RICE UNIVERSITY

ANALYSIS OF GRAVITY, MAGNETIC AND SURFACE GEOLOGIC DATA, NORTHERN CHIHUAHUA, MEXICO

by

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ABSTRACT

ANALYSIS OF GRAVITY, MAGNETIC AND SURFACE GEOLOGIC DATA, NORTHERN CHIHUAHUA, MEXICO.

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The basic effort of this work is to apply the results of the interpretation of the gravity and magnetic surveys to the previous geologic studies of the area. The gravity map shows a series of highs that correlate with the ridges formed by outcrops of igneous and/or pre-Cenozoic sedimentary rocks, and gravity lows which correlate with valleys filled by rocks of Cenozoic or Quaternary age. A series of profiles, chosen perpendicular to the strike of the anomalies, include the following information: surface topography, surface geology, magnetic basement which would indicate the thickness of the sedimentary section, and the corresponding gravity profile.

Gravity differences between the regional curve and the observed gravity profile are used to compute depths to the density discontinuities with the formula to calculate the gravity effect of a horizontal slab of infinite dimensions. The results of this analysis are illustrated along four geologic cross sections running approximately NW-SE across the area.
ACKNOWLEDGEMENTS

I wish to express my thanks to Petroleos Mexicanos for permitting me to participate in this program of study and for allowing me to publish the results of this analysis. In particular I want to thank Ing. Santos Figueroa and Ing. Jesus Basurto of the Exploration Department of Petroleos Mexicanos.

I want to express my deep gratitude to Dr. L. L. Nettleton who generously guided and contributed to this study from its start to its completion.

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INTRODUCTION

The northern part of the state of Chihuahua, Mexico has been extensively surveyed with gravimetric methods, and a surface geologic map has been prepared based on aerial photographs. In 1967 an aeromagnetic survey was conducted over the area with the purpose of determining, from measurements of the variations in the total intensity of the earth's magnetic field, the depth's to the magnetic basement. A major part of the present work is to incorporate the basement depths into quantitative estimates of the thicknesses of the principal components of the sedimentary section.

When correlating gravity data with geologic and magnetic data, the formation densities are fundamental in determining the sources of gravity disturbances. As there are no published density values for any of the formations in the area studied, it was necessary to assume densities on the basis of the general lithology and by trial calculations where relatively good gravity and geologic control was available. For this study the following density values were used: basement rocks, 2.7; pre-Cenozoic, 2.6; and bolson fill, 2.0.

The larger gravity anomalies are accounted for by calculating a distribution between the surface and the magnetic basement of the two principal components i.e. bolson fill and pre-Cenozoic rocks. The calculations were made with an approximating formula
corresponding to the effect of horizontal slabs of infinite width with approximate corrections for finite width. The use of simple calculations rather than more elaborate models is justified because of uncertainties in other factors, particular by the density values used.
GEOLOGICAL SETTING

Geography

The area of study is located in the northern part of the state of Chihuahua, Mexico immediately south of the U. S. states of New Mexico and Texas (Figure 1). Physiographically, it belongs to the Basin and Range province, with narrow elongated NNW-SSE trending ranges consisting mainly of igneous intrusives and extrusives, and Cretaceous sedimentary rocks. The ranges are separated by wide, generally interconnected, internally drained basins. The eastern part of the area is drained by the Rio Bravo and its tributaries. To the south, near Ojinaga, it is joined by the Rio Conchos which is the largest drainage system in the state of Chihuahua.

Geological History

Evidence from Paleozoic sediments outcropping in the area of study shows that the seas during this Era extended to the north and northwest of the Placer de Guadalupe area where there are about 850 meters of sediments ranging in age from Ordovician to Permian (Bridges, 1962). During the Devonian and most of the Mississippian periods the seas withdrew and the basins received little sediment, whereas in the Marathon Basin,
Figure 1. Location of Area with outline of Basin and Range Province. (After Imlay, 1944).
200 kilometers to the east, 1700 meters of sediments of Mississippian age have been measured (Thomson and McBride, 1964). Paleozoic rocks outcrop in the Franklin Mountains just north of the City of El Paso, Texas. In the area of study the oldest rocks outcrop near the Palomas region in the northwestern part of the state of Chihuahua. These rocks range in age from Mississippian to Permian. At the end of the Mississippian period the seas withdrew from the area and the early Pennsylvanian sediments consist of about 35 meters of conglomerates and sandstones (Diaz, and Navarro, 1964). During the latest Permian, Triassic, and most of Jurassic time the area was probably being eroded. Near the end of the Jurassic period the seas covered most of the eastern part of Chihuahua resulting in a sequence of evaporites of unknown thickness (Bridges, 1962). A well drilled by Petroleor Mexicanos near Ojinaga encountered evaporites, largely halite, from depth's of 150 meters to about 2580 meters (Salas, 1955). During the Cretaceous period great quantities of sediments accumulated in Chihuahua; more than 3000 meters have been measured. A major regression of the sea occurred in early Cretaceous time, when more than 700 meters of redbeds accumulated. Throughout the remaining Cretaceous time the seas covered the area and great quantities of limestone
were deposited (Haenggi, 1964). At the end of the Cretaceous or early Cenozoic the rocks in the area were deformed; this deformation is probably Laramide in age. Intense igneous activity during Cenozoic time occurred in parts of the area. Outcrops of intrusive and extrusive igneous rocks occur mostly in the western half of the area. Cenozoic deposits of the continental origin outcrop over much of the area; these sediments were deposited as alluvial fans along the mountain edges or in the basins between them (Bridges, 1962). A lake covered part of northwestern Chihuahua and southwestern New Mexico during Pleistocene time; remnants of this lake include ancient shorelines and playas. The ancient Rio'Bravo was probably an affluent of this lake before it acquired its present course (Reeves, 1965).

