block. Intrusion probably began at the intersection of the Cuatralbo fault and Comedor thrust faults with the eastern limit of the evaporite basin and continued on trend with the Cuatralbo fault, spreading upward and laterally along the Comedor thrust fault zone.

Diapiric injection of evaporites during thrust faulting is implicit in the above interpretations. This is only one interpretation. Diapiric intrusion could be younger than thrust faulting; or it could have begun during thrust faulting and continued afterward.

A system of east-trending "subsidence faults" south of Arroyo Cuatralbo probably developed in a "rim syncline" adjacent to the Cuatralbo diapir system.

Simultaneously, evaporites were flowing from the southern Sierra Pinosa toward diapirs along arroyos Navarrete and Cuatralbo. The complicated pattern of faulting between the western parts of the Navarrete and Cuatralbo structures is thus the result of differential settling of blocks as evaporities flowed out.

La Chiva-Navarrete faulting and transverse deformation.

The interpretation that a fold system north of Arroyo La Chiva southeast of Navarrete represents drag along a right-lateral strike-slip fault presumes tear faulting along the La Chiva-Navarrete structural complex during thrust faulting. Supporting evidence is:

1. The transverse trough along Arroyo Navarrete trends parallel to the probable direction of overthrusting along the Comedor and Banquete fault systems. If there was faulting along this structure during Laramide deformation, it was probably strike-slip.

2. A small tear fault east of Navarrete proves that some tear faulting took place. The transverse trough has the same trend as the tear.

3. The great structural discontinuity across the La Chiva-Navarrete complex supports this interpretation.

Displacement of the Comedor thrust fault system, north of the La Chiva fault, is not significantly different from that of the Banquete fault system. If the Comedor and Banquete thrust faults developed simultaneously and if movement on them was synchronous, this concurrence condemns the hypothesis that the La Chiva fault was a tear during thrust faulting. Figure 12 illustrates a hypothesis of relationships between the Comedor, Banquete, and La Chiva faults and postulates the following events:

Event 1. If the block to the south was relatively stationary but underwent intense folding, the block north of the La Chiva-Nararrete complex moved eastward, thus a right-lateral tear fault originated the La Chiva-Nararrete structure.

Event 2. The Banquete fault then developed near the base of the folds south of the La Chiva-Navarrete complex. The southern block moved eastward while the northern block was relatively stationary. Th[illegible] left-lateral tear during thrust faulting along Banquete fault system completed the Laramide Chiva-Navarrete structure.

During these events there were significant dip components of net slip on the La Chiva fault, and final relative vertical movement is up to the so[illegible] Sipperly (1967, p. 59-62) described a similar history structural relations in the northern Sierra del Alam[illegible]

This hypothesis explains most of the com[illegible] structural features in the vicinity of Navarrete. It le[illegible] to:

1. Development of La Parra anticline as a br[illegible] symmetrical fold and initiation of flow of evapor[illegible] from area below the northwestern part of the Sierra la Parra into core of anticline.

2. Event 1. accompanied by development of f[illegible] system north of La Chiva fault as drag folds on ri[illegible] lateral tear, and continued development of La Pa[illegible] anticline, south of the tear. Initiation of intrustion evaporites along western part of La Chi[illegible] Navarrete "tear" and development of "rim syncli[illegible] along north edge of diapir.

3. Continued intrusion of evaporites along transve[illegible] structure results in development of Pinosa reverse fa[illegible] system and evaporites continue to flow into core of Parra anticline, causing overturning of east fla[illegible] Development of Abuja fault as evaporites flowed aw[illegible] from vicinity of northwestern Sierra de la Parra a foundering of the northwest part of the Sierra.

4. Event 2 triggered by continued flow of evapori[illegible] into core of La Parra anticline and diapir.

5. Continued flow of evaporites into La Parra a[illegible] ticline and diapir accompanied by secondary faulti[illegible] and left-lateral tear faulting along La Chiva fault.

Pilares Fault

North of the Cuatralbo transverse structure, t[illegible] major structural feature of the southern Sierra Pilar[illegible] is the Palares fault, a thrust fault trending N. 3[illegible] W. across the sierra. Overthrust toward the northeas[illegible] the fault has an extimated maximum displacement [illegible] 10,000 feet. The lower member of the Las Vig[illegible] Formation crops out on the hanging wall adjacent [illegible] the fault trace, formations cropping out on the footwa[illegible] are the Loma Plata, Del Rio, and Buda. Northwestwa[illegible] the exposed formations of the footwall adjacent to th[illegible] fault are progressively older until the Cox Formatio[illegible] crops out below the fault at its western terminatio[illegible] against a normal fault. This configuration may indica[illegible] that the Pilares fault dies out to the northwest. Withi[illegible] the mountains its trace is offset by three norther[illegible] trending normal faults, each down to the east. The di[illegible] of the Pilares fault ranges from 25° to 5[illegible] southwest and is parallel to bedding.

Quemado Fault

The vertical Quemado fault trends northeast, pe[illegible] pendicular to the structural grain of the southern Sier[illegible] Pilares. The most plausible explanation seems to [illegible] that it is a tear fault associated with faulting along t[illegible] Pilares thrust fault, but the following lines of eviden[illegible] indicate that the lat[illegible]

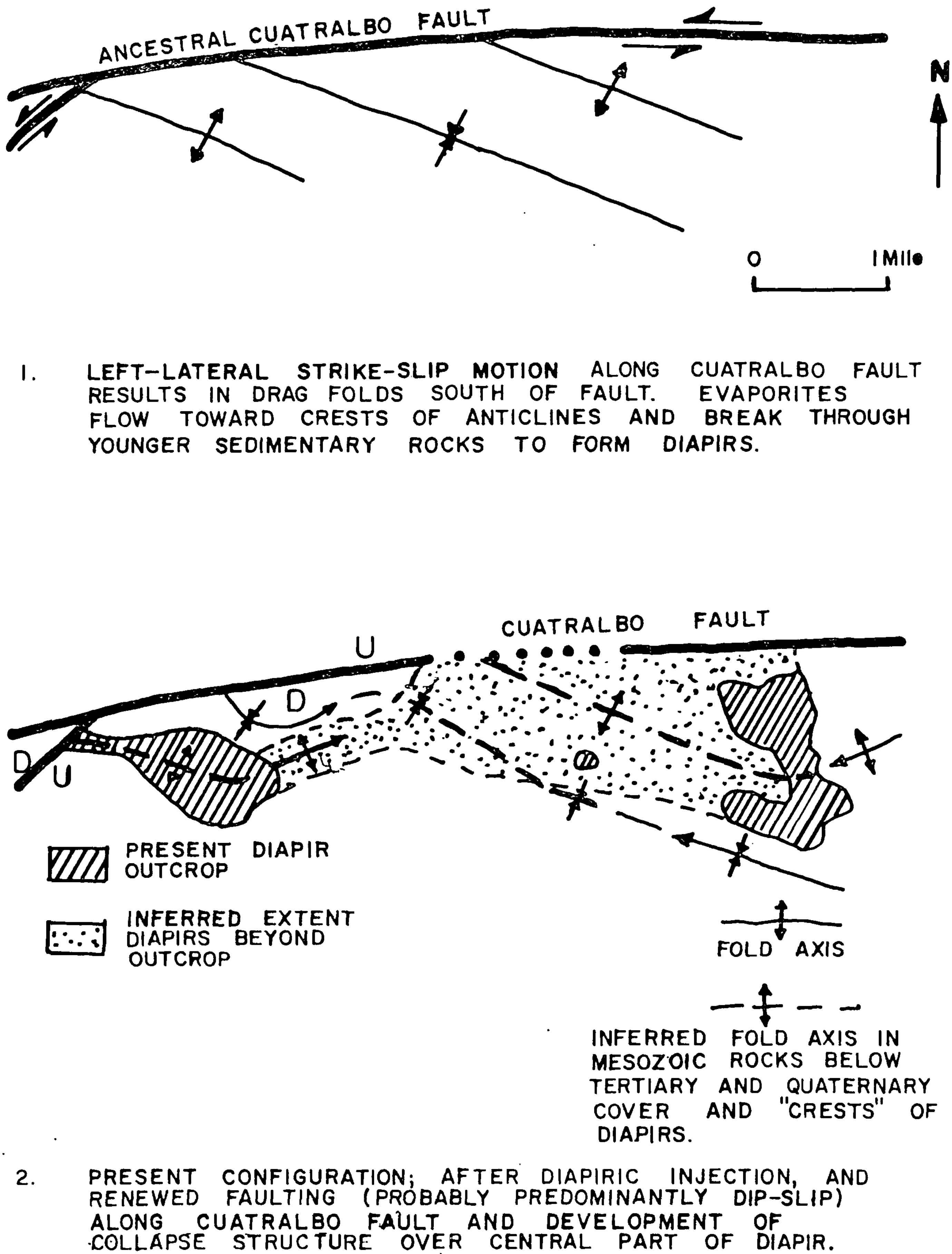


Figure 11. Hypothesis of origin of diapirs east of Cuatralbo and west of El Sauce.

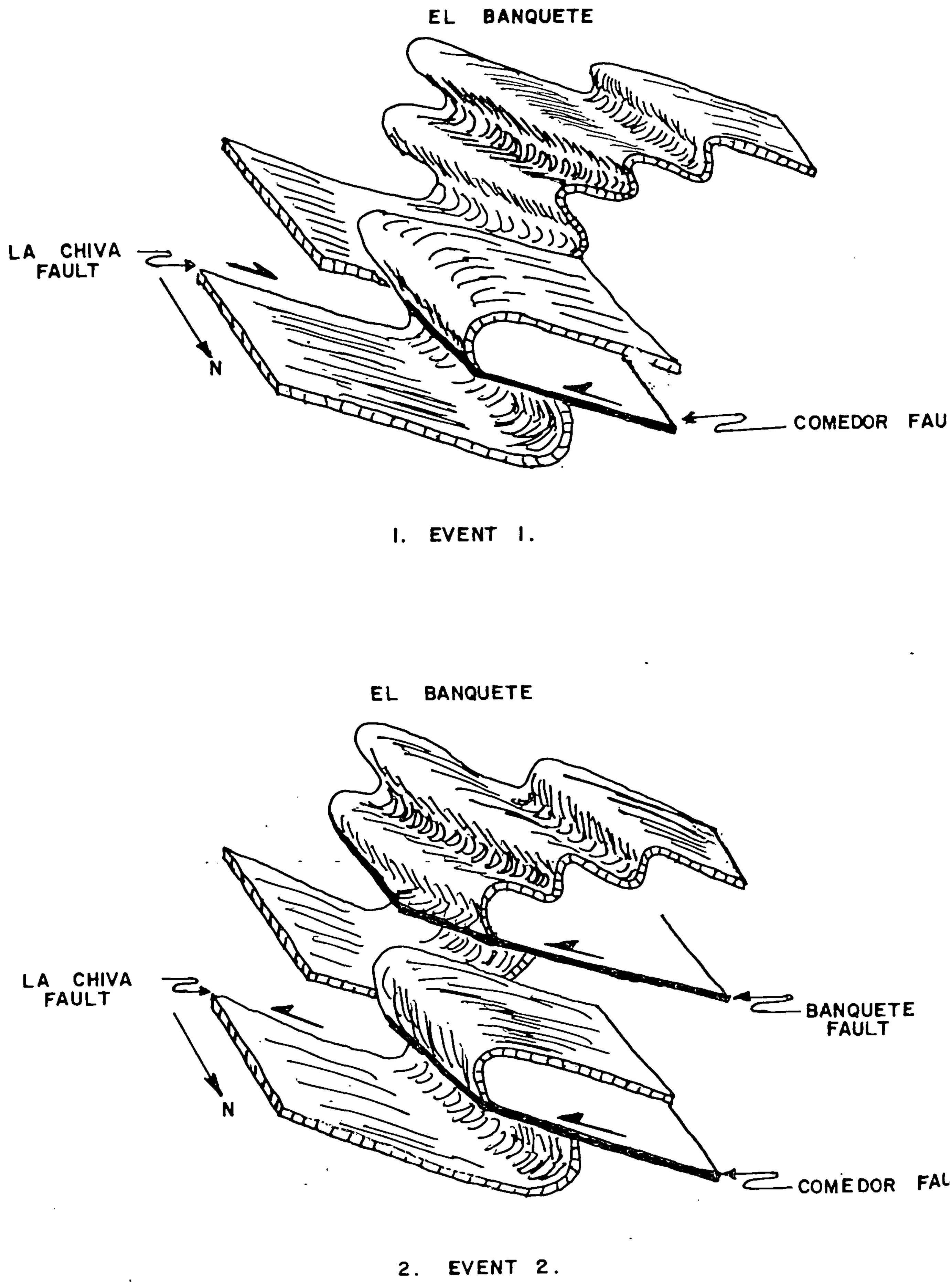


Figure 12. Hypothesis of relations between Comedor, La Chiva, and Banquete faults.

predominately dipslip:

1. From stratigraphic evidence the fault is down to the south 1,000 to 1,500 feet and there is no need to invoke strike-slip displacement to explain outcrop patterns north and south of the fault.

2. When observed in detail the fault has a sinuous trace, it trends N. 65° to 85° E. near Rancho Quemado and beds to N. 60° E. about 0.6 miles east of the ranch. "Typical" tear faults have no such irregular traces.

3. The axis of the Filo syncline trends into the axis of the syncline north of the fault with no obvious lateral offset (providing the Filo syncline is the same structure as the Barco syncline).

4. Several folds adjacent to the fault trend parallel and subparallel to it. Although it is possible to interpret these folds as drag folds on a strike-slip fault, the theoretical angle between drag fold axes and strikeslip faults is 15° and these folds are essentially parallel to the fault. They are better interpreted as drag folds associated with predominant dip-slip movement along the Quemado fault.

Laramide tectonism in the eastern Chihuahua Trough was marked by the movement of Cretaceous rocks toward the east on a décollement zone formed in the underlying evaporite succession. A series of large anticlines developed along the eastern limit of evaporite deposition from the La Mula- Sierra Blanca Range. The north and south ends of this range terminated by the Quitman Mountains and the Sierra Grande, respectively, stabilized as large anticlines with the limb forming Quitmans being partly overturned to the east. Only small "foreland" thrust faults developed east of these folds. In the middle part of the La Mula-Sierra Blanca Range from the Sierra Pilares to immediately south of the La Parra Fault, a series of thrust faults developed. The largest eastward displacement was along the Comedor thrust between Cuatralbo and Navarrete transverse structures. The thrusts gradually die out both north and south of this block.

Collapse along arroyos Navarrete and Cuatralbo

Collapse deformed Tertiary volcanic and associated rocks, and deformed some Cretaceous formations in areas of diapiric intrusion. Figure 13 presents a hypothesis for the formation of the collapse structure. The basic interpretation is that the evaporite mass (probably mostly salt) was eroded away rapidly (possibly as it was intruded) by groundwater solution and mechanical processes. Incompetent rock adjacent to the diapir was eroded more rapidly than resistant beds, so that blocks of resistant beds broke loose and migrated downslope into the exposed evaporites. Resistant beds highly fractured in "rim synclines" along the boundaries of the diapir are not preserved because they eroded more rapidly than other resistant beds. At some stages in the development of the structure, volcanic and associated rocks were deposited in the central topographic low and then took part in later stages of the collapse. After the topographic low

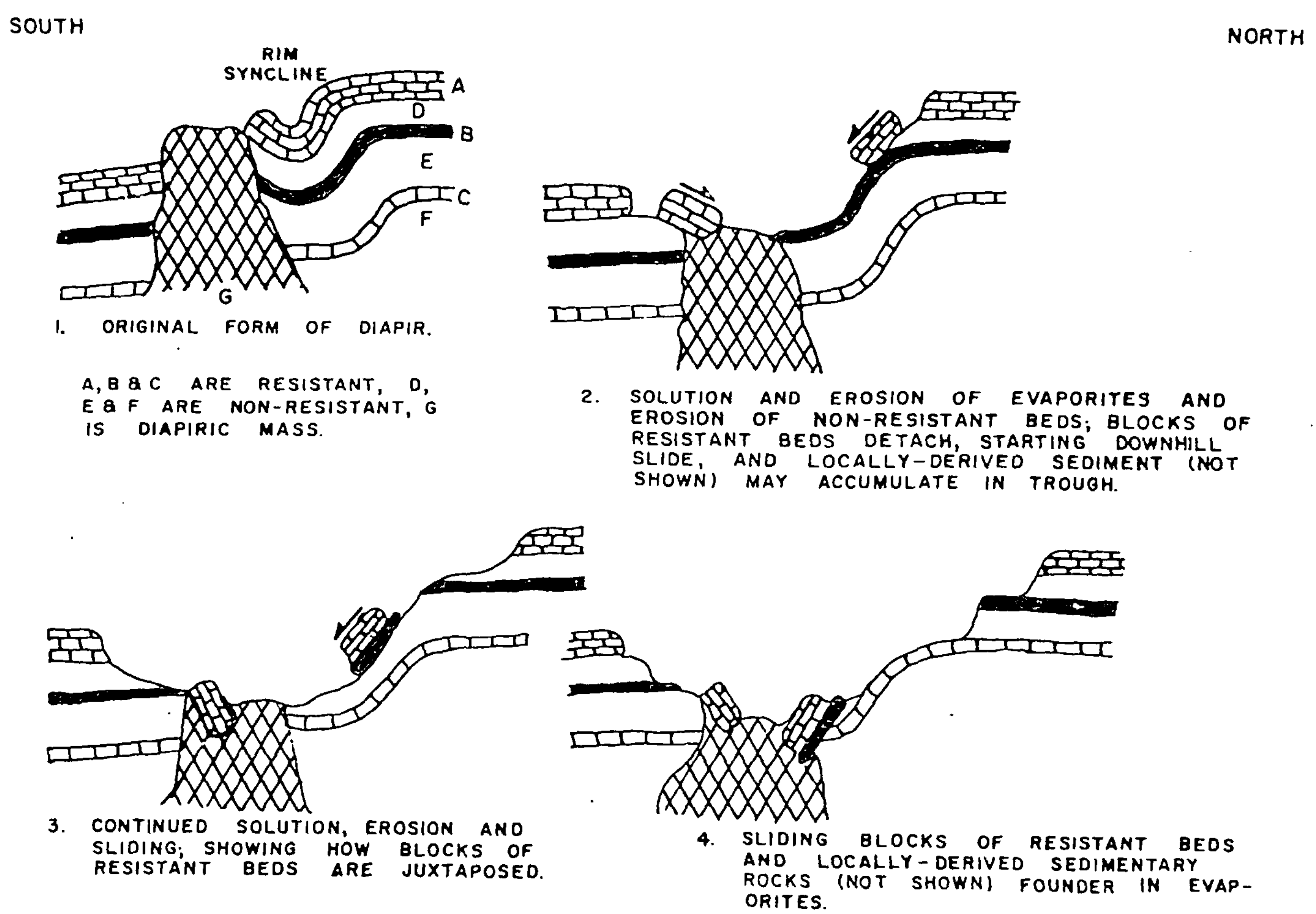


Figure 13. Generalized schematic illustration of coll[illegible]

formed over the diapir, tilting of adjacent blocks triggered low-angle normal faults within incompetent formations, and beds adjacent to the collapse moved toward it, possibly over some of the blocks previously foundered in evaporites.

This hypothesis explains all the observed relations, but a major problem still exists. Are the "rim synclines" Laramide features that formed during diapiric intrusion or are they part of the collapse? The answer may be that they are both; i.e., they initially developed during diapiric intrusion as relatively gentle "rim synclines" and were amplified during post-orgogenic collapse rather than to intrusion of evaporites. If this is true, then a previous interpretation is doubtful. This interpretation postulated that the east-trending faults along the southern edge of Cuatralbo transverse structure are "subsidence faults" associated with diapiric intrusion in a "rim syncline."

POST - LARAMIDE TECTONICS

Post-Laramide structure is the result of three different kinds of tectonism: diaporic activity, gravity tectonics, and block faulting. The first was a continuation of the evaporite flowage and resultant deformation that began in the Laramide and is described in previous sections. Structures influenced by gravity are features that do not affect strata below relatively shallow depths. Block faulting produced new faults and reactivated old faults in the western half of Trans-Pecos Texas during the Cenozoic Era, pro post-Early Miocene.

