Geophysical Studies in the Yuma Area, Arizona and California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 726-D

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By R. E. MATTICK, F. H. OLMSTED, *and* A. A. R. ZOHDY

GEOPHYSICAL FIELD INVESTIGATIONS

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Geophysical studies, including gravity, aeromagnetic, seismic-refraction, seismic-reflection, and resistivity surveys, of the Yuma area, Arizona and California, in support of a geohydrologic investigation

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By R. E. MATTICK, F. H. OLMSTED, and A. A. R. ZOHDY

ABSTRACT

During 1963-67, gravity, aeromagnetic, seismic-refraction, seismic-reflection, and resistivity surveys were made in the Yuma area, Arizona and California, in support of a geohydrologic investigation by the U.S. Geological Survey. The primary object of the geophysical study was to investigate the regional geology, particularly the gross distribution and thickness of Cenozoic sediments, which contain the major aquifers.

The following major structural features in the area were revealed by the study.

1. Shallow channels into bedrock beneath the Gila River where it crosses the Gila and Laguna Mountains at the Gila River narrows and beneath the Colorado River where it crosses the Chocolate and Laguna Mountains between the Laguna and Imperial Dams. Between these dams on the Colorado River, a channel has been incised into rocks of the basement complex to a depth of about 600 feet and filled with Cenozoic sediments. At the Gila River narrows on the Gila River, a channel has been incised into Tertiary breccia and conglomerate (of undetermined thickness) to a depth of 320 feet, and the fill consists chiefly of alluvium.
2. A significant trough west of the Gila Mountains, designated the Fortuna basin, that is estimated to contain about 16,000 feet of Cenozoic sediments, the lower seven-eighths of which is pre-Colorado River marine and nonmarine deposits.
3. A shallow extension of the Fortuna basin, designated the Picacho-Bard basin, that extends northwest between the Cargo Muchaco and Chocolate Mountains and has considerable basement relief.
4. A multiple-crested basement high, designated the Yuma basement high, extending roughly southward from Yuma and comprising two main parts: the northern part, associated with basement outcrops, and the southern part, associated with basement rock at depths of less than 100 feet. Geophysical data in the vicinity of the Yuma basement high show that considerable basement relief, probably resulting from a highly complex fault pattern traversing a buried erosion surface, is associated with this high.
5. A basement high centered on a row of basement outcrops on the southerly international boundary, designated the Boundary basement high, and separated from the Yuma basement high by a deep, broad saddle.
6. A deep basin along the southerly international boundary, south of the Yuma basement high and west of the Boundary basement high, estimated to contain about 13,500 feet of Cenozoic sediments and designated the San Luis basin.
7. A trough west of the Yuma basement high designated the Yuma trough.

In addition, the top of the Bouse Formation (Pliocene) was mapped in most of the studied area. The top of the Bouse Formation is important because it is an indicator of the maximum amount of deformation in post-Bouse time (the time since the Colorado River entered the Yuma area) and because this horizon may be considered as the effective floor of the main part of the ground-water reservoir.

A lineament in the magnetic data and a gravity nose north of Somerton are interpreted as reflecting right-lateral movement along the Algodones fault, a major northwest-trending fault in the Yuma area and a possible branch of the San Andreas fault system. A westward offset of the southern part of the Yuma basement high relative to the northern part of the high can also be explained by right-lateral movement on a parallel fault. Seismic-refraction data at the south end of the Yuma basement high reveal that the basement on the southwest side of the Algodones fault is downthrown 350 feet, and gravity data about one-half mile farther south suggest an additional 1,000 feet of throw on a parallel fault.

INTRODUCTION

Beginning in 1963 and continuing intermittently through 1967, geophysical surveys were made to obtain subsurface information in support of a geohydrologic investigation of the Yuma area by the U.S. Geological Survey. Results of the geohydrologic investigation are given by Olmsted, Loeltz, and Irelan (1973); results of the geophysical surveys are summarized in the present report.

The area studied is in the southwest corner of Arizona and the southeast corner of California, about 70 airline miles north-northeast of the mouth of the Colorado River (fig. 1). An initial regional gravity survey was made in 1963, and an aeromagnetic survey was made in 1964. In the years 1964-67, seismic-refraction and seismic-reflection profiles, resistivity soundings and profiles, and detailed gravity surveys were made at selected places to complement the earlier regional work. Gravity observations cover an area of about 900 square miles (most of the area of investigation shown in fig. 1), and the aeromagnetic survey covers an area of about 300 square miles in the southwest corner of Arizona.

The gravity and aeromagnetic surveys were directed by D. R. Mabey, and the seismic-refraction surveys by