Previous Work

In 1848, A. Wislizenus, dated the outcropping limestone of Northern Mexico as Silurian. When the new boundary between Mexico and the United States was surveyed, William H. Emory (1857) described the geology along the border, made several journeys into Mexico, and collected and described Cretaceous rocks. The limestone of northern Mexico which was incorrectly
dated as Silurian by Wislizenus was dated, based on fossil content, as Cretaceous by James P. Kimball in 1869. He also outlined the distribution of volcanic rocks of a great portion of the state of Chihuahua.

From 1891 to 1907, R. T. Hill conducted several expeditions into Chihuahua correlating the ore bearing limestone of the Santa Eulalia mining district with the Edwards limestone of Texas. E. O. Hovey (1907) published a report on a reconnaissance survey into the Sierra Madre Occidental. His report included a geologic map of Chihuahua. In 1910, R. H. Burrows named the Plomosas Formation and suggested the possibility of pre-Cretaceous origin for slates found along the Rio Conchos. Emil Böse (1921, 1923) studied Paleozoic outcrops in northern Mexico and showed that none of these rocks were older than Permian.

In 1933, W. S. Adkins correlated the thick sequence of Cretaceous rocks in Chihuahua with those in West Texas. He and R. E. King published from 1942 to 1946 two papers on the geology of the area (King, R. E., 1942; King, R. E., and Adkins, 1946). P. B. King (1947) published a geologic map of the northern part of Mexico. A detailed geologic map of the state of Chihuahua
was published in 1956 by Ramírez and Acevedo.

In recent years, work in the area or adjacent to it has been by several geologists. Ing. Teodoro Diaz during the XX International Geological Congress in 1956, led an excursion throughout parts of the state of Chihuahua. The field manual included a discussion on the general geology of northern Mexico and road logs of the routes covered by the excursion (Diaz, 1956). In 1964 he described the stratigraphy of the upper Paleozoic rocks of the northwestern part of Chihuahua (Diaz and Navarro, 1964). Robert A. Zeller described the geology of the Big Hstchel Mountains of New Mexico (Zeller, 1965). R. K. DeFord and L. W. Bridges have worked together on the Paleozoic rocks of central Chihuahua and the Tertiary formation along the Rio Bravo (De Ford and Bridges, 1958, 1959; Bridges and De Ford, 1961). Robert Balk (1961) published a geologic map of Tres Hermanas Mountains of New Mexico bordering the state of Chihuahua.

Geologic maps along the United States-Mexico border have been published by the Bureau of Economic Geology at the University of Texas: Geology of Wiley Mountains and Vicinity, Culberson and Jefferson Counties (Hay-Roe, 1957); Geology of the Pinto Canyon Area, Presidio County (Amsbury, 1958); Geology of Van Horn Mountains (Twiss, 1959); and Geology of Eagle Mountains
and Vicinity, Hudspeth County (Underwood, 1963).