Gravity Tectonics

Subaerial deformation of resistant limestone under the influence of gravity (fig. 14) produc overturned monocline and slide blocks in the vicin La Bamba and a slide block east of the Sierra Ventana, south of Los Fresnos.

South of La Bamba, ingimbrite and basalt rest detached block (slide) of Finlay Limestone. probably age of the volcanic units is Oligocene an fold on which the flap at La Bamba formed Laramide. Therefore development of the flap complex near La Bamba was subsequent to Lara folding and prior to Oligocene vulcanism. It is possible to date the slide east of the Sierra Ventana, but it probably developed about the time as the La Bamba flap.

Block Faulting

In addition to the post-Laramide movemen Laramide faults mentioned above, the following show evidence of post-Laramide movement:

1. The Palo Pegado fault has offset Cenozoic b fill.

2. The Cipress fault has offset Cenozoic bolsc and the Murcielago fault has offset bolson fill volcanic rocks.

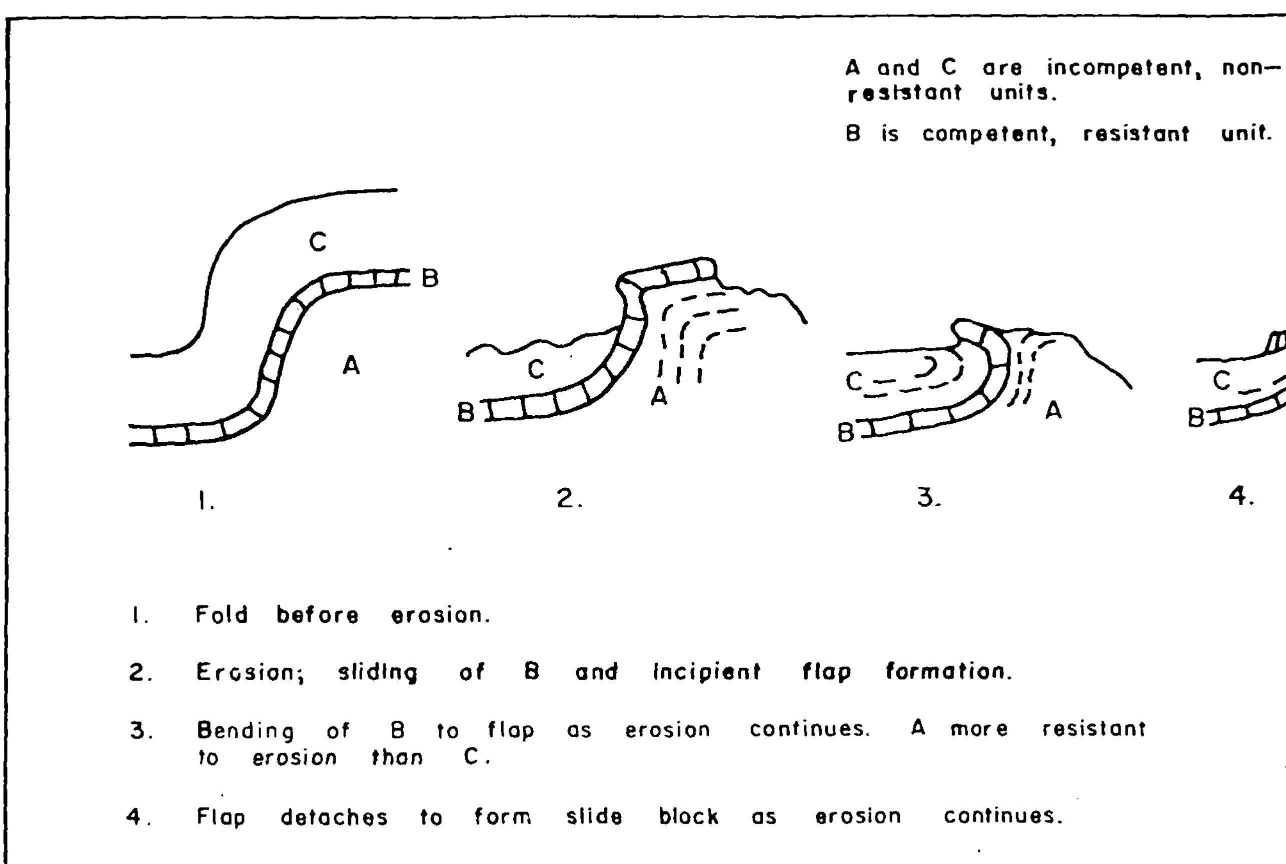


Fig. 14. The development of the overturned monocline near La Bamba and slide blocks near La Bamba and Los Fresnos. (modified after Harrison and Falcon, 1939, p. 97).

3. A fault trending S. 20° E. from the north end of Cerro Alto to Sierra de la Cruz places Cenozoic fill against Upper Cretaceous Ojinaga Formation.

4. The Gatún fault, along the eastern boundary of the Benigno bolson, is readily inferred to extend northeast of El Cuervo area into fault systems of the Rim Rock Country that displaced formations of the Vieja Group (Ferguson, 1957, map 4).

5. Northwest of Pilares several faults have displaced Vieja strata and also Cenozoic bolson fill.

6. An offset gravity slide, north of La Abuja fault and south of the Navarrete structure, indicates post-orogenic movement on several normal faults within the La Mula-Sierra Blanca Range.

7. A large number of relatively minor faults offset Oligocene volcanic rocks immediately west of the Cipress fault and in area north of Rancho Murciélago.

The Palo Pegado, Cipress, and unnamed fault south from Cerro Alto form the western boundary of the Presidio Graben (Amsbury, 1958; Dietrich, 1965; Dickerson, 1966; Groat, 1970). The major features that developed along the eastern Chihuahua Tectonic Belt during block faulting are the Benigno and Presidio grabens. This Tertiary block faulting was accompanied by a regional uplift of several thousand feet (DeFord and Bridges, 1959, p. 293). The boundary faults of these grabens are subparallel to regional Laramide structural trends; possibly, they are controlled by pre-existing Laramide structural trends.

Movement on the Cipress fault that displaces bolson fill and faulting along the Murciélago fault, indicates that at least some of the block faults were probably controlled by pre-existing faults. Furthermore, the Palo Pegado fault is on trend with a system of postulated thrust or reverse faults in the Rim Rock Country (Ferguson, 1957, fig. 2, map 4). The Palo Pegado fault affects Cenozoic bolson fill and may have developed along an older thrust zone.

The age of block faulting is extrapolated to the La Mula-Sierra Blanca Range from Trans-Pecos Texas. In the Rim Rock Country, adjacent to the La Mula-Sierra Blanca Range, block faulting was subsequent to the accumulation of Vieja volcanic rock and prior to the filling of the bolsons that block faulting created (DeFord and Bridges, 1959, p. 292-294; i.e., post-Eocene and pre-Pleistocene). The Rim Rock fault, the eastern boundary of the Presidio graben, offsets Oligocene strata and is intruded by Miocene dike swarm 18 - 23 m.y. old (Dasch, and others, 1969).

According to Wilson (1965, p. 36) block faulting in the Big Bend "Park" area is post-Early Miocene:

> Basin-and-Range faulting developed in the post-Early Miocene. Perhaps associated with the faulting was the accumulation of the Older Gravels which can only be dated as certainly post-Early Miocene and perhaps pre-Pleistocene.

It is reasonable to assume that the age of the block faulting in the Sierra de la Parra area is post-Early Miocene. Minor faulting probably started with the initiation of volcanic activity and it has locally continued into the Quaternary. Quaternary fault scarps are present along the Tertiary fault trend at Sierrita.

The eastern edge of the Chihuahua Tectonic Belt has been suggested as the boundary between basin and range-type block faulting to the north and east, and the Laramide décollement style of structure to the southwest (Haenggi, 1966; DeFord, 1969). The following points out some of the problems of block faulting associated with evaporite.

A fault displacing "basement" blocks under a thick sequence of evaporite would probably not carry through the evaporite as a fault. The displacement of "basement" blocks might be totally adjusted for by flowage of evaporite from above the upthrown block to the downthrown block so as not to disrupt the overlying rock. It is more likely that a partial adjustment by evaporite would result in folds or lesser faults in the overlying rocks. These structural features would not necessarily be coincident with the underlying "basement" fault.

Webb (1969, p. 185) reported that linear features seen in satellite photographs south and west of Juárez, Mexico, are faults offsetting Cenozoic fill. These linear features and faults trend N. 30° W. paralleling Laramide structure in this area. It should be noted that these features lie immediately northwest of the inferred limit of the evaporite basin in the Chihuahua Trough. Therefore, one should expect Cenozoic block faulting to appear "normal" in this area unmodified by mobile evaporite.

We suggest that Cenozoic block faulting probably has taken place in the Sierra de la Parra and to the west; but, the presence of thick evaporite strata over the block faulted "basement" has modified the effects of faults in the overlying Cretaceous rocks. The problem is further complicated by the masking effect of Laramide structure associated with the decollement.

TECTONIC HISTORY

Summarizing the proposed sequence of events of the tectonic development of the Sierra de la Parra area:

1. Nearby areas show a tectonically complex Precambrian history, but nothing is known of the Precambrian basement of the map area.

2. During the Paleozoic Era, movement took place along (a.) the Texas lineament to the north, the western boundary fault zone of the Diablo Platform as the platform was uplifted with respect to the ancestral Chihuahua Trough and (b.) the Quachita structural belt south of the map area, and (c.) perhaps along a zone of weakness trending N. 40°-50° W. in the northern Sierra de la Parra.

3. During the Late Jurassic Epoch and the Cretaceous Period the Chihuahua trough deepened with respect to the adjacent Diablo Platform as first evaporite and then carbonate and siliclastic sediment accumulated to a thickness of 12,000 to 21,000 feet.

4. Sometime between Senonian and Late Eocene the sub-evaporite "basement" was tilted to the east. This may have involved a broad arching from the center of the Chihuahua Trough and perhaps some relatively minor "basement" deformation.

5. Décollement on the evaporite sequence induced an eastward gliding of the overlying Cretaceous rock. At the eastern limit of the evaporite complex folding with subsequent shearing and eastward overthrusting developed with associated tear faults where the

overlying rock no longer had the evaporite gliding surface. Minor thrust faults developed in strata up to 10 miles east of this limit. The Pilares and Comedor faults probably developed first, and Banquete fault afterward. Intrustin of evaporites along tear and thrust faults was initiated. Simultaneously, evaporite flowed into the cores of the anticlines therby amplifying them. A few older fault trends were reactivated.

6. Continued evaporite flowage and gliding of superincumbent rock produced imbricate thrust faults behind the original line of thrust faults, increased the complex folding in the upper plates and developed evaporite diapirs.

7. Evaporite flowage into anticline crests resulted in continued uplift of crestal parts of the anticlines along normal faults at the expense of large blocks in the west limbs, which foundered from loss of evaporite. This flowage and resultant movement continued after Laramide deformation ceased.

8. Post-Laramide normal faulting of basement blocks began with extensive volcanic activity and continued after it. A post-volcanic regional uplift of several thousand feet was accompanied by block faulting. The effects of "basement" faulting are masked by evaporite flowage and Laramide structure in the folded belt. At least one major pre-Laramide fault was reactivated.

9. Late Cenozoic erosion filled grabens produced by block faulting and the lowest parts of adjacent higher blocks. A Pleistocene integrated drainage system developed between these bolson fills, crossing the uplift blocks at the fill-covered, structurally low areas. Movement along the normal faults has continued into the Quaternary Period.

ACKNOWLEDGMENTS

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;TRATIGRAPHIC NOMENCLATURE OF CRETACEOUS ROCKS IN NORTHEASTERN CHIHUAHUA

1971 - in The Geol. Framework of the Chihuahua Tectonic Belt: West Tex Geol Soc p. 175-196

By
Ronald K. DeFord[1] and Walter T. Haenggi[2]

INTRODUCTION

·ly a million people live on Río Bravo del Norte near Cd. Juarez and El Paso, Texas. Starting we can bound northeastern Chihuahua by ıg in imagination south on the highway to Cd. hua, thence via Aldama, Coyame, and Cuchillo ·, to Ojinaga, and thence up Río Bravo to the of beginning (fig. 1 and 2). Most of the ants of this part of the Chihuahua desert live on ed ranches. Twenty years ago, more than three d years after the first mining and a hundred after st geological report (Wislizenus, 1848), the / and geography of large parts of northeastern hua were still scarcely known.
xample, consider the valley of Río Bravo. Both f the river are well traveled for 100 km below El ıd Cd. Juarez, but the rest of the river course on to Ojinaga is known to few people. At Ojos es 145 km miles below Cd. Juarez, Río Bravo rough the southern Quitman Mountains in a teep-walled canyon. Another 30 km down- it passes between the Indio Mountains and ²ilares in a less spectacular canyon, and from follows the east flank of a border range to
..
e Mexican mountains that tower above Río rom Pilares to Ojinaga are part of a continuous ıat extends all the way from Sierra Blanca, a ıwn in Texas, 200 km southward to La Mula, a n Chihuahua (fig. 2). The components of this rom north to south are Devil Ridge, Eagle ins, Indio Mountains (Underwood, 1963), ilares, Sierra Pinosa (Haenggi, 1966), Sierra de (Gries, 1970), and Sierra Grande. Sierra de ı is a short northward spur of Sierra Pinosa that es en echelon between the southern Sierra and Río Bravo.
ropose to call the 225-km chain of mountains ıprises all the sierras from Devil Ridge to Sierra the "Sierra Blanca-La Mula range." Río Bravo n two. Devil Ridge and the Eagle and Indio ns compose the northern part, which is in here different facies of older formations bear names. Sierras Pilares, de Ventana, Pinosa, rra, and Grande compose the southern part, in Chihuahua. For the sake of brevity, we may call the southern part the "Pilares-La Mula" range and the northern part of the southern part the "Pilares-Pinosa" range. The stratigraphic nomenclature proposed in this report is based on the sequence of formations that crop out in the Pilares-Pinosa range. If modified to express facies changes, the same set of names may be usefully applied in much of northeastern Chihuahua.

Only fifteen years ago the maps ignored most of the Pilares-La Mula range, showing hardly a peak of Sierras Pilares, Ventana, Pinosa, or de la Parra. They showed the high Vieja Rim in Texas, which is nearly 2,000 m above sea level, but omitted Sierra Pinosa, which rises in Chihuahua nearly to 2,500 m. The elevation of the Río Bravo between these mountains is about 1,000 m. The recent aeronautical charts of the United States Coast and Geodetic Survey and the topographic atlas of the Estados Unidos Mexicanos correct these omissions. Moreover, the field studies of Pemex geologists and those of the Instituto de Geologia are continually adding to the geology of the region.

Most of the mountains of Chihuahua are composed of intensely folded Cretaceous limestone with interbedded sandstone and siltstone. The long northwesterly trends of the mountains are separated by fairly wide bolsons. The shale of the Cretaceous System is younger than most of the carbonate rock and most of this younger shale has been eroded away. A little shale is interbedded with the older limestone, siltstone, and sandstone. Gypsum crops out inconspicuously here and there. There are few large but many small igneous intrusions and some volcanic rocks.

TWO DIFFERENT TAXONOMIC PROCEDURES

After R. T. Hill and his successors established the lithostratigraphic classification of the Cretaceous rocks exposed in central Texas and subdivided them into two provincial series called Comanchean and Gulfian, the central-Texas sequence became a standard of reference for the southern United States and adjacent Mexico. Since then geologists have often used paleontologic correlations to try to make the Cretaceous rocks of northeastern Chihuahua and Trans-Pecos Texas fit the whole lithostratigraphic classification and nomenclature of central Texas, instead of making a nomenclature to fit the local sequence (DeFord, 1964,

1 - The University of Texas at Austin
2 - Dow Chemical Co., Houston, Texas

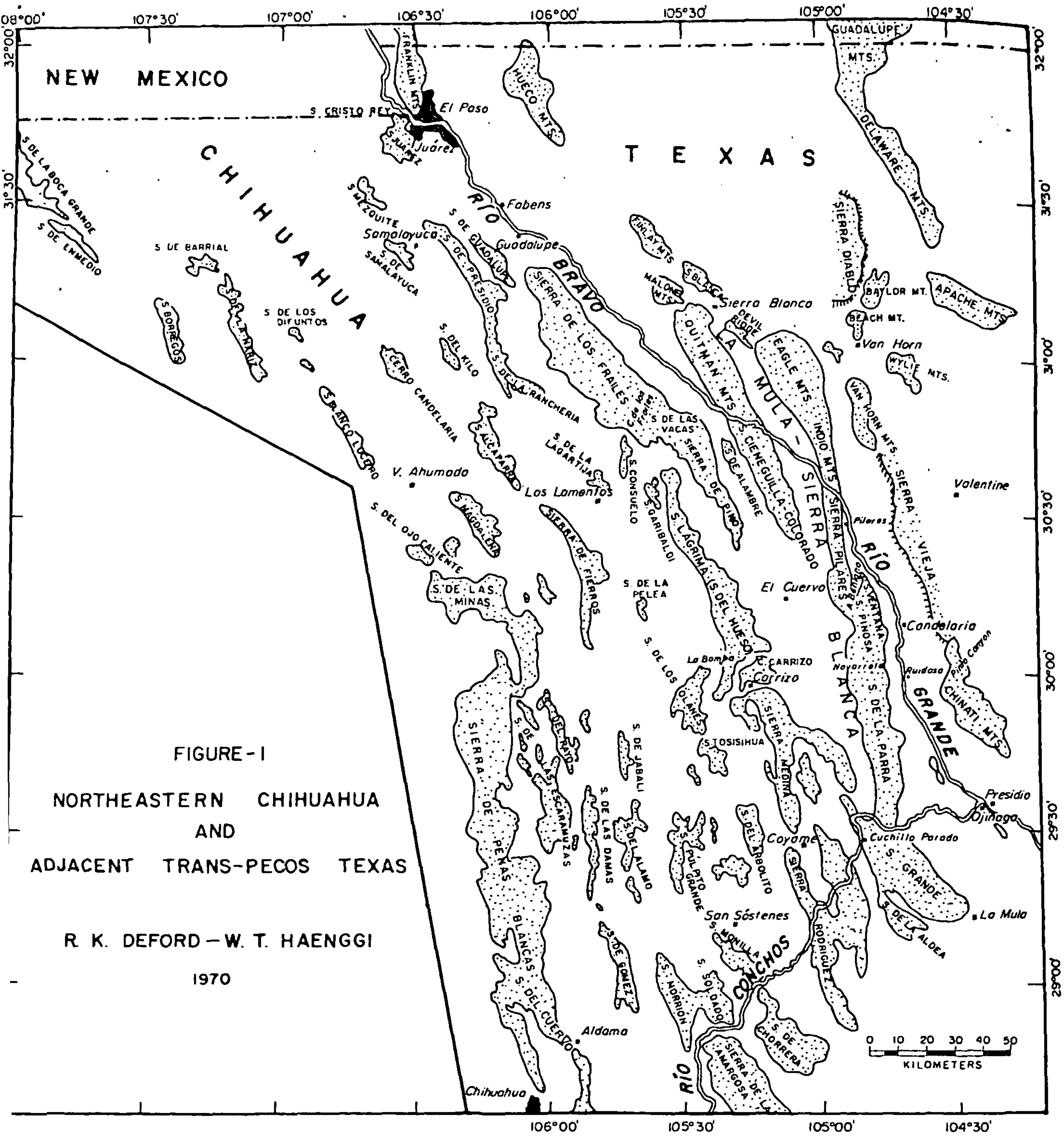

Figure 1 — The mountain ranges of northeastern Chihuahua.

p. 119). The geologic reports on the vicinity of Cuchillo Parado, Sierra Grande and Ojinaga basin, Chihuahua, and Sierra Vieja and the vicinity of Sierra Blanca, Texas, were exceptions (Taff, 1891; Vaughan, 1900; Richardson, 1904; Burrows, 1909; Vivar, 1925; Smith, 1940).

Guiding the explorations of our University of Texas students, we followed a different course. We tried to use local formation names and to correlate these formations with those in central Texas and other more distant places. Where the choice of name was not clear, we made up a field name for temporary use in preliminary study with no intent to clutter up the literature permanently. This method has its dangers as well as its advantages. An outside observer may fix on the temporary name, use it, and even publish it without proper concern for formally defining it and proposing it. Thus he may introduce **nomina nuda** into the stratigraphic literature.