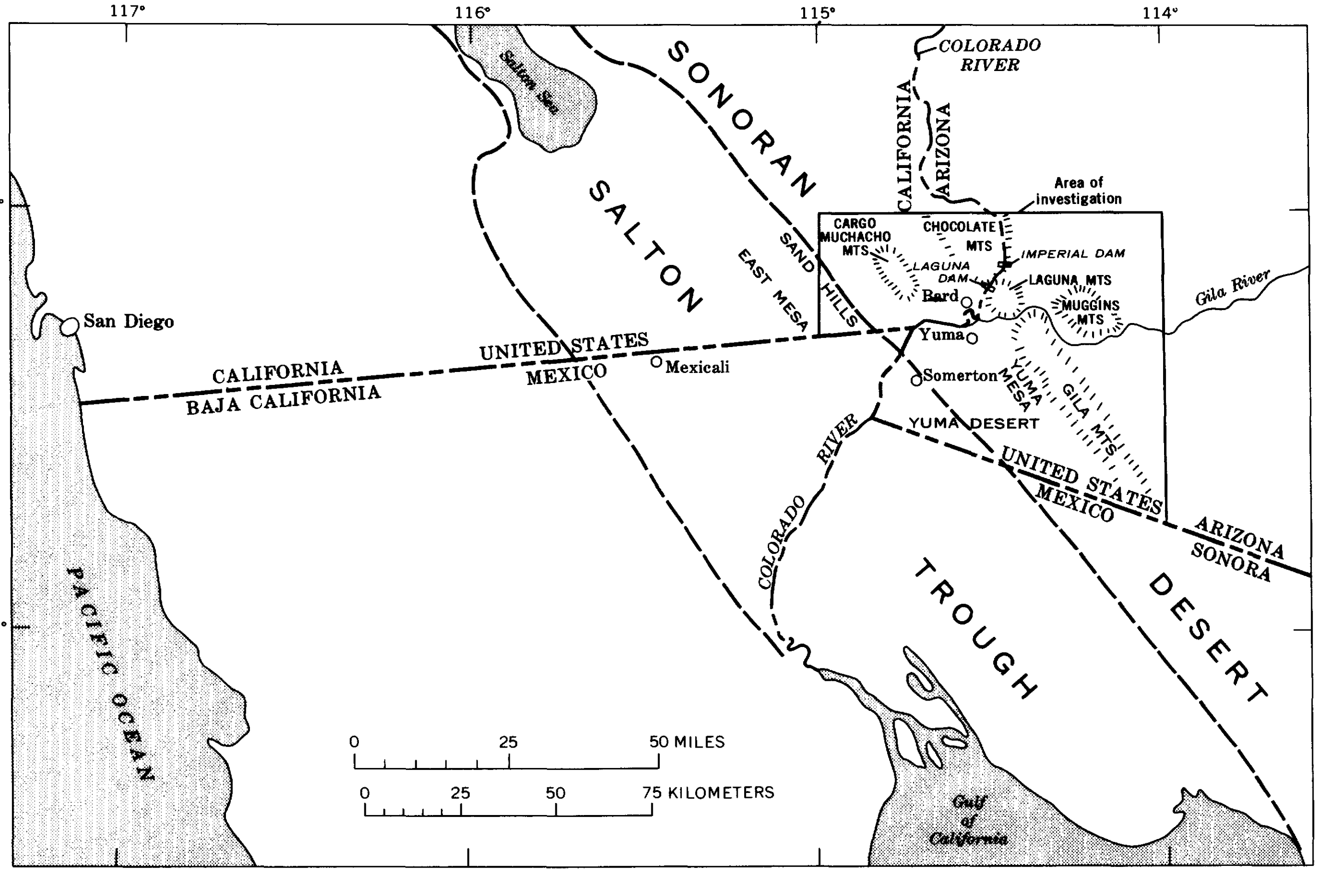


FIGURE 1. — Map of the lower Colorado River region, showing location of the Yuma area and part of the boundaries (dashed lines) of the Salton Trough and Sonoran Desert sections of the Basin and Range physiographic province (from Fenneman, 1946).

R. E. Mattick and J. S. Watkins. The resistivity surveys were made and interpreted by A. A. R. Zohdy and D. B. Jackson, and part of the seismic-reflection survey was made by J. C. Roller. Some of the gravity observations were made by Arthur Conradi, Jr., and D. L. Peterson. Geologic studies were made by F. H. Olmsted as part of the geohydrologic investigation.

The gravity and aeromagnetic surveys were used primarily to investigate the regional geology, particularly the gross distribution and thickness of the Cenozoic sediments, which contain the major aquifers. Seismic and resistivity surveys were used to obtain more detailed information in local areas or along profiles. Test wells drilled for or by the U.S. Geological Survey, the U.S. Bureau of Reclamation, and various oil companies provided valuable information on the thickness and character of the geologic units and were used as control in interpreting the geophysical data.

In addition to the geophysical studies by the U.S. Geological Survey, seismic-reflection surveys were made in 1965 and 1966 by General Atomic Division of General Dynamics Corp. (in 1966 subcontracted to Rogers Explorations, Inc.), under contract to the U.S. Bureau of Reclamation. These surveys were made in support of a special joint geohydrologic study by the U.S. Geological Survey, the U.S. Bureau of Reclamation, and the U.S. Section of the International Boundary and Water Commission. Results of the joint study were described by Herschel Snodgrass (written commun., 1965) and R. D. Davis (written commun., 1966), and their data form the basis of some of the interpretations in the present report.

GEOLOGY

PHYSICAL FEATURES

The area of investigation lies along the east side of the Salton Trough section and along the west margin of the Sonoran Desert section of the Basin and Range physiographic province (Fenneman, 1946). (See fig. 1.) The city of Yuma, near the center of the studied area, is located near the junction of the Colorado and Gila Rivers, near the apex of the Colorado delta. The area is characterized geomorphically by broad desert plains and river flood plains, above which rise low but rugged mountains. The main features, described briefly in the following paragraphs, are shown in figure 1.

The Colorado River enters the main part of the Yuma area through a gap about 1 mile wide between the Laguna and Chocolate Mountains and then flows across its recent flood plain, which widens southwest of Yuma to form the broad, low, fan-shaped subaerial part of its delta. The Gila River enters the main part of the area through a similar gap between the Gila and Laguna Mountains and then flows westward across its flood plain to join the Colorado Rovier just east of Yuma. The river flood plains are bordered by terraces and piedmont slopes — the broad desert plains. The desert plains and river flood plains range in elevation from about 90 feet at the southwest corner of Arizona to about 1,000 feet at the base of the Chocolate Mountains.

With a few exceptions, the southwestern part of the Sonoran Desert east of Yuma is characterized by elongate low mountain ranges trending generally about north-northwest (N. 20°-40° W.). This average structural grain seems to continue farther west; but regional subsidence has occurred in the Salton Trough and bordering area, and as a result, only the summits of some of the mountain blocks now extend above the surrounding alluvial fill; other blocks are completely buried and are revealed only by geophysical data and test drilling.

Average summit elevations of the main mountain masses are less than 2,000 feet above sea level; the maximum elevation within the area of investigation is 3,150 feet, in the southeastern Gila Mountains. Although the total relief is small compared with that of many other parts of the Basin and Range province, slopes on exposures of plutonic, metamorphic, and volcanic rocks in the mountains are steep, locally exceeding 40°. Data from test wells and geophysical surveys indicate that some of the buried slopes of these rocks are equally steep.