Stratigraphy

One of the first problems was that of obtaining lithologic information on the formation in the area so that some approximations could be made of the probable density contrasts responsible for the gravity disturbances. The author was furnished by Petroleos Mexicanos with a surface geologic map based on aerial photographs. This map contained no lithologic information, and there has been very little other mapping in the area. The stratigraphic information was obtained from published studies of various parts of the area, or adjacent areas mentioned above (Plate I); particularly Amsbury, 1958; Bridges, 1962; Underwood, 1963; Diaz and Navarro, 1964); Zeller, 1959, 1965; and Haenggi, 1966. Even though these areas are widely separated, a complete section with some information on the lithology of each formation was obtained. A general stratigraphic column is given in Figure 2. The major geologic trends and areas of igneous outcrops are shown in Figure 3. The lithologic description of each formation is included in the appendix.
<table>
<thead>
<tr>
<th>PERIOD</th>
<th>NAME</th>
<th>THICKNESS</th>
<th>GENERAL LITHOLOGY</th>
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<td>QUATERNARY</td>
<td></td>
<td></td>
<td>? GRAVEL, SAND, SILT, AND CLAY, MOSTLY FLOOD PLAIN AND VALLEY FILL Deposits</td>
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<td>CENOZOIC</td>
<td>'SEDIMENTARY'</td>
<td>?</td>
<td>LACUSTRINE, FLUVIAL, AND AEOLIAN DEPOSITS RANGING WIDELY IN SIZE AND COMPOSITION</td>
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<td>CENOZOIC</td>
<td>'IGNEOUS'</td>
<td>?</td>
<td>RHYOLITIC TUFFS, ANDESITE PORPHYRY, RHYOLITE PORPHYRY</td>
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<tr>
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<td>EL PICACHO</td>
<td>85 m</td>
<td>YELLOWISH, MASSIVE, GYPSIFEROUS MARL</td>
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<td>OJINAGA</td>
<td>650 m</td>
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<td>15-67 m</td>
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<td>COX-LAGRIMA</td>
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<td>BENIENO</td>
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<td>JURASSIC</td>
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<td>LIMESTONES, CONGLOMERITE SAND AND SHALE, EVAPORITES IN WESTERN PART OF AREA OF STUDY</td>
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<td>TRIASSIC</td>
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<td></td>
<td></td>
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<td>CONCHA</td>
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<td>35 m</td>
<td>CONGLOMERATES AND CONGLOMERITE SAND</td>
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<td>PARADISE</td>
<td>107 m</td>
<td>GRAY LIMESTONE</td>
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<td>MISSISSIPPI</td>
<td>KEATING</td>
<td>33 m</td>
<td>DARK GRAY, FINELY CRYSTALLINE LIMESTONE</td>
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Figure 2. Stratigraphic Column for Northern Chihuahua.
Figure 3. Major Geology Trends and Areas of Igneous Rock Outcrop (After Ramirez and Acevedo, 1956)
GEOPHYSICAL INFORMATION

The Gravity Survey

A gravity survey was carried out over the area of study by Petroleos Mexicanos. The net of gravity traverses has lines ranging from two to twenty kilometers apart, with stations every 500 meters. The coverage is adequate to show the gravity pattern quite well. Plate II shows the principal gravity features of the study area.

GENERAL GRAVITY PATTERN

In general, the anomalies shown on the map are a series of elongated, NW-SE trending highs and lows. The gravity highs are caused by the effects of both igneous and pre-Cenozoic rocks. Since both types of rock have about the same density the gravity does not distinguish between them. The gravity lows reflect the effects of the low density rocks in the basins between the ridges. In the western part of the area the anomalies are sharp, indicating a highly disturbed geologic pattern. In the eastern part the anomalies are broader and longer. Along the Rio Bravo (Mexico-Texas border) there is a single broad feature, suggesting a deeper basin and that this portion of the area in the continuation into Mexico of the Hueco Basin
of West Texas. The relief of the major features is in the order of 30 to 40 milligals.

REGIONAL GRAVITY MAP

Plate III is a smooth gravity map obtained by plotting gravity profiles on a network of intersecting lines and drawing a smooth curve through most of the gravity highs. The gravity values of these curves were plotted on a map and adjusted until a very smooth pattern was obtained. The differences in gravity between the regional curve and the observed profile represent the anomalies caused by the density contrasts within the sedimentary section.

The Magnetic Survey

An aeromagnetic survey was made for Petroleos Mexicanos by Aeroservice Corporation of Philadelphia, Pennsylvania, with
the purpose of determining the structure of that portion of the earth which is made of great quantities of ferromagnetic minerals known as the magnetic basement. It is composed of rocks of igneous origin, like gabbro and basalt, which are magnetic enough to affect the magnetic field of the earth even when these are buried under a considerable thickness of sedimentary rocks. With the exception of formations which contain great quantities of iron, sediments are relatively nonmagnetic (Vacquier et al., 1951).

SURVEY METHODS

Before the survey was started, base maps, aerial photographs and surface geologic maps of the area had to be studied in order to determine the line direction, line spacing, flight altitude and location system.

Line Direction. In order to obtain the maximum signal strength from the magnetic bodies, the traverse lines should be flown at right angles to the geologic trends. Variations from this perpendicular direction can be as much as 30 degrees without serious impairment of results. In the area of study the outcropping rocks trend mostly NW-SE to NNW-SSE; the traverse lines were
flown in an E-W direction.

Line Spacing. When a detailed aeromagnetic survey is conducted all suprabasement features should be detected and evaluated. The half amplitude width of the narrowest suprabasement anomaly is nearly equal to its depth of burial. In other words, if the traverse lines have a separation approximately equal to the depth of burial then all these anomalies should be evident in the mapping. Another factor which affects the choice of spacing is that most of the magnetic features should be detected while keeping the costs of operations at a minimum (Reford and Summer, 1964).

