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GEOPHYSICS
THE CERRO PRIETO GEOTHERMAL FIELD. GEOPHYSICAL STUDIES CONDUCTED

The Cerro Prieto geothermal field, which currently produces 180 megawatts, is one of the largest fields in the world. Between 1973, when initial production began, and 1981, it generated approximately 5 million megawatt-hours of electricity, which represents a savings of 9 million barrels of oil. It is expected to produce 620 megawatts in 1984.

The Comisión Federal de Electricidad (CFE) has conducted surface geophysical studies and drilled wells in the Cerro Prieto field and the Mexicali Valley since 1962. The initial studies consisted of seismic refraction and gravity surveys of the area of the geothermal field. Since then, several geophysical techniques have been applied, including resistivity, magnetometry, magnetotellurics, self potential and seismic reflection surveys, in order to delineate the reservoir boundaries and characteristics, the depths of the basement, the contact of unconsolidated sediments with those of greater consolidation and the general form of the subsoil structures. With the results obtained, it has now been found that the most practical methods for exploring this region are seismic reflection and refraction, gravity surveys, magnetometry, and resistivity.

From 1978 to 1981, the CFE conducted gravity surveys and magnetometric studies in the Mexicali Valley and Altar Desert at a rate of 3,500 km^2 per year and completed approximately 400 linear km using seismic reflection and refraction. The seismological profiles were programmed to cross through the main structures and go over certain gravity anomalies using the GEOCOR II system of 256 traces.

A synthesis of the geophysical studies conducted is presented in this paper.

INTRODUCTION

With the experience acquired over 15 years of detailed investigations, which led to the construction of the Cerro Prieto geothermal power plant with a capacity of 180,000 kilowatts, positive results made the Comisión Federal de Electricidad decide to develop an accelerated program to construct two new geothermal plants in Cerro Prieto, which would provide a totall installed capacity of 620,000 KW by 1984.

At the same time, different geological, geophysical and geochemical exploration programs have been carried out in the Mexicali Valley and the Altar Desert, aimed chiefly at estimating the potential of some areas with thermal anomalies. If results are positive and steam is found there, it is estimated that there will be sufficient steam, taking into account the reserves that have already been verified, to reach an installed capacity greater than 1,000 MW for generating electric power in the region.

The geophysical methods that have been applied to study the Cerro Prieto geothermal field and their results are discussed in this paper in order to make such experience available to the Mexicali Valley, the Altar Desert and other geologically similar places in the search for new areas with potential for geothermal development (Table 1).

Background for this study is provided by the information obtained from the wells drilled to date and it is correlated with all the current geological, geophysical and geochemical information.

GEOLOGICAL PREMISES

Although a great deal has been published on the geology of the Cerro Prieto field and its surrounding area, would seem useful to summarize such information in this report in order to incorporate it into an understanding of the results obtained through the geophysical methods applied in the zone.

The Mexicali Valley, in which the Cerro Prieto geothermal field is located, forms part of a basin with very thick sediment (7,000 m) called the Salton Trough, which is in the physicographic province of the Gulf of California. Topographically, it is a flat surface and the only elevated point is the Cerro Prieto volcano, which is 225 m above sea level. It is part of the Delta region of the Colorado River whose meandering courses have accumulated sediments since the Tertiary Era with intercalations of other sediments deposited by the invasion and withdrawal of sea waters. Such deposits, which are constituted predominantly of rocks of deltaic, peidmont and marine origin, have been divided into two lithologic units:

CHRONOLOGICAL SUMMARY OF GEOPHYSICAL TECHNIQUES USED IN THE CERRO PRIETO GEOTHERMAL FIELD UP TO 1982

YEAR	METHOD USED	DEVELOPMENT
1962	Seismic refraction.	Four profiles in the Cerro Prieto area.
1963	Gravity survey.	340 gravity stations.
1972	Aeromagnetic survey.	Cerro Prieto area.
1972	Electric resistivity.	Vertical electric probing with Schlumberger and dipole-dipole methods.
1973	Aeromagnetic survey.	Delta of the Colorado River area.
1973	Electric resistivity.	Vertical electric probing with Schlumberger and dipole-dipole methods.
1974	" "	" " " "
1975	" "	" " " total of 133.
1977	Microseismicity study.	Five stations installed in the Cerro Prieto field.
1977	Self potential.	Two lines over the Cerro Prieto field.
1977	Electric resistivity.	Vertical electric probing with Schlumberger's method.
1978	" "	" " " total of 114.
1978	Gravity and magnetic surveys.	Five lines over the Cerro Prieto area.
1978	Self potential.	All along the same five lines mentioned above.
1978	Seismic reflection.	180 km of profiles in the Cerro Prieto area.
1978	Precision gravity.	60 observation stations in the Cerro Prieto field.
1979	Electric resistivity and self potential.	110 Schlumberger probings, 6 self potential lines.
1979	Gravity and magnetic surveys.	Reobservation from previous gravity survey stations.
1980	Seismic reflection and refraction.	220 km of profiles.
1980	Magnetotellurics.	10 probings.
1980	Gravity and magnetic measurements.	Details of the south and northwest of Cerro Prieto (Rifto and the western part of Mexicali).
1980	Resistivity monitoring.	One line over the geothermal field, using dipole-dipole.
1981	Precision gravity.	Reuse of previous stations.
1981	Gravity and magnetic measurements.	East and southeast of Cerro Prieto (Aeropuerto-Algodones, San Luis R.C. and Altar Desert).

YEAR	METHOD USED	DEVELOPMENT
1981	Resistivity monitoring.	One line over the geothermal field using dipole-dipole.
1982	Gravity and magnetic	Northwest and southeast Cerro Prieto (Tulecheck, Ríto and the Altar Desert).
1982	Seismic reflection and refraction.	92 km to the northwest and southeast of Cerro Prieto (Tulecheck and Ríto).

TABLE 1

unconsolidated sediments (Unit A) and consolidated sediments (Unit B), the later being where overheated aquifers may exist. The consolidated rocks (shales and sandstone), in turn, lie unevenly over an Upper Cretaceous granite and metasedimentary basement (Fig. 2).

Hydrogeologically, the aquifers of the Valley are the infiltrations of the Colorado River and are located, for the most part, to the east within a wide belt whose central axis lies along the current crest of the Delta to the east of the Cerro Prieto volcano, while to the north and northwest of the belt, salt water aquifers may be found, which are vestiges of former invasions of the sea that formed the confined Salton Sea with its hypersaline water in the Imperial Valley. To the south of the volcano and, in general, to the southwest of the Delta crest, there are saline aquifers that come from the Gulf of California and enter into the permeable sediments and into fresh water aquifers located on the banks of the Colorado River and its former branches.

Tectonically, the Valley is characterized by a series of grabens and horsts produced by zones of crustal openings associated with the southeast-northwest movements of the Cerro Prieto, Imperial and San Andrés Faults. These faults and those of the area in general are part of the San Andrés system that penetrates into the Gulf of California as a retinue of large faults arranged en-echelon, which, in turn, constitute an overall network of volcanic chains, fissures in the ocean floor and deep ocean troughs, all of which mark the boundaries between the broad shifting Pacific and American tectonic plate (Fig. 3). Consequently, this zone has been characterized by vertical tectonics of geometrical configurations characteristic of transform basins of great seismic activity and by earthquakes close to the surface, where the earth's crust has become thinner and closer to the mantle, thus creating some areas of high thermal flow (Fig. 4).

Since the Gulf of California is located in the zone where the plates are pulling apart, their movement has caused stresses in the crust and mantle, resulting in the shifting of large blocks, which have formed troughs, such as the Wagner Trough that is connected to the Mexicali Valley through the Cerro Prieto Fault.

It should be pointed out that the most important geological foundation for this work is based chiefly on an outline of openings in the crust and continental separation, the effects of which led to the formation of the Gulf of California. On the basis of regional profiles and data and arguments gathered, a geological model has been constructed, whose main feature is that during the Miocene-Pliocene epoch (?), the peninsula of Baja California originally formed part of a continental granite massif that, because of complex stresses in the crust of mantle, began to separate. As a consequence, fissuring, the shifting of large blocks, uncovering of the ocean floor and the penetration of magma took place during the separation process and continue to take place, the evidence of which has been widely published.

The local effects of this model is that a number of tectonic phenomena have occurred in the Imperial Valley and the Mexicali Valley, precisely in the northwestern part of the Gulf of California, as in the case of the San Andrés faults, including high seismicity in the zone, basement detachments along the sides of the Valleys to the southeast and northwest, transform faults with vertical and horizontal shifting, magmatic intrusions, volcanos and a variety of zones with high thermal flow, which give rise to geothermal environments. The presence of such high thermal flow areas led to explorations both in the Imperial and Mexicali Valleys and resulted in the discovery of eight geothermal regions in the Imperial Valley called Salton Sea, Heber, East Mesa, North Brawley, Glamis, Dunnes and Border, some of which have recently started to be exploited (Fig. 5).

Although the exploitation of the Mexicali Valley began in 1973 at the Cerro Prieto field, the most recent explorations have indicated that the field extends toward the east from its present location and four prospective areas were detected named Tulecheck, Riíto, Aeropuerto-Algodones and San Luis Río Colorado.

Analysis of the local geology of the Cerro Prieto field has led to an understanding that evidence for the Cerro Prieto Fault (San Jacinto), which runs from southeast to northeast, is to be found in different studies from the Gulf of California to the Cerro Prieto volcano and that, contrary to what was previously believed, it does not provide fluid, but rather serves as a boundary of the field (Fig. 6).

On the basis of geophysical and correlation studies of the wells, another fault called Morelia was identified in the northern section of the producing field. It runs from southwest to northeast and, in addition, has three fault zones called Delta, Pátzcuaro and Hidalgo. This system of faults, which lies obliquely to the regional tectonic pattern, is clear evidence of the en-echelon shifting characteristics of the transform faults in the Mexicali Valley and suggests that the faults of the Volcano system, which lie in what has been considered the spreading center, may be principal conductors of heat and overheated fluids.

GEOPHYSICAL STUDIES CONDUCTED

Since 1960, when exploration was initiated in the Cerro Prieto geothermal zone with geological and geochemical surveys through which the first well with steam-water production was obtained, two additional wells, 450 m and 700 m deep, were drilled and encouraging temperatures were found, which led to the decision to conduct detailed geological, geophysical and geochemical studies, which began in 1962 with a seismic refraction project (Calderón, A., 1962), the results of which made the initial development of Cerro Prieto possible because of the sharp contrast in speeds observed in the subsoil layers (Fig. 7). Information from this study provided some sites for deep wells such as M-3, which penetrated into the granitic basement at a depth of 2,547 m with production between 700 and 900 m and temperature inversion below that depth. Later, well M-4 was sited 19 km northwest of M-3 in an attempt to cross an important fault detected in the study mentioned. A depth of 2,000 m was reached without recording any temperatures of interest. The following well was M-5, located 2.5 km to the southeast, where the bases were established for the future development of the field, because of its unprecedented and excellent characteristics of temperature, pressure and production.

The following geophysical work carried out in the Cerro Prieto field was a very local gravity survey in 1968 in which the areas of greater or lesser sedimentary fill around the field were detected. This work, correlated with the refraction data already obtained, created interest in drilling outside the production area and well M-53 and well M-51 were thus sited, which marked the beginning of another stage of possibilities for expanding Cerro Prieto.

In 1971, an aeromagnetic study of the entire region of the Delta of the Colorado River was conducted (Summer J., 1971) in order to detect whether there was any relation between the structure and the lithology of the basement and the source of geothermal heat. Subsequently, a theory on the origin of the heat with a dispersion center was set forth. The information supplied by this study was consistent with a series of intrasedimentary igneous intrusions, some of which are located next to the Cerro Prieto and San Andrés Faults, and with the morphology at the depth of a predominantly granite basement along the northeast, west and southwest edges of the Mexicali Valley.

From 1972 to 1975, both the Cerro Prieto field and the Mexicali Valley were studied with electric resistivity techniques using Schlumberger, dipole-dipole, and Wenner methods (García Durán S., 1975). The results showed a series of minimum resistivity readings associated with traces of the Cerro Prieto and Imperial Faults, which was of geothermal interest because of its possible relation with high temperature zones, as has occurred in the geothermal zones of The Geysers in California, in Broadlands, New Zealand and in several geothermal fields in Italy (Fig. 9). Although, at the beginning, it was believed that liquid-dominated geothermal reservoirs could be identified by their low resistivity resulting from high temperatures, porosity and salinity and, even though this was true in volcanic areas, observations in the Mexicali Valley and information supplied from other studies showed that minimums were found in areas with the greatest salinity, evidence of previous marine incursions, and could only be associated with possibly high temperatures when the surface layer was resistive in comparison to deep layers and under certain circumstances. Moreover resistivity observed in the Cerro Prieto field was not well defined. Thus, this information proved to be of little importance at that time in the geothermal exploration of the Mexicali Valley.

On the basis of experience gained up to that time, in 1977, it was decided to continue exploration using the same techniques and to initiate efforts with gravity surveys and land magnetometry, without yet discarding resistivity. The only additional method used was self potential. The areas of greatest sedimentary thickness and the main structures that cross the Cerro Prieto field were confirmed and, with the new method, a dipolar anomaly was observed in the exploitation area (Fig. 10), which was attributed to the combination of fluid flows (electrokinetic effect) and to the scale of temperatures (thermoelectric effect), which had been observed in other fields such as East Mesa and Tulecheck (Corwin R., et al, 1979). In the gravity surveys, some models were made using Talwani's method and the sedimentary thickness could be quantified in general terms (Fig. 11).

In regard to resistivity, AB/2 was opened up to 5,000 m with Schlumberger's method and coverage of the area previously surveyed was expanded. In 1979, the CFE abandoned the method, although a good correlation between minimum resistivity and an anomalous temperature zone 35 km southeast of Cerro Prieto in the Riíto area had been found (Fig. 12).

In 1977, the Centro de Investigación Científica y Estudios Superiores de Ensenada (CICESE) was entrusted with a study of seismicity in the Mexicali Valley to obtain information on earthquakes and provide a structural interpretation of them. This information was proved to be important, since, apart from the data it provided on seismicity, tectonic patterns and regional stresses (Fig. 13), work is currently under way in the Cerro Prieto field and the Mexicali Valley on earthquake swarms and their aftershocks, as well as the attenuation of compressional waves ($Q\alpha$), cutting stress ($Q\beta$) and "coda" waves ($Q\gamma$) and the possible relation of the last waves to areas of geothermal activity.

In 1977, a technological agreement with the United States Department of Energy (DOE) was entered into with implications for work on geophysical methodology applied to obtain data regarding the changes that occur in the geothermal field due to exploitation of the reservoir.