MAJOR ROCK UNITS

For the purpose of the present study the rocks are grouped into the following major rock units: (1) Basement complex, composed of metamorphic, plutonic, and dike rocks (pre-Tertiary); (2) nonmarine sedimentary rocks (Tertiary); (3) volcanic rocks (Tertiary); (4) older marine sedimentary rocks (Tertiary); (5) Bouse Formation (younger marine sedimentary rocks of Pliocene age); (6) transition zone (Pliocene); (7) conglomerate of Chocolate Mountains (Tertiary and Quaternary); and (8) alluvium deposited by the Colorado and Gila Rivers and their tributaries, and minor windblown deposits (Pliocene to Holocene). The inferred stratigraphic relations of these units are shown in figure 2, and their surface extent, on plate 1.

The pre-Tertiary basement complex consists of a variety of igneous and metamorphic rocks, of which granitic rocks and various kinds of gneiss and schist are most abundant. The entire complex has been invaded by dikes and sills composed chiefly of pegmatite, aplite, and now-altered fine-grained mafic rocks. A distinctive

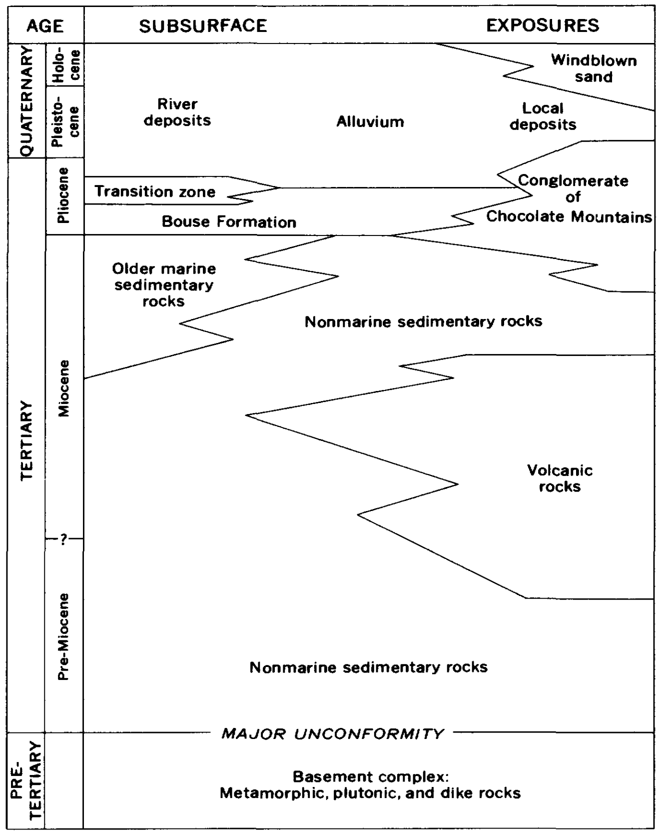


FIGURE 2. — Stratigraphic relations of the major rock units in the Yuma area.

porphyritic quartz monzonite, locally gneissic and containing large phenocrysts (or porphyroblasts) of potassium feldspar and irregular patches and streaks of fine-grained biotite, is perhaps the most widespread basement rock type. This rock constitutes virtually all the detritus in some of the coarse breccia and conglomerate in the Tertiary nonmarine sedimentary rocks.

The ages of most of the basement rocks are unknown, although all these rocks appear to predate the Late Cretaceous to early Tertiary Laramide orogeny. The only two radiometric dates available are for the porphyritic quartz monzonite from a locality at Yuma. Biotite from this rock gave a rubidium-strontium age of 73 m.y. (million years) (Wasserburg and Lanphere, 1965), but zircon from the same locality yielded a uranium-lead age of 1,440 m.y. (L.T. Silver, written commun., 1968). The zircon age (Precambrian) probably reflects the time of original crystallization, whereas the biotite age (Late Cretaceous) appears to indicate Laramide metamorphism. Some of the dikes and sills, and possibly some irregular small intrusive bodies, may be earliest Tertiary but, for convenience, are grouped with the pre-Tertiary basement complex.

The Tertiary nonmarine sedimentary rocks are exposed in parts of the mountains and hills, and they un-

TABLE 1. — *Depths of Tertiary and pre-Tertiary horizons in wells in the Yuma area*

[Location of wells shown on pl. 1. Leaders (.......) indicate not penetrated; query (?) alone indicates that penetration is questionable; with figures, that depth is questionable. USGS LCRP, U.S. Geological Survey lower Colorado River project test well; USBR, U.S. Bureau of Reclamation test well]

Well No.	Name of well or owner	Land surface elevation (ft)	Total depth (ft)	Depth, in feet, to top of unit: Transition zone	Bouse Formation	Older marine sedimentary rocks	Nonmarine sedimentary rocks	Basement complex	Remarks
DH-1	USGS LCRP 14	155.1	505	....	209	....	471	....	
2	USGS LCRP 23	143.8	715	....	548	....	687	(?)	Possible basement complex at 703 ft.
3	Tanner Paving Co.	195	396	....	....	....	(?)	....	Possible nonmarine sedimentary rocks at 207 ft.
4	Gila Valley Oil & Gas Co. Kamrath 1.	145	2,140	....	422	....	482	....	
5	USBR CH-6	140.5	501	....	422	....	497	....	
6	B. Palon	423	603	....	....	....	....	563	
7	do	395	1,085	....	700	....	....	1,082	
8	USBR CH-704; USGS LCRP 29.	150.8	1,997	794(?)	1,045	1,396	....	....	Top of transition zone may be at 885 ft.
9	USBR CH-8RD	128.5	360	....	(?)	....	....	....	Basalt 342-360 ft. Possible Bouse Formation at 328 ft.
10	San Carlos Hotel	145	173	....	....	....	173	....	Granite boulder at 173 ft.
11	Yuma School District No. 1	175	404	....	....	....	(?)	....	Possible nonmarine sedimentary rocks at 280 ft.
12	Abe Marcus Pool	175	478	....	....	....	(?)	470	"Granite" at bottom. Possible nonmarine sedimentary rocks at 300 ft.
13	S & W Ranches	141	191	....	....	....	....	190	Do.
14	Stardust Hotel; USGS LCRP 13.	197	1,090	....	....	....	....	1,085	Porphyritic quartz monzonite at bottom.
15	Sinclair Oil Co. Kryger 1	120	1,400	....	(?)	....	1,243	1,398	"Granite" at bottom. Possible Bouse Formation at 972 ft.
16	Yuma County Fairgrounds	212	306	....	....	....	....	292	Do.
17	USGS LCRP 26	125.4	1,777	1,033	1,115	....	1,380	....	
18	Arizona Public Service Co.	117	978	(?)	....	....	....	....	Bottom in alluvium or transition zone.
19	USGS LCRP 28	118.7	2,466	1,927	....	....	....	....	
20	Colorado Basin Associates Elliott 1.	110	3,277	....	....	....	....	1,431	Drilled 1,846 ft into granitic basement.
21	Old oil test	118	730	....	....		....	730	Reported in Kovach, Allen, and Press (1962).
22	USBR CH-21YM	188	285	....	....	....	....	267	Cored porphyritic quartz monzonite.
23	USGS auger hole	195	90	....	....	....	....	90	
24	do	196	79	....	....	....	....	79	
25	USBR CH-20YM	196	64	....	....	....	....	47	Cored porphyritic quartz monzonite.
26	USGS LCRP 25	204.6	2,318	2,101	....	....	....	....	
27	Colorado Basin Associates Federal 1.	170	6,007	2,367	3,112	3,802	4,937(?)	....	Top of nonmarine sedimentary rocks may be at 4,302 ft.
28	M. P. Stewart Co. Federal 1.	181	3,660	(?)	(?)	(?)	....	....	Possible transition zone at 1,748 ft; possible Bouse Formation at 2,515 ft.
29	USGS LCRP 17	94	2,946	2,514	....	....	....	....	
30	Yuma Valley Oil & Gas Co. Musgrove 1.	90	4,868	2,525	3,395	4,350	....	....	
31	USBR CH-28YM	577.5	1,427	1,285	....	....	....	....	