The area of study has numerous outcrops of volcanic rocks in its western and southwestern part (see Figure 3). Where the volcanic rocks cover large areas, the aeromagnetic records are so greatly disturbed that it becomes impossible to detect the sedimentary section, if any, below them. For this reason, and based on surface geologic maps, a preliminary reconnaissance survey was planned to delineate the areas where the volcanic rocks no longer affected the aeromagnetic records too much to permit determination of thicknesses of sediments. This made it possible to add additional lines in the less disturbed areas to permit detailed mapping of the magnetic anomalies and
determination of basement depths. The reconnaissance lines were flown in pairs, 2 kilometers apart, with a separation of 16 kilometers between pairs. The detailing was done by flying additional traverses, 2 kilometers apart, forming groups of three lines in order to have a symmetric pattern.

Flight Altitude. While the aeromagnetic survey was being conducted, lines were flown in blocks at the same barometric altitude in order to provide a fixed datum for basement depth calculations. The flight altitude chosen is controlled by the topographic elevation; a minimum of 1000 feet of ground clearance is common. The area of study was divided into three blocks and flown at 7,000, 7,500, and 8,500 feet above sea level.

Location System. Flight lines were first drawn onto base maps and aerial photographs. A continuous strip camera made a record of the actual path of the airplane during the survey. This path was reconstructed by finding corresponding points on the air photos and on the film and transferring them to the base maps.
Airplane and Instruments. The aeromagnetic survey was made with a two motor aerocommander. The magnetometer, a Gulf Mark III Fluxgate type, for the recording of the aeromagnetic observations was mounted on the tail of the airplane.

Diurnal Effects. The magnetic field of the earth is always fluctuating. Some of these variations are cyclic and occur from day to day while others are irregular over shorter or longer periods of time. The effects of cyclic changes can be removed by repeating observations at the same place. Variations which occur every few seconds, minutes or hours are called "diurnal" variations and their effects can be removed by flying control lines across the traverses. Closure adjustments correct instrument drift or well as diurnal changes (Reford and Summer, 1964). The control lines in the area of study were flown in a N-S direction with a separation of 10 kilometers between lines.

A ground magnetometer was kept at the base station to make a continuous recording of the magnetic variations and to monitor the magnetic "weather." This information was used to avoid flying lines when the magnetic disturbances were too strong or to check if such a disturbance occurred while
the airplane was surveying and decide if any lines had to be flown again.

GENERAL MAGNETIC PATTERN

Magnetic anomalies that are sharp and of high relief indicate shallow basement; when they are of low relief deeper basement is indicated. Plate IV shows the general magnetic pattern of the study area. In the western and central parts of the area the magnetic and gravity patterns are similar. This indicates that the ridges of largely igneous material are also of relatively high density in order to produce a similar pattern of gravity anomalies. Over the eastern and southeastern parts the magnetic features are flatter, indicating that the sources of disturbances are deeper. On this map (Plate IV) the areas where the basement surface is deeper than sea level have been shaded.

Interpretation and Application to Sections

The results of the aeromagnetic survey were a series of records, one for each line, with the changes in the total field recorded as a continuous profile. The magnetic field is mapped from these records after a correction for the broad effects caused by the earth's main magnetic field. To identify
magnetic features with ground position, numbered points are marked on each record at a fixed distance. These points are then transcribed to the map.

The first phase of the interpretation of the aero-magnetic data is a qualitative one. It involves the study of the magnetic contours. The bands of steep gradient shown by the magnetic contours generally follows the boundaries of the major rock bodies. These boundaries can be sketched on the intensity map. Topographic features, geology and gravity of the area should be checked against the magnetic data. A basement structure may be related to a surface feature; the gravity and magnetic fields are often related because basement relief and volcanic rocks are involved in the same structural disturbances which produce gravity anomalies.

The next step in the interpretation involves the computation of basement depths from the magnetic data. The locations of maximum and minimum values are shown on the intensity map. Depth calculations of narrow bodies can be made from half amplitude widths found from the map. For the broader bodies one must use the profiles which show a continuous recording of the earth's magnetic field. Magnetic anomalies are caused by:
1) a change in composition within the basement rocks, the resulting anomaly generally has an amplitude of 100 gammas or more, this source is called an intrabasement body; 2) a rise in the basement surface, this is called a suprabasement body. The amplitude of these anomalies is generally in the order of 50 gammas or less. A basement fault can be detected by an abrupt change in the slope of the profile, the measured depth corresponds to the center of the fault; 3) magnetic material at or near the surface, it usually corresponds to outcropping volcanic rocks and may produce anomalies of a small to large amplitude.