With the completion of Haenggi's mapping (1966), and Gries's (1970), and the approaching publication of geologic maps of El Cuervo and Casa de Piedra quadrangles (fig. 2), we feel that a discussion of stratigraphic nomenclature in northeastern Chihuahua

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is now due. We base our lithostratigraphic classification on the outcrops in the nexus of the Sierras Pilares, de Ventana, and Pinosa, and we extend it from there by correlation to those nearer parts of Chihuahua that we have studied or looked at. We hope that others will extend it with suitable modification to the rest of northeastern Chihuahua.

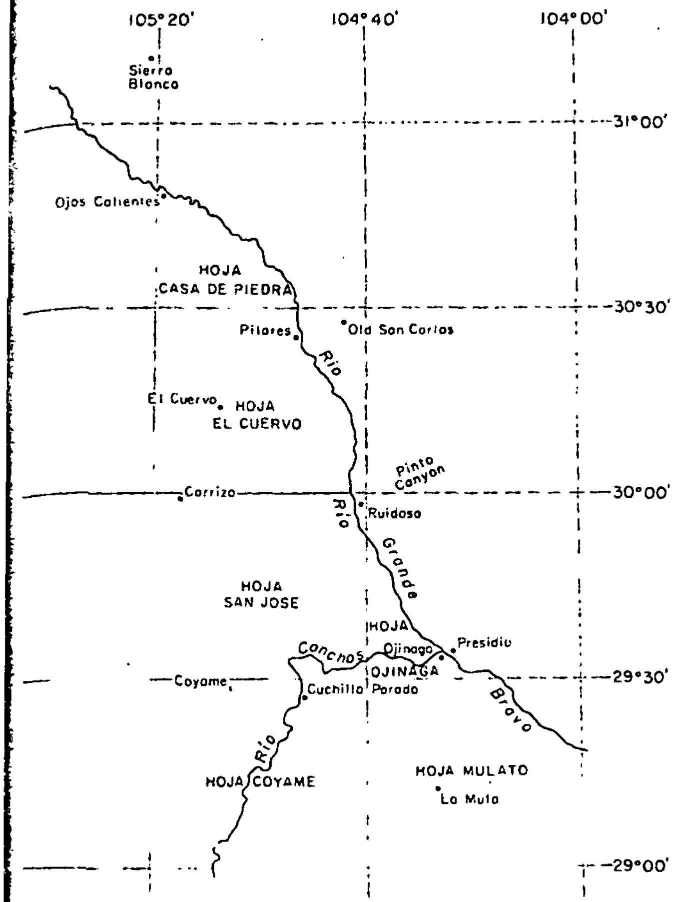


Figure 2. — El Cuervo quadrangle and adjacent areas. The term hoja indicates a sheet of the Carta Geológica de México, Serie de 1:100,000 (a 30' by 40' quadrangle) that the Instituto de Geologia has published or plans to publish.

NOMENCLATURE IN TRANS-PECOS TEXAS

At the turn of the century Vaughan (1900, p. 81) named the San Carlos Formation. This is the Upper Cretaceous coal-bearing sandstone that crops out under the Vieja Rim. Ten years later Burrows (1909; 1910) named the formations at Cuchillo Parado in ascending order as the Las Vigas Formation, the Cuchillo Formation, and the Aurora Formation adding the Ojinaga Formation on top the Aurora in the Ojinaga Basin on the northeast side of Sierra Grande; that is, on the other side of the range from Cuchillo Parado. Then Vivar (1925) proposed the names "El Nogal" and "Picacho" for formations above the Ojinaga. Wolleben (1965) has replaced "El Nogal" with "San Carlos Formation" and has called the overlying beds "El Picacho Formation".

About 15 km northwest of Sierra Blanca, Texas, Richardson (1904, p. 47), a contemporary of Vaughan, named the Campagrande Formation (limestone), the Cox Formation (sandstone), and the Finlay Formation (limestone), in ascending order. Two decades later Baker (1927, pl. 1) extended the names "Cox" and "Finlay" southward into the Quitman Mountains and into the Indio Mountains clear to the north bank of Rio Bravo.

More recently Amsbury (1958) described the outcrops in Pinto Canyon, Texas, 25 km northeast of Sierra de la Para and 15 km northeast of Rio Bravo opposite Ruidosa, which is 55 km upstream from Ojinaga (fig. 2). He divided the Cretaceous sequence into eight formations, which he called in ascending order: Yucca Formation, Bluff Formation, Cox Formation, Finlay Limestone, Benevides Formation, Loma Plata Limestone, Grayson Formation, and Buda Limestone. "Yucca" and "Bluff" are old names. Taff (1891) had proposed them a decade before the work of Vaughan and Richardson; he so named two of his "beds" about 10 km south of Sierra Blanca, Texas. "Benevides" and "Loma Plata" are newer names proposed by Amsbury.

NOMENCLATURE IN CONTIGUOUS CHIHUAHUA

We propose that the stratigraphic nomenclature of Cretaceous rocks in northeastern Chihuahua should be based on Haenggi's lithostratigraphic classification (1966) of these rocks in the El Cuervo quadrangle (fig. 3). He brought in three formation names (Las Vigas, Cuchillo, Ojinaga) from the San Jose quadrangle in Chihuahua next south of the El Cuervo quadrangle. A fourth (Picacho) has since come via Sierra Vieja, Texas; it was slightly modified (to El Picacho) on the way. The rest Haenggi took from adjacent Trans-Pecos Texas, excepting two new names (Navarrete, Benigno) that we propose hereinafter. The San Carlos Formation is present in northeastern Chihuahua but is missing in the El Cuervo quadrangle.

Formations in the Pilares-Pinosa Range

Proposing the new names "Navarrete" and "Benigno", we classify the marine and juxtamarine rocks exposed in the Sierra Pilares, the Sierra de Ventana, and the Sierra Pinosa into 13 formations in stratigraphic order, with established ages, as follows:

Not older than late Cretaceous, not younger than Eocene:
- El Picacho Formation.
- (fault contact.)

Late Cretaceous:
- Ojinaga Formation,
- Buda Limestone,
- Del Rio Formation.

Mostly Early Cretaceous:
- Loma Plata Limestone.

Early Cretaceous:
- Benevides Formation,
- Finlay Limestone,
- Cox Formation,
- Benigno Formation (upper member of Bluff Formation),
- Cuchillo Formation (lower member of Bluff Formation),
- Las Vigas Formation.

Early Cretaceous or older:

Navarrete Formation,
unnamed evaporite.

Paleontologists who studied the contained fossils established the ages stated above. Probable ages are more precise in statement than these established ages but actually less certain in fact, because probable ages involve more interpretation. We discuss the probable ages in the following paragraphs of this report.

LITHOSTRATIGRAPHY IN NORTHEASTERN CHIHUAHUA

Evaporite

There are two extensive outcrops of evaporite in Sierra Pinosa, one in the vicinity of Canon de Navarreté, the other along Arroyo Cuatralbo. In each of these outcrops the evaporite is in contact with younger rocks, and it appears below the Navarrete Formation, the oldest non-evaporite formation mapped.

We have not named the evaporite because of uncertainty as to the sequence within it and as to its exact stratigraphic position. The thickness is unknown. The base or a "normal- contact" top of the section is not exposed in either outcrop. In both outcrops the rock is granular, white gypsum, with interbeds of highly contorted, in part brecciated, dark gray to black, thin-bedded to thick-bedded, laminated, carbonaceous dolomite and dolomitic limestone and, locally, with laminae of dull gray anhydrite.

In Canon de Navarrete, gypsum is in contact with intrusive igneous rock, with volcanic rock, and with the Navarrete, Las Vigas, Cuchillo, Benigno, and Finlay formations. The masses of amphibole-rich intrusive igneous rock within the gypsum may be exotic blocks carried in by intrusive evaporite, or they may be intrusions into the evaporite that were deformed by subsequent movement. Volcanic rock rests on the gypsum and dips steeply into it. The contacts with the Las Vigas, Cuchillo, Benigno, and Finlay formations are diapiric, but the contact between evaporite and the Navarrete Formation along an arroyo northeast of La Abuja may not be diapiric. At all localities along the arroyo where this contact is exposed, gypsum shows evidence of movement, but it does not pierce the basal beds of the Navarrete Formation.

Along Arroyo Cuatralbo, gypsum is in diapiric contact with all formations from the Las Vigas upward to the Finlay inclusive. One small outcrop of black dolomite is surrounded by beds of Tertiary conglomerate. An extremely disturbed Navarrete outcrop includes several outcrops of gypsum in diapiric contact with the rock of the Navarrete Formation.

Evaporite has been found in the vicinity of Sierra Soldado (Humphrey, 1964, p. 38), in the wells Cuchillo Parado Nos. 1 and 2 (Perez, 1950, p. 107; Salas, 1955, p. 98-103; Ramirez and Acevedo, 1957, p. 664-667), and in the Malone Mountains (Taff, 1891, p. 721-723; Adkins, 1933, fig. 14, p. 289; Sellards, 1933, p. 163; Albritton, 1938, p. 1753-1757; Albritton and Smith, 1965, p. 15-23). Moreover, evaporite crops out about 6 miles N 35° W of San Sostenes, in Canon de los Frailes between Sierra de los Frailes and Sierra de las Vacas, and in several localities near Canon de los Frailes; and Rodriquez (1969; Cordoba et al, 1970) has described a poorly exposed outcrop of gypsum at the base of the section on the eastern flank of Sierra de la Alcaparra (30° 40'N, 106° 9'W). He called it the "Loma Blanca Formation" (not to be confused with the Loma Blanca Sandstone in Nuevo Leon; Kane and Gierhart, 1935, p. 1375). The gypsum is capped by an elongate apophysis of intrusive granodiorite, which separates it from the overlying Jurassic (?) or Lower Cretaceous rock.

The late Mesozoic sequence from Navarrete Formation to El Picacho Formation is concordant. The ammonites from the basal and near-basal beds of the correlative sequence in eastern Chihuahua (Bridges and DeFord, 1961) indicate that the late Mesozoic sea first invaded this region during the Late Jurassic Epoch. At Sierra Soldado about 125 km south-southeast of Canon Navarrete there is an evaporite between the Las Vigas Formation and strata bearing late Jurassic ammonities (Humphrey, 1964, p. 38). Late Jurassic or Neocomian deposition of evaporite in the Chihuahua trough is probable.

To a geologist familiar with the Permian salt and anhydrite in west Texas and the Permian gypsum (Albritton and Smith, 1965) that crops out in the Malone Mountains 20 km west of Sierra Blanca, Texas, a Permian age also seems reasonable. Haenggi (1966), however, suggested that the gypsum in the Malone Mountains may be younger evaporite intercalated between Permian strata. Figure 4 shows the postulated extent of the pre-Navarrete evaporite in the Chihuahua trough.

Outcrops Just North of Sierra de Samalayuca

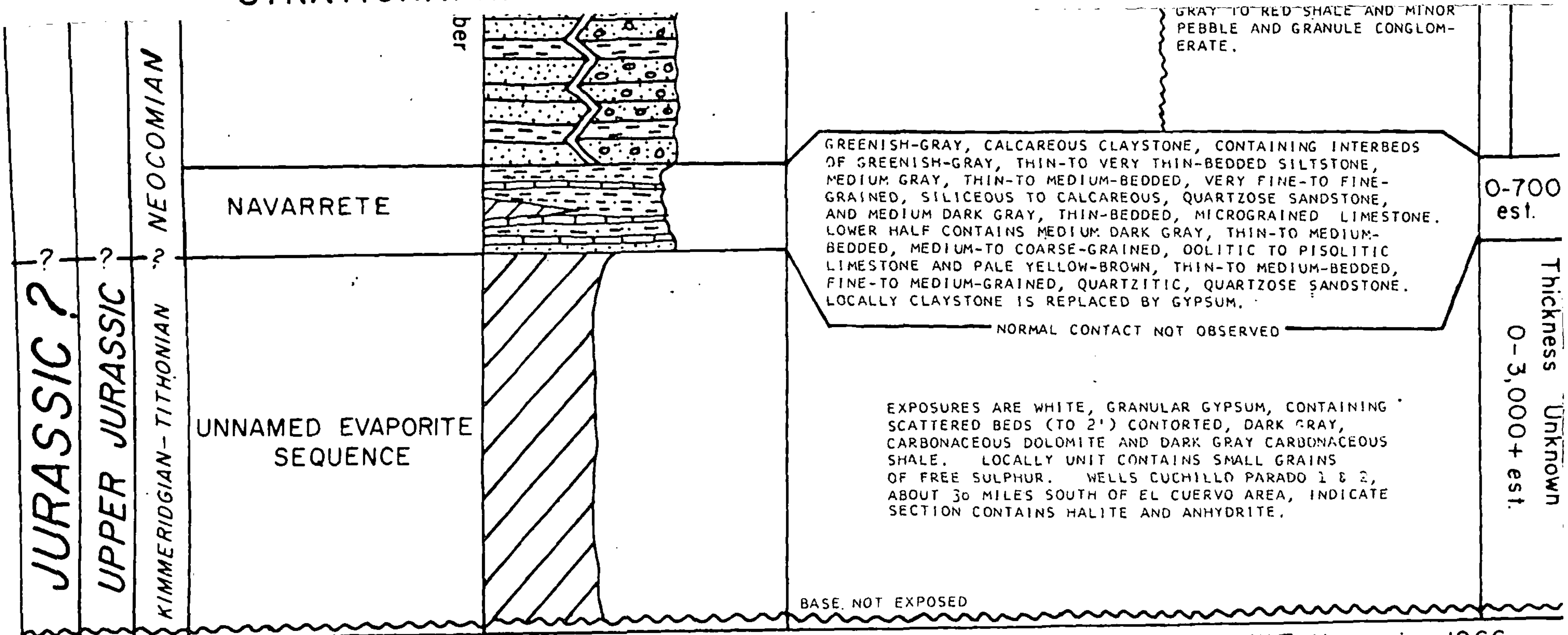
A. Cantu Chapa has examined ammonites from the two end outcrops (Cantu, 1970, fig. 1) of a line of outcrops in low hills about 2 km northeast of Sierra de Samalayuca (our fig. 1). The outcrop at the southeast end of the line is just east of the Juarez-Chihuahua highway and about 4 km south of Samalayuca (31° 18'N, 106° 30'W), whence the line extends 9 km northwestward, paralleling the sierra. Cantu's other ammonite-bearing outcrop is at the northwest end.

Webb (1969a) described the rock as "siltstone and sandstone with scattered interbeds of limestone and conglomerate." He collected ammonites (1969b) from the same outcrop at the southeast end of the line that yielded some of Cantu's specimens. Webb (1971) also collected from the outcrop next northwest, just across the highway and railroad track, where "shale, sandstone, and graded beds contain exotic blocks of limestone up to 60 cm in diameter." A diabase stock that intersects one corner of this outcrop (Berg, 1969, fig. 1; 1970a, pl. 1). In the same outcrop is a separate "gypsum diapir", the "only outcrop of gypsum that I am certain is intrusive" (Berg, 1970b). The outcrops on to the northwest expose some seemingly concordant layers of gypsum (Webb, 1971).

Among the ammonites collected by Webb, Young (1969) identified "a good specimen of **Leopoldia vic-**

Figure 3 — Columnar section of Cretaceous rocks in El Cuervo quadrangle, Chihuahua. The age of the pre-Navarrete evaporite is not established; it could be Cretaceous or Permian.

STRATIGRAPHIC SECTION OF MESOZOIC ROCKS



W.T. Haenggi, 1966

Department of Geology,
The University of Texas

ısis Imlay" and also **Neocomites** sp., asserting a urassic Neocomian age (early Hauterivian). g remarked that earlier he had misidentified the fossils in similar rock at Placer de Guadalupe (S. lla, our fig. 1), calling them Jurassic. Cantu has adicted Young's identifications of the Samalayuca :. Identifying **Idoceras** spp., Cantu has posited an Kimeridgian age and correlated the outcrops with ıalone Formation in the Malone Mountains (our) near Sierra Blanca, Texas.

ıe Malone formation is a mixture of many dif- kinds of rocks complexly interbedded" (Albritton and Smith, 1965). Its thickness ranges from 120 to 300 m. The lower member is mostly gray sandy shale, siltstone, sandstone, and conglomerate; the upper member is predominantly gray to black limestone, generally arenaceous. The **Idoceras**-bearing beds are in the lower part of the lower member. Beds in the upper part of the upper member 120 m above **Idoceras** have yielded the ammonites **Kossmatia** spp. of Tithonian age (i.e., post-Kimeridgian Jurrassic).

Some quotations will indicate a problem of nomenclature: those in English are from Albritton and Smith (1965, p. 25; see also their fig. 9, p. 16); and those

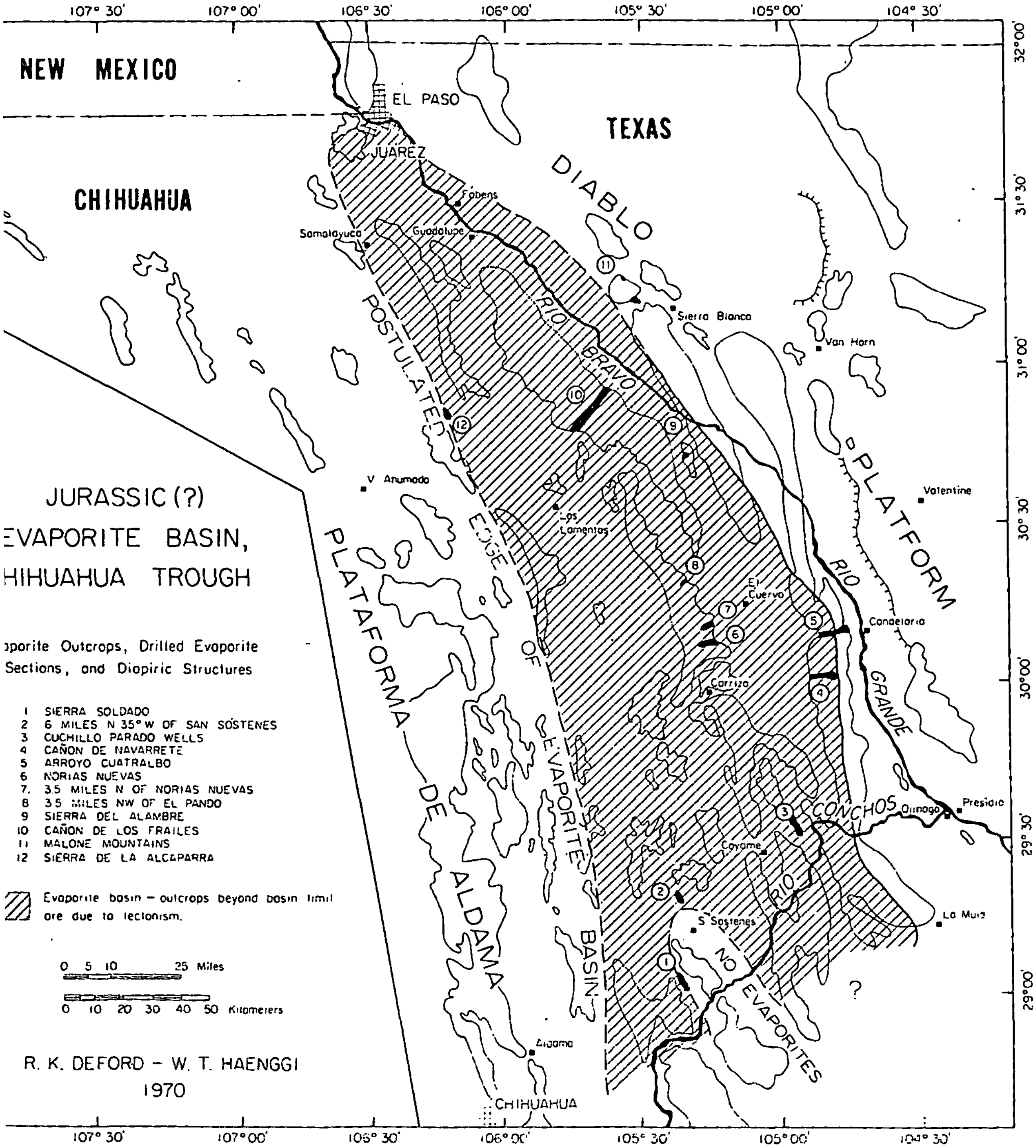


Figure 4 — Distribution of evaporite in the Chihuahua trough.

in Spanish are from Cantu (1970, p. 44). "Taff (1891) first applied the name Malone Bed" to Permian rock in the Malone Mountains. "Cragin (1905) described a large Jurassic fauna from strata overlying Taff's Malone Bed and used the name for all the rocks of the Malone Mountains area; thus he implied a Jurassic age for all these beds", which actually range in age from Permian to Cretaceous. "En efecto, Cragin (1887 y 1905) describio la Formación Malone, tomando el nombre de las montanas que están al Sur de Texas, aproximadamente a 100 km al E en linea recta de Samalayuca." "... las areniscas y calizas, que afloran al E y al NE de la Sierra de Samalayuca. . .deben denominarse Formación Malone, de acuerdo al principio de prioridad que indica el Código de Nomenclatura Estratigrafico." "Los lomerios situados al E y al NE de la Sierra de Samalayuca pertenecen por su litofacies y por su biofacies, a la parte inferior de la formacion Malone, del Kimeridgiano Inferior."