derlie most of the alluvium beneath the desert plains and river flood plains. This unit is composed of strongly to weakly indurated clastic rocks ranging from mudstone and shale (in part, of lacustrine origin) to megabreccia and boulder conglomerate. Fanglomerate, composed of angular to subrounded clasts of igneous and metamorphic rocks of local origin, seems to be the most widespread type.

The Tertiary nonmarine sedimentary rocks have an upper surface with at least several hundred feet of local relief and overlie a basement surface of even greater relief. The maximum thickness of this unit is not known, but at least 5,000 feet of the unit is exposed in both the Chocolate and the Laguna Mountains, and the aggregate stratigraphic interval exposed in these mountains may be more than 10,000 feet.

The Tertiary volcanic rocks, exposed most extensively in the Chocolate Mountains, are interbedded with the nonmarine sedimentary rocks. Included in this unit are tuffs and flows ranging in composition from basalt or basaltic andesite to rhyolite. Although an aggregate thickness of more than 2,000 feet is exposed in the Chocolate Mountains, the only known subsurface occurrence of this unit is an altered basalt penetrated at a depth of 342-360 feet in well DH-9, 3 miles north of Yuma (table 1).

Potassium-argon dates for several of the volcanic rocks from the Chocolate and Laguna Mountains range from 23 to 26 m.y. (Olmsted and others, 1973); a middle Tertiary age is therefore indicated for the volcanic rocks and associated nonmarine sedimentary rocks.

The older marine sedimentary rocks are composed of somewhat indurated fine-grained sandstone and interbedded siltstone and claystone. Their age is uncertain, but their stratigraphic position suggests that they probably intertongue with the upper part of the nonmarine sedimentary rocks of Tertiary age. The older marine sedimentary rocks occur entirely in the subsurface in the Yuma area; they have been penetrated in wells DH-8, DH-27, and DH-30, and possibly in DH-28 (table 1). The maximum known thickness of this unit within the area of well information is about 1,000 feet.

The Bouse Formation is a younger marine unit exposed in parts of the Colorado River valley north of the Yuma area (Metzger, 1968), but except for one small exposure near Imperial Dam (fig. 3), it occurs only in the subsurface within the area of the present investigation. The Bouse Formation is more extensive than the underlying older marine sedimentary rocks and represents the deposits of a marine embayment that existed after the mountains and basins had assumed approximately their present outlines (fig. 3). The unit consists of silt and clay, which contain thin interbeds of find sand, hard calcareous claystone, and, locally in the basal part, limy sandstone or sandy limestone, tuff, and, possibly, conglomerate of local provenance. Invertebrate fossils indicate a marine to brackish environment but are not diagnostic as to age. However, stratigraphic position (Metzger, 1968; Olmsted and others, 1973) indicates that the Bouse Formation is Pliocene.

Because of the usefulness of the top of the Bouse Formation as an indicator of the maximum amount of deformation in post-Bouse time (the time since the Colorado River entered the Yuma area) and because this horizon may be considered as the effective floor of the main part of the ground-water reservoir, a special effort was made to determine the configuration of this surface (fig. 3). Subsurface data from test wells, summarized in table 1, were supplemented by interpretations of geophysical data discussed later in this report. The known thickness of the Bouse Formation ranges from zero, where it pinches out or has been removed by erosion, to about 1,000 feet, in the southwestern part of the area.

Throughout the central and southern parts of the study area, the Bouse Formation is overlain by a transition zone of intertonguing marine and nonmarine (fluvial) strata. The base of this transition zone is marked by the lowest stratum of identifiable alluvium from the Colorado River; the top, by the uppermost bed of fossiliferous marine clay or silt. The greatest known thickness of the transition zone, in the southwestern part of the area, exceeds 850 feet.

The conglomerate of the Chocolate Mountains occurs on the flanks of the Chocolate Mountains, near the north-central margin of the study area. Volcanic detritus makes up most of the unit, which includes strata probably equivalent to both the upper part of the Tertiary nonmarine sedimentary rocks and the lower part of the alluvium. This unit has not been identified in any wells in the area.

The alluvial deposits range from clay to cobble and boulder gravel; sand is the predominant fraction at most places. Clay and silt constitute less than 20 percent of the total thickness at most places, but they are somewhat more abundant in the lower part of the unit, below depths of 1,500 feet. Cementation is uncommon, except in some of the beds of well-sorted gravel and coarse sand in the southwestern part of the area and in finer grained deposits beneath parts of the "Upper Mesa" (pl. 1) in the southeast. The alluvium contains most of the usable ground water of the Yuma area and includes gravel beds that yield copious quantities of water to irrigation, drainage, and supply wells.