The interpretation of the aeromagnetic survey was made commercially by Gravity Meter Exploration Company, by application of the principles described at some length by Vacquir et al. (1951). The method used determines, from the magnetometer record as made on the airplane, the parameters $S$ and $P$ indicated in Figure 4. The distance between the points at which the curve departs from a straight line is called $S$; $P$ is the distance between the points at which a line with half the maximum slope is tangent to the magnetic intensity curve. It is found empirically that these distances are linearly related to the depth to the magnetic bodies. The result of
this interpretation was a contour map of the basement surface over the area. From this map the basement profile was plotted on the geologic sections (Plates V, VI, VII, and VIII).
Figure 4. Total Intensity Model Curve and Parameters used for Depth Calculations.
GEOLOGICAL INTERPRETATION OF GEOPHYSICAL RESULTS

Densities and Density Contrasts

The large gravity anomalies are caused by density differences between the rocks which form the ridges and those which fill the valleys between them. In the area of study there are no published density values for any of the sediments; therefore, it was necessary to assume densities on the basis of published lithographic descriptions. It is obvious from the general lithology, that the greatest density contrast is that between the bolson fill deposits and the older rocks, principally limestone or volcanics, of the ridges. Careful consideration was given to possible density differences between the elements of the stratigraphic column. However, since the section is largely limestone throughout there is no clear basis for division into major components or groups with different densities. To test for density differences within the pre-Cenozoic sediments, a series of gravity profiles were drawn in places with good gravity control over outcropping pre-Cenozoic rocks. These profiles showed no systematic correlation of gravity details with outcropping contacts. From this it was concluded that there is no major density contrast between these
rocks. This was further confirmed by the lack of consistent gravity anomalies corresponding to structural features shown by the outcrops. Attempts to assign densities on the basis of lithologic description does not result in a definite density column; no actual density measurements of samples from any of the sediments are available in the literature. Therefore, the only workable basis to account for the gravity anomalies was to assume that the entire pre-Cenozoic section is more or less homogeneous and of relatively high density.

Experience in gravity surveys in the basin and range province of Nevada and Utah, with some density measurements there, has shown that a very thick bolson fill can have densities as low as 2.0 or even less (L. L. Nettleton, personal communication).

Initial calculations were made by assuming -0.1, and -0.2 for the density contrast of the pre-Cenozoic rocks with respect to the basement, and -0.4, -0.5, and -0.6 for the density contrast of the bolson fill with respect to the pre-Cenozoic rocks. These assumptions were made over areas where the basement depths are known from the magnetic interpretation. Better fits over
the trial areas were obtained with a density contrast of
-0.1 for the pre-Cenozoic sequence with respect to the base-
ment rocks, and -0.6 for the bolson fill deposits with respect
to the pre-Cenozoic rocks. These differences correspond with
assumed densities of 2.7 for the basements rocks, 2.6 for the
pre-Cenozoic sequence, and 2.0 for the bolson fill deposits.

Using the latter figures the residual gravity along each
profile was accounted for by a geologic section controlled
by surface outcrops, the basement depths, and variable thick-
nesses of the bolson fill deposits.

System of Calculations

The depths to the density contrasts based on gravity dif-
ferences between the regional curve and the observed gravity
profile were computed with the use of the formula to calculate
the effect caused by a horizontal slab of infinite dimensions:

\[ G = 2\pi \rho \gamma T \]

where

\[ G = \text{Gravity in milligals}, \]
\[ \gamma = \text{Universal gravitational constant, } 6.67 \times 10^{-8} \text{ (c.g.s.)}, \]
\[ \rho = \text{Density, and} \]
\[ T = \text{Depth to the density discontinuities}. \]
Assuming a unit density contrast, it will take 78 feet (23.9 meters) of material to produce an effect of one milli-gal. This effect is produced by a body whose width-to-depth ratio is infinite. Keeping all parameters equal, but making the width-to-depth ratio finite, the values of gravity obtained are a percentage of the maximum gravity obtained when the state is infinite in length. Figure 5 shows the percentage of maximum gravity obtained by varying the width-to-depth ratio of the body. As this ratio increases and approaches infinity, the value of "percent maximum gravity" obtained asymptotically approaches 100 percent.

The gravity effects of finite bodies with width-to-depth ratios in the general range of four to eight is roughly 75% that for an infinite slab (see Figure 5). For this reason a figure of 100 feet, instead of 78, for the thickness of material of unit density contrast necessary to produce an effect of 1 milli-gal is a reasonable approximation for the effects of the width-to-depth ratios such as those encountered in the area of study (Nettleton, 1940). This simple approximation is justified because: 1) for the most part the width-to-depth ratio across the valleys is greater than 5 making the
Figure 5. Percent of Maximum Gravity vs. Width-to-Depth Ratio.
approximation reasonably close, and 2) the density contrasts are not sufficiently well-known to give much validity to more elaborate calculation methods.

Revision of Geologic Sections by Gravity Only

Earlier geologic sections constructed from surface geologic information show thickness of bolson fill as being very thin. Gravity profiles on these sections showed large negative anomalies indicating that the bolson fill must be much thicker than it was shown by the original geologic interpretation. Depths estimated from the gravity profiles in the manner described earlier are of the order of 500 to 1300 meters thick rather than of the order of 100 to 150 meters estimated from the geology only. Accommodating these thicknesses of Cenozoic rocks required major changes in the details of the sections as drawn without reference to the geophysical data.

Geologic Sections Controlled by Surface Geology, Gravity and Magnetic Basement.