To correlate is quite in order: but at this juncture, Cantu to the contrary notwithstanding, to use any but a local name for the beds at Samalayuca diverts attention from the question at issue. When geologists differ about correlation or when opinion changes, a local name stands as a valid starting point of agreement.

These beds may be correlative (1) with the La Casita Formation (Imlay, 1936; Bridges and DeFord, 1961) and Malone Formation, or (2) with the Aleja Formation (Rodrigues, 1969). Or (3) they may be correlative with the Alcaparra Formation of Rodriguez (1969) as well as the Navarrete Formation and the Torcer Formation (Albritton and Smith, 1965).

Navarrete Formation

We propose the name Navarrete Formation (Haenggi, 1966) for a sequence of claystone interbedded with limestone and sandstone associated with the evaporite at both outcrops in Sierra Pinosa. In each place the Navarrete Formation lies conformably under the Las Vigas Formation, but Haenggi did not recognize the base of the Navarrete at either place.

The type section 1.3 km N 20° E of Rancho La Abuja is overturned. Its average strike is N 20° E; the average overturned dip is 45° W. The type Navarrete Formation is conformable with the Las Vigas Formation. The somewhat gradational contact is at a change in slope at the base of a 9-m pale brown (5YR5-2), medium-grained, subangular to subround, faintly laminated, siliceous, quartz sandstone in the Las Vigas. Haenggi measured the type section of the Navarrete with a Jacob staff and described it in detail (1966, p. 328-331); his description is summarized in appendix 1.

Table 1 gives the location of six outcrops of Navarrete in northeastern Chihuahua. Several other outcrops are not yet located or described.

Table 1. - Six outcrops of Navarrete Formation in northeastern Chihuahua.

VICINITY	APPROXIMATE N LATITUDE, W LONGITUDE	REMARKS
(1) 1.5 km N of Cerro La Abuja	30° 02' 104° 49'	Type section
(2) near Tarais	30° 09' 104° 46'	In Arroyo Cuatralbo, Sierra Pinosa.
(3) W of El Sauce	30° 08' 104° 49'	In Arroyo Cuatralbo, Sierra Pinosa.
(4) near Norias Nuevas	30° 06' 105° 12-16'	15 km N of Carrizo, east slope of Sierra Lagrima. Navarrete in diapiric contact with Las Vigas.
(5) 6 Km N of Norias Nuevas	30° 10' 105° 13'	East slope of Sierra Lagrima. Part of Navarrete in diapiric contact with Las Vigas and Cuchillo formations.
(6) Sierra del Alambre	30° 42-47' 105° 18-19'	Along axis of anticline. Navarrete is disharmonically folded but in gradational contact with Las Vigas.

two outcrops of the Navarrete Formation in
nosa along Arroyo Cuatralbo, one near Tarais
other west of El Sauce, the Navarrete is in
contact with younger formations and is in-
eformed. The Navarrete outcrop near Tarais
sses several outcrops of diapirically injected
Similar gypsum intrusions in the Navarrete
west of El Sauce are too small to map. There
rrete is in contact not only with Cretaceous
ns but also with volcanic and associated
at are presumably correlative with part of
Tertiary (late Eocene-Oligocene) Vieja Group.
between the Navarrete and conglomerate and
rrete and siltstone are discordant adjacent to
here the Tertiary rock foundered into
s. The contact between the Navarrete and
angular unconformity along the surface on
f was deposited. Along Arroyo Cuatralbo the
e resembles the type Navarrete, but the
west of El Sauce has many beds of
eratic sandstone, and there the weathered
the Navarrete is a distinctive pale yellow-

Perkins identified several Early Cretaceous
genera in thin sections from the type section
(1). The age of most of the Navarrete For-
Neocomian or Aptian. The age of unit 1 and
posed part beneath unit 1 is undetermined.
ds from an outcrop of Navarrete west of
ievas (no. 4, table 1) resemble the pulmonate
ds at the base of the original Las Vigas For-
one place near Cuchillo Parado; indeed, the
Navarrete may be exposed at that place.
orcer Formation (Albritton and Smith, 1965)
correlative with the Navarrete. If the am-
near Samalayuca are Neocomian as identified
g (1968, p. 98), the beds may be correlative
of the Navarrete.

Las Vigas Formation

border range Haenggi (1966) mapped a lower
and an upper member of the Las Vigas For-
Farther west in the Sierra Lagrima and Sierra
he mapped the formation as a single unit but
d that it could also be divided into two
there. Figure 5 shows Haenggi's in-
on of the location and thickness of the Las
nosome. The stratigraphic position of the
establishes the age as Neocomian or Aptian

Cuchillo Formation

s (1909) described the best section of the
Formation "near Cuchillo Parado, on the road
iver to the Aurora mine, where the formation
depression in the Cuchillo Parado range. This
ormed by two parallel ridges, the westernmost
constitutes the outcrop of the Las Vigas
s; the other forming the summit of the range,
isting off the Aurora limestones. Between
ridges and running throughout the entire
the range, a considerable depression exists,
occupied by the beds of the Cuchillo formation, including a thickness of about 2000 ft. (600 m). The lower 1500 ft. (450 m) of the formation is an almost pure gypsum, which at the surface breaks into a white sugary mass. A few thin beds of limestone course through the centre of the gypsum, showing quantities of fossil shells. The summit of the formation consists of alternate beds of gypsum and limestone, the latter becoming thicker as they approach the top, gradually passing into the massive limestones of the Aurora formation. At Chorreras the Cuchillo formation consists almost entirely of clays, gypsum being practically absent." Chorreras is up the Rio Conchos about 80 km SW of Cuchillo Parado.

The two parallel ridges are prominent and straight and about 40 km long. Viewed from the air or on air photographs the constant width of the Cuchillo depression between the ridges is conspicuous. The gypsum does not persist but lenses out along the strike. Many geological writers since Burrows have associated the name "Cuchillo" with gypsum only — perhaps with the wrong gypsum in places — and have invoked other names than Cuchillo where gypsum is lacking. It needs to be emphasized that gypsum is not the essential constituent of the Cuchillo Formation as Burrows defined it.

In some outcrops in the Pilares-Pinosa range Haenggi (1966) placed the top of the Las Vigas Formation and the base of the Cuchillo Formation at the base of the first fossiliferous limestone of the Cuchillo. In other outcrops he placed it beneath the first considerable increment of limestone; that is, where limestone interbeds first made up more than 5 percent of the stratigraphic sequence. The contact is everywhere gradational.

The Cuchillo consists of dark gray to black shale interlayered with thin-bedded to thick-bedded dark gray limestone and calcareous quartz sandstone. The proportion of sandstone decreases upward, but sandstone and siltstone increases as shale decreases northward. In northern Sierra Pilares, where sandstone predominates, Haenggi (1966) mapped the whole Cuchillo sequence as the lower member of the Bluff Formation.

The Cuchillo is less resistant to erosion than the contiguous adjacent formations. It crops out on slopes below the Benigno Formation. In the middle part of the Cuchillo, limestone and sandstone layers form low cuestas with long dip slopes. At several places in the Pilares-Pinosa range patch reefs of limestone 50 to 60 m in diameter and about 15 m thick crop out near the top of the formation.

Tectonically the Cuchillo is incompetent; it is faulted and disharmonically folded in many places. Accurate measurements of thickness are difficult to make. In the Pilares-Pinosa range the thickness ranges from 250 to 450 m.

Imlay's proposal (1940, p. 124-125; 1944, p. 1005, 1007) of a "Coahuilan series" to include all "Cretaceous strata older than the **Dufrenoyia texana** zones" amounts to a restriction of the Comanchean Series to upper Aptian, Albian, and lower Cenomanian rocks. We prefer the two-fold provincial subdivision of the Cretaceous System into Gulfian and Comanchean. When Chamberlin and Salisbury (1906) introduced the Mississippian and Pennsylvanian systems between the

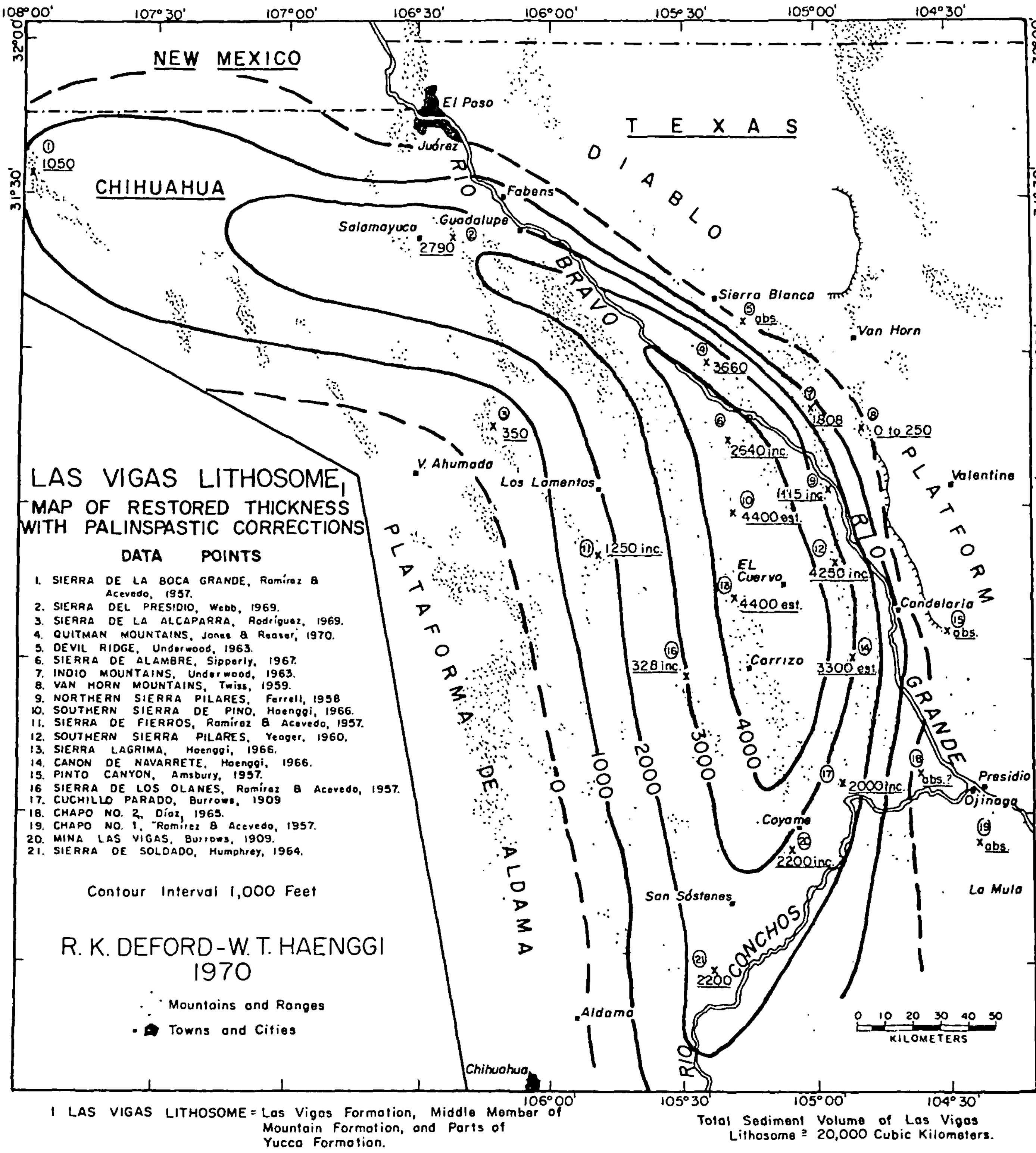


Figure 5. — Configuration of the Las Vigas lithosome.

ınian and Permian, they tried also to place a ıanchean system" between the Jurassic and the ıceous. They did not succeed, but the historical incial Comanchean Series remains to denominate time-stratigraphic interval.

northern Sierra Pilares the zone of **Exogyra nanensis** Cragin is 2.5 m thick, and its base is the of the Cuchillo Formation. Southward this zone :ens to 30 m and rises in the formation. In southern a Pilares the base of the zone is 10 m above the of the formation. At that place the ammonite **enoyia justinae** is associated with the oyster **E. nanensis,** and the ammonite **Douvilleiceras ımillatum** is about 27 m above **Dufrenoyia** (Yeager, , p. 30). The Aptian-Albian stage-boundary ıgs in this 27-m interval.

urray (1961, p. 307-309) designated Imlay's series-ıdary as the base of the "Trinity stage"; that is, the of the "Trinitian". We prefer to regard Washita, ericksburg, and Trinity as central-Texas groups o try to correlate our formations with them.

·aduate students used many temporary field names : working out the stratigraphy of Sierra Pilares. ıng these was "Porvenir". Unfortunately other ɔgists have taken up the name, and occasionally it appear in print. An example is the correlation : on the endpaper of a recent guidebook (WTGS,). Neither Diaz nor DeFord intended to publish :hart. The term "Porvenir" is not formally defined; ould be avoided.

Benigno Formation

he same chart misuses the term "Benigno". The ıgno Formation that we propose in this paper is ɘath the Cox. The Benigno Formation and the Cox nation are **not** lateral equivalents. Together the ıgno and Cuchillo Formations are correlative with Bluff Formation on the north.

'e propose the name Benigno Formation for the -forming limestone between the Cuchillo Format- and the Cox Formation. The source of the name is ɔyo Benigno, which drains northward between ra de Ventana on the east and Sierra Pilares on the t and swings around the north end of Sierra Pilares he west and swings around the north end of Sierra Ventana to join the southeastward course of Rio ,o. The Benigno Formation crops out northwest southeast of Arroyo Benigno in Sierra de Ventana, ra Pinosa, and Sierra Pilares. In the summer of), J. C. Yeager and S. C. Hamilton measured the : section west of Arroyo de los Alamos in southern ra Pilares, about 30° 17' N, 104° 55'W (appendix The top of their measured section is at the top of a e of resistant limestone covered by colluvium. The of the type Benigno Formation is exposed and 'ormable: it is at the bottom of a slope where the resistant limestone of unit 1 rests on a more ·tant bed of sandstone. Appendix 2 summarizes ger's description (1960, p. 85-86).

ıe predominant rock of the Benigno Formation ;es in composition from fine-grained calcarenite to ·ite and biomicrite; it is medium gray to dark gray; much of it is thick-bedded to very thick-bedded. usual outcrop of this sequence of thick limestone rs is a series of cuestas and hogbacks. The contact with the Cuchillo at the base of this sequence is gradational. The Benigno thickens from 73 m in northern Sierra Pilares to 230 m in southern Sierra Pinosa.

The foraminifer **Orbitolina texana** Römer **s.l.** is by far the most abundant taxon in the Benigno Formation. In one place or another it is present at every horizon, but at a single place it is not present in every bed. The shells compose as much as 25 percent of some beds. The Benigno also contains fossil sponges, echinoids, gastropods, and pelecypods. In Sierra Lagrima Haenggi (1966) collected **Caprinuloidea** sp. and **Toucasia** sp. Stratigraphic position establishes the age of the Benigno as Albian.

Cox Formation

At the northern end of Sierra Pilares and on north into Texas the undivided Cox Formation is very fine-grained to fine-grained thick-bedded calcareous quartz sandstone. Haenggi (1966) has subdivided the Cox in Sierra Pinosa into three members. The lower member consists of 490 to 550 m of alternating beds of gray to yellow-brown, very fine-grained to fine-grained, calcareous quartz sandstone, and light-gray to medium-gray shaly micrite and biomicrite. The member also contains small amounts of gray to maroon shale. The sandstone is thin-bedded to thick-bedded and in part laminated; the micrite and biomicrite are thin-bedded to medium-bedded. The contact between the lower and middle members of the Cox is the top of a gentle slope formed on the relatively non-resistant beds of the lower member and at the base of cliffs formed on the middle member.

The middle member of the Cox Formation is a 30-m to 120-m sequence of medium to dark gray thick-bedded micrite to very fine-grained limestone, containing a few interbeds, 3 to 6 m thick, of light gray calcareous shale. The contact between the middle and upper members of the Cox at the top of cliff-forming limestone is a prominent topographic break.

The upper member of the Cox Formation consists of 60 to 115 m of interbedded sandstone, limestone, shale, and marl. Exposures are poor because slopes of many outcrops are covered with colluvium derived from it and from the overlying Finlay Limestone. Shale and marl of the upper member are predominantly light to medium gray. The upper contact of the upper member is at the base of cliffs formed by the extremely resistant Finlay Limestone.

In the Cox Formation the foraminifer **Orbitolina texana** Römer **s.l.** is restricted to the lower member, but the upper limit of its range varies considerably from place to place, rising stratigraphically southwestward from the southern Sierra Pilares. Besides **Orbitolina texana** the lower member has yielded the gastropod **Lunatia** sp. cf. **L. pedernalis** Romer, the pelecypod **Liopistha** sp. cf. **L. (Psilomya) walkeri** Whitney, and the oyster **Exogyra weatherfordensis** Cragin.

The middle member of the Cox Formation contains the rudistid **Toucasia** sp., the caprinid **Caprinuloidea** sp., the gastropod **Nerinoides** sp., and the oyster **Exogyra texana** Römer. The upper member contains the oyster **Exogyra texana** Römer; the gastropod **Actaeonella dolium** Römer; and several unidentified gastropod and pelecypod species.

The age of the Cox Formation is Albian. We correlate the beds that bear **Orbitolina texana** with the Glen Rose Formation in the upper part of the Trinity Group of central Texas; and we correlate the upper part of the Cox Formation with the lower part of the Fredericksburg Group.

Lagrima Formation

The abrupt westward transition within the Cox Formation from dominant sandstone to dominant limestone takes place between the Pilares-Pinosa range and Sierra Lagrima and Sierra del Pino. We propose the name **Lagrima Formation** for the lateral limestone equivalent of the Cox Formation. The Lagrima is well exposed along the entire length of the Sierra Lagrima (Sierra del Hueso); we propose this range as the type locality. The detailed measurement and description of a type section waits on more field work. Haenggi (1966) traced the three members of the Cox Formation into the Lagrima Formation. They are mappable subdivisions of the Lagrima, but Haenggi did not map them.

In northern Sierra Pilares the proportion of sandstone in the undivided Cox Formation ranges from 50 to 80 percent. In Sierra Pinosa the proportion of sandstone in the lower member of the Cox is from 60 to 70 percent; in Sierra Lagrima its equivalent, the lower member of the Lagrima Formation, has less than 15 percent. In Sierra Pinosa the upper member of the Cox has about 25 percent; in Sierra Lagrima the upper member of the Lagrima has less than 5 percent.

The estimated overall thickness of the Lagrima Formation in Sierra Lagrima is 1,000 to 1,100 m. The formation thins toward the north and east and is probably only 600 m thick in southern Sierra del Pino.

Aurora Limestone

Southward the Benigno, Cox (Lagrima), Finlay, Benevides, Loma Plata, Del Rio, and Buda formations grade into the Aurora Limestone. Figure 6 divides the Aurora Limestone into eleven units numbered 1 to 11 in ascending order. Units 2, 3, 4, 5, and 6 together are laterally equivalent to the Cox (Lagrima) Formation. The Lagrima Formation could be subdivided into five members corresponding to these five units. The lower member of the Cox Formation grades laterally into units 2, 3 and 4; the middle member, into unit 5; the upper member, into unit 6.