REGIONAL STRUCTURE

The area of investigation includes parts of both the southwest margin of the Sonoran Desert and the northeast margin of the Salton Trough, a landward extension of the Gulf of California (fig. 1). These two physiographic units differ somewhat, both in the trend of their structural features and in the time of their latest structural activity.

The southwestern part of the Sonoran Desert east of Yuma is characterized generally by long, narrow mountain ranges separated by more extensive desert plains. The mountain ranges, most of which are oriented north-northwest, are elevated or tilted blocks bounded by steep faults; the intervening desert plains are basins containing thick Cenozoic fill (Thornbury, 1965). The mountains are composed chiefly of pre-Tertiary plutonic and metamorphic rocks, although Cenozoic volcanic and minor sedimentary rocks are locally extensive (Wilson, 1960). The mountains and basins of the southwestern Sonoran Desert appear to have been outlined by structural activity consisting chiefly of extensive faulting and tilting in middle Tertiary and earlier time. Later movements have consisted chiefly of minor warping and normal faulting and of probable regional subsidence near the west margin of the area, adjacent to the Salton Trough.

The Salton Trough, which contains most of the Colorado River delta, is a deep basin which subsided rapidly during Cenozoic time and accumulated as much as 20,000 feet of fill, most of it nonmarine (Biehler and others, 1964). In contrast to the Sonoran Desert, the Salton Trough has been tectonically active to the present time. The trough is traversed at actue angles by northwest-trending faults of the San Andreas system, on which the major component of movement has been right-lateral (Crowell, 1962). The Gulf of California — the southern extension of the Salton Trough — has been interpreted as having been formed by oblique rifting across the fault system (Hamilton, 1961) and probably also by ocean-floor spreading (Larson and others, 1968). The trend of the faults of the San Andreas system is somewhat more northwesterly than that of the mountains of the Sonoran Desert and their bordering faults, but the two trends may converge toward the southeast, in Sonora, Mexico.

The northeasternmost major fault in the San Andreas system in the Yuma area, which was identified and named the Algodones fault by Olmsted, Loeltz, and

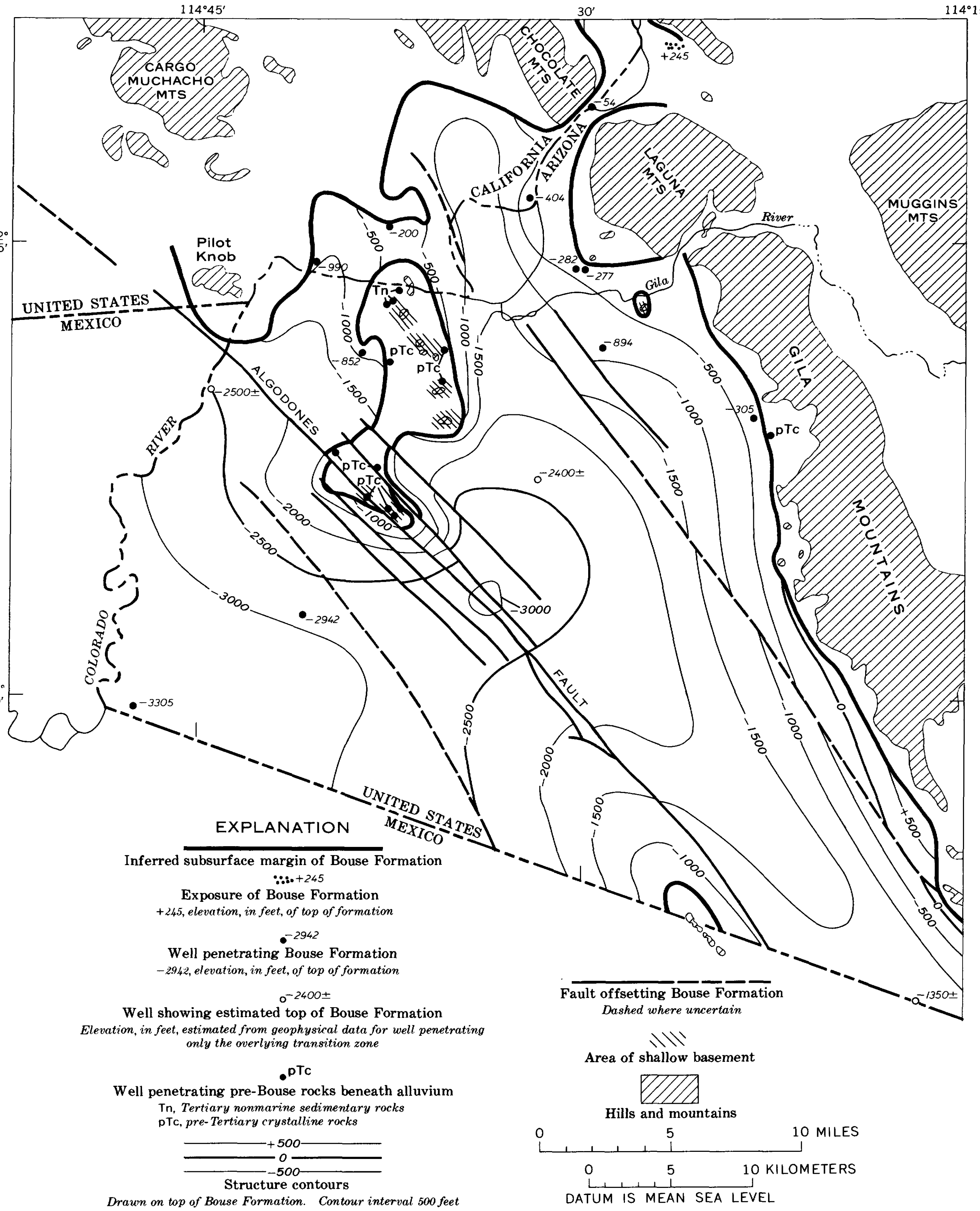


FIGURE 3. — Map of the Yuma area, showing inferred extent and configuration of the top of the Bouse Formation.