Under the DOE, a technical group from the Lawrence Berkeley Laboratory (LBL) of the University of California has made repetitive measurements of resistivity from 1977 to date, using the dipole-dipole method and the most important results have served to improve the definition of the deep structure in the eastern part of the field (Fig. 14-A), since models indicate that a resistive body, which has been associated with the production area, is submerged toward the east at an angle of between 30° and 50° up to a depth of 2,000 m and that a narrow and steeply dipping conductive area lies immediately to the east of the resistive body and could be associated with a recharging or faulting zone (Wilt, M., 1979) in spite of the salinity (up to 30,000 ppm) and the temperature of the aquifers of the field, which could mask the electric properties of the rocks and the variety of the numerical solutions in the model applied.

Application of the magnetotelluric method (MT) was programmed in 1978 in order to supplement the resistivity survey already conducted. An advantage of this method, which is a passive technique based on natural low frequency electromagnetic oscillations, is that it allows for greater depth in exploration, which, together with remote magnetic reference, makes results precise even in the presence of interference (Gamble, T., et al, 1978). LBL staff developed this method in order to obtain deep resistivity information on the field and to experiment with the MT method with remote reference in a noisy environment.

The preliminary results of this study (MT) show similarities to those obtained in the resistivity surveys with direct current (dipole-dipole, Schlumberger). Although this MT method needs to improve information at depths obscured by saline layers of low resistivity near the surface (<1,000 m), it provided a model to verify the consistency of the resistivity models based on other methods (Fig. 14-B). The greater saline concentration observed in the deep overheated aquifers, however, tended to discredit the geological interpretation of these magnificent MT field data. In conclusion, excellent information was obtained on deep resistivity that had not previously been clearly explained. There are a number of responses to the situation described above which, in view of the complexity of the geological structure, deltaic stratigraphy, salinity, temperatures and other inherent properties of the rocks, lead to the conclusion that resistivity methods, both DC and magnetotelluric, should be restricted to a qualitative application in the Cerro Prieto field.

Precision gravity studies also carried out by the LBL since 1978 have been programmed each year in order to observed differences in terms of microgals caused by possible changes in the reservoir that could be attributed to removal of mass, densification of permeable rocks, and the formation of gaseous phases due to a reduction in the pressure of the reservoir. The data on Bouguer anomalies could also be taken advantage of (Chase, D.S., and others, 1978).

Although it is premature to mention the results of this last project, the first data obtained in the yearly repetition of readings at the gravity stations to indicate differences associated with land subsidence that are consistent with a precision leveling study, which was also repeated yearly at the same gravity stations (De la Peña, A., 1981). It has been observed that the rate of exploitation at different geothermal fields causes slight land subsidence and in the Cerro Prieto field and the Mexicali Valley, subsidence is also still taking place, but it has been occurring since remote geological times. This situation could thus cause some ambiguity in results, bearing in mind the original objective, although correcting for the effect of subsidence, in accordance with the interpretation of the results, seems to indicate that the fluids extracted from the reservoir are being completely replaced by fresher waters that enter the geothermal reservoir from the sides and from above (Zelwer, R. and others, 1982).

Seismic monitoring carried out by the LBL group from 1977 to date in the Cerro Prieto region was aimed at investigating the seismicity and propagation characteristics of the seismic waves in the Cerro Prieto field. The main purpose of the study was to determine, in relation to regional values, the level and nature of microseismicity activity in the area and the speed and attenuation of P and S waves in the production zone (Major, E., 1979). The first results indicate structural complexity associated with the Cerro Prieto field itself; moreover, in comparison with the surrounding areas, microseismic activity is lower in the production zone even with the high levels of cultural noise that have limited the quantity of useful information on speed and attentuation. Nonetheless, the small amount of data gathered to date suggests anomalies in the speed and attenuation of P waves in the production zone and the V_p/V_s values are higher and imply shallow hypocentral distances perhaps caused by the saturation of fluids.

Microseismic activity in the Cerro Prieto field has been studied both by the LBL and CICESE. Although the approaches of the groups have differed in some factors related to interpretation and dimensions of the monitoring zone, both studies may be considered complementary.

The Cerro Prieto field has been an exciting experimental site for diversifying geothermal exploration methodology. The techniques applied have been used in an effort to delineate the configurations of the contact of unconsolidated sediments (Unit A) with those of greater consolidation in which overheated aquifers are found (Unit B); and to define the subsoil structures, to map the basment (Unit C) and to determine the configuration of the reservoir boundaries and characteristics.

Lithologic Units A, B and C in this region show acceptable contrast in the density and speed of acoustic wave propogation and of magnetic susceptibility between B and C, in spite of the great structural complexity. Although there is no well-defined contrast as a pattern in the electric properties of the units, when correlating the information on wells, including aquifer-exploiting wells, it is possible to attempt to distinguish the nature of the subsoil fluids (salt or fresh water) by some structural traits and, under certain circumstances, these properties may be affected by temperature itself.

Bearing in mind the above factors, experience has now shown that the most useful short-term geophysical techniques for targeting exploratory wells have been seismic reflection and refraction, gravity surveys, magnetometry and resistivity.

Gravity survey studies in the Imperial Valley (Biehler, Shawn, 1964) demonstrated that Bouguer anomalies not only suggested the form and regional tendency of the sediment thickness and main structures that cross the area, but in some cases, the maximum values also showed a close correlation with high temperature zones. This phenomenon was explained as being due to densification in the sediments produced by the high temperatures of waters in the formation, which in a convective process, deposit silica and carbonates in solution in the intergranular porosities of the sediments, thus increasing the density of the sediments and consequently the gravitational field. This interpretation, combined with magnetometry and resistivity studies, resulted in the discovery of 8 geothermal regions called Salton Sea, Heber, East Mesa, North Brawley, East Brawley, Glamis, Dunes and Border, each located within an area of maximum gravity measurements, while only the Salton Sea showed surface thermal evidence (Fig. 15).

The use of magnetometry was focused on attempting to differentiate the origin of gravity anomalies, since some of them did not represent the morphology of the basement and were thus sometimes of interest, especially when they were associated with minimum resistivity in the subsoil (Fig. 16).

In the case of the Mexicali Valley, which is in the same physiographic province, it seemed probable that results would be similar, since the Cerro Prieto field is located in an area with maximum gravity. Some other maximum gravity areas were studied with magnetometry because of their geological position and those that are located along the northwest and northeast edges of the valley (Figs. 17 and 18) have been interpreted as representing the morphology of the granite basement at a depth where the blocks have shifted vertically toward the center of the depression as a consequence of great tectonic stresses that predominate the region. In some of the maximum gravity areas toward the center of the valley near large faults, gradient wells have been drilled and show thermal potential, which, together with other data, led to seismic reflection and refraction studies directed toward determining the depth and profile of the contact (UA-UB), the geological structure and the thickness and speeds of the sediments.

Between 1978 and 1981, the CFE conducted 3,500 km^2 of gravity and magnetometry surveys a year and completely approximately 400 linear km of reflection and refraction surveys in which the seismic lines were programmed perpendicularly to the regional structures and an effort was made to make them cross the gravity anomalies in which thermal activity had been confirmed. In the sections obtained to date, the GEOCOR II system was used with long stretches of 256 traces and short detection patterns with a maximum of 80' per trace, using a total of 1,024 detectors per stretch for a Common Reflection Point (CRP) arrangement, with which it is possible to obtain the maximum clarity in the refracted and reflected waves, while at the same time, reflection and refraction information is obtained with a different process in each case (Fig. 19).

These last geophysical techniques have already been integrated and have made it possible to quantify the thickness and morphology of the strata and have provided detailed knowledge of the structures that cross the field (Fig. 6). With this information correlated with that from the wells, it was possible to verify that the Cerro Prieto field extends eastwardly from its present location through a maximum gravity area in the form of a dome and it has been established that Unit C (UC) to the west of the plant is composed of a granite basement and Upper Cretaceous metasedimentary material with speeds that vary from 5,000 to 5,700 m/sec, while to the east, the same range of speeds is found, although sometimes greater, and there is an abrupt fall observed at a much greater depth (5,000 m).

Unit B (UB) lies unevenly distributed over Unit C and consists of a sequence of Tertiary consolidated sedimentary deposits and, in some permeable zones, overheated aquifers are found. The thickness of Unit B, which has seismic speeds that vary from 3,100 m/sec to 4,300 m/sec, has been calculated at approximately 2,000 to 2,500-m and it has been observed that the highest seismic speeds are found in areas with a low degree of metamorphism.

Unit A is an uneven sequence of Quaternary continental sediments whose compactness varies from unconsolidated to semiconsolidated and has a variable thickness of ± 2,500 m and speeds from 1,750 to 2,750 m/sec.

It is important to mention that the main objective of the seismological studies using the GEOCOR II system was to obtain reflection and refraction information on the behavior and characteristics of lithologic units A, B and C. In addition to such information, it was observed that the information gathered in the production zone was weaker (Figs. 21 and 22), although a good group of reflectors was used. This phenomenon was also observed at the East Mesa geothermal field (Howard J., et al, 1978) and was attributed to dense sediments, highly altered and cemented together, that have been subjected to alteration processes through temperature, since reflections weaken when the contrast between lutite and sandstone speeds diminishes, and such processes contribute to porosity, permeability and the existing degree of fracturing which cause the spreading of seismic energy. A good correlation with maximum gravity measurements was also found.

This phenomenon was not only found in the production zone of Cerro Prieto, but also in the dome-shaped area of maximum gravity that lies to the east of the field.

Although it is premature to indicate if this phenomenon found in what has been called the Zone of Attenuated Reflection (ZAR) actually fits the description in the previous paragraph the form and conditions observed make it comparable to the observations in East Mesa and may indicate that the Cerro Prieto ZAR has dense, porous and permeable rocks and high temperatures that cause attenuation in the reflections and could be a geothermal reservoir.

Finally, the use of these exploration methods and their correlation with the geology and some evidence of geothermal activity outside the Cerro Prieto field has now led to the detection of four potential geothermal regions called Tulecheck, Riíto, Aeropuerto-Algodones and San Luis Río Colorado and deep exploratory wells are being drilled in the first two regions.

CONCLUSIONS

The geological framework for this work has restricted the geophysical methods for exploring the Cerro Prieto field in a practical manner to those that have responded well to changes in density, magnetic susceptibility and the speed of propagating acoustic waves at depth, specially gravity surveys, magnetometry and seismic reflection and refraction, since the methods that record responses caused by changes in the electric properties of rocks, such as the D.C. and magnetotelluric methods, have not given clear results because of saline conditions in the area. Nonetheless, such methods could be used in future exploration programs in the Mexicali Valley when there is no conductive surface layer that would cause ambiguity in the geological and geothermal data if they are interpreted in isolation from other data. Some form of methods could also be used in qualitative studies related to gaining knowledge of areas with greater or lesser salinity both at the surface and underground.

Seismic monitoring and precision gravity methods in the long term will require interspersed experimental observation studies focused on analyzing the consequences of the rate of reservoir exploitation.

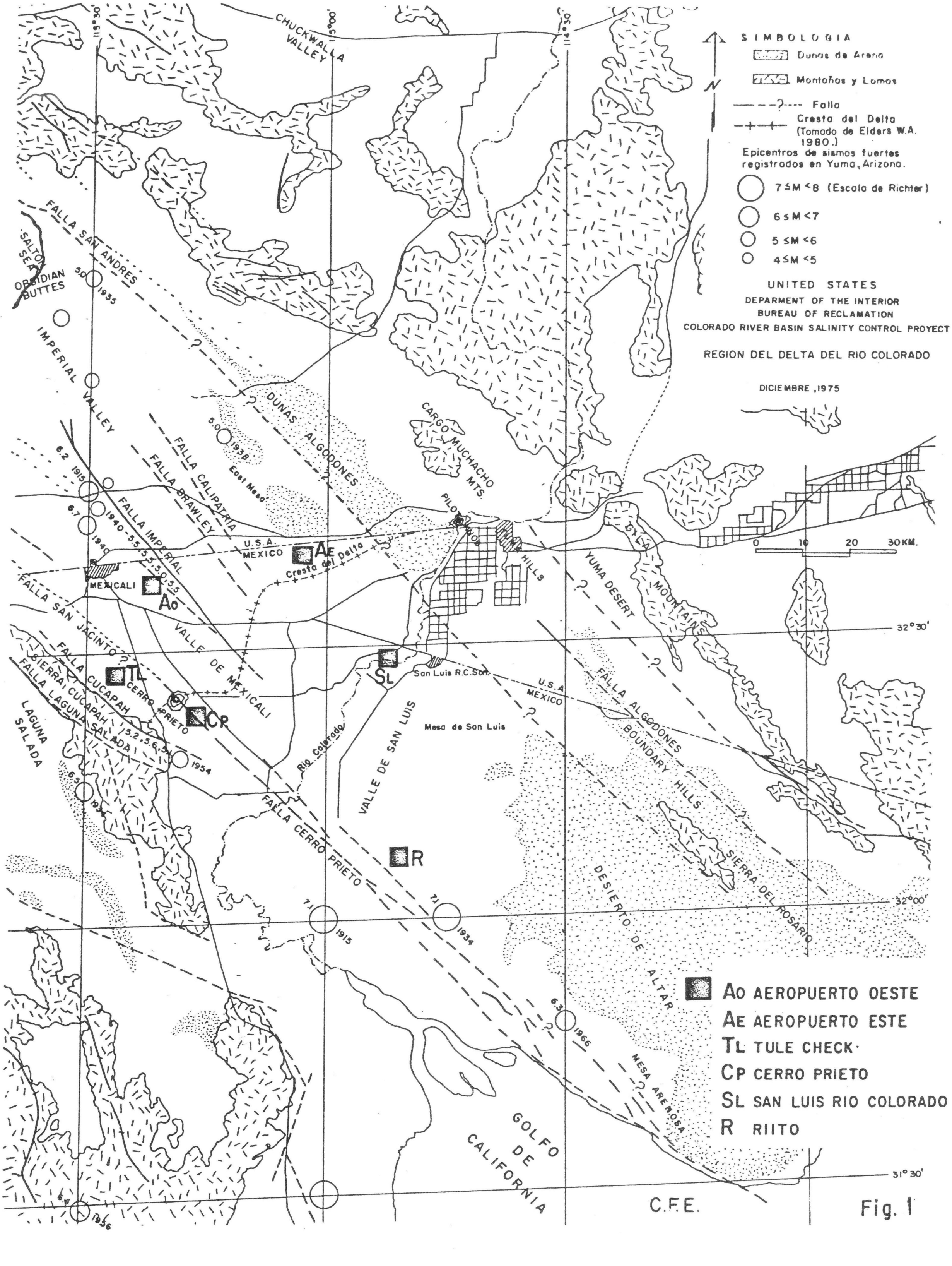
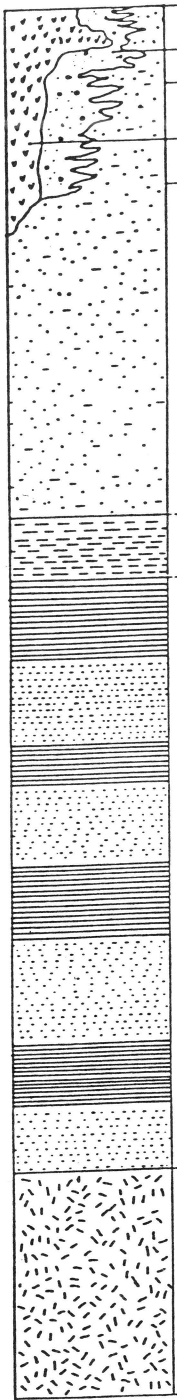