Unit 2 consists of about 500 m of light-gray shaly thin-bedded to medium-bedded nonresistant micrograined limestone interbedded with subordinate light gray shale and marl. The foraminifer, **Orbitolina texana** Romer **s. l.**, is present in limestone beds throughout the member.

Conformably overlying unit 2, unit 3 is about 170 m of light to medium-gray thick-bedded massive resistant micrograined to very fine-grained limestone. The foraminifer, **Orbitolina texana** Römer **s. l.**, the rudistid **Toucasia** sp., and the caprinid **Caprinuloidea** sp. are abundant in unit 3, which closely resembles the limestone of Benigno Formation.

Next above, unit 4 is about 260 m of light-gray shaly thin-bedded to medium-bedded nonresistant micrograined limestone interbedded with shale and marl, the lower part containing **Orbitolina texana** Romer **s. l.** Unit 4 is characterized by a banded pattern of outcrop of shale-marl-limestone sequences.

In Sierra Lagrima unit 5, consists of 100 to 150 m of dark-gray thick-bedded resistant limestone interbedded with a few beds of shale 3 to 10 m thick. Unit 6 is 50 to 100 m of light-gray nonresistant interbedded shale, marl, and limestone. **Exogyra texana** Romer is present in the upper part of unit 6.

Finlay Limestone

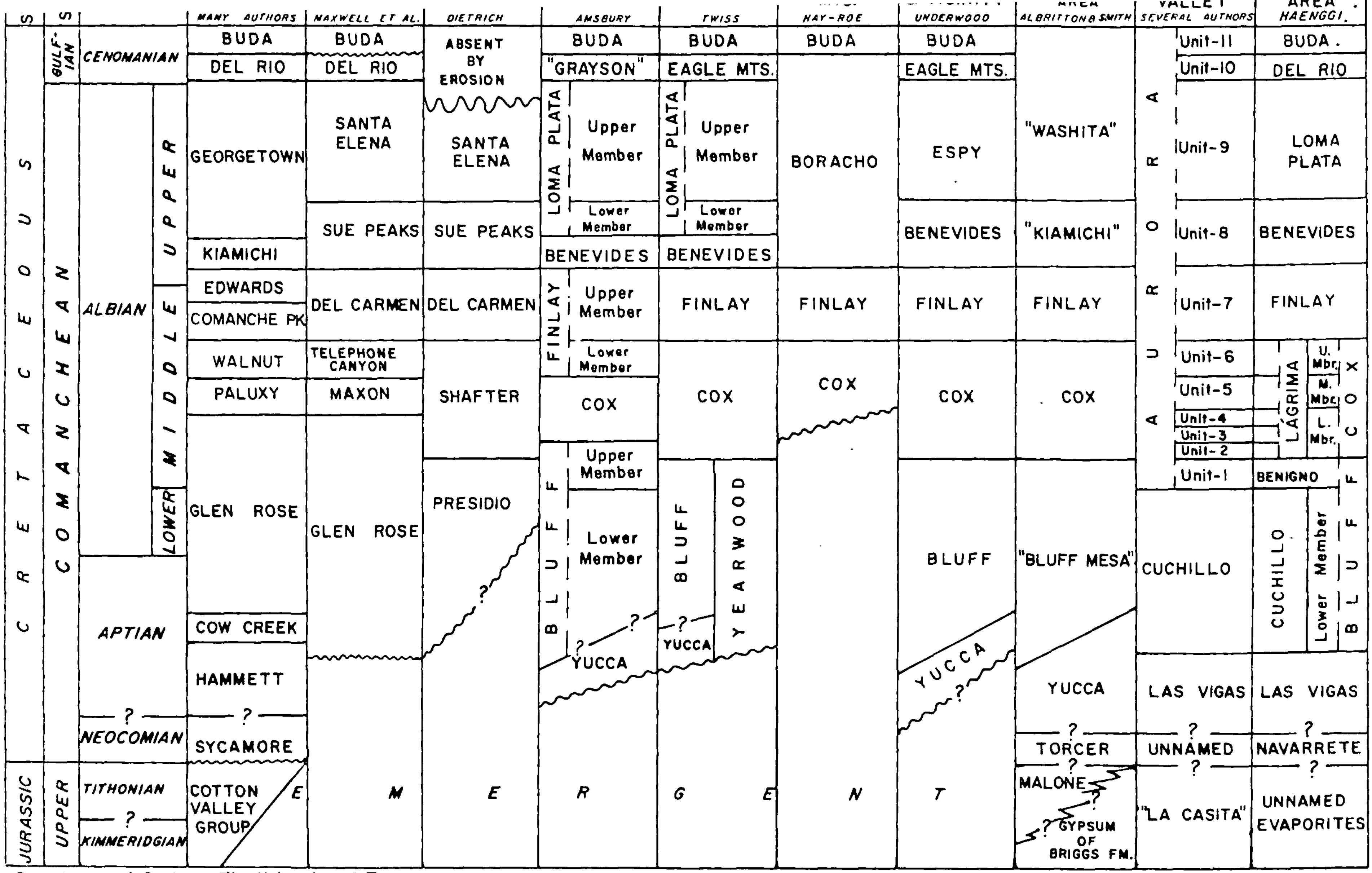
The thick cliff-forming Finlay Limestone between the Cox Formation and the Benevides Formation is medium-gray to dark-gray thick-bedded massive resistant fine-grained to micrograined. Some of it is nodular. It commonly weathers to rough "pock-marked" surfaces. Locally along bedding it contains irregular elongate chert nodules up to 0.3 m long, and chert bands about 10 mm thick and a meter or more long.

The thickness of the Finlay is remarkably uniform over much of northeastern Chihuahua. In general, it gradually thickens toward the south and west. In central and southern Sierra Pilares it is 220 to 235 m thick; in northern Sierra Pinosa, 186 to 203 m thick; and south of there along the eastern front of the range, about 150 m thick. In the Sierra Lagrima and Sierra del Pino, it is 180 to 200 m thick. The upper contact of the Finlay is sharp but conformable. At the base of non-resistant shale and marl of the Benevides the top of the Finlay is exposed in many places as a dip slope above the steep Finlay cliff-face.

Fossils are plentiful in the Finlay but difficult to collect. Details of many fossils are obliterated by calcite and silica replacement. The best guide fossil is **Dictyoconus walnutensis** (Carsey). This large pyramid-shaped foraminifer (Douglass, 1960) is confined to a zone 6 to 9 m thick, 30 to 45 m above the base of the formation in Sierra Pilares, Pinosa, and Lagrima. The **Dictyoconus** zone rises stratigraphically toward Sierra Blanca. Abundant rudistids and caprinids, **Toucasia** sp., **Monopleura** sp., and **Caprinuloidea** sp., are in large banks. The oysters **Exogyra** sp., **Exogyra texana** Romer, and **Texigryphaea** (?) sp. are sporadic in the lower part of the formation. The age of the Finlay is Albian. We correlate it with the upper part of the Fredericksburg Group in central Texas. It grades into unit 7 of the Aurora Limestone.

Benevides Formation

In the Pilares-Pinosa range the Benevides Formation can be divided into a lower shale and flaggy limestone member and an upper nodular limestone member. In places a resistant reef limestone appears between the lower and upper members. Haenggi did not map the members or the reef separately. The lower member is light-gray to medium-gray nonresistant thin-bedded fine-grained to micrograined limestone interbedded with varying amounts of medium-gray to dark-gray shale. Some of the limestone is nodular. The upper member is light-gray to medium-gray nonresistant thin-bedded to thick-bedded, fine-grained to micrograined nodular limestone with a few interbeds of medium-gray to dark-gray shale. The reef limestone is medium-gray



Department of Geology, The University of Texas

Figure 6. - Chart showing correlation of pre-Gulfian rocks of El Cuervo quadrangle in northeastern Chihuahua with outcrops in the valley of Rio Conchos and at seven localities in trans-Pecos Texas, and with the standard section in central Texas.

to dark-gray and thick-bedded.

The Benevides Formation has yielded an abundant and varied fauna. Ammonites include **Adkinsites** sp. aff. **A. belknapi** (Marcou), **Adkinsites bravoensis** (Böse), **Adkinsited diazi** Young, **Craginites serratescens** (Cragin), **Diploceras** sp. cf. **D. fredericksburgense** Scott, **Idiohamites fremonti** (Marcou), **Manuaniceras** sp. aff. **M. multifidum** (Steinmann), **Prohysteroscerns** sp. cfr. **P. austinense** (Römer), and **Venezollceras chihuahuaense** (Böse); typical pelecypods are **Cardita staffordi** Whitney, **Cyprimeria texana** Römer, **Neithea** spp., **Texigryphaea** spp., and **Trigonia** spp.; gastropods, **Lunatia pedernalis** (Römer), **Lunatia** sp., **Turritella** spp., and **Tylostoma** spp.; echinoids, **Enallaster texanus** (Römer), **Pedinopsis symmetrica** (Cragin), and **Tetragramma streeruwitzi** (Cragin); and from central Sierra Pilares, the brachiopod **Kingena** sp. cf. **K. wacoensis** (Römer). In the Pilares-Pinosa range the upper member is relatively unfossiliferous. (The abbreviation cf. indicates that the species is not necessarily the same as the species named; and cfr. means that poor preservation prevented positive identification of the species.)

The ammonites indicate middle to late Albian age. Paleontologically we correlate the Benevides with the Kiamichi and Duck Creek Formations of north Texas, with the lower part of the Georgetown Limestone of central Texas, and with the Sue Peaks Formation of the Big Bend region, west Texas. A horizon correlative with the contact between the Fredericksburg Group and Washita Group would fall within the Benevides Formation. It grades into unit 8 of the Aurora Limestone.

Loma Plata Limestone

In the Pilares-Pinosa range the Loma Plata Limestone is light-gray to medium-gray thick-bedded massive micrograined and resistant with a few thin interbeds of shale. It weathers yellowish-brown. Some of it is nodular. Silicified fossils, chert nodules, and bands of ropy chert are common in massive reef facies. In several places the limestone contains distinctive flat circular hematite nodules up to 15 cm in diameter.

In the Pilares-Pinosa range the Loma Plata thickens from 300 m on the east to more than 400 m on the west. The top of the Loma Plata is at the base of the first light-gray shale of the Del Rio Formation. The gradational contact is at the abrupt topographic break from ridge-forming Loma Plata limestone to slope-forming Del Rio shale.

Except for the locally abundant rudistid **Toucasia** sp. and caprinid **Caprinuloidea** sp., the Loma Plata Limestone is relatively unfossiliferous in the Pilares-Pinosa range. In central Sierra Pilares shale partings near the top of the formation yielded the nautiloid **Paracymatoceras** sp. cf. **P. hilli** (Shattuck), and reef limestone near the base yielded the echinoids **Holectypus planatus** (Giebel) and **Enallaster** sp. cfr. **E. bravoensis** Bose.

Because geologists in Trans-Pecos Texas and Chihuahua have found the ammonite **Plesioturrilites bravoense** (Romer) in the upper part of the Loma Plata Limestone, we place the Albian-Cenomania boundary within the formation; probably it is near the top. Southward the Loma Plata grades laterally into unit 9 of the Aurora Limestone and northward into the Espy Limestone of Underwood (1963). We correlate both formations with the Georgetown Limestone of central Texas.

A Useful Name: Aurora, Sierra Grande, or Chihuahua

Much of the scenery in eastern Chihuahua, Coahuila, and Nuevo Leon is dominated by the outcrops of massive Albian limestone. In Chihuahua this limestone has been, and occasionally still is, inexpediently encumbered with central-Texas names, such as "Edwards" or "Edwards and Glen Rose". An Aptian-Albian sequence has even been described as "Aurora, Glen Rose, Cuchillo". In places a shaly or marly layer within the Albian has received the north-Texas name "Kiamichi".

South of Cuchillo Parado as far as Torreon and southeast as far as southern Nuevo Leon the name **Aurora Limestone** is applied to part of the Albian sequence. Aurora would be a suitable group name for northeastern Chihuahua although somewhat inconsistent with the usage on the south and southeast.

The type Aurora Limestone composes Sierra Grande which bounds the Ojinaga basin on the southwest, but Vivar (1925) did not use the name Aurora. He called this carbonate sequence the Sierra Grande Group. Cordoba (1969a, 1969b) has proposed the name Chihuahua Group for the formations from Benigno Limestone to Loma Plata Limestone, inclusive. A group name will be useful. Where the carbonate deposition was hardly interrupted and siliciclastic interlayers are hard to find, or where not enough field work has been done to effect subdivision, the limestone sequence may be called simply "Chihuahua Limestone" or "Chihuahua Formation" or "Sierra Grande Formation or "Aurora Limestone" (American Commission on Stratigraphic Nomenclature, 1961, art. 9 remark c).

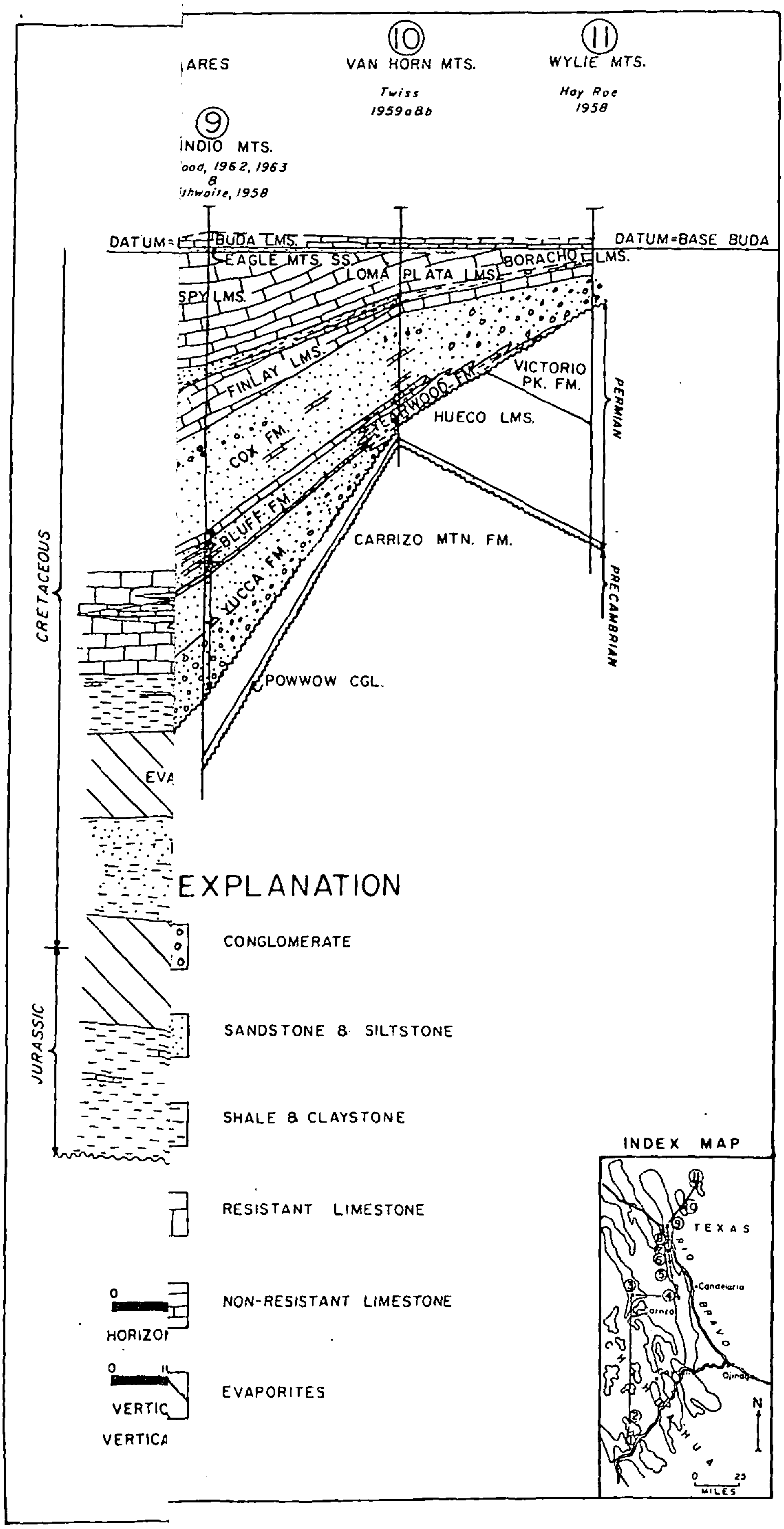
Del Rio Formation

The Buda Limestone can be traced readily from central Texas to the vicinity of Del Rio, Texas, and Ciudad Acuna, Coahuila, where the type Del Rio Formation capped by Buda is well exposed. It is fairly easy to trace both formations on west to northern Chihuahua, although the thickness of the Del Rio varies greatly from place to place; locally it is absent.

In the Pilares-Pinosa range the Del Rio and the Buda crop out in four small areas. Outcrops are poor, for the Del Rio is largely covered with colluvium or bolson fill in these areas.

The Del Rio consists of interbedded flaggy siltstone, thin-bedded limestone, and light-gray marl. In the Pilares-Pinosa range the thickness of the formation ranges between 5 and 15 m; in the Sierra Lagrima it is

Figure 7. - Generalized cross section of Upper Jurassic Series and Comanchean Series from Sierra Soldado north to Sierra Lagrima, thence east to Canon de Navarrete, thence north to Wylie Mountains. Position and thickness of pre-Navarrete evaporite are hypothetical.



ARES
10
VAN HORN MTS.
Twiss
1959a&b
11
WYLIE MTS.
Hay Roe
1958
9
INDIO MTS.
ood, 1962, 1963
&
thwaite, 1958
DATUM=
BUDA LMS.
DATUM=BASE BUDA
EAGLE MTS. SS.
BORACHO LMS.
LOMA PLATA LMS.
SPY LMS.
FINLAY LMS.
VICTORIO
PK. FM.
PERMIAN
COX FM.
HUECO LMS.
BLUFF FM.
CARRIZO MTN. FM.
YUCCA FM.
PRECAMBRIAN
POWWOW CGL.
CRETACEOUS
EVA
JURASSIC
EXPLANATION
CONGLOMERATE
SANDSTONE & SILTSTONE
SHALE & CLAYSTONE
RESISTANT LIMESTONE
NON-RESISTANT LIMESTONE
HORIZO
EVAPORITES
VERTIC
VERTICA
INDEX MAP
TEXAS
RIO
BRAVO
Candelaria
Ojinaga
CHIHUAHUA
N
0
25
MILES

›out 60 m. The top of the Del Rio at the base of the sistant Buda Limestone is sharply defined but con- rmable.

In the Pilares-Pinosa range the Del Rio has yielded e foraminifer **Haplostiche texana** (Conrad); the lecypods **Exogyra arietina** Römer, **Exogyra** car- **edgei** Bose, and **Neithea** spp.; the gastropods, ırritella sp. and **Tylostoma** sp.; and the echinoid eteraster sp. At Rancho La Bamba (30° 34'N, 5° 19'W) a bed near the base of the Del Rio has elded an abundant micromorph fauna of ammonites. ;ith Young identified the following ammonites; ıgonoceras sp., **Eoscaphites subevolutus** Böse, ıbaculites sp., **Ficheuria kiliani** (Pervinquiere), raysonites sp., **Metengonoceras** sp., **Plesioturrilites** ., **Prinocycloides pgoratus** (Pervinquiere), oturrilitoides (?) sp., **Scaphites** sp. cfr. **S. bosquensis** öse), and **Scaphites** n. sp. The micromorph bed has ;o yielded many unidentified ammonites, five identified gastropods, and a brachiopod **Kingena** (?)

The age of the Del Rio is early Cenomanian. It is erally continuous with the Eagle Mountains Sand- ›ne (Underwood, 1963) in Texas at the north and of : Sierra Blanca-La Mula range. At the south end it ıdes into unit 10 of the Aurora Limestone. We rrelate it with the Grayson Formation in North xas.

Buda Limestone

In the Pilares-Pinosa range the cuesta-forming Buda ıestone is 15 to 30 m thick. The limestone is light- ıy to medium-gray micrograined thin-bedded to :dium-bedded. Some of it is nodular. The top of the da is well exposed at several places notably at the rth end of the Sierra de Ventana. The abrupt ntact between the resistant Buda limestone and the erlying interbedded calcareous siltstone flags and rk-gray fissile Ojinaga shale appears to be con- mable.