Irelan (1973), crosses the area of the present study diagonally (pl. 1). This fault, which may be a continuation of the San Andreas fault to the northwest, as interpreted by Dibblee (1954), is a feature of major hydrologic significance in the Yuma area.

PHYSICAL PROPERTIES OF MAJOR ROCK UNITS

Physical properties of rocks pertinent to the geophysical investigation include density, magnetic properties, electrical resistivity, and acoustic or seismic velocity. Laboratory measurements of these properties were not made as part of the present investigation, but field measurements and other sources of data were available from which reasonable estimates could be made; these estimates are summarized in the following paragraphs.

DENSITY

Density measurements have been made by the U.S. Geological Survey and the U.S. Bureau of Reclamation as part of their ground-water studies of the Yuma area, and data are also available from nearby areas. Kovach, Allen, and Press (1962, table 2) reported that the densities of 33 surficial samples of plutonic and metamorphic rocks of the basement complex from the Colorado delta region range from 2.40 to 2.92 g cm $^{-3}$ (grams per cubic centimeter) and average 2.67 g cm $^{-3}$. Two cores of porphyritic quartz monzonite from wells DH-22 and DH-25 (table 1), south of Yuma, have densities of 2.7 and 2.6 g cm $^{-3}$, respectively (U.S. Bur Reclamation, unpub. data, 1966) — close to the average value for basement rocks reported by Kovach, Allen, and Press (1962).

The bulk density of saturated Cenozoic sediments, from five wells in the Colorado River delta region, averages 2.37 g cm $^{-3}$ for well samples obtained from depths of 0-4,000 feet, 2.44 g cm $^{-3}$ for samples from 4,000-8,000 feet, and 2.47 g cm $^{-3}$ for samples from 8,000-12,000 feet (Kovach and others, 1962, table 2). The average density value of 2.37 g cm $^{-3}$ for samples from 0-4,000 feet appears to be substantially higher than the average density value for surface or near-surface unconsolidated alluvium of the Yuma area; in general, the data of Kovach, Allen, and Press (1962) probably apply to deposits deeper than about 1,000 feet rather than to surface or near-surface unconsolidated alluvium. In the Yuma area, 25 samples of sand, silt, and clay obtained by the Geological Survey from near-surface alluvium have a grain density that ranges from 2.66 to 2.81 g cm $^{-3}$ and averages about 2.7 g cm $^{-3}$ (Olmsted and others, 1973); the bulk density ranges somewhat widely, owing to variations in porosity, but probably averages about 2.0 g cm $^{-3}$ (which corresponds to an average porosity of about 41 percent). This value of 2.0 g cm $^{-3}$ for the near-surface alluvium in the Yuma area agrees with the average value for similar deposits obtained by the Bureau of Reclamation in the Phoenix, Ariz., area 150 miles to the northeast. According to Earl Komie (oral commun., 1969), near-surface samples of unconsolidated alluvium in the Phoenix area have densities that range from 1.71 to 2.20 g cm $^{-3}$ and average 2.01 g cm $^{-3}$.

The density data are summarized in figure 4; the graph shows the average density contrast, as a function of depth, between basement rock (assumed density of 2.67 g cm $^{-3}$) and Cenozoic sediments.

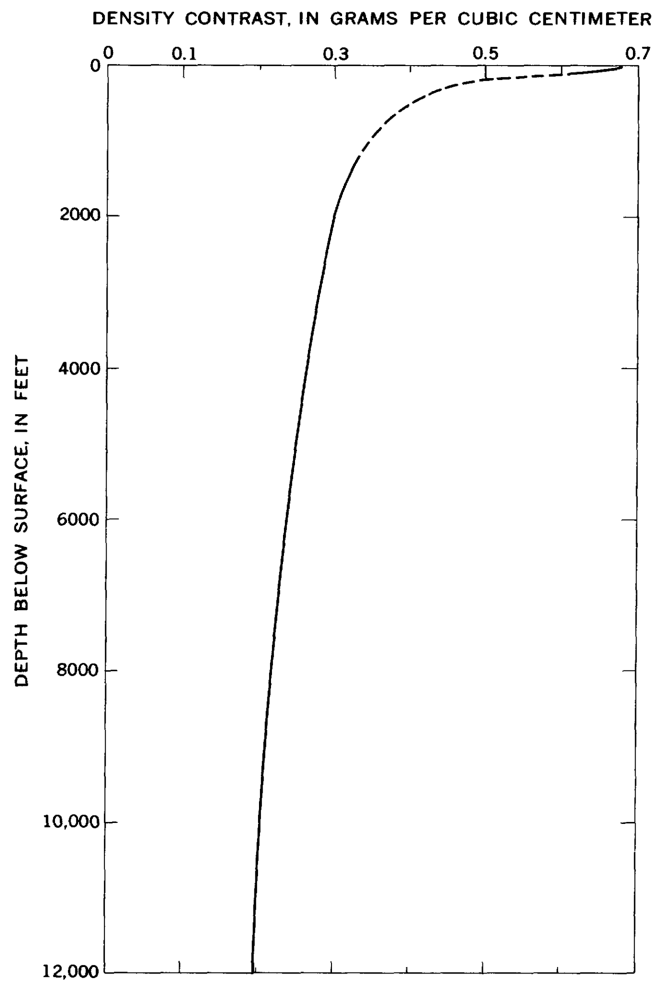


FIGURE 4. — Average density contrast, as a function of depth, between basement rock (assumed density of 2.67 g cm $^{-3}$) and Cenozoic sediments. Data for 1,000-12,000 feet are from the Colorado River delta region, as reported by Kovach, Allen, and Press (1962). Dashed lines indicate sufficient data are not available to show density contrast.

For purposes of interpreting thicknesses of Cenozoic sedimentary deposits, we have used the vertical density distribution shown in figure 4. Although these data rely heavily on the work of Kovach, Allen, and Press (1962), who were dealing with stratigraphic units that differ somewhat from those present at depth in the Yuma area, the density distribution in figure 4, which appears to be attributable to compaction of Cenozoic sediments with depth, probably is applicable to the Yuma area.

The effects of lateral density variations within the Cenozoic sediments are neglected in the present report, even though this neglect may give rise to local errors in depth estimations. The effects of lateral density variations within the pre-Tertiary basement rocks are considered linear along the various profiles and are removed or partly removed in subtracting a linear regional gradient along profiles that extend from basement outcrop to basement outcrop.