SIMBOLOGIA
Dunas de Arena
Montañas y Lomas
Falla
Cresta del Delta (Tomado de Elders W.A. 1980.)
Epicentros de sismos fuertes registrados en Yuma, Arizona.
7≤M<8 (Escala de Richter)
6≤M<7
5≤M<6
4≤M<5
UNITED STATES
DEPARMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER BASIN SALINITY CONTROL PROYECT
REGION DEL DELTA DEL RIO COLORADO
DICIEMBRE ,1975
N
0
10
20
30 KM.
115°30'
115°00'
114°30'
32°30'
32°00'
31°30'
CHUCKWALLA VALLEY
SALTON SEA
OBSIDIAN BUTTES
FALLA SAN ANDRES
IMPERIAL VALLEY
DUNAS ALGODONES
CARGO MUCHACHO MTS.
PILOT KNOB
East Mesa
FALLA CALIPATRIA
FALLA BRAWLEY
FALLA IMPERIAL
U.S.A.
MEXICO
Cresta del Delta
MEXICALI
VALLE DE MEXICALI
FALLA SAN JACINTO
FALLA CUCAPAH
SIERRA CUCAPAH
FALLA LAGUNA SALADA
LAGUNA SALADA
CERRO PRIETO
San Luis R.C.Son.
Mesa de San Luis
VALLE DE SAN LUIS
Rio Colorado
FALLA CERRO PRIETO
HILLS
YUMA DESERT
GILA MOUNTAINS
FALLA ALGODONES
BOUNDARY HILLS
SIERRA DEL ROSARIO
DESIERTO DE ALTAR
MESA ARENOSA
GOLFO DE CALIFORNIA
5.0 1935
5.0 1938
6.2 1915
6.7 1940
1940-5.5,5.5,5.0,5.5
5.2,5.6,5.3
1954
6.5 1934
7.1 1915
7.1 1934
6.3 1966
6.5 1956
Ao
Ae
TL
Cp
SL
R
Ao AEROPUERTO OESTE
Ae AEROPUERTO ESTE
TL TULE CHECK
Cp CERRO PRIETO
SL SAN LUIS RIO COLORADO
R RIITO
C.F.E.

Fig. 1



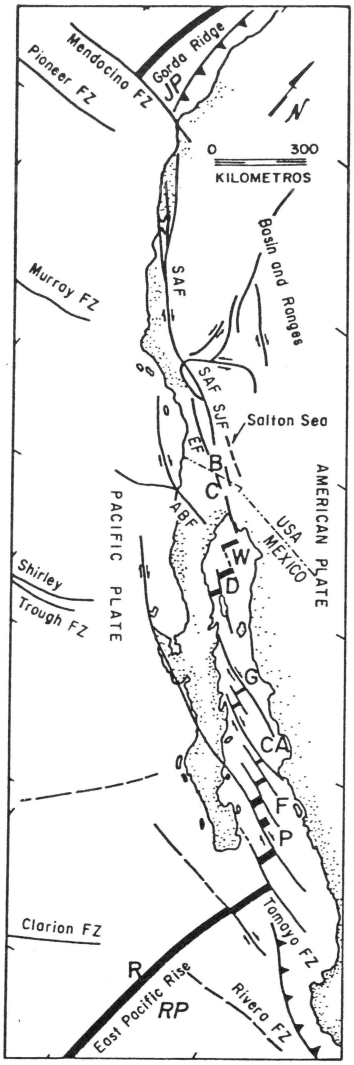
ABANICOS ALUVIALES DE LA SIERRA CUCAPA DE ORIGEN GRANITICO Y METASEDIMENTARIO	RECIENTE		CENOZOICA
ROCAS RIODACITICAS	PLEISTOCENO	CUATERNARIO	
DEPOSITOS NO CONSOLIDADOS CONSTITUIDOS POR ARCILLAS, ARENAS Y GRAVAS.			
ZONA DE TRANSICION, SEDIMENTOS SEMICONSOLIDADOS CONSTITUIDOS POR LODOLITAS CAFE CLARO.			
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 EN LA PARTE SUPERIOR POR CARBONATOS Y A PROFUNDIDAD POR SILICE.	TERCIARIO	NO DIFERENCIADO	
ROCAS IGNEAS Y METAMORFICAS CONSTITUIDAS POR GRANITO, GRANODIORITAS, GNEISSES Y ESQUISTOS.	CRETACICO	SUPERIOR	MESOZOICA

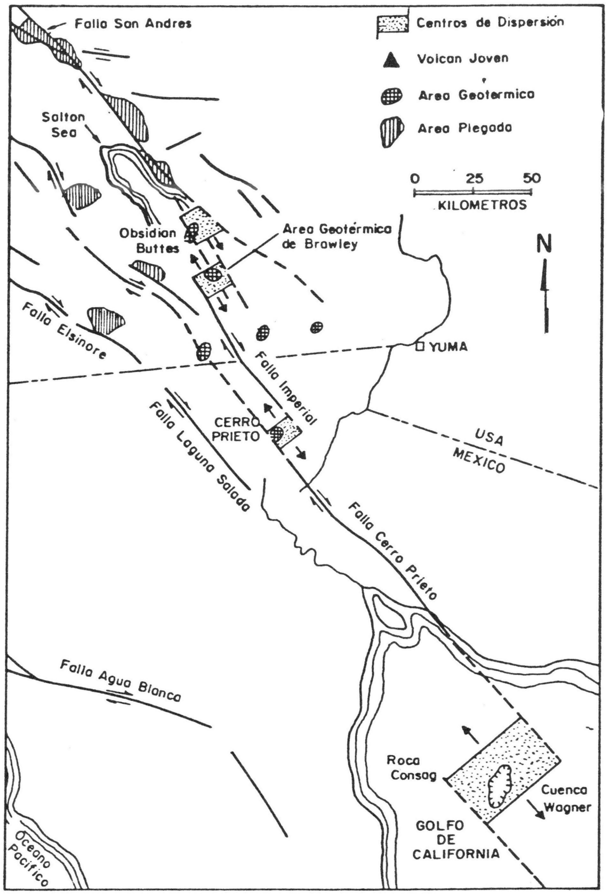
"COLUMNA ESTRATIGRAFICA
GENERALIZADA DEL AREA DE CERRO PRIETO."

"GENERALIZED STRATIGRAPHIC COLUMN OF THE CERRO PRIETO AREA."

Fig.2

C.F.E.





B) Modelo de fallas transformes y centros de dispersión propuestos por Elders, W y otros, 1972.

Transform fault and spreading center model proposed by Elders, et al (1972).

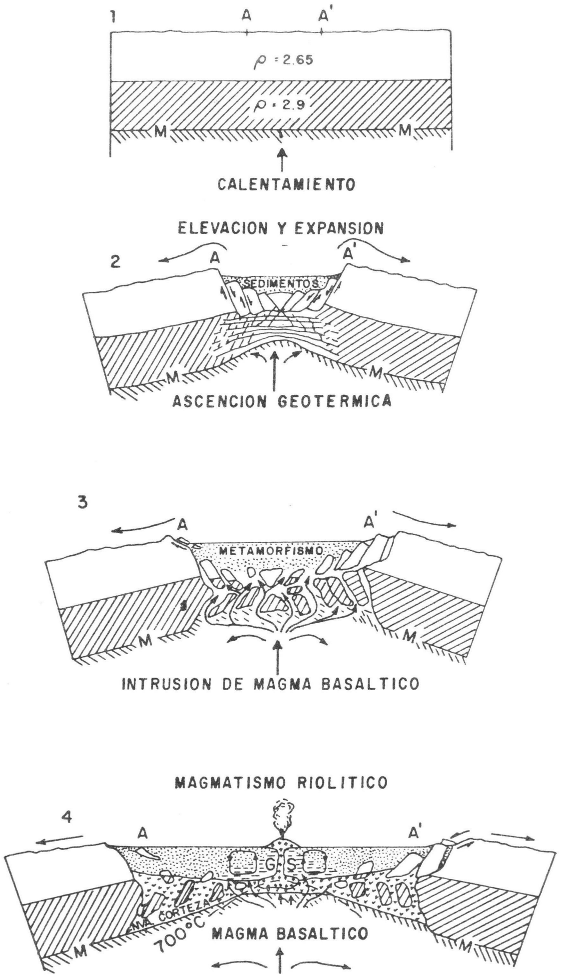
A) Ambiente tectónico general de la depresión Salton y el Golfo de California. La Costa del Pacífico en Norteamérica está dominada por sistema de fallas transformes y conecta a la triple unión Mendocino con la triple confluencia Rivera. Asimismo, muestra las zonas de distensión (pull apart basins) entre los segmentos de falla en Echelon en el Golfo de California.

Las zonas de fractura oceánica (FZ) y fallas continentales (F) son líneas negras continuas. Las que están en duda son representadas por líneas discontinuas.

Otras abreviaciones: SAF = Falla de San Andrés; EF = Falla Elsinore; SJF = Falla San Jacinto; ABF = Falla de Agua Blanca; JP = Placa de Juan de Fucca; RP = Placa Rivera; W = Cuenca Wagner; D = Cuenca Delfín; G = Cuenca de Guaymas; CA = Cuenca Carmen; F = Cuenca Farallón; P = Cuenca Pescadero; Volcán Holeocénico; B = Salton Buttes; C = Cerro Prieto y R = Revillagigedo (Tomado de Elders y otros, 1972, Lawver y Williams, 1979 y Dickinson y Snyder, 1979).

A) Gross tectonic environment of the Salton Trough. The Pacific Coast of North America is dominated by transform fault systems, which connect the Mendocino triple junction to the River triple junction. Also shown are pull-apart basins between en echelon fault segments in the Gulf of California. Ocean fracture zones (FZ) and continental faults (F) are solid black lines, dashed where uncertain. Other abbreviations: SAF = San Andreas Fault; EF = Elsinore Fault; SJF = San Jacinto Fault; ABF = Agua Blanca Fault; JP = Juan de Fucca Plate; RP = Rivera Plate; W = Wagner Basin; D = Delfin Basin; G = Guaymas Basin; CA = Carmen Basin; F = Farallon Basin; P = Pescadero Basin; Holocene volcanoes; B = Salton Buttes; C = Cerro Prieto and R = Revillagigedo. (From Elders, et al., 1972; Lawver and Williams, 1979, and Dickinson and Snyder, 1979).

Fig. No.3 C.F.E.



Modelo de agrietamiento y generación de magma. Las secciones son trazadas paralelas a las fallas de desplazamiento de rumbo. (Paso 1) Dos capas de la corteza descansan sobre una zona caliente en el manto. M, discontinuidad Moho; A A', puntos de referencia para movimientos posteriores. (Paso 2) Expansión hacia arriba y lateral una depresión se inicia y se llena parcialmente por sedimentos. (Paso 3) La depresión es invadida por magma basáltico, luego ocurre el metamorfismo de los sedimentos y el deslizamiento gravitacional de las paredes en declive. (Paso 4) Derretimiento del basamento y la expulsión del magma riolítico. Salmuera caliente ascendente cause metamorfismo de esquistos verdes a profundidades superficiales. (Tomado de Elders, 1972).

Model of rifting and magma generation. The sections are drawn parallel to strike-slip faults. Stage 1: Two layers of crust overlie a hot zone in the mantle. M. Moho discontinuity; A and A', reference points for later movements. Stage 2: Upward and lateral expansion; a trough is initiated and partly filled in by sediments. Stage 3: The widening trough is invaded by basaltic magma; metamorphism of the sediments and gravitational sliding of the tilted walls occur. Stage 4: Melting of the basement and Extrusion of rhyolitic magma. Ascending hot brines cause greenschist metamorphism (GS) at shallow depth. (From Elders, 1972).

Fig. No. 4   C.F.E.