In the border range the Buda has yielded the am- ›nites **Faraudiella texana** (Shattuck) and **Budaiceras** . the oyster **Arctostrea** sp. aff. **A. carinata** ımarck), and the pecten **Neithea** sp. Fossil siliceous ›nges are useful in identifying the Buda Limestone; y are abundant in the middle member, sparse in the ›er and upper members (Reaser, 1970).

The Buda grades into unit 11 of the Aurora ıestone. Its age is early Cenomanian. The Buda- naga contact is the Comanchean-Gulfian provincial- ies boundary.

Ojinaga Formation

The Ojinaga Formation named by Burrows (1909), tricted by Vivar (1925), consists of medium-gray to k-gray shale that weathers olive-gray. The lower 30 15 m and a zone 15 to 30 m thick about 250 m above base of the formation contain interbeds of silty estone and flaggy calcareous siltstone. Many crops have secondary gypsum along bedding planes l joints. Locally the formation contains calcareous ıcretions up to 30 cm in diameter. No complete section of Ojinaga is exposed in the Pilares-Pinosa range. The estimated original thickness is about 600 m.

The age of the Ojinaga formation near Ojinaga, Chihuahua, and in adjacent Texas ranges from Cenomanian through Turonian into Senonian; that is, through Turonian and Coniacian into early Campanian (Powell, 1965; Wolleben, 1966).

Inoceramus sp. is locally abundant in the Ojinaga Formation and several localities yielded ammonites which have not been identified. The ammonite **Placenticeras sancarlosense** Hyatt came from an outcrop of shale in Sierra Pinosa. The shale, which is immediately below a thrust fault under Finlay Limestone, appears to rest on the Navarrete Formation o.3 km W of Tarais (Haenggi, 1966, H-11 pl. 1; NE cor. pl. 5).

San Carlos Formation

In the El Cuervo quadrangle the Ojinaga Formation is in fault contact with superincumbent beds, and the San Carlos Formation is missing. Across the Río Bravo in Sierra Vieja it is 215 m thick; in the Ojinaga Basin, 130 m thick (Wolleben, 1965, p 72). It also crops out in the Casa de Piedra quadrangle.

The San Carlos consists of medium-bedded to thick-bedded yellowish-gray sandy fine-grained calcareous sandstone and yellowish sandy friable clay with concretions (Wolleben, p. 72). In Sierra Vieja the middle part has alternating marl and carbonaceous shale with some coal.

El Picacho Formation

In the Pilares-Pinosa range El Picacho Formation crops out in the foothills of the Sierra de Ventana, where it is in fault contact with the Ojinaga Formation.

The formation consists of 80 m of variegated (grayish orange, dusky yellow, and pale olive) marl containing varying amounts of secondary gypsum along joints. El Picacho Formation is unconformably overlain by volcanic rock of the Vieja Group and by bolson fill. Its probable age is Campanian. It may range into the Maestrichtian, but its ceratopsians are not so young as the latest ceratopsians in Montana and Canada (Langston, 1970).

Cordoba (1970) intends to assemble the Gulfian Formations of northeastern Chihuahua into a "Rio Bravo" Group. If he proposes this term, it will be useful.

APPENDIX 1. - TYPE SECTION OF NAVARRETE FORMATION

Overturned section measured from top to bottom by Haenngi (1966, MS-1, p. 328-331) with Jacob's staff in March 1965. 1.3 km N 20° E of Rancho La Abuja. Approximate location: 30° 02'N, 104° 49'W. Average strike N 20° E; average dip 45° W overturned.

Conformable contact with Las Vigas Formation placed at base of 9 m bed of pale brown (5YR5-2), medium-grained, well sorted, hard-resistant, medium-bedded, subangular to subround, faintly laminated, siliceous, quartzose sandstone. Although the contact is gradational, it is marked by a topographic break along a ridge.

UNIT NO.	KIND OF ROCK	THICKNESS METERS	LITHOLOGY
39	claystone & siltstone	16.8	Claystone greenish-gray (5GY6-1), massice calcareous, soft, weathers white (N-9). Siltstone in middle of unit 39 is greenish-gray (5GY6-1), very thin-bedded, calcareous.
38	sandstone	1.2	Medium gray (N-5), fine-grained, well sorted, resistant, thin-bedded to medium-bedded, laminated, siliceous to slightly calcareous, quartz sandstone.
37	claystone & sandstone	6.1	Claystone as in unit 39. Sandstone as in unit 38 in 20-cm bed 4 m above base and 15-cm bed 5 m above base.
36	siltstone	1.5	Greenish-gray (5GY6-1), thin-bedded (shaly), clayey, noncalcareous siltstone.
35	claystone & siltstone	7	Claystone as in unit 39. Siltstone as in unit 36 interbedded with lower meter of claystone.
34	sandstone	0.3	Very light gray (N-8), fine-grained to medium-grained, well sorted, subround, calcareous, slightly pyritic, quartz sandstone.
33	claystone & siltstone	6	Claystone as in unit 39. Siltstone as in unit 36 interbedded with lower 2 m of claystone.
32	sandstone & siltstone	1	Medium gray (N-5) to greenish-gray (5GY6-1), very fine-grained, quartz sandstone interbedded with siltstone.
31	claystone	1.8	As in unit 39.
30	micrite	0.3	Medium dark gray (N-4) micrite.
29	claystone & siltstone	5.5	Claystone in unit 39. Lower 0.3 m of claystone contains very thin interbeds of greenish-gray (5GY6-1) siltstone.
28	micrite	0.2	Medium gray (N-5) micrite, weathers pale brown (5YR5-2).
27	claystone	4.3	As in unit 39.
26	sandstone	0.3	Greenish-gray (5GY6-1), fine-grained, well sorted, subround, thin-bedded, quartzitic, calcareous, quartz sandstone.
25	claystone	0.6	Pale red-brown (10R5-4) calcareous claystone.
24	sandstone	0.3	As in unit 26.
23	claystone	1	As in unit 25.
22	sandstone	1.5	Greenish-gray (5GY6-1), fine-grained, well sorted, subangular to subround, resistant, thin-bedded to medium-bedded, calcareous, quartz sandstone.
21	claystone & siltstone	11.6	Claystone as in unit 39 with 30-cm interbed of greenish-gray (5GY6-1), thinbedded siltstone 30 cm above base.
20	micrite	0.1	Medium gray (N-5) micrite.
19	claystone	4.6	As in unit 39.
26-19	(gypsum)	(20.)	Locally along strike units 19 through 26 are replaced by white (N-9), granular gypsum.

UNIT NO.	KIND OF ROCK	THICKNESS METERS	LITHOLOGY
18	limestone	2.1	Medium dark gray (N-4), medium-grained to coarse-grained, thin-bedded to medium-bedded, oolitic to pisolitic especially near top, resistant, limestone. Thin sections show echinoderm and mollusk fragments, and Early Cretaceous miliolids identified by B. F. Perkins.
17	claystone	3	As in unit 39 unit 17 grades downward into unit 16.
16	sandstone	1.5	Very light gray (N-8), fine-grained to medium-grained, well sorted, subround, thin-bedded to medium-bedded, calcareous, quartz sandstone.
15	claystone	4.3	As in unit 39.
14	claystone, siltstone & sandstone	1.5	Claystone as in unit 39 with interbeds of greenish-gray (5GY6-1), very fine-grained, thin-bedded, slightly resistant, calcareous, quartz sandstone, and siltstone. Proportion of sandstone increases gradually toward base.
13	claystone	5.2	As in unit 39.
12	claystone, siltstone, & sandstone	1.5	As in unit 14.
11	claystone & siltstone	4.6	Claystone as in unit 39, with few interbeds of greenish-gray (5GY6-1) siltstone.
10	micrite	0.2	Medium light gray (N-6) micrite, containing abundant algal heads (?) and calcite-lined cavities.
9	claystone	6.1	As in unit 39.
8	micrite	1	Medium light gray (N-6), thin-bedded, slightly resistant micrite, contains some calcite-filled cavities near base.
7	claystone	2.3	As in unit 39.
6	limestone	0.6	Medium dark gray (N-4), thin-bedded limestone.
5	claystone	1.5	As in unit 39.
4	limestone	2.7	Medium dark gray (N-4) to medium gray (N-5), medium-bedded to thick-bedded micrite.
3	claystone	3	As in unit 39.
2	limestone	10.4	Medium dark gray (N-4) to medium gray (N-5), medium-bedded to thick-bedded, micrite to micritic skeletal limestone. Oolitic to pisolitic near top, locally slightly siliceous and slightly pyritic. Thin sections show miliolids and mollusk fragments. Micritic-skeletal limestone contains spired gastropods and thin-shelled pelecypods.
1	sandstone	9	Pale yellow-brown (10YR6-2), fine-grained to medium-grained, well sorted, thin-bedded to medium-bedded, quartzitic, slightly calcareous, quartz sandstone. Base of unit 1 is probably a diapiric contact.
39-1	Navarrette formation	132.5	Incomplete thickness; the base is not exposed.

APPENDIX 2 - TYPE SECTION OF BENIGNO FORMATION

Section measured in summer of 1959 by J. C. Yeager (1960, Measured Section 6, p. 85-86) and S. C. Hamilton with Brunton compass and Jacob's staff, beginning at 30° 17' 12" N, 104° 55' 22" W, and measuring up a resistant ridge west of Arroyo de los Alamos.

UNIT NO.	KIND OF ROCK	THICKNESS METERS	LITHOLOGY
9	limestone	81	Dark gray (N3), weathers medium gray (N5) thick-bedded, micrograined, resistant; **Orbitolina texana** found in lower 65.5 feet of unit 9.
8	limestone	11	Dark gray (N3), weathers medium gray (N5), nodular, micrograined, non-resistant; contains abundant **Orbitolina texana.**
7	sandstone	4	Very light gray (N8) that weathers pale yellowish brown (10YR6-2); and greenish gray (5GY6-1) that weathers grayish brown (5YR3-2); thin-bedded, very fine sand; has limonitic spots and streaks; calcareous cement; resistant.
6	covered	18	Sandstone and nodular limestone float.
5	sandstone	1.2	Dark medium gray (N4) weathers moderate brown (5YR4-4), thick-bedded, fine sand; calcareous cement; resistant.
4	limestone	3.4	Dark gray (N3), weathers medium gray (N5), thin-bedded, resistant, paurograined (i.e., silt size to fine-sand size).
3	covered	6	Nodular limestone float.
2	limestone	9	Dark gray (N3), weathers medium gray (N5), thin-bedded, paurograined, resistant; contains scattered **Orbitolina texana.**
1	limestone	24.4	Dark gray (N3) that weathers medium light gray (N6) and yellowish gray (5Y7-2), nodular to thin-bedded, paurograined, non-resistant; contains **Orbitolina texana** at top.
9-1	Benigno Formation total thickness	158	Mostly limestone.

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September 27, 1978

MEMORANDUM

To: ESL Staff

From: Bruce Sibbett

Subject: Cerro Prieto Geothermal Field Symposium

Cerro Prieto is a hot water geothermal system located in Baja, Mexico, about 30km south of U.S. border.

The current output is 75 MWe, and this will be expanded to 150 MWe in 6 mo. Further expansion is planned in the 1980's. The fluid production rate is 2,392 metric tons/hr from 19 wells. Out of this production about 700 tons/hr flashes to steam and powers the generator. The liquid fraction of the production goes into an evaporation pond. There is no reinjection at the present time. Reservoir temperatures range from 250° to 350°C and well head pressures are 100 to 290 p.s.i.

The stratigraphy consists of three general units. The basement rocks are granitic and metamorphic, and 1500 to 2000m or more below the surface. The second unit is consolidated tertiary siltstone, shale and sandstone of deltaic origin. This unit is on the order of 1000m thick, and the reservoir occurs within it. The upper unit is unconsolidated, Quaternary clay, sand and gravels of deltaic origin. These were deposited by the Colorado River and are 500m or more thick in the field.

The producing zone is a sandstone unit about 200m thick, and between 800 and 1500m deep. The reservoir sandstone is thought to be a paleochannel(s) of the Colorado River. A shale unit up to 40 m thick splits the producing zone into a upper and lower reservoir. There is probably some difference in temperature, pressure and chemistry between these two producing zones. However, because all but one of the wells are producing from both reservoirs, little could be determined about these differences from the mixed fluids produced.

The main structure is a NNW normal fault system. In detail the consolidated units are faulted into a series of horst and grabens and lesser NE trending faults cut these (see the accompanying cross sections). In general however the field can be thought of as located in a large block bounded by NNW trending faults with the block to the west up, and the block to the east down.

The producing paleochannel continues to the SE where it is about 2000m deep in the graben to the east of the current producing field. The permeability is greater in this deep zone than in the present field, and the temperature is about $340^{o}C$.

After 5 years of production the hydrologic head has dropped about 50m and temperatures are decreasing slowly. It is thought that the fluid source is from the sourtheast, and/or feeders come up the faults. The limits of the field are not totally defined and a major extention to the southeast seems likely.

Bruce Sibbett

Bruce Sibbett

BS/smk

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U.S.-MEXICO

REVIEW OF U.S.-MEXICAN COOPERATIVE PROGRAM AT CERRO PRIETO

(1979

(Lawrence Berkeley Laboratory
Program Review

PROGRAM OBJECTIVE

PROGRAM SUMMARY

- ACCOMPLISHMENTS TO DATE
- FY 1979 FUNDED ACTIVITIES
- FY 1980 AND OUTYEAR RECOMMENDATIONS

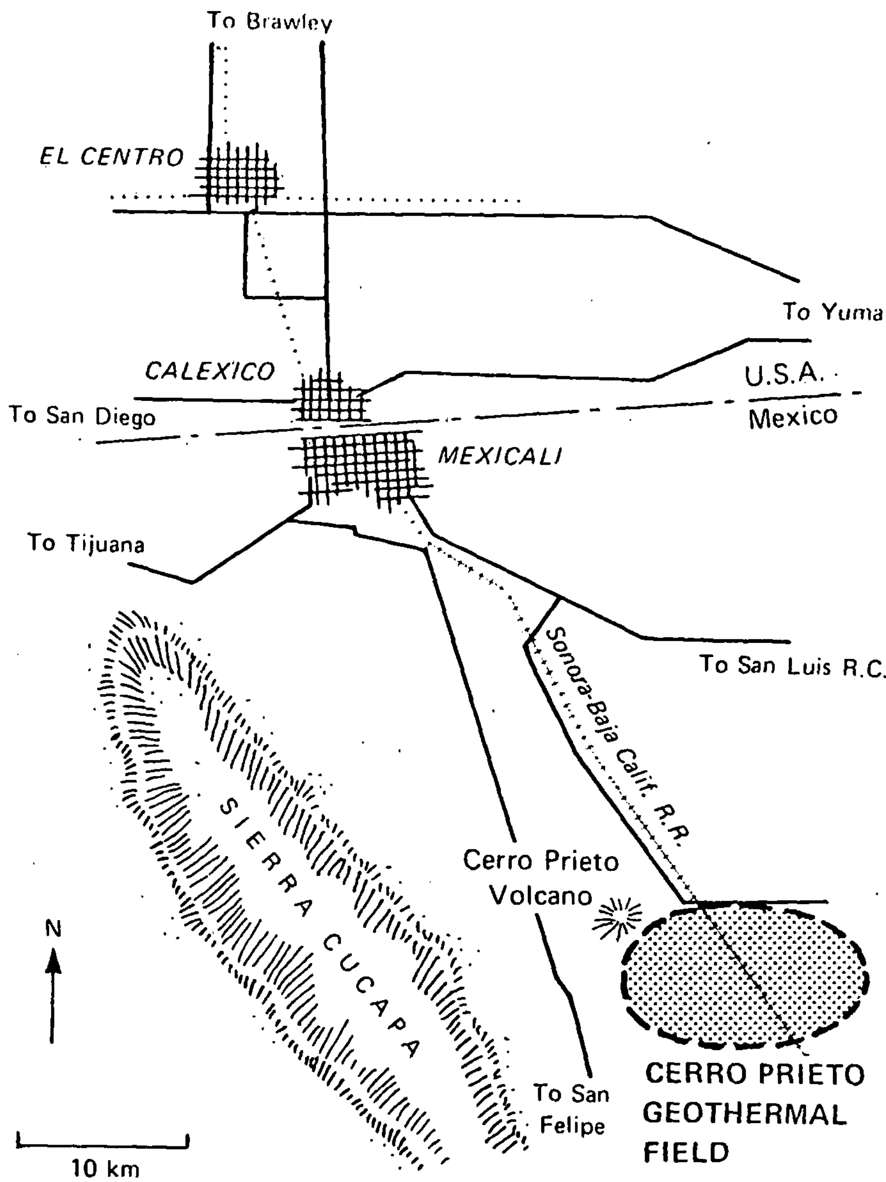
INTERACTION WITH OTHER PROGRAMS AND INDUSTRY

U.S.-MEXICAN COOPERATIVE PROGRAM AT CERRO PRIETO

PURPOSE

THE PRIMARY OBJECTIVE OF THE PROGRAM IS TO DEVELOP AN UNDERSTANDING OF THE GEOLOGIC SETTING AND HYDROTHERMAL CIRCULATION OF THE CERRO PRIETO GEOTHERMAL SYSTEM.

CERRO PRIETO IS CONSIDERED AN IDEAL SYSTEM FOR STUDYING THE LONG-TERM RESPONSE OF A LIQUID-DOMINATED GEOTHERMAL FIELD IN CONTINUOUS PRODUCTION. MUCH OF THE INFORMATION OBTAINED HERE WILL BE APPLICABLE TO THE DEVELOPMENT OF GEOTHERMAL RESOURCES IN THE IMPERIAL VALLEY OF CALIFORNIA.