MAGNETIC PROPERTIES

Magnetic properties of rocks in the region have not been measured, but depth analyses based on magnetic data (Vacquier and others, 1951) do not involve assumptions of the magnetization and are not strongly dependent on the type of magnetization. For interpretive purposes, the sedimentary rock in this area is assumed to be virtually nonmagnetic, and all magnetic anomalies are attributed to the basement complex or to Tertiary volcanic rocks.

ELECTRICAL RESISTIVITY

Correlation of electric and geologic logs of test wells with electrical soundings indicates that resistivity values for unconsolidated sandy and gravelly alluvium generally range from about 20 to 40 ohm-m (ohm-meters). Electric logs indicate values of 50-60 ohm-m for beds of somewhat cemented gravel and 100-250 ohm-m for more strongly cemented gravel beds in test wells DH-29 and DH-30, southwest of Somerton, Ariz. Local zones of about 1,000 ohm-m have been mapped by electrical soundings beneath parts of Yuma Mesa, but these values are exceptional and represent dry sand and cemented gravel above the water table.

Electric-log data from wells penetrating the Bouse Formation indicate that this unit is highly conductive; resistivity values for the clay and silt (the predominant fractions) range from 2 to 5 ohm-m and average about 3 ohm-m. Electric logs of wells DH-8, DH-27, and DH-30 show that the siltstone and claystone beds in the underlying older marine sedimentary rocks have even lower resistivities (commonly in the range of 1-3 ohm-m), probably owing to the more saline water generally present in this unit, but the interbedded soft sandstone has resistivities of about 8-15 ohm-m. Because sand (or sandstone) is much more abundant in the older marine sedimentary rocks than in the Bouse Formation (more than half the total thickness, as compared with less than one-fifth), the average resistivity of the older marine sedimentary rocks is greater than that of the Bouse Formation, despite the fact that the older unit probably contains more highly saline water.

The resistivity of the Tertiary nonmarine sedimentary rocks varies widely, depending on the salinity of the interstitial water. In much of the northern part of the area, electric logs of test wells and electrical soundings recorded values of 15-30 ohm-m (pl. 2) — approaching those cited for the sandy and gravelly alluvium. The cementation and lower porosity of the Tertiary deposits (which tend to increase the formation resistivity) largely offset the effect of the slightly more saline water they contain (which tends to decrease the formation resistivity). Farther south, however, the nonmarine sedimentary rocks contain warm saline water, and the formation resistivity is correspondingly low, despite the overall coarseness of the unit. In well DH-27, the coarse-grained beds (probably fanglomerate) that were penetrated near the bottom of the hole, below a depth of 5,800 feet, have an average resistivity of about 3 ohm-m; a few thin beds, probably cemented, have a resistivity of about 6 ohm-m.

Rocks of the basement complex generally have a resistivity of more than 300 ohm-m, as recorded on resistivity curves from deep electrical soundings.

These data are summarized in table 2.

TABLE 2. — *Summary of resistivity data from selected wells and electrical soundings*

Rock unit or subunit	Resistivity (ohm-m)	
	Range	Average
Alluvium	....	30, with local variation
Clay	3-10	....
Sand and gravel	20-40	....
Partly cemented	50-60	....
Strongly cemented	100-250	....
Sand and cemented gravel (above water table)	>1,000	....
Bouse Formation	....	3
Clay and silt	2-5	....
Older marine sedimentary rocks	....	8
Siltstone and claystone	1-3	....
Sandstone	8-15	....
Nonmarine sedimentary rocks	3-30	Local variation
Basement complex	....	>300

ACOUSTIC VELOCITY

Velocity data for the rocks of the Yuma area are available from the seismic-refraction surveys and from acoustic-velocity logs of wells DH-17 (about 3 miles west of Yuma) and DH-31 (near the southeast corner of the study area). Data from the log of DH-17 (pl. 2) are summarized in table 3.

These velocities are in good agreement with velocity data obtained from a seismic-refraction survey about one-half mile south of DH-17, which recorded velocities of 6,700 fps (feet per second) for the alluvium and 12,800 fps for the fanglomerate and megabreccia. (See fig. 19.) (Owing to probable anisotropy, one would not expect the acoustic-log velocities, which are measured in a vertical direction, to correspond precisely with the seismic-refraction velocities, which are measured along horizontal paths.)

Because the Bouse Formation is characterized by an average velocity lower than that of the overlying alluvium, the top of this important unit could not be delineated by seismic-refraction techniques. For this reason, seismic-reflection surveys were used to map this horizon.

TABLE 3. — *Acoustic velocities of major rock units penetrated in well DH-17*

Rock unit or subunit	Depth (ft)	Acoustic velocity (fps) Range	Average
Alluvium	0-1,033	5,200-10,200	7,500
Transition zone	1,033-1,115	6,400-10,400	8,000
Bouse Formation:			
Clay, silt, and sand	1,115-1,343	5,500- 7,400	6,500
Tuff(?)	1,343-1,352	8,500- 9,300	9,000
Limestone	1,352-1,380	9,500-11,400	10,500
Nonmarine sedimentary rocks:			
Fanglomerate	1,380-1,665	10,600-15,500	13,000
Megabreccia	1,665-1,777	10,100-20,400	13,700

Basement velocities of 14,000-18,000 fps were measured along several seismic-refraction profiles in the Yuma area. Basement outcrops in the vicinity of these profiles imply that velocities of 14,000-16,000 fps probably represent granitic rocks and that velocities of 17,000-18,000 fps probably represent gneiss and schist.

GEOPHYSICAL SURVEYS

GRAVITY SURVEY

In the vicinity of Yuma about one gravity station per square mile was established. This density was adequate to define most of the larger gravity anomalies. Outward from Yuma the station density decreases, and over much of the surveyed area only the more extensive gravity features are defined (pl. 1). About 7 miles south of Yuma the density was increased to about two stations per square mile to define a local basement high.

Most of the gravity stations are located where elevation control is available from topographic maps or at bench marks, section corners, or road intersections. Positional control for the remaining stations was obtained by either transit or altimeter surveys.