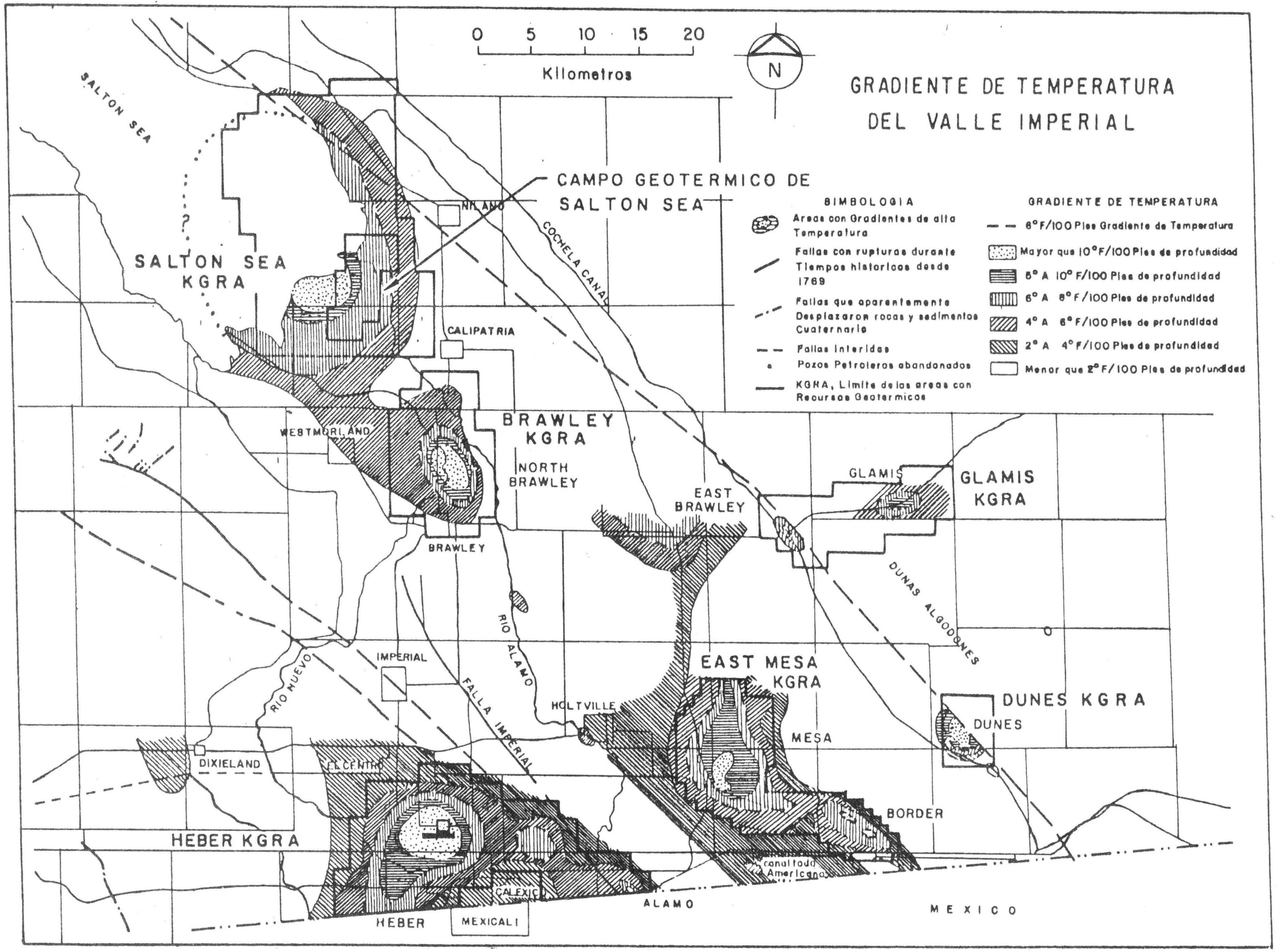
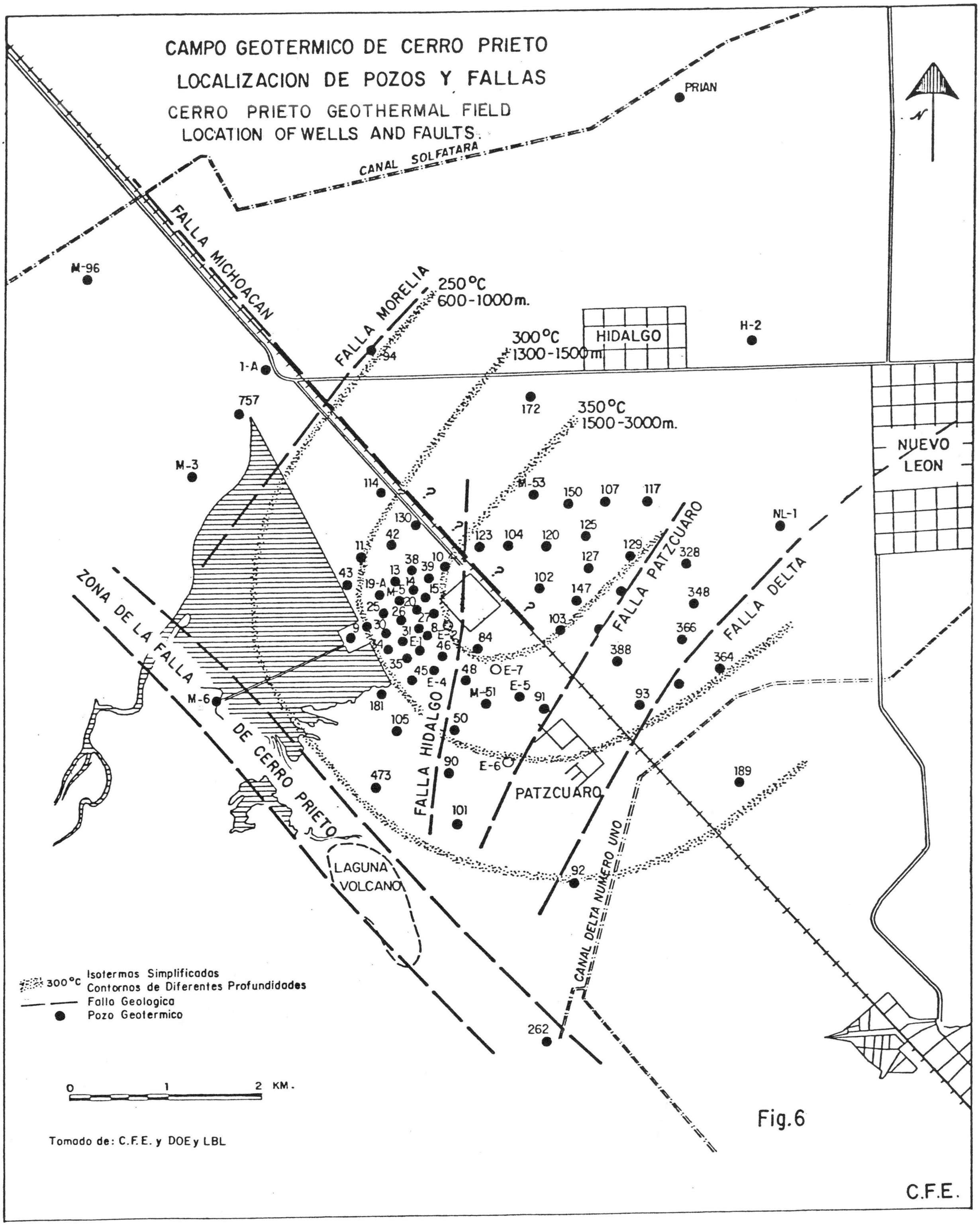
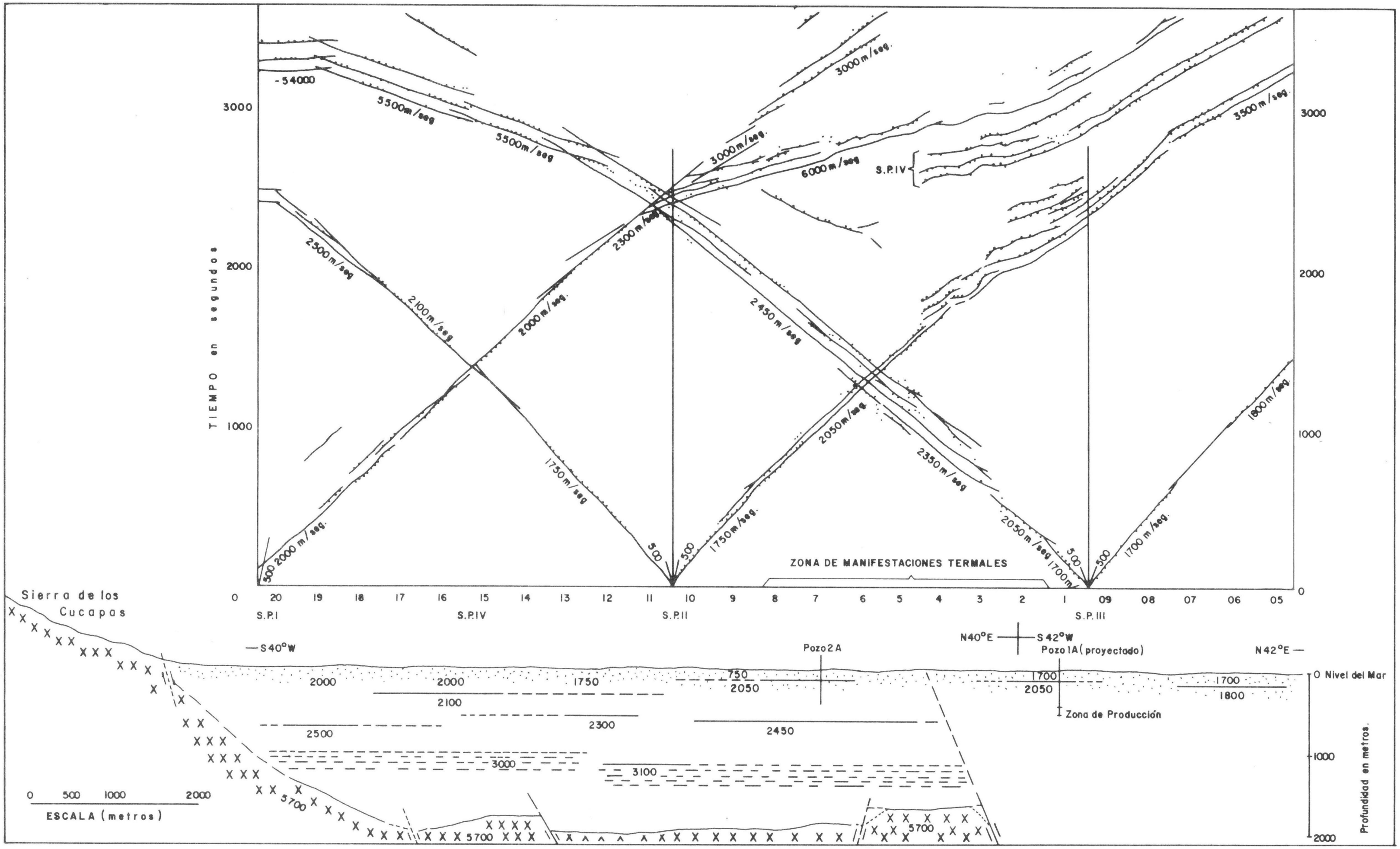


Fig. 5 Temperature Gradient map of the Imperial Valley, showing the geothermal resources of the Salton Sea area (taken from Combs, 1971)

Plano de Gradieme de Temperatura del Valle Imperial, mostrando las áreas con recursos Geotérmicos de Salton Sea (tomado de Jim Combs, 1971)

C. F. E.


CAMPO GEOTERMICO DE CERRO PRIETO
LOCALIZACION DE POZOS Y FALLAS
CERRO PRIETO GEOTHERMAL FIELD
LOCATION OF WELLS AND FAULTS.
CANAL SOLFATARA
PRIAN
FALLA MICHOACAN
FALLA MORELIA
250 °C
600-1000m.
300 °C
1300-1500m
350 °C
1500-3000m.
HIDALGO
H-2
NUEVO LEON
M-96
1-A
54
757
172
M-3
114
M-53
150
107
117
130
123
104
120
125
NL-1
42
129
328
11
38
10
39
127
43
13
14
102
19-A
M-5
15
147
348
25
20
26
27
103
9
30
31
8
E-2
E-1
366
34
46
84
388
35
45
48
E-7
364
E-4
M-51
E-5
91
93
M-6
181
105
50
E-6
189
473
90
101
92
262
FALLA HIDALGO
FALLA PATZCUARO
FALLA DELTA
PATZCUARO
ZONA DE LA FALLA DE CERRO PRIETO
LAGUNA VOLCANO
CANAL DELTA NUMERO UNO
?
300 °C Isotermas Simplificadas Contornos de Diferentes Profundidades
Falla Geologica
Pozo Geotermico
0
1
2 KM.
Tomado de: C.F.E. y DOE y LBL
Fig. 6
C.F.E.



VER FIG. 8 PARA LOCALIZACION

Fig. 7 Interpretación de los datos de Refracción de la Linea 1 (Calderon A., 1962, Geologos Consultores Asociados S. A.) C.F.E.

Interpretation of refraction data of line 1 (Calderon, A., 1962, Geologos Consultores Asociados S. A.)

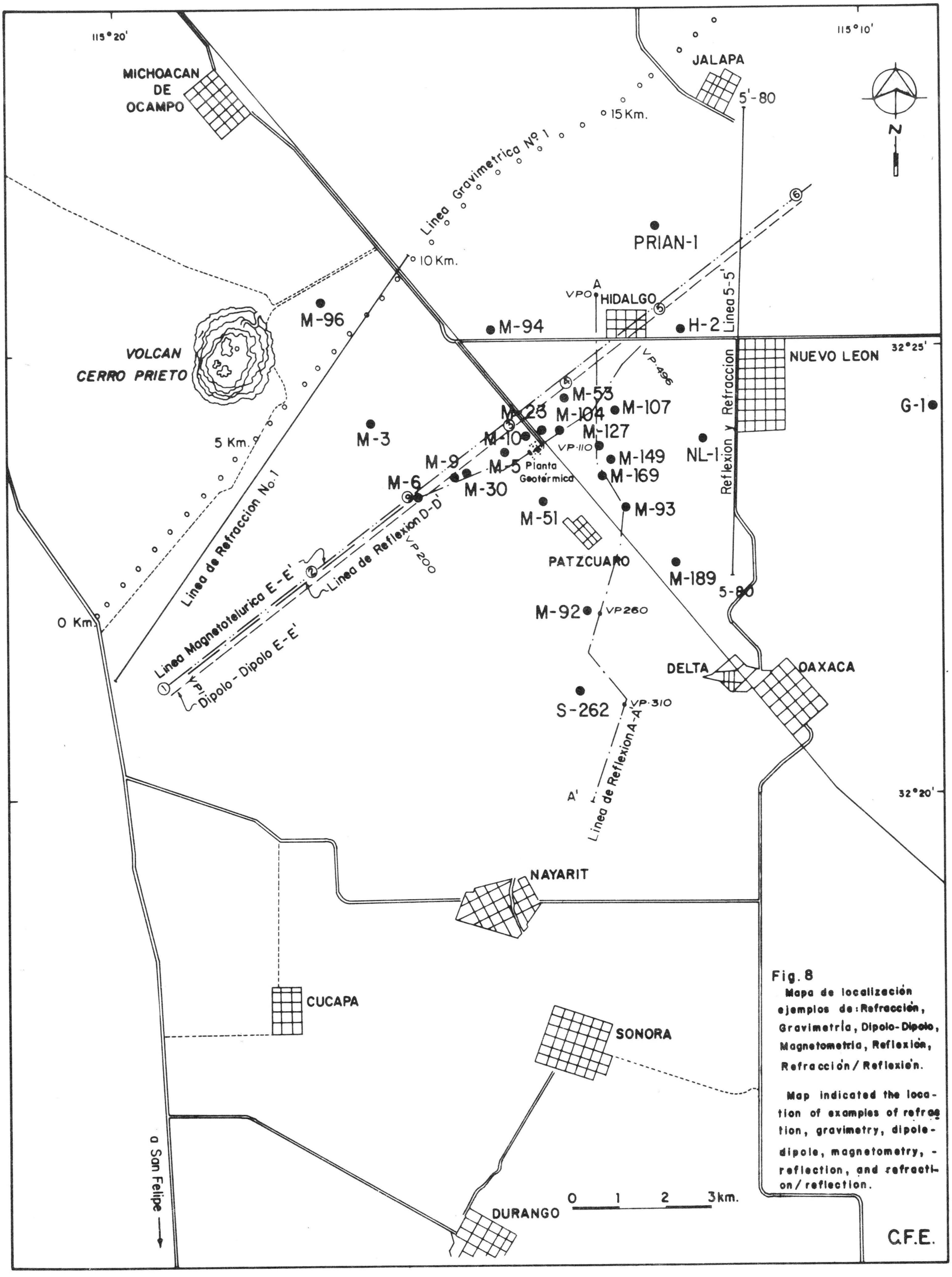
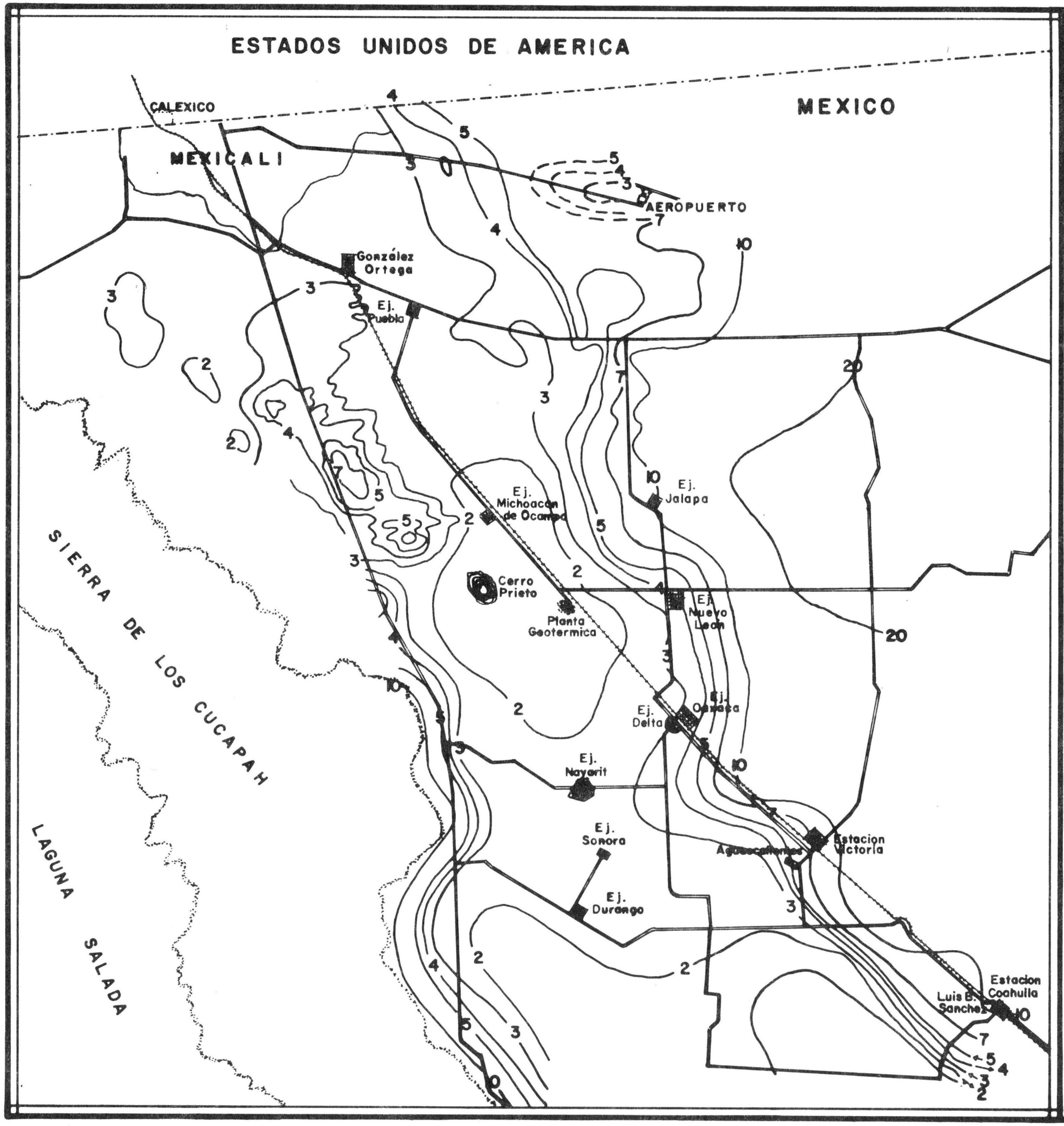