Since the gravity laws associated with the valley fill are the most prominent features, a series of cross sections were drawn perpendicular to the strike of the gravity anomalies and intersecting as many gravity laws as possible (see Figure 6). The surface topography, surface geology from the map
Figure 6. Area of Study Showing Location of Sections Based on Surface Geology, Gravity and Magnetic Basement
based on aerial photographs, magnetic basement from the interpretation made by Gravity Meter Exploration Co., and the corresponding gravity profile were plotted on each line of section. Thus the quantitative interpretation is based on the thickness of the sedimentary section, and the residual gravity values based on the difference between the observed and regional profile curve for each section.

The assumed density of the basement rocks is 2.7, and that for the pre-Cenozoic sequence is 2.6. By calculating at several points the gravity effect of filling the entire sedimentary section with basement rocks having a density contrast of 0.1, and adding these values to the observed gravity profile, the effect due to the pre-Cenozoic sequence was removed. The gravity differences between this new curve and the regional curve represent the effect from the low density Cenozoic or Quaternary sediments. Knowing the value of gravity, one can solve for the thickness of the layer by the horizontal slab formula. Figure 7 is an idealized section illustrating the method for calculating the thickness of the bolson fill deposits.

Results

Four sections based on surface geology gravity and magnetic basement (Plates V, VI, VII, and VIII) show the results of this analysis. Also, in these sections, an attempt
$\Delta g_a = K(t_1 + t_2)\sigma_2 = \text{CORRECTION TO SURFACE FOR LAYER } a$

$\Delta g_b = \Delta g - \Delta g_a$

$\Delta g_b = K t_1 \sigma_1$

WHERE: $\sigma$ = DENSITY CONTRAST

$t$ = THICKNESS

$\rho$ = DENSITY

EQUATING II AND III, WE GET: $t_1 = \frac{\Delta g - \Delta g_a}{K \sigma_1}$ = THICKNESS OF THE LOW DENSITY LAYER IN KILO-FEET

Figure 6. Area of Study Showing Location of Sections Based on Surface Geology, Gravity and Magnetic Basement.
has been made to interpret the pre-Cenozoic layer of sediments. The control is based on surface outcrops and the basement surface. Since no information is available on subsurface stratigraphic sequence and thicknesses of the pre-Cenozoic sediments, the same sequence and thicknesses observed from the outcrops has been used throughout the area. The general thicknesses of bolson fill deposits should be more accurate.

For some test sections more elaborate calculations were made with a line integral computer program (Talwani et al., 1959). This method computes the gravitational attraction of a two-dimensional body whose shape can be approximated by an n-sided polygon. The operations can be put in a form suitable for solution by a computer and the gravity effects of several bodies can be computed very rapidly. The results are plotted along the observed gravity curve. For narrow bodies the computed gravity values are in the order of 10 to 15 percent less than the observed gravity values, and for the broader bodies the computed values are 5 to 15 percent greater than the observed gravity values. This indicates that although the percent error is acceptable, the approximated value of 100 feet instead of 78 for the thickness of the slab of finite dimensions is greater than it should
be for the broad bodies but smaller than it should be for the narrower bodies.

SECTION 1

Plate V shows a generally deep eastern part with a thickness of sediments, east of coordinate 110,000 ranging from 2,000 to 3,000 meters. The sedimentary section contains a moderate thickness of bolson fill deposits which is in the order of 200 to 1250 meters; except in the east end where these deposits have been interpreted to be of up to 1700 meters thick. The rest of the sedimentary section consists of pre-Cenozoic sediments ranging in thickness from 1,500 to 2,650 meters. Around coordinate 165,000 the surface outcrops show a probable complex structure. There is a broad area from coordinates 40,000 to 100,000 where the basement is at or near the surface, and the section shows very little thickness of sediments. The gravity profile in this area may be influenced by different rock types within the basement or different types of volcanic rocks. The interpretation, with the assumed densities, of the western end of the gravity low near coordinate 100,000 results in a thickness of bolson fill deposits that extend to a depth greater than the known basement
surface, as indicated by the dotted line. The reason is probably that the basement rocks near this part have a density smaller than the assumed 2.7.

SECTION 2.

Plate VI also shows a deep eastern half with thicknesses of sediments ranging from 1250 to 2,500 meters; becoming thicker to about 4,500 meters as the basement surface is deeper towards the east. The bolson fill deposits have a thickness of 250 to 1,100 meters, except in the eastern end where they are up to 2,000 meters thick. In this section the gravity profile has been continued into the United States to the Diablo Platform of West Texas. The gravity low in the eastern end of this section is probably a continuation into Mexico of the Hueco Basin of West Texas that has a similar thickness of bolson fill deposits.

From coordinates 157,000 to about 168,000, the interpretation, with the assumed densities, results in a thickness of bolson fill deposits that extends to a depth greater than the known basement surface. As in section 1, the gravity profile in this part is influenced by different rock types within the basement with a density smaller than the assumed 2.7.
There is a broad area in the western half where the basement is at a shallow depth and a very thin sedimentary section is shown; except for two grabens where there are 1350 and 2450 meters of sediments. With the exception of places where there are outcrops of igneous rockes, the western half of this section is covered by a thin layer of low density sediments.