XBL 788-10409

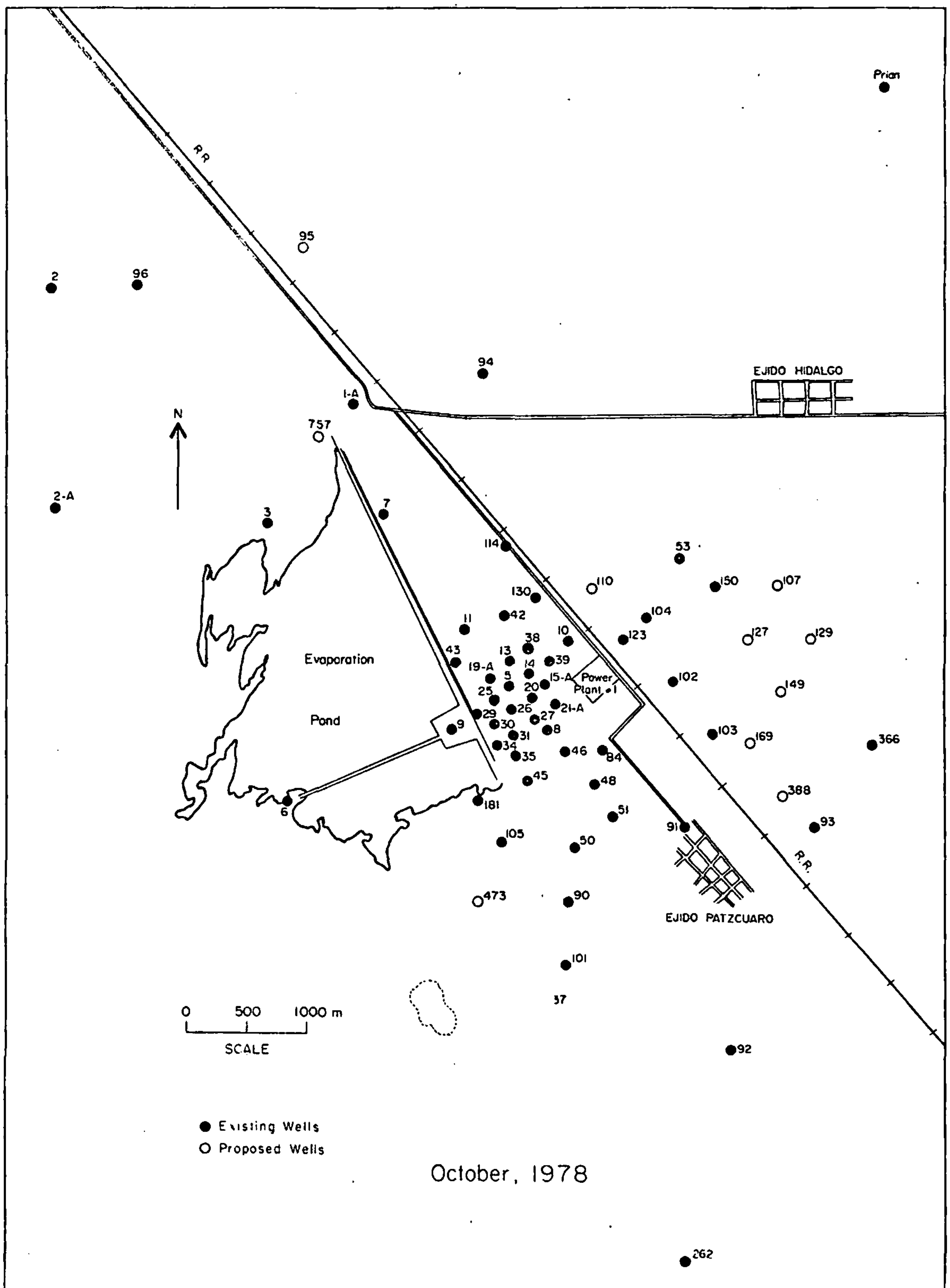
CERRO PRIETO GEOTHERMAL FIELD

GENERATING CAPACITY

YEAR	MW_e
1978	75
1979	150
1981	180
1983	290
1985	400

DRILLING PROGRAM

YEAR	NUMBER OF WELLS
1978	14
1979	~20
1980	~20



CERRO PRIETO GEOTHERMAL FIELD WELL LOCATIONS

XBL 7811-12804

U.S.-MEXICO

DOE-CFE CERRO PRIETO COOPERATIVE PROGRAM

(1977-1982)

TASKS

I - GEOLOGY-HYDROGEOLOGY

II - GEOPHYSICS

III - RESERVOIR ENGINEERING

IV - REINJECTION

V - GEOCHEMISTRY

VI - SUBSIDENCE

VII - CONFERENCES

U.S.-MEXICO

CERRO PRIETO

TASK DESCRIPTIONS

GEOLOGY-HYDROGEOLOGY

DEVELOPMENT OF GEOLOGICAL AND HYDROGEOLOGICAL MODEL

MINERALOGICAL, PETROGRAPHICAL AND PETROPHYSICAL STUDIES OF CORES AND CUTTINGS

WELL LOG ANALYSIS

GEOCHEMISTRY

ISOTOPIC STUDIES

TRACE ELEMENTS STUDIES

RESERVOIR ENGINEERING

WELL TESTING

MATHEMATICAL MODELING

DISSEMINATION OF RESULTS

OPEN FILE DATA BANK

CONFERENCES

REPORTS

GEOPHYSICS

RESISTIVITY

SELF POTENTIAL

PRECISION GRAVITY

INDUCED SEISMICITY

MAGNETOTELLURICS

PASSIVE SEISMIC

SUBSIDENCE

REGIONAL TRILATERATION SURVEY

LOCAL HORIZONTAL SURVEY

REINJECTION

CHEMISTRY STUDIES

MATHEMATICAL MODELING

FEASIBILITY STUDIES OF LARGE SCALE INJECTION

JANUARY 1979

GEOLOGY-HYDROGEOLOGY

OBJECTIVES

DEFINE STRUCTURE, LITHOLOGIC CONTROLS, DIMENSIONS, MINERALOGY, AND REGIONAL HYDROLOGY OF THE CERRO PRIETO SYSTEM.

BENEFITS TO THE US GEOTHERMAL PROGRAM

LEARN ABOUT THE GEOLOGICAL AND HYDRO-GEOLOGICAL CHARACTERISTICS OF A PRODUCING GEOTHERMAL FIELD IN THE SALTON TROUGH.

GEOPHYSICS

OBJECTIVES

DETERMINE STRUCTURE AND DIMENSIONS OF THE FIELD. MONITOR CHANGES DUE TO FLUID PRODUCTION.

BENEFITS TO THE US GEOTHERMAL PROGRAM

LEARN ABOUT THE GEOLOGICAL CHARACTERISTICS OF CERRO PRIETO. ALSO, ESTABLISH WHICH CHANGES IN GEOPHYSICAL CHARACTERISTICS OF THE FIELD RESULT FROM FULL SCALE EXPLOITATION OF WATER DOMINATED SYSTEM. COMPARE AND EVALUATE DIFFERENT GEOPHYSICAL TECHNIQUES BY FIELD STUDIES OF A DEVELOPED GEOTHERMAL SYSTEM.

GEOCHEMISTRY

OBJECTIVES

ESTABLISH AGE, ORIGIN AND CHEMICAL CHARACTERISTICS OF THE GEOTHERMAL FLUIDS. ESTIMATE RATES, SOURCES, AND ROUTES OF FLUID RECHARGE.

BENEFITS TO THE US GEOTHERMAL PROGRAM

DETERMINE THE HYDROTHERMAL CIRCULATION AND MONITOR CHEMICAL CHANGES IN A PRODUCING WATER DOMINATED GEOTHERMAL FIELD.

RESERVOIR ENGINEERING

OBJECTIVES

DETERMINE GEOMETRY AND PHYSICAL CHARACTERISTICS OF THE RESERVOIR AND HYDROLOGICAL BOUNDARIES. ESTIMATE SAFE PRODUCTION RATES, OPTIMAL DISTANCE BETWEEN WELLS AND USEFUL LIFE OF THE RESERVOIR(S).

BENEFITS TO THE US GEOTHERMAL PROGRAM

EVALUATE WELL TESTING EQUIPMENT UNDER HIGH TEMPERATURE AND PRESSURE CONDITIONS. VALIDATE COMPUTER CODES AGAINST OBSERVED FIELD PERFORMANCE. STUDY RESERVOIR RESPONSE TO FULL SCALE EXPLOITATION.

REINJECTION

(PLANNING FOR A LARGE SCALE OPERATION)

OBJECTIVES

EVALUATE DIFFERENT WELL PATTERNS AND BRINE TREATMENT METHODS. OPTIMIZE RESERVOIR RECHARGE AND HEAT EXTRACTION FROM THE ROCK MATRIX. STUDY FEASIBILITY OF A FULL SCALE REINJECTION EXPERIMENT.

FUTURE BENEFITS TO THE US GEOTHERMAL PROGRAM

IF A FULL SCALE REINJECTION TEST APPEARS FEASIBLE AND IS APPROVED BY CFE, U.S. WILL HAVE THE OPPORTUNITY TO MONITOR AN INJECTION EXPERIMENT IN THE SALTON TROUGH. IT WILL PERMIT THE EVALUATION OF THE PERFORMANCE OF WELLS, BRINE TREATMENT PLANT(S), AND SURFACE EQUIPMENT. EVENTUALLY IT MIGHT LEAD TO A LARGE SCALE INJECTION OPERATION AT CERRO PRIETO.

SUBSIDENCE

OBJECTIVES

MEASURE HORIZONTAL AND VERTICAL GROUND DEFORMATIONS IN THE MEXICALI VALLEY. DISTINGUISH GEOTHERMAL SUBSIDENCE FROM OTHER MAN-MADE AND NATURAL CAUSES OF SUBSIDENCE.

BENEFITS TO THE US GEOTHERMAL PROGRAM

STUDY THE DEFORMATION OF THE SALTON TROUGH RESULTING FROM BOTH TECTONIC CAUSES AND FROM THE EXTRACTION OF FLUIDS FROM A WATER DOMINATED GEOTHERMAL SYSTEM.

DISSEMINATION OF RESULTS

OBJECTIVES

MAKE ACCESSIBLE TO EVERYONE THE DATA COLLECTED, RESULTS AND EXPERIENCES OBTAINED AT THE CERRO PRIETO FIELD.

BENEFITS TO THE US GEOTHERMAL PROGRAM

DATA NEEDED TO UNDERSTAND THE BEHAVIOR AND CHARACTERISTICS OF A WATER DOMINATED SYSTEM UNDER PRODUCTION WILL BE AVAILABLE TO THE GEOTHERMAL COMMUNITY.

MAJOR ACCOMPLISHMENTS TO DATE

THE US-MEXICAN COOPERATIVE PROGRAM WAS CONCEIVED, ORGANIZED, INITIATED, AND IS PROGRESSING SATISFACTORILY.

A NUMBER OF MEETINGS BETWEEN U.S. AND MEXICAN SCIENTISTS HAVE BEEN HELD TO DISCUSS RESULTS AND PLAN FUTURE ACTIVITIES.

FIRST YEAR OF FIELD AND LABORATORY ACTIVITIES HAVE BEEN COMPLETED. (LIST OF REPORTS AVAILABLE)

THE FIRST SYMPOSIUM ON THE CERRO PRIETO FIELD WAS HELD IN SEPTEMBER 1978 AT SAN DIEGO, CA. (ABSTRACT VOLUME AVAILABLE)

JAN 1979

FY 79 DOE FUNDED ACTIVITIES

Geology

Development of geologic model of the Cerro Prieto Field

Digitization and analysis of geophysical well logs

Mineralogic and petrographic analysis of cuttings and cores

Laboratory measurements of thermal and hydraulic properties of cores

Paleomagnetic study of the Cerro Prieto volcano to establish its age

Update of open-file data bank

Geochemistry

Collect and analyze additional fluid samples of geothermal and ground water wells

Perform isotopic studies on fluid and rock samples

Reservoir Engineering

Complete fully monitored well test

Advise CFE on their well-test activities

Simulate numerically present and future reservoir behavior

Conferences

No symposium planned for FY 79. Various internal meetings with CFE will be held to discuss topical subjects (i.e. reinjection)

January 1979

Geophysics

Complete second phase of:

- Precision gravity measurements
- D.C. resistivity measurements
- Magnetotelluric resistivity measurements

Install five station downhole seismographic network

Interpret field data, develop geologic model, compare results with those of previous surveys

Subsidence

Complete second horizontal control surveys of:

1) Trilateration regional network

2) Local network

Compare results with those of first surveys to establish magnitude and rate of ground deformation

Reinjection

Chemical studies of:

1) Compatibility of treated brines and reservoir waters

2) Elimination of silica from flashed brines

Numerical simulation studies of different well reinjection patterns

Participation in a committee to study feasibility of a full-scale reinjection field test at Cerro Prieto (recommendations are expected in June/July 1979, test would begin as early as September 1979)

FY 80 AND OUTYEAR RECOMMENDATIONS

Geology

Update of geologic and hydro-geologic model of Cerro Prieto field

Digitization and analysis of geophysical well logs

Analysis of cores and cuttings

Update of open-file data bank

Geochemistry

Continue sampling and laboratory analysis activities to:

1) Improve understanding of hydrothermal circulation within the field
2) Monitor changes related to ongoing fluid production

Reservoir Engineering

Perform well tests:

1) In new areas of the Cerro Prieto field
2) Of reinjection well(s) drilled by CFE

Simulate future field behavoir as updated geologic models become available

Conferences

October 79-Mexicali (Second symposium on the Cerro Prieto Geothermal field.

Annual symposia should continue; to be held alternatively in California and Baja California, Mexico.

Periodic internal DOE/CFE meetings should continue as required.

Geophysics

Continue gravity, resistivity and passive seismic surveys to monitor changes related to reservoir exploitation.

Extend networks to cover new producing areas within the Cerro Prieto field.

Subsidence

Complete third and subsequent horizontal control surveys to:

1) Establish magnitude and rate of ground deformation in the Mexicali Valley
2) Differentiate, if possible, deformations due to geothermal activities from those of natural and other man-made causes.

Reinjection

If CFE agrees on a full-scale reinjection test at Cerro Prieto, DOE/LBL should participate in the following selected activities:

1) Well testing and well monitoring
2) Chemical studies (treatment of and compatibility of brines)
3) Surface monitoring (ground surface deformations, gravity, resistivity surveys)
4) Monitoring of surface installations performance

January 1979

INTERACTION WITH OTHER GEOSCIENCES PROGRAMS

USGS GEOTHERMAL RESEARCH PROGRAM

GEOTHERMAL SUBSIDENCE RESEARCH PROGRAM (LBL)

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AREA .
MEX
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C.P.

(1) Bermejo De La Mora, B.D.A.; "Present Methods of Opening and starting Production in Wells a Cerro Prieto Geothermal Field, Baja California, Mexico" p. 169

(2) Jorge Guiza, L.; "Power Generation at Cerro Prieto Geothermal Field". p. 1983

(3) Salvador Garcia, D.; "Geoelectric Study of Cerro Prieto Geothermal Area, Baja California, Mexico; p. 1003

(4) Bernardo Dominguez, A.; Francisco Vital, B.; Repair and Control of Geothermal wells at Cerro Prieto, Baja California, Mexico; p. 140

(5) Sergio Mercado, G.; "Movement of Geothermal Fluids and Temperature Distribution in the Cerro Prieto Geothermal Field, Baja California, Mexico" p. 487

(6) Eduardo Paredes, A.; "Preliminary Report on the Structural Geology of the Cerro Prieto Geothermal Field" p. 515

(7) Reed, M.J.; "Geology and Hydrothermal Metamorphism in the Cerro Prieto Geothermal Field, Mexico." p. 539

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EARTH SCIENCES

LAWRENCE BERKELEY LABORATORY / UNIVERSITY OF CALIFORNIA

EARTH SCIENCES DIVISION

THIRD CERRO PRIETO SYMPOSIUM

The Third Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, will be held in San Francisco on March 24-26, 1981, hosted by the U.S. Department of Energy and LBL in cooperation with the Comisión Federal de Electricidad de México. The meeting will concentrate on results obtained during the first three years of the U.S./Mexican Cooperative Agreement. Simultaneous English/Spanish translations will be provided for the 250 participants expected. A field trip to The Geysers has been scheduled for Friday, March 27, 1981. Proceedings of the Second Symposium, held in Mexicali in October 1979, will be published by CFE during 1980.

Land Subsidence and Related Effects Due to Subsurface Fluid Exploitation

T. N. Narasimhan and K. P. Goyal

The exploitation of natural resources profoundly modifies the subsurface fluid flow regime. This results from simply pumping out oil, gas, or water from the underground by means of wells, or from more sophisticated activities such as solution mining of copper or uranium, underground disposal of toxic wastes, and so on. Until a few decades ago, exploitation strategy was primarily geared toward removing the resource as rapidly as possible from the underground. However, it soon became apparent that alteration of the fluid flow regime can affect the human environment in many ways, often leading to heavy damage to property and even loss of life. As a result, there is now an acute awareness in the United States and elsewhere of the fact that resource exploitation strategies should be suitably tempered with a consideration of the environmental consequences.

In general, subsurface fluid extraction can lead to two broad classes of environmental effects. The first is that of chemical contamination of the native groundwater, with which we shall not be concerned in this paper. We shall direct our attention to one aspect of the second class of effects: deformation of soil and rock masses in response to changes in fluid flow. These effects are manifested in such diverse phenomena as ground subsidence, earth fissuring, induced earthquakes, soil liquefaction, stability of

Continued on p. 5

Geology of the Cerro Prieto Geothermal Field

Stephen Vonder Haar

The Cerro Prieto geothermal field is presently producing 150 MW of electric power from brines contained in altered deltaic sediments at depths ranging from 1.8 to 3 km. With brine temperatures from 280° to 350°C, the exploited reservoir is the only liquid-dominated one currently in operation in North America. In contrast, The Geysers field in California produces a dry steam because the liquid boils deep within the reservoir region. The latest plans call for a total electricity production of 660 MW by 1984, equal to the present electrical power generated at The Geysers. Much of the power generated at Cerro Prieto is likely to be sold to utilities in southern California and Arizona. As shown in Figure 1, the close proximity of Cerro Prieto to the extensive geothermal fields in the Imperial Valley of southern California and the similarity in faulting as well as sedimentary rock type to the Heber and Salton Sea fields has made Cerro Prieto an ideal site for testing hydrothermal geologic concepts relevant to the geothermal fields in the Imperial Valley.

A comprehensive effort to understand the geology at Cerro Prieto began in 1977 with the signing of a cooperative agreement between the Comisión Federal de Electricidad de México (CFE) and the U. S. Department of Energy, Division of Geothermal Energy. Results of ongoing studies that include geophysics, geochemistry, well testing, and reservoir engineering are discussed in the proceedings of the first two symposia on the Cerro Prieto geothermal field (Lawrence Berkeley Laboratory, 1979; Comisión Federal de Electricidad, 1980). This article focuses briefly on the

Continued on p. 2

CONTENTS

Cerro Prieto *(Continued from p. 1)*

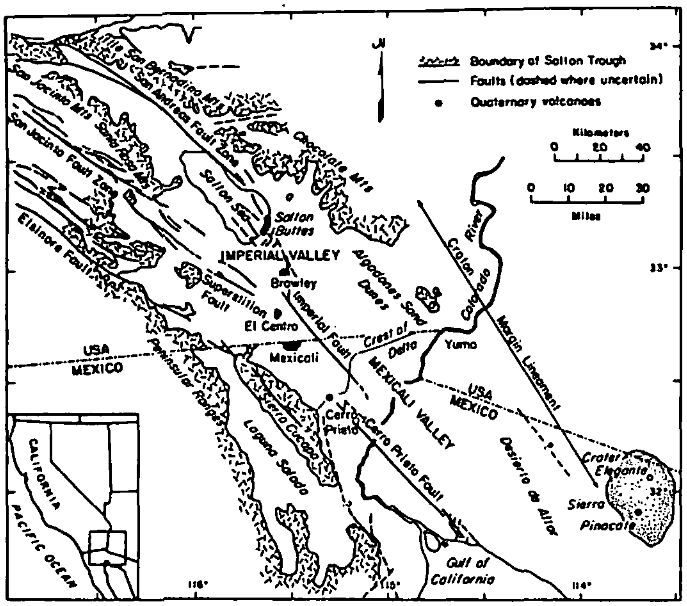

Figure 1. Regional geology of the Cerro Prieto geothermal field. Note the prevalent and long NW-SE trending faults with much shorter intersecting faults of NE-SW trends.

tectonic regime of the Cerro Prieto field and on the altered porosity and permeability within the reservoir.

The wedge-shaped region termed the Salton Trough extends southward from the Salton Sea to the Gulf of California (Fig. 1) and is noted for recent volcanism, strike-slip faulting, and geothermal fields. This region is bounded on the east by the poorly defined Craton Margin Lineament and the Sierra Pinacate volcanics. On the west, the San Felipe basin fault zone and the combined Elsinore/San Jacinto fault zones form a sharp boundary. Slicing through the trough are the Cerro Prieto and Imperial faults, among others. These major faults may be thought of as hybrids, having features of both San Andreas-style wrench faults and oceanic transform faults. The Cerro Prieto geothermal field is thus localized between major faults in a zone of crustal spreading, most likely at an offset of the landward extension of the East Pacific Rise. The field lies about 5 km southeast of the rhyodacite Cerro Prieto Volcano, which has been estimated by paleomagnetic dating as having a maximum age of 110,000 years.

Areas similar to the Cerro Prieto region were investigated in relation to both early rifting phases and transform faulting. In addition to studies of basins in the Gulf of California, the in situ structural observations along transform fault "A" in the FAMOUS area of the Mid-Atlantic Ridge have provided clear insights into fault style and dynamics (Fig. 2). Geophysical studies and well drilling in the Cerro Prieto region have furnished a model that compares favorably with these analogs if the increasing rate of deltaic sedimentation and the thickening of the continental basement near Cerro Prieto are considered.

The structural framework of the field, derived from interpretation of geophysical studies and subsurface data from well logs, is illustrated in Figure 3. The presently producing area of the field is located between the Cerro Prieto and the Michoacan faults, which are approximately 3 km apart and nearly parallel. The high productivity of certain wells, such as M-103 (Alonso et al., 1979), is most likely due to their proximity to the intersection of either the Cerro Prieto or the Michoacán fault and the northeast-striking set of faults. Such intersections furnish a fracture zone of relatively high permeability that serves as a preferential conduit for convective circulation of geothermal fluids.