Fig. 8

Mapa de localización ejemplos de: Refracción, Gravimetría, Dipolo-Dipolo, Magnetometria, Reflexión, Refracción/Reflexión.

Map indicated the location of examples of refraction, gravimetry, dipole-dipole, magnetometry, - reflection, and refraction/reflection.



CURVAS DE ISO-RESISTIVIDAD DE LA PARTE NW DEL VALLE DE MEXICALI

ISORESISTIVITY CURVES IN THE NW PART OF THE MEXICALI VALLEY.

CURVAS DE ISORESISTIVIDAD APARENTE EN OHM-METRO. CONFIGURACION REALIZADA POR MEDIO DE MEDICIONES EN PERFIL A PROFUNDIDAD CONSTANTE EMPLEANDO EL DISPOSITIVO SCHLUMBERGER. DISTANCIA SEMIELECTRODICA (AB/2) = 500 m.

Apparent isoresistivity curves in ohms-m, prepared through profile measurements at a constant depth using Schlumberger's device. Semielectrode distance (AB/2) = 500 m.

Nota: CONFIGURACION TOMADA DE;

Ing. SALVADOR GARCIA DURAN

(1975)

FIG.9

C.F.E.

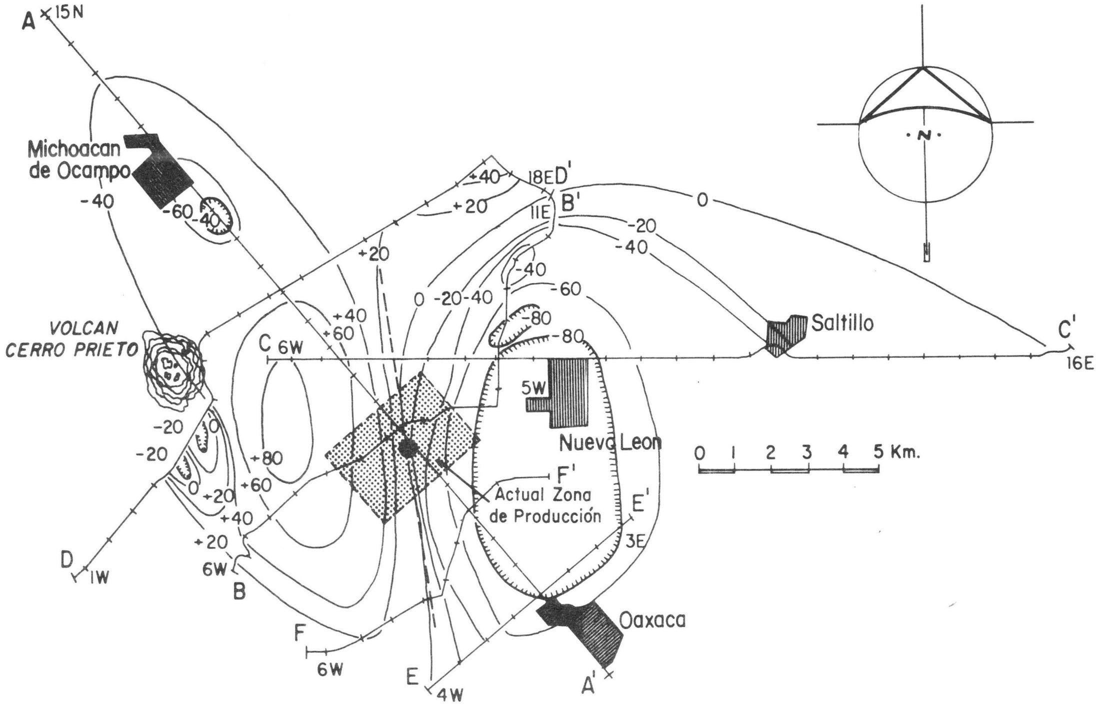
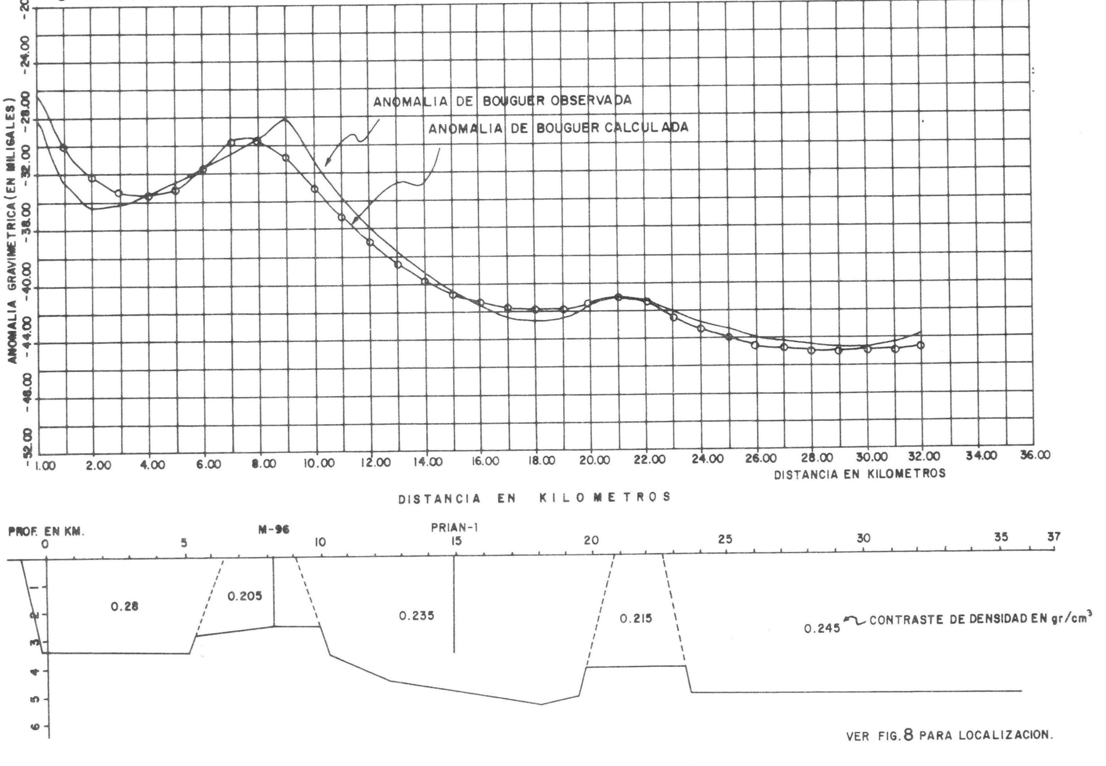


Fig. 10 CURVAS DE POTENCIAL ESPONTANEO EN EL AREA DE CERRO PRIETO. EL INTERVALO DE CONTORNO ES 10 MV. LA LINEA DISCONTINUA REPRESENTA LA TRAZA DEL PLANO FUENTE INFERIDO DEL POTENCIAL ESPONTANEO. LAS LINEAS A-A' HASTA LA F-F' SON LAS DEL LEVANTAMIENTO. ● = CENTRO DE LA FUENTE DE POTENCIAL ESPONTANEO. (CORWIN R., Et. al, 1979).

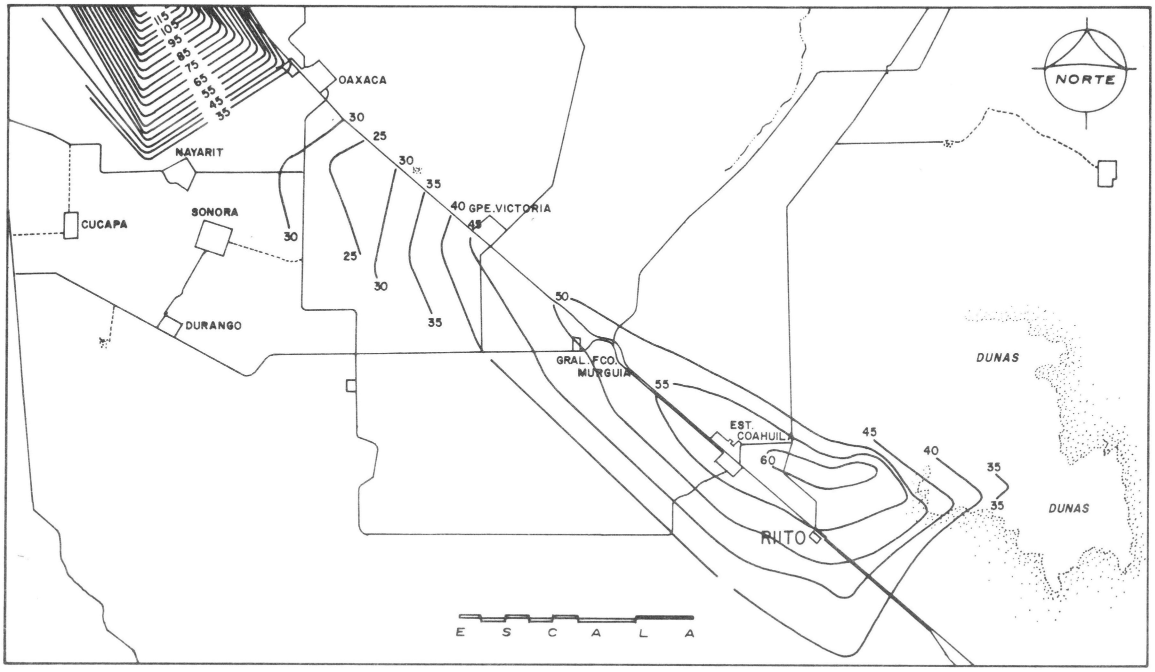


VER FIG. 8 PARA LOCALIZACION.

Fig. 11 MODELO GRAVIMETRICO DE LA LINEA # 1 USANDO EL METODO DE TALWANI (H. FONSECA, 1978).

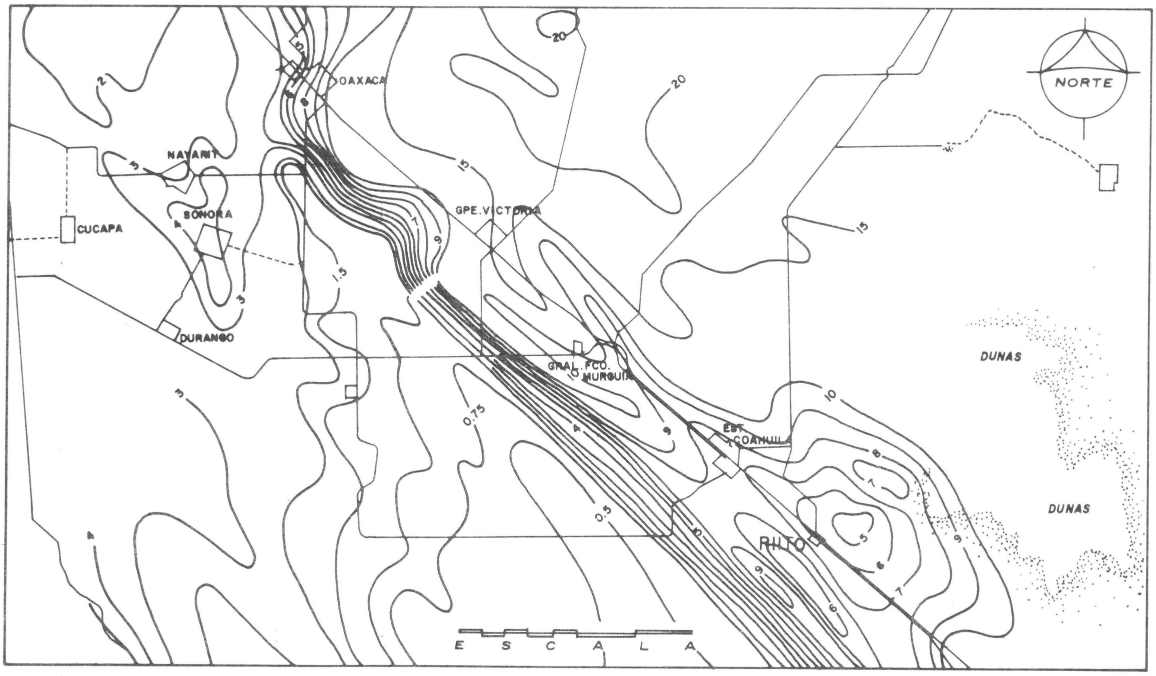
GRAVIMETRIC MODEL OF LINE # 1 USING TALWANI'S METHOD (H. FONSECA, 1978)

C.F.E.