SECTION 3

The eastern half of Plate VII shows basins 14 to 13 kilometers long separated by basement highs, with thicknesses of sediments ranging from 750 to 1900 meters, having a thickness of 3,500 meters around coordinate 230,000. The bolson fill deposits range in thickness from 200 to 1,125 meters; these deposits are not as thick toward the eastern end as in sections 1 and 2. Around coordinate 235,000 there is an intrusion of igneous material which has caused a complex structure shown by the surface geologic outcrops. From coordinates 195,000 to about 203,000 the interpretation again results in a thickness of bolson fill deposits extending to a depth greater than the basement surface, as indicated by the dotted line. The densities of the basement rocks in this part are probably smaller than the assumed 2.7.
From coordinates 165,000 to 190,000 the basement surface is very shallow and except in two grabens, there is a very thin sedimentary section. On the western end there is a basin 18 kilometers long with a thickness of sediments of 2,500 meters, 500 of which are of bolson fill type.

SECTION 4

This short section (Plate VIII) was chosen where the results of the aeromagnetic survey indicated the greatest thickness of sediments.

The basement is at 3,500 to 4,400 meters below sea level and the surface of the earth is at 1,150 to 1,200 meters above sea level. Thus we have 4,600 to 5,600 meters of sediments. There are two valleys filled with bolson fill deposits with thicknesses from 400 to 650 meters.
SUMMARY AND CONCLUSIONS

In general the area of study can be divided into zones with relatively shallow and deep basement. These are:

a) a broad western area with a highly disturbed geologic pattern and very thin or no sedimentary section, b) an eastern part of a relatively thick sedimentary section with up to about 5,000 meters of sediments in the southeastern portion of the area, and c) an interruption within area b with outcrops of igneous rocks and a very thin sedimentary section.

The gravity data in this study was basic to the interpretation of the subsurface geology between the surface of the earth and the magnetic basement. The major gravity anomalies are caused by density differences between the rocks which form the ridges and those which fill the valleys between them. Since there are no published density values for any of the sediments in the area it was necessary to assume densities on the basis of the general lithology and by trial calculations where relatively good gravity and geologic control was available. From these considerations the principal gravity anomalies are accounted for by the calculated thicknesses of bolson fill and pre-Cenozoic rocks, obtained with assumed
densities of 2.7 for the basement rocks, 2.6 for the pre-
Cenozoic sequence and 2.0 for the bolson fill.

Four geologic sections based on surface geology, gravity
and magnetic basement show the major features of the geology
of the area. These sections are illustrated along profiles
running approximately NW-SE across the area.
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APPENDIX

General Stratigraphy of Northern

Chihuahua
The only outcrops of Paleozoic rocks that have been mapped and described occur in the northwestern part of the area. These sediments were described by Ings. Teodoro Diaz and Arsenio Navarro (1964) and the stratigraphic units were zoned and correlated with sediments of similar age that occur in the Big Hatchet Mountains of southwestern New Mexico (Zeller, 1965).

MISSISSIPPIAN

Keating Formation: 33 meters of finely crystaline, dark gray limestones with abundant chert at some stratigraphic levels (Diaz and Navarro, 1964).

Paradise Formation: 107 meters of sediments distinctly separated into two members. The lower member consists of 90 meters of shale with a few interbeds of limestone; the upper member consists of about 17 meters of gray limestones (Diaz and Navarro, 1964).
PENNSYLVANIAN

On top of the Paradise Formation and separated by an unconformity, the base of the Pennsylvanian consists of 35 meters of conglomerates and conglomeritic sands (Diaz and Navarro, 1964).

Horquilla Formation: Overlying the conglomerates, 1035 meters of fine-grained, gray limestones were measured near the Palomas area. Beds of chert modules are scattered throughout the unit, sometimes reaching a thickness of four to six meters. The boundary between the Upper Pennsylvanian and Lower Permian is not well-defined in the Horquilla Formation. The upper part may be Lower Permian in age (Diaz and Navarro, 1964).

PERMIAN

Earph Formation: 215 meters of gray, thin bedded, finely crystalline limestone and dolomite that has a few thin interbeds of shale and gypsum (Diaz and Navarro, 1964)

Colina Formation: 185 meters of gray, medium-to thick-bedded limestones that in its upper part has interbeds of limestones and shales (Diaz and Navarro, 1964).

Epitaph Formation: 475 meters of sediments that can be separated into two members. The lower member consists of 155 meters of gray, silty shales with interbeds of dolomite, sandstone, conglomerates, and breccia. The upper member consists of 320 meters of gray, fine-grained dolomites with interbeds of sandstones and shales (Diaz and Navarro, 1964).
MESOZOIC

JURASSIC

Surrounding the Sierra de Samalayuca, south of Ciudad Juarez; and in the Sierra de la Alcaparra, east of Villa Ahumada, about 70 meters of Jurassic rocks have been measured. These outcrops consist of limestones, conglomeritic sands, and shales (ing. A. Madrid, Personal Communication). Underlying the Cretaceous, in the southeastern part of the area, there are outcrops of evaporites of unknown thickness. Most of these evaporites consist of gypsum and shale (Haenggi, 1966).