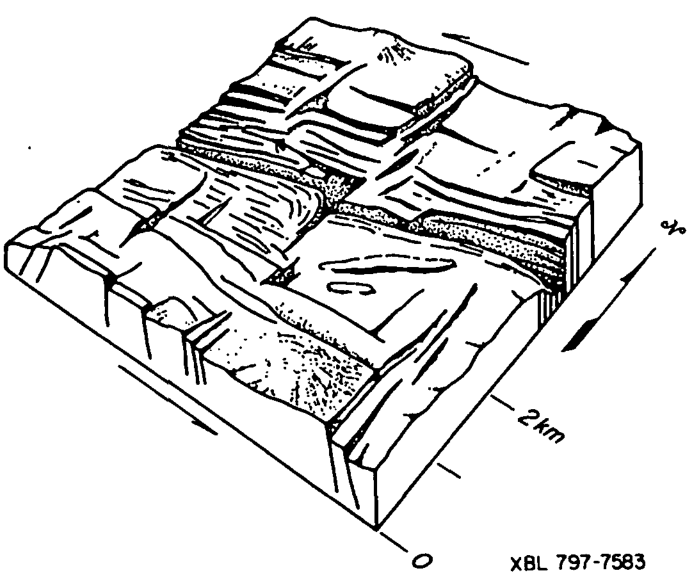

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Figure 2. Interpretive block diagram of the oceanic Transform fault "A" in the Mid-Atlantic Ridge showing structural domains. The ramps, cross-faults, and 200-m-wide active zone of strike-slip movement within a 4-km-wide fault trough suggest the possible complexity of faulting along the Cerro Prieto and Imperial faults and within the producing geothermal fields (after Choukroune et al., 1978).

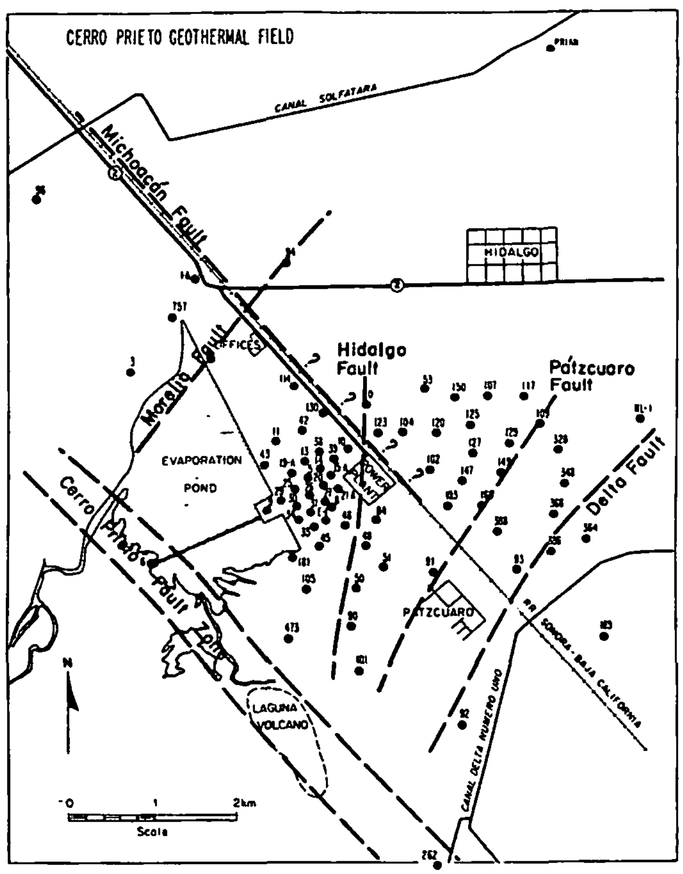


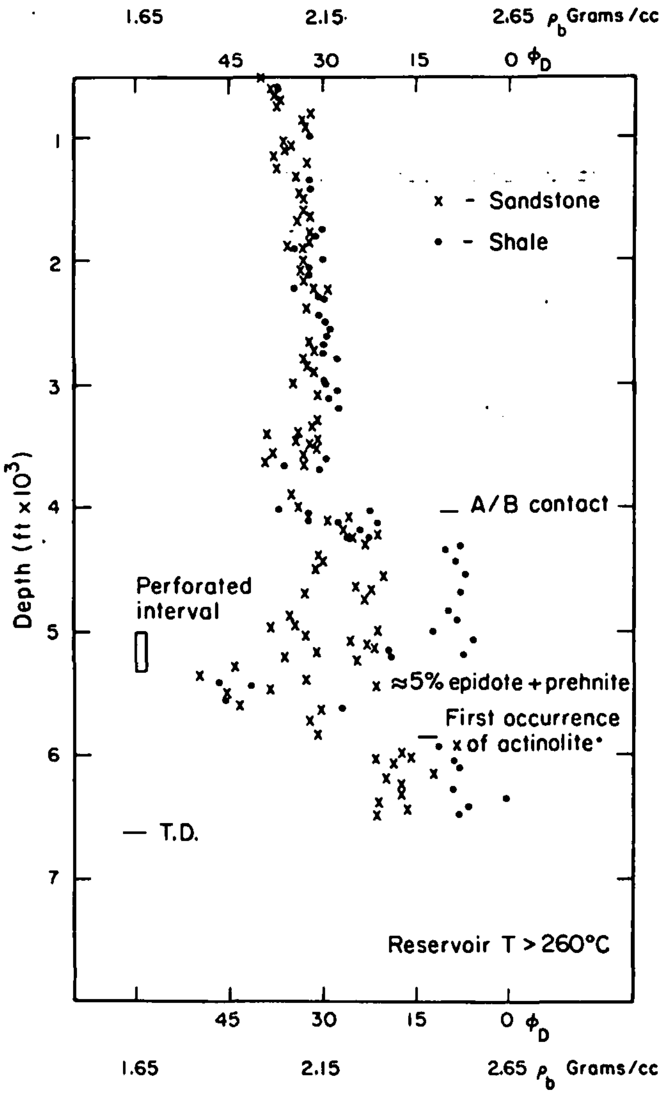
Figure 3. Map of the Cerro Prieto geothermal field with a simplified fault system.

Although only the dip-slip component of faulting is evident from well log correlations, there may also be significant lateral slip in some cases. Vertical offsets range up to several hundred meters. Only a few wells have penetrated the basement rocks and these indicate a general deepening of the sedimentary section from west to east, with fault blocks bounded by the northwesterly striking faults displaced progressively downward to the east. Seismic refraction surveys indicate that the depth to the basement east of Cerro Prieto fault is approximately 5 km. West of the fault the basement refractor (5700 m/sec) is at a depth of 1.5 to 3 km.

The stratigraphic section of Cerro Prieto is divided into three broad units: unconsolidated sediments (silts, clays, sands) that extend from the surface to a depth of approximately 800 m; underlying consolidated sandstones and shales; and granodioritic basement rocks. Within the consolidated sedimentary rocks, there are two principal reservoirs: an upper reservoir from which most of the present production from the field is derived, and a hotter, deeper reservoir where temperatures reach 350°C. The two zones are separated in some locations by approximately 50 m of relatively impermeable shale. From well log analyses, Lyons and van de Kamp (1980) have determined five classes of lithofacies, each with a characteristic lithology and apparent thickness. Present production is limited to the thicker, sandier classes representative of a delta plain depositional environment.

Of major importance to the regional stratigraphy was the discovery, in well cuttings from the Cerro Prieto geothermal field, of a mid-Tertiary foraminifer approximately 15 million years old — *Cassigerinella chipolenis* — a planktonic marine microfossil (Fig. 4). If the presence of this foraminifer is confirmed by more extensive sampling, the current conceptualization of the opening of the Gulf of California and the Pacific coast mid-Tertiary history will need to be revised.

Within the deltaic sedimentary rocks of the reservoir there are diverse porosities and permeabilities. Much of the matrix porosity at depth (as in well M-103 at 5200 ft, Fig. 5) is due to alteration by hot fluids. Scanning electron microphotographs (Fig. 6) vividly document the clogging of openings between sand grains by hydrothermally precipitated clays.



*Mineral data after Elders and others (in press)

Figure 5. Plot of porosity and density versus depth for well M-103 as determined from well logs and cuttings. The high porosity in the perforated interval represents extensive secondary-matrix porosity.

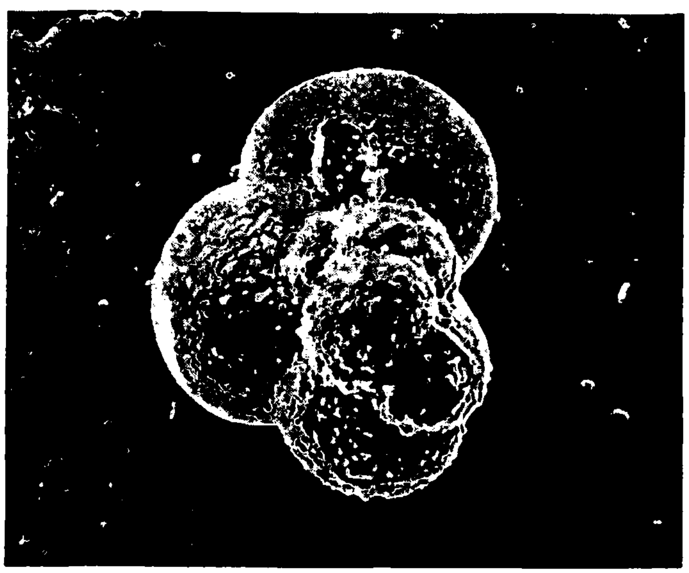


Figure 4. *Cassigerinella chipolensis*, a Mid-Tertiary planktonic microfossil found in Cerro Prieto geothermal well cuttings. Scanning electron microphotograph provided by J. L. Lamb, Exxon Production Research; actual diameter of the microfossil is 0.7 mm.

The geothermal reservoir is now believed to be recharaged by waters primarily from the east and northeast. The waters are partly of Colorado River origin and partly derived from sea water having chemical constituents concentrated by solar evaporation in coastal lagoons.

From petrographic and mineralogic analyses of well cuttings, four zones of alteration have been recognized by Elders et al. (1980). In order of increasing threshold temperature, these are (1) a diagenetic zone, (2) an illite-chlorite zone (> 150°C), (3) a calc-aluminum silicate zone (> 230°C), and (4) a biotite zone (> 325°C). Diagrams of depths to the first appearance of diagnostic alteration minerals (Fig. 7) illustrate the temperature distributions within the field. The configuration of the alteration-mineral horizons generally conforms to the dome-like pattern of relatively high density and high electrical resistivity associated with the producing field as indicated by surface geophysical surveys.

Fractures in the reservoir rocks often appear to be sealed by hydrothermal mineralization. Therefore, although fracture per-

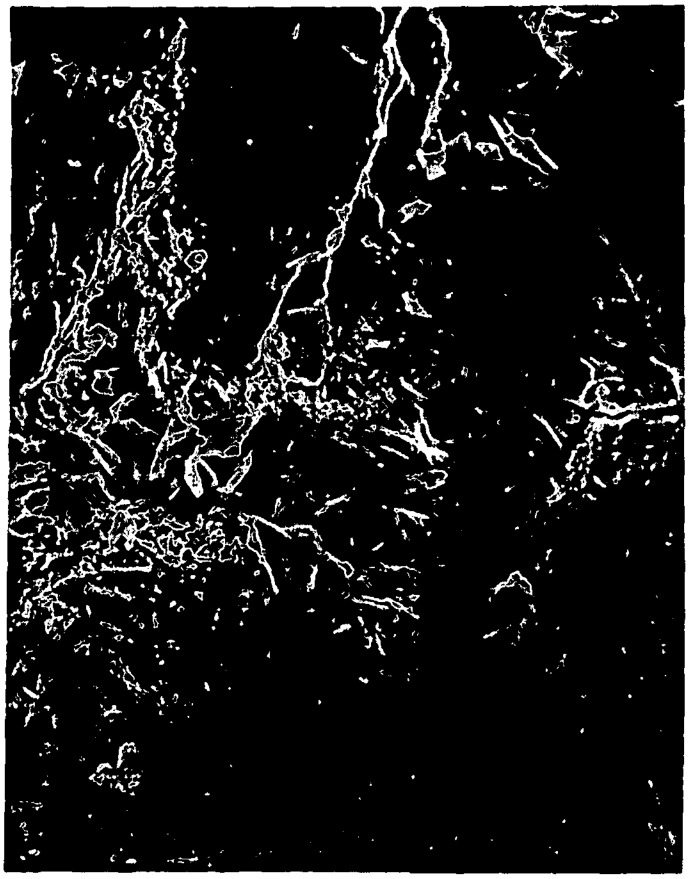


Figure 6. Scanning electron microphotograph of a core chip from well NL-1 at 2720 m below the surface; the field of view across the photograph is 40 μm (= 0.04 mm). This reservoir quartz sandstone lies within the 250°C epidote mineral horizon. Note the hydrothermally precipitated platy and needle-shaped clay particles clogging the opening between the sand grains, thus reducing permeability.

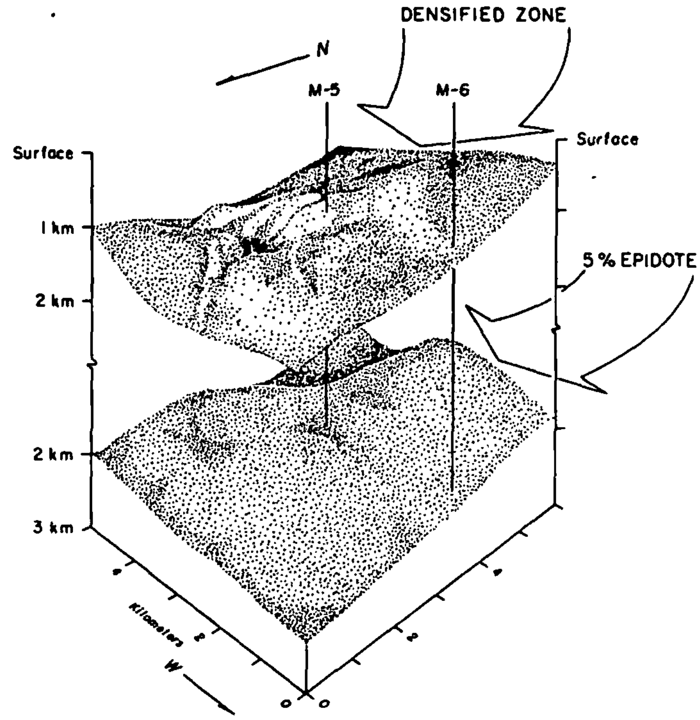


Figure 7. This three-dimensional perspective of the present Cerro Prieto geothermal field indicates an upper densified dome-like surface at approximately 1 km that serves as a low permeability barrier, partially capping the reservoir. Between the densified zone and the 5% epidote surface is the zone of secondary matrix porosity with its zone of variable permeability.

meability undoubtedly plays a role, the secondary matrix porosity due to the solution effects of the geothermal fluids in the sandstone is also a major factor in providing reservoir permeability.

The main geologic and economic significance of secondary matrix sandstone porosity is that it extends the depth range for effective sandstone porosity 1 to 3 km below the depth limit for effective primary porosity. Generation and migration of both petroleum and geothermal water occurs mainly below the range of effective primary porosity. The migration and the accumulation sites of geofluids are thus commonly controlled by the distribution of secondary porosity. The distribution of secondary matrix porosity in a productive sandstone formation may not necessarily show a direct relationship with the original depositional layering or burial history and is difficult to predict. However, our detailed geological analyses at Cerro Prieto have met with success. An initial summary of these ideas is shown in Figure 8. This diagram will be refined as more geothermal fields come into operation (such as the Heber and Salton Sea fields north of Cerro Prieto).

Our recently acquired knowledge of cross-faulting, secondary matrix porosity, and altered permeability zones now permits more realistic numerical modeling of the Cerro Prieto field. This will enhance our scientific contribution to the maximization of the energy available from geothermal reservoirs.

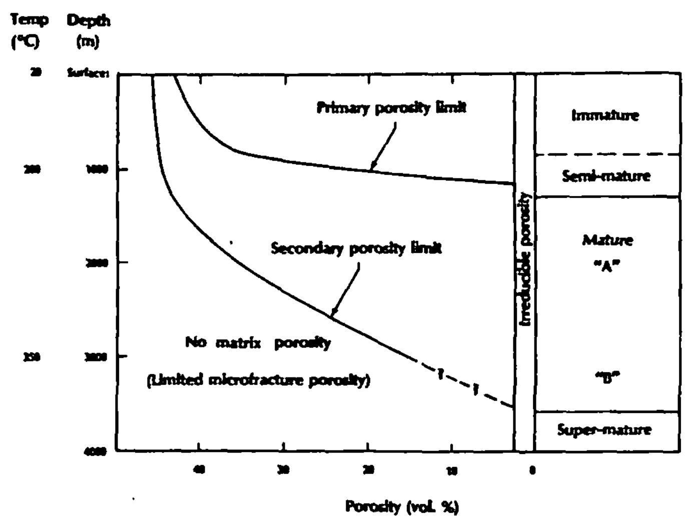


Figure 8. Accelerated porosity alteration in the deltaic quartz sandstone of the Cerro Prieto geothermal field: the immature stage represents mainly mechanical reduction of primary porosity; the semimature stage, mainly chemical reduction of primary porosity. Mature "A" is a zone of dominant carbonate mineral dissolution and mature "B" is of silicate mineral dissolution. Super mature is a metamorphic zone of very low matrix porosity, yet a key zone for microfracture porosity.

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INTERNATIONAL MEETING

The Second Italian/American Invitational Meeting on Geothermal Resource Assessment and Reservoir Engineering will be held October 20-22, 1980, at LBL's Building 50 Auditorium. The meeting is jointly sponsored by the U.S. Department of Energy and the Ente Nazeonale ter l'Energie Elettrica of Italy. Simultaneous English/Italian translations will be provided for the over 200 participants expected. A field trip to The Geysers is planned for Thursday, October 23, 1980.

Subsidence *(Continued from p. 1)*

slopes, and so on. To researchers working in the Earth Sciences Division at LBL, these problems are of practical as well as academic interest. The purpose of this paper is to focus attention *on the problem of land subsidence due to fluid withdrawal, and to* outline the physical basis on which scientists seek to understand it. A short outline of relevant ongoing research efforts at LBL is also presented.

Land Subsidence

Perhaps the simplest phenomenon to visualize is that fluids such as water or gas or oil occupy void spaces in rocks. If these fluids are withdrawn in large amounts, the reserves of these fluids in the subsurface are depleted. Such depletion is often called "mining." Mining of fluids naturally leads to a reduction in the volume of the void spaces, and hence, the bulk volume of the reservoir rocks that originally contained the fluids. As the rocks overlying the reservoir rocks (the overburden material) deform in order to accommodate the reservoir volume change, the reservoir deformation is transmitted to the land surface, giving rise to land subsidence and related horizontal earth movements. The actual subsidence observed at the earth surface, of course, depends on the total volume of the fluid mined, the rigidity of the reservoir rocks, the depth of burial of the reservoir, the rigidity of the overburden material, the thickness of the reservoir, the thickness of the overburden, and so on.

Commonly, "land subsidence" suggests merely the vertical downward movement or sinking of the land surface. However, vertical movements are often accompanied by related effects such as horizontal displacements, earth fissuring, formation of activated fault scarps and so on.

Fluids that occupy voids in soils and rocks exert pressure on the walls of the pores, tending to open up the pores from within. The pores, however, are simultaneously subject to external compressive forces due to the weight of the overburden and other geologic causes which tend to close the pores. At any given time, the actual size of the pores, usually expressed in terms of porosity, depends on the difference between the external compressive stresses and the fluid pressure. This difference is usually called effective stress. Obviously, as effective stress changes porosity must change. The rate at which porosity changes in response to effective stress is called rock compressibility. In general, the more compressible a rock is the greater is the subsidence potential.

The basic approach used by earth scientists in subsidence prediction is (1) to estimate the pore-pressure decline and hence the increase in the effective stress due to withdrawal of known amounts of fluid from underground, (2) to obtain reservoir volume change by multiplying effective stress change by compressibility, and (3) to estimate how the reservoir volume change will be manifested as subsidence at the land surface.

The rate at which land subsidence evolves in time at a given location depends on the rate at which a given quantity of the fluid can be extracted from the reservoir. This depends on the ability of the reservoir to transmit fluid in response to decline in fluid pressures. The ability to transmit fluid depends, in turn, on the reservoir permeability and thickness. Therefore, the magnitude of land subsidence and the manner in which it evolves in time at a given location is governed by the complex interactions among *permeability, reservoir thickness, compressibility, and rate of fluid* production.

Reservoir rocks are seldom uniform in physical properties. Some portions of the reservoir may be occupied by sandy materials