A) CURVAS ISOTERMAS EN °C A 450m. DE PROFUNDIDAD EN EL AREA DE RIITO (DIAZ C.E.,1981).

ISOTHERM CURVES IN °C AT A DEPTH OF 450m IN THE RIITO AREA.



B) ISORESISTIVIDADES APARENTES PARA AB/2 = 1000 m. LOS CONTORNOS SON EN OHM - METRO (ARELLANO F., 1979)

APPARENT ISORESISTIVITY FOR AB/2 = 1000m. THE COUNTOURS ARE IN OHM-M.

Fig.12

C.F.E.

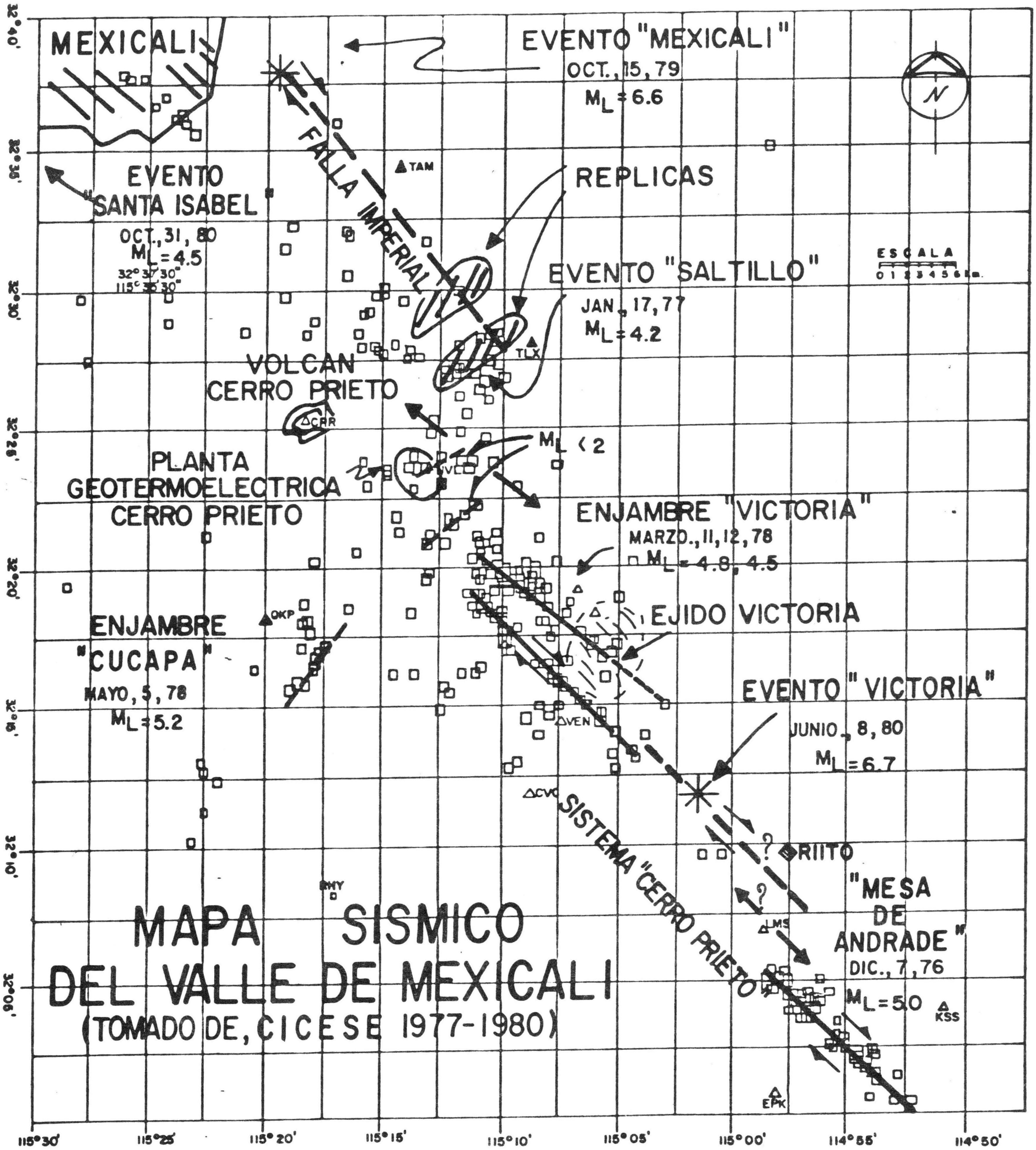
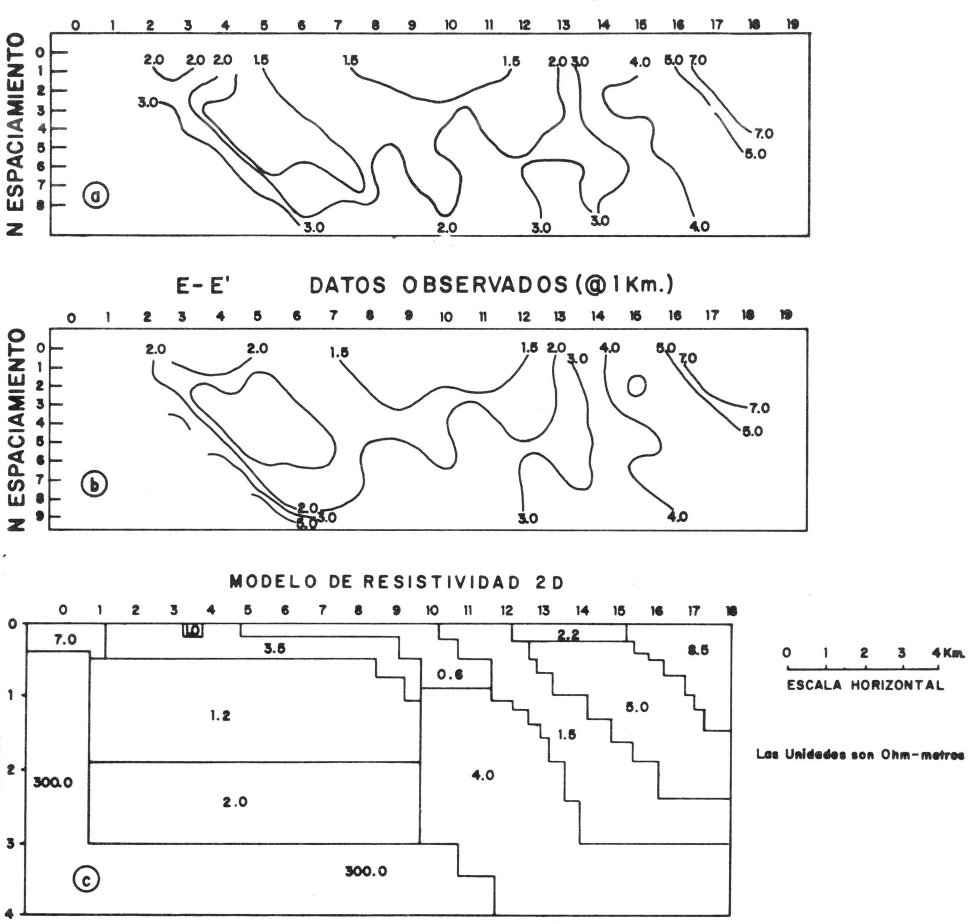


Fig. 13 Mapa Sismico del Valle de Mexicali, (Tomado de CICESE 1977-1980)
Seismic map of the Mexicali Valley, (CICESE, 1977 – 1980).

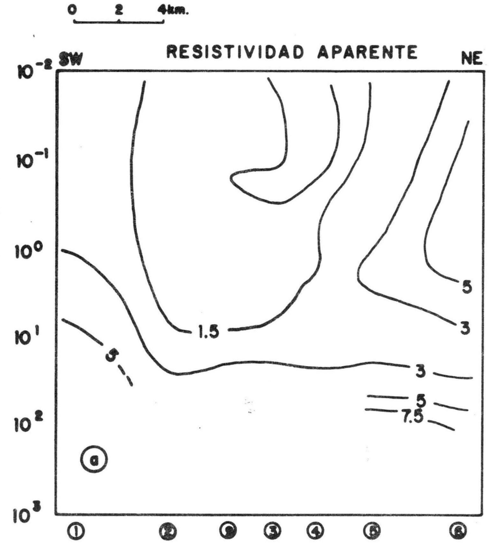
C.F.E.

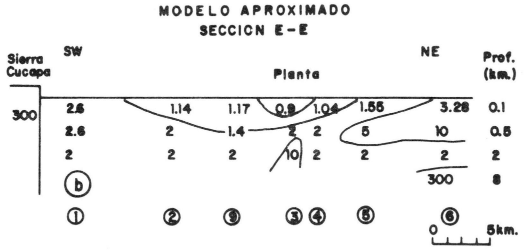

E-E' 1 Km. DATOS OBSERVADOS (@1Km.) 1979

E-E' DATOS OBSERVADOS (@1Km.)

MODELO DE RESISTIVIDAD 2D

A) Pseudo-sección de resistividades aparentes de Dipolo-Dipolo para dipolos de 1 Km a lo largo de la linea E-E', 1979.
a) Datos de campo; b) Modelo generado de los datos; c) Modelo bidimensional de los datos de resistividad (Tomado de Wilt, M., 1979)


RESISTIVIDAD APARENTE


MODELO APROXIMADO
SECCION E-E

B) Ejemplos de resultados de resistividad del método Magnetotelúrico; Despues de las pseudosecciones de magnitud "Tipper" Observada y Calculada.

a) Pseudosección de resistividad aparente a lo largo de la linea E-E'

b) Estimación semicuantitativa de la distribución de la resistividad en el subsuelo a lo largo de la linea E-E'. Escala vertical logarítmica (Tomado de GAMBLE y otros, 1979)

Incisos A) y B) Ver Fig. 8 para localización

Fig. 14

C.F.E.

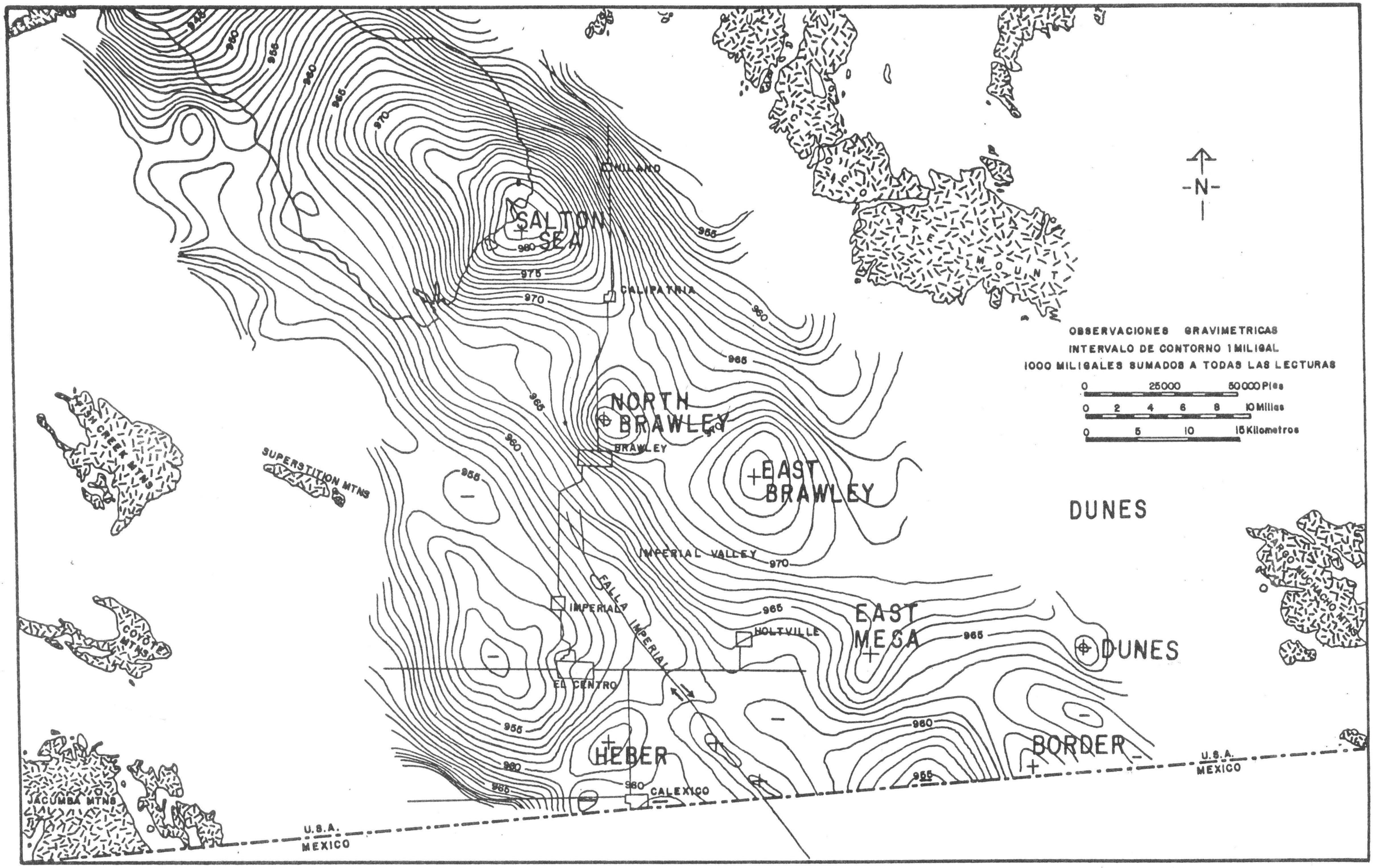
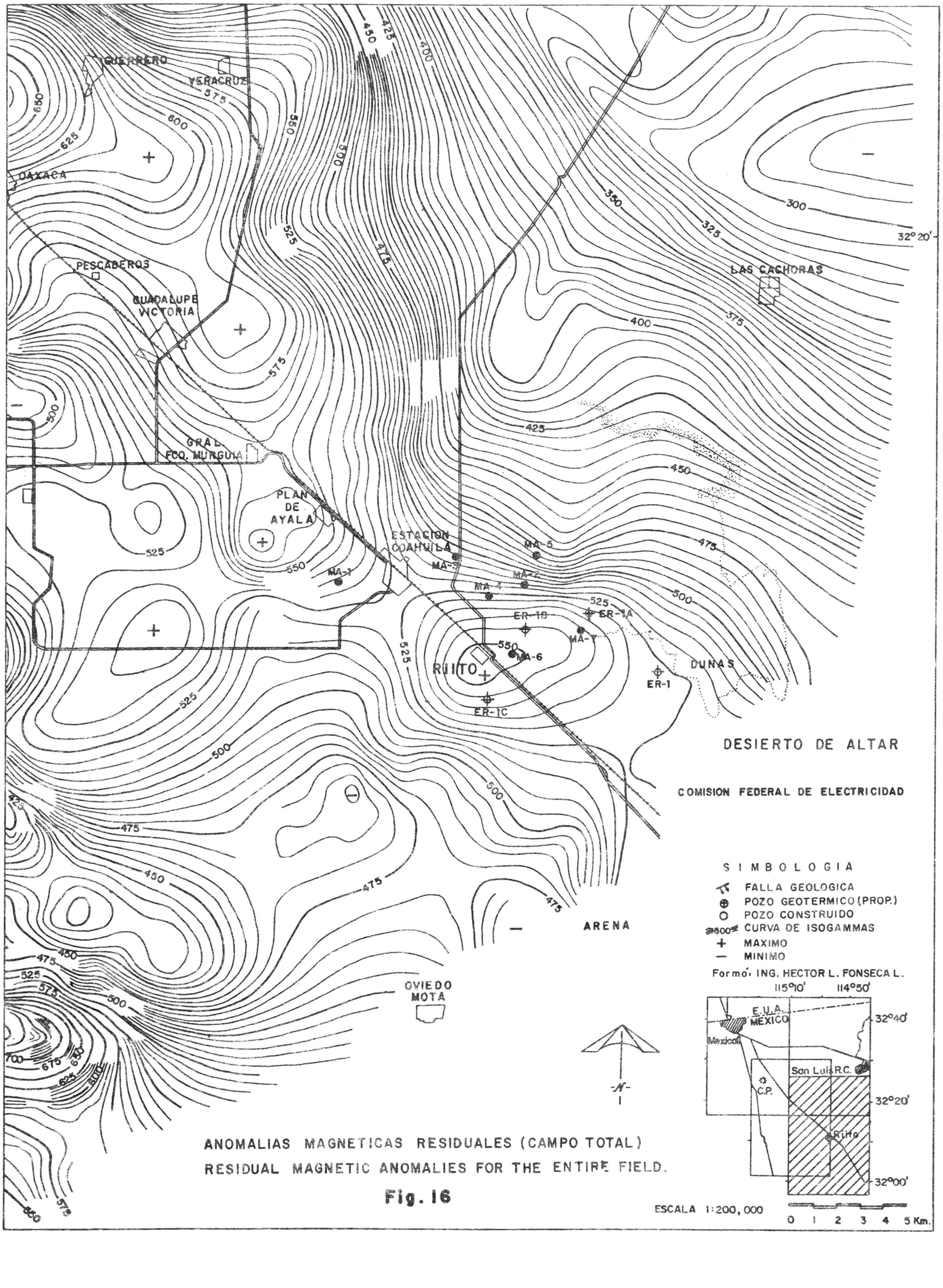