CRETACEOUS

Above the evaporites there is a 130 meter sequence of claystones with interbedded sandstone and limestone. Walter T. Haenggi (1966, p. 36) proposed the term Navarreta for this formation.

Vigas Formation: This formation consists of about 1,000 meters of sediments that can be separated into two members. A lower member consisting of 550 meters of sandstone, conglomeritic sand, and shale; and an upper member which consists of 450 meters of very fine to fine-grained sandstone, interbedded with shale and siltstone (Haenggi, 1966).

Cuchillo Formation: In the El Curevo area, the Cuchillo Formation consists of 490 meters of dark gray shale with minor interbeds of dark limestone and sandstone (Haenggi, 1966).

Benigno Formation: In the El Curevo area, the Bluff Formation consists of 250 meters of sediments that can be separated into two members. The lower member is the lateral
equivalent of Cuchillo-Formation, and the upper member is
the stratigraphic and lithologic equivalent of the Benigno-
Formation (Haenggi, 1966).

Cox-Lagrima Formation: In the southeastern part of
the area, the Cox Formation consists of three members of
varying thickness. The lower member is made up of about 590
meters of alternating beds of sandstone to dominant lime-
stone; westward, there is a transition from dominant sand-
stone to dominant limestone. This stratigraphic equivalent
of the Cox Formation in the West has been given the name
Lagrima. The middle member is comprised of 30-130 meters
of limestone with interbeds of shale. The upper member
consists of about 60-130 meters of interbeds of limestone,
shale, sandstone and marl (Haenggi, 1966).

Benevides Formation: 200 meters of sediments that
can be divided into two members. The lower member consists
of 115 meters of shale and limestone. The remaining 85 meters
which make the upper member consist of gray, fine-grained
limestone with interbeds of dark shale. At some places there
is a resistant reef-forming limestone between the upper and
lower members (Haenggi, 1966).

Loma Plata Formation: 280-590 meters of gray, massive
limestone with interbeds of shale (Haenggi, 1966).

Del Rio Formation: This formation consists of from
5-67 meters of light gray, caleareous shale and claystone
with local interbeds of limestone and siltstone (Haenggi,
1966).
Ojinaga Formation: 650 meters of grayish green, calcareous shale with interbeds of siltstone and limestone in the lower half (Haenggi, 1966).

El Picacho Formation: This Upper Cretaceous formation consists of about 85 meters of yellowish, massive, gypsiferous marl (Haenggi, 1966).

CENOZOIC

IGNEOUS ROCKS

After the Cretaceous Period the western part of the area was subjected to intense igneous activity; As a result, there are many outcrops of intrusive and extrusive igneous rocks. Outcrops of these rocks are confined to the western and southwestern part of the area. The most common types of rock are rhyolitic tuff, andesite porphry and rhyolite porphyry.

SEDIMENTARY ROCKS

Lacustrine, fluvial, and aeolian deposits, the results of erosion of high areas, were deposited as alluvial fans or in the valleys between the mountains. The material composing these deposits ranges widely in size and composition, depending on the type of rock being eroded (Underwood, 1963).

Along the Rio Bravo, the stratigraphy of Cenozoic and Quaternary rocks has been described by students at the University of Texas. Nichols (1958) in the Sierra de Los Fresnos area, measured 10 meters of tuff and tuffaceous conglomerate with layers of sand at its base, and a 4.5 meter
thick layer of phorphyritic rhyolite underlined by about 137 meters of tuff. Harwell Jr. (1959), in the Sierra del Porvenir area, measured 100 meters of volcanic glass, alternating in some places with thin sandstone layers overlying the upper part of the Cox sandstone of Cretaceous age. Along the eastern flank of the mountains he measured 73 meters of pebble and cobble conglomerate.

QUATERNARY

There are great portions in the area mapped as alluvium which is made of the youngest products of the erosion of high areas. There is a wide range in composition and size of this material. Gravel, sand, silt, and clay, mostly flood plain and valley fill deposits. This type of deposits have been found to be as much as 50-feet thick locally in wells drilled in southeastern New Mexico. In other places along the border of Mexico with the United States the thickness of the alluvium ranges from 80 to 220 feet (Underwood, 1963).

Two wells drilled in southwestern New Mexico (see Plate 1), showed great thicknesses of bolson fill and probably low density material similar to those found in the valleys between the ridges in the area of study. The first, located in Township 255, Range 6W, drilled through 1052 meters of this type of sediment. The second located in Township 215, Range 10W, drilled through at least 1723 meters; the drilling was stopped before the bottom of the low density layer was reached (Wengerd, 1962).