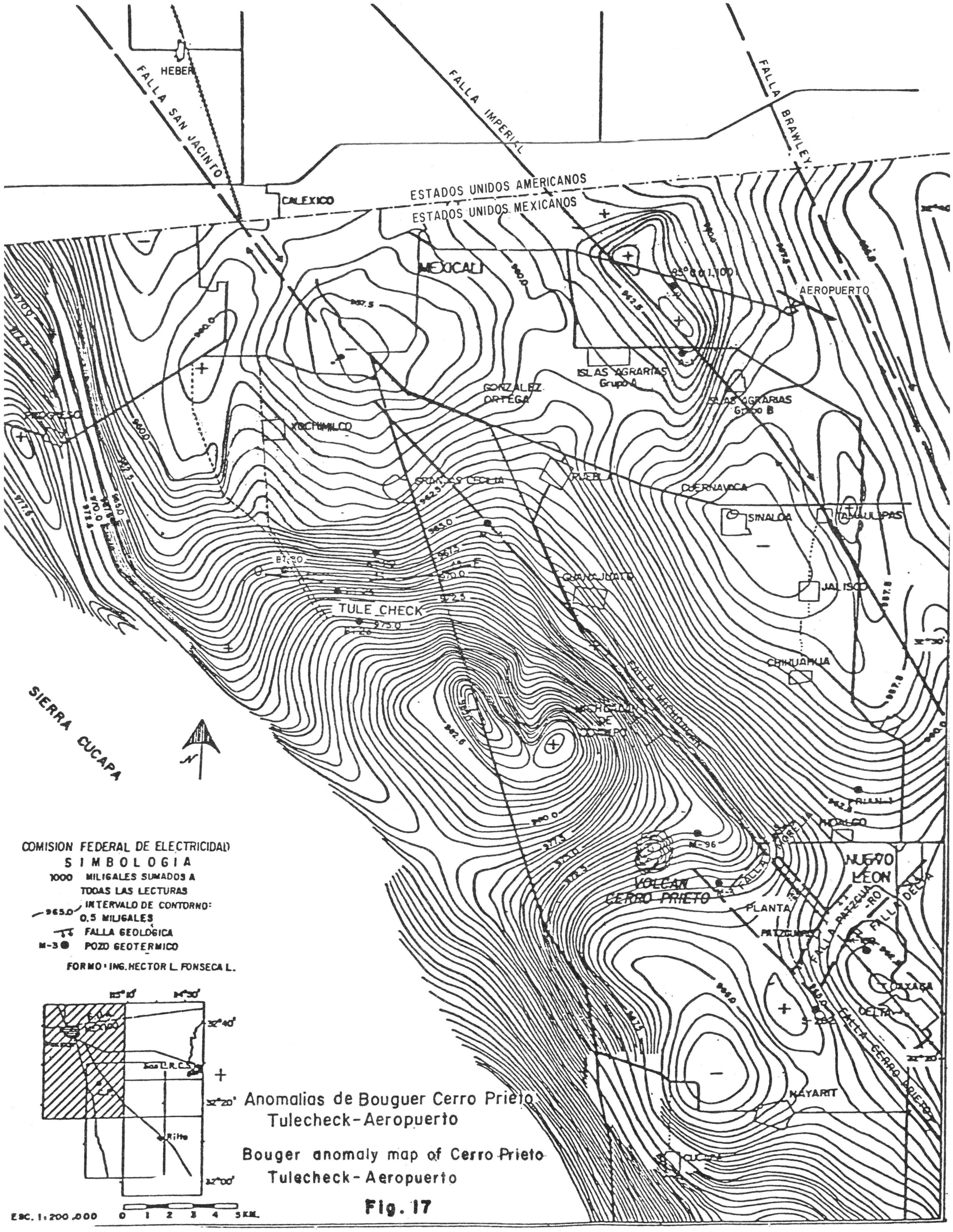
Fig. 15 ANOMALIAS DE BOUGUER DEL VALLE IMPERIAL, S. BIEHLER Octubre 1971

BOUGER ANOMALY MAP OF THE IMPERIAL VALLEY, S. BIEHLER OCTOBER 1971.



ANOMALIAS MAGNETICAS RESIDUALES (CAMPO TOTAL)
RESIDUAL MAGNETIC ANOMALIES FOR THE ENTIRE FIELD.

Fig. 16



Anomalias de Bouguer Cerro Prieto
Tulecheck-Aeropuerto

Bouger anomaly map of Cerro Prieto
Tulecheck-Aeropuerto

Fig. 17

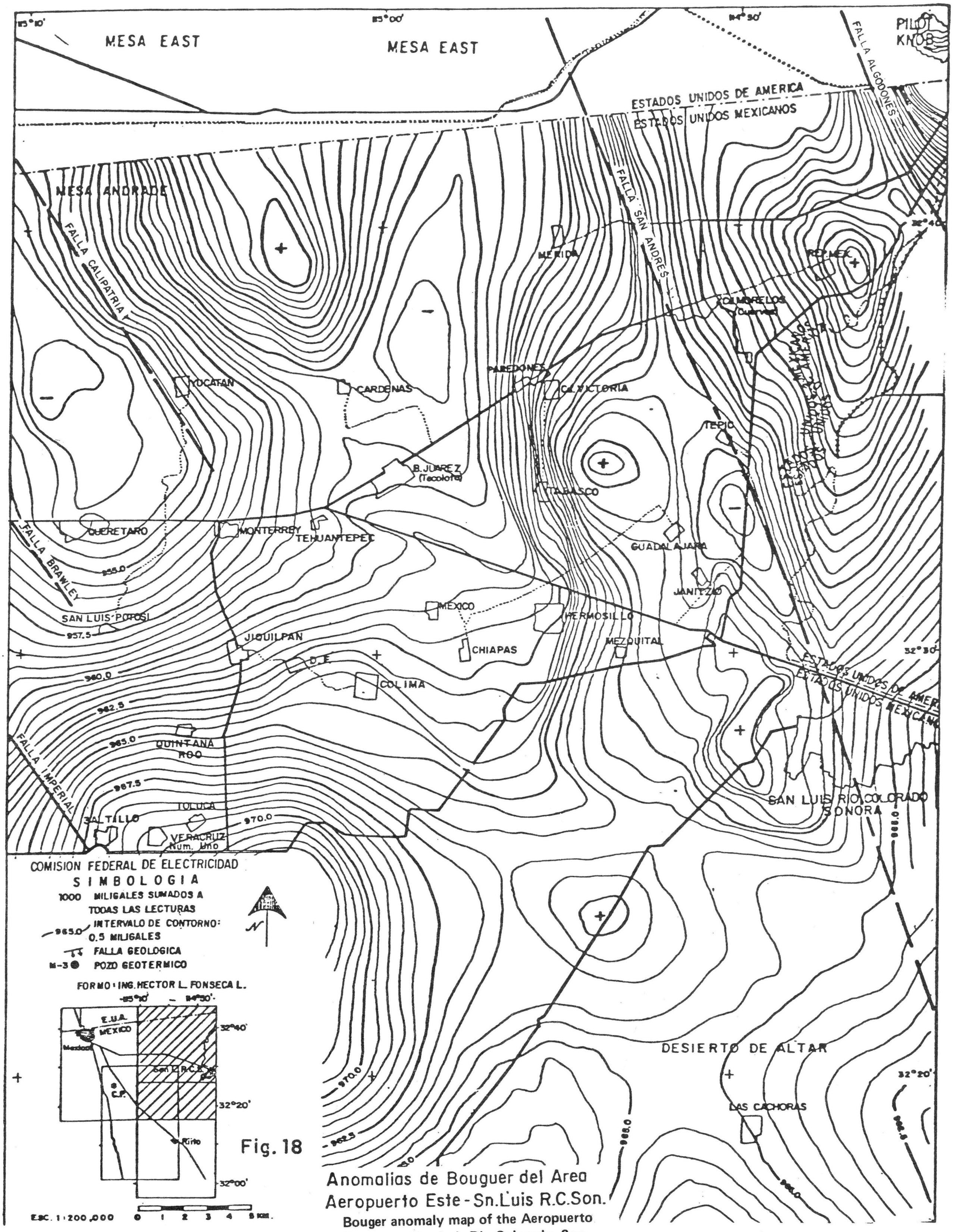
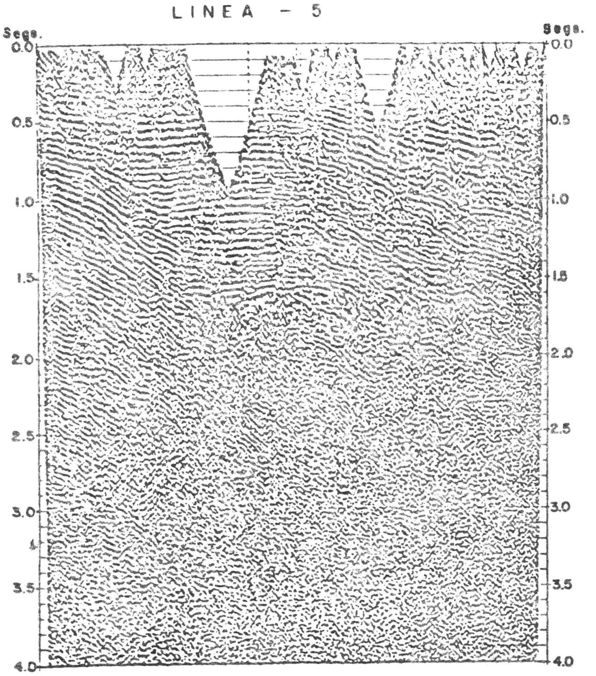
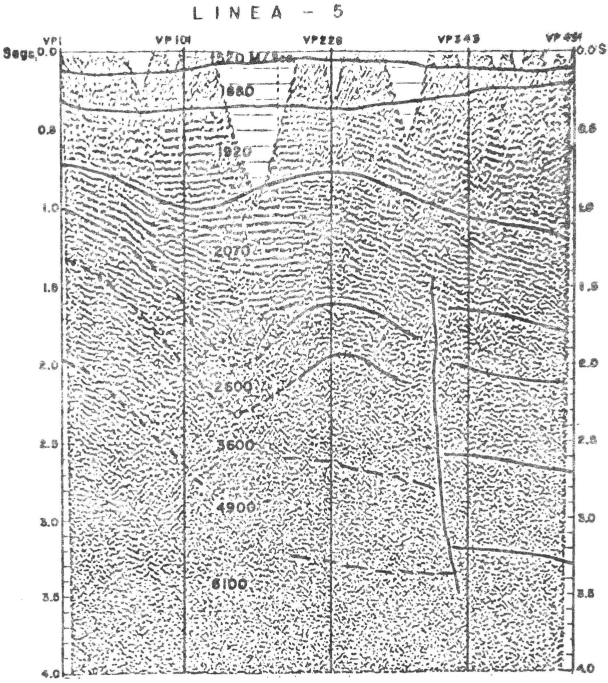


Fig. 18

Anomalias de Bouguer del Area Aeropuerto Este - Sn. Luis R.C. Son.

Bouger anomaly map of the Aeropuerto East area - San Luis Rio Colorado, Son.



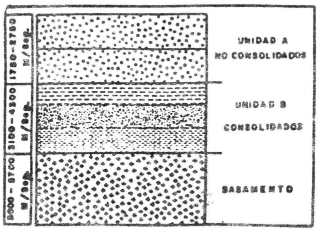


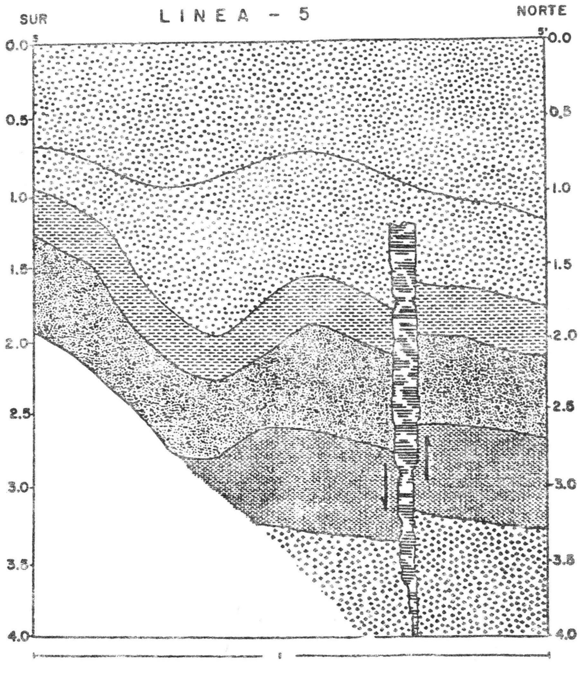
Ver Fig. 8 para Localización

Secuencia del Procesado

1. Demultiplex (in field)
2. Varisweep- crosscorrelation
3. Line geometry
4. Elevation static corrections
5. Residual static corrections
6. CDP gathers (for analysis)
7. NMO velocity analysis
8. Front and Tail mute analysis
9. NMO and 64 fold stack
10. Frequency filtering
11. Final display

TIEMPO (segs.)	PROFUNDIDADES VP 1 y 101 (metros)	PROFUNDIDADES VP 228 (metros)	PROFUNDIDADES VP 343 y 431 (metros)
0.5	600	500	400
1.0	950	900	950
1.5	1425	1450	1500
2.0	1900	2400	2450
2.5	2750	3350	3500
3.0	3750	4300	4600
3.5	4650	5300	5550
4.0	5300	6105	6450





C.F.E.

Fig. 19 Interpretración Geológica al este de la actual zona de producción basado en datos combinados de Reflexión y Refracción (Gymsa,1980)

Geological interpretation of the present productive zone based on combined reflection and refraction data (Gymsa,1980).

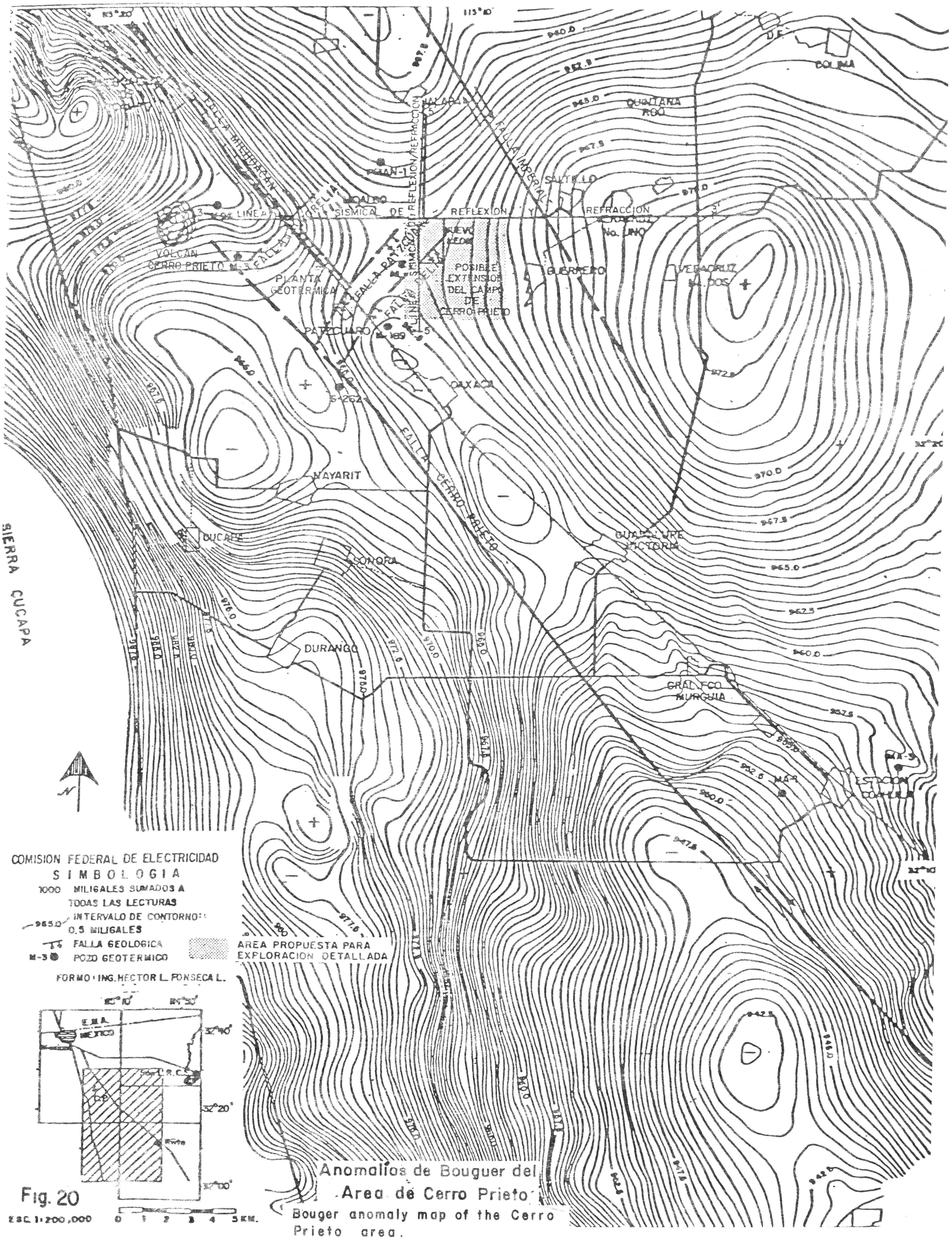


Fig. 20

Anomalias de Bouguer del Area de Cerro Prieto

Bouger anomaly map of the Cerro Prieto area.

LINEA A'-A

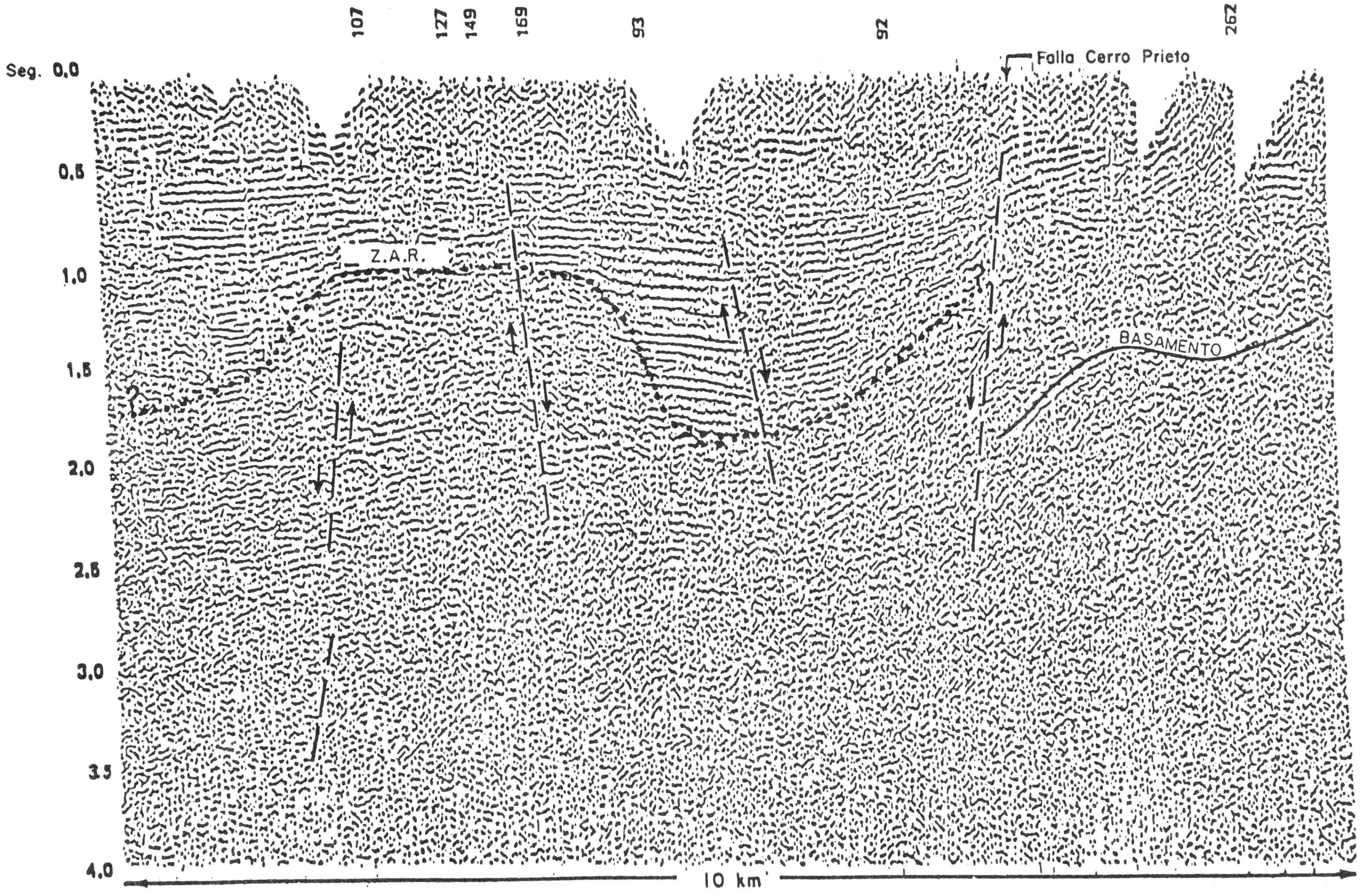


Fig 21 LINEA SISMICA A'-A MOSTRANDO LA ZONA DE ATENUACION DE REFLEJOS (Z.A.R.) Y EL BASAMENTO. LOS NUMEROS 107, 127, 149, Etc., INDICAN LOS POZOS PROYECTADOS

Seismic Line A-A' showing the zone of attenuated reflection (ZAR.) The numbers 107, 127, 149, etc., indicate projected well sites.

C.F.E.

LINEA D'-D

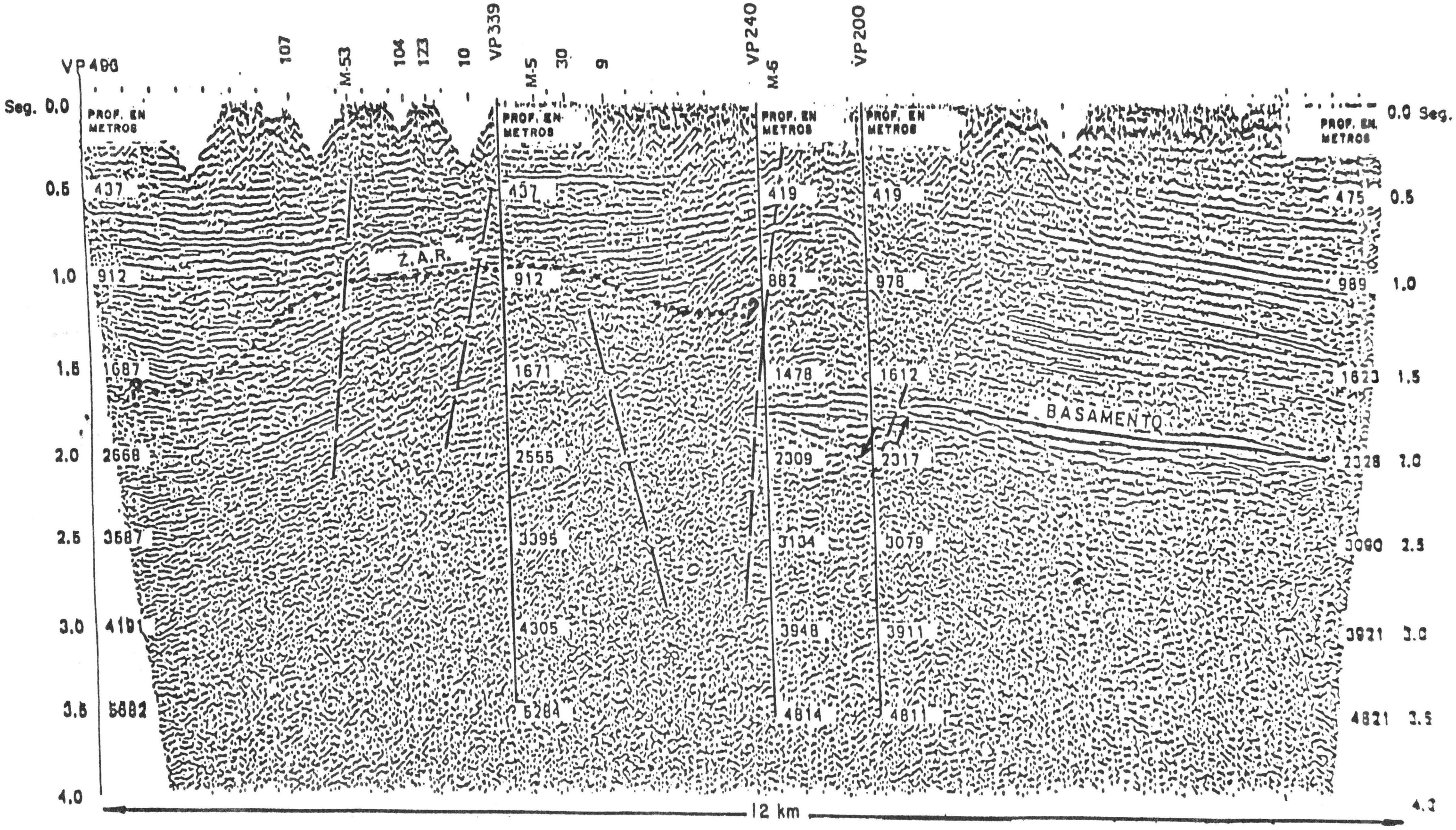


Fig. 22 LINEA SISMICA D'-D MOSTRANDO LA ZONA DE ATENUACION DE REFLEJOS (Z.A.R.) Y EL BASAMENTO. LOS NUMEROS 107, 53, 104, Etc., INDICAN LOS POZOS PROYECTADOS

C.F.E.

Seismic Line D'-D showing the zone of attenuated reflection (ZAR.) The numbers 107, 53, 104, etc. indicate projected well sites.