The gravity data were reduced to the simple Bouguer anomaly by standard techniques. The data are referenced to base station WU 7 in Golden, Colo. (Behrendt and Woollard, 1961). A density of 2.67 g cm^{-3} was assumed in making the Bouguer correction. Terrain corrections have not been applied, but the terrain effect is not significant except at a few stations on or adjacent to the larger mountains. The relative Bouguer anomaly values probably are accurate to within 0.5 mgal (milligal).

AEROMAGNETIC SURVEY

Aeromagnetic data were obtained along 29 flightlines spaced about one-half mile apart, flown 1,000 feet above the ground surface, and oriented N. 37° E. The magnetic survey was made with an ASQ-8A magnetometer in the tail boom of a Convair aircraft. The flightpath of the aircraft was recorded by a gyrostabilized continuous-strip-film camera. The magnetic data were compiled relative to an arbitrary datum at a 1:62,500 scale, and the contour map was reduced to a 1:125,000 scale (pl. 3).

RESISTIVITY SURVEY

The resistivity equipment consisted of a 2.5-kilowatt generator for power supply, a pulser for stepping up the impressed voltage and regulating the current, a potentiometric chart recorder for recording the potential difference, and more than 20,000 feet of cable for connecting the electrical equipment to the electrodes, which were stainless steel rods 2 feet in length and three-fourths inch in diameter. The maximum electric current put into the ground was about 1.2 amperes, and the smallest potential difference measured was about 0.01 millivolt.

Electrical soundings were made using both symmetric Schlumberger and bipole-dipole equatorial arrays (Berdichevskii and Petrovskii, 1956; Dakhnov, 1953; Kunetz, 1966; Zohdy and Jackson, 1968). Electrode spacings reaching 10,000 feet allowed exploration to depths exceeding 7,000 feet. To detect lateral variations, horizontal profiling was employed.

Resistivity profiles across a basement high south of Yuma were made for comparison with the other geophysical surveys of this feature (profiles *c-c'* through *f-f'* on pl. 5). Profiles were also made across the inferred trace of the Algodones fault south of Yuma (profiles *g-g'* through *k-k'* on pl. 5). In addition, lines of electrical soundings were made near Bard, Calif. (profile *b-b'* on pl. 1), and along the border with Sonora, Mexico (profile *a-a'* on pl. 1).

SEISMIC-REFRACTION SURVEY

Seismograms were recorded on photographic paper using a 12-channel HTL 7000B seismograph, and for most of the fieldwork, a constant geophone spacing of 820 feet was used. Profiles ranged in length from about 1,000 feet to 8 miles; for the longer profiles the scheme for shooting each profile was as follows: First, a 9,020-foot geophone cable with 12 geophones was laid along one end of the profile, and the *P*-waves propagated from buried dynamite charges that were exploded at each end of the profile were recorded. Then the geophone cable was moved forward 9,020 feet, and the previously used shotpoints at each end of the profile were reloaded and reshot. This procedure of moving the cable and reshooting at the same shotpoints was continued until the entire distance along a profile was covered. In addition, intermediate shots at 9,020-foot intervals were used to record velocity changes in the near-surface materials. The dynamite charges ranged from 5 to 100 pounds and were loaded in holes drilled to depths of 10-40 feet.

In general the resulting field seismograms were of good quality and showed easily identifiable first arrivals. The traveltimes from shotpoint to seismometer were picked to the nearest 0.001 second, and traveltime curves were constructed for each profile. Velocities were determined by visual fitting of straight-line segments to the traveltime data, and because there was little relief along the profiles, no elevation corrections were applied. The intercept time of the first velocity horizon was between 0.010 and 0.100 second on all the traveltime curves. This intercept time, or weathering correction, is attributed to a thin surface layer of dry, unconsolidated, low-velocity material often referred to as the weathering layer. Corrections for the weathering layer, assuming a velocity of 2,000 fps, were applied to the traveltime data prior to making depth calculations. The base of the weathering layer probably corresponds to the top of the water table. The graphical interpretation method of Slotnick (1950) and the time-depth method of Hawkins (1961) were used in calculating depths and dips of the refracting horizons. Some of the final interpretations were checked by fitting theoretical ray paths to the computed models.

The seismic-refraction surveys were made to supplement the information obtained from the gravity and magnetic surveys and, particularly, to determine the nature and thickness of sedimentary fill in alluvial gaps through which ground water moves. Nine profiles were made, and these were numbered 1 through 9 for easy reference (pl. 1). Six of the profiles are across alluvial gaps: (a) between the Laguna Mountains and a low basement ridge east of the Yuma Proving Ground Headquarters (labeled "Yuma Test Station" on pl. 1) (profile 1); (b) between the Laguna and Chocolate Mountains at Laguna Dam (profile 2); (c) between the Gila and Laguna Mountains at the Gila River narrows (profile 3); (d) between Pilot Knob and the Cargo Muchacho Mountains, through which ground water now moves westward from the Yuma area toward Imperial Valley (profile 5); (e) between two basement outcrops in Yuma (profile 7); and (f) between Pilot Knob and an outcrop of Tertiary nonmarine sedimentary rocks (breccia and conglomerate) near the north end of the Yuma basement high (profile 9). Profile 4 is along the suspected northward continuation of a basement high in the vicinity of Yuma. Profile 6, westward from Pilot Knob, was made in an attempt to delineate the buried basement slope and the position and nature of the Algodones fault. Profile 8 is on the south flank of a basement high near Somerton and crosses the inferred trace of the Algodones fault. All the profiles were reasonably successful; the results are described in the section "Interpretation of Structural Features."

SEISMIC-REFLECTION SURVEYS

In early 1965 an attempt was made to record seismic reflections using the same equipment used in the refraction survey. However, these tests produced reflections of very poor quality that were of no value in this investigation. The tests did indicate that more sophisticated instrumentation using nonexplosive energy sources might produce useful data. Later in 1965 the Bureau of Reclamation contracted with the General Atomic Division of General Dynamics Corp. to make a trial seismic-reflection survey. The purposes of the survey were (1) to determine the applicability of that corporation's seismic-reflection system to the problems in the Yuma area, and (2) to make a profile extending southwest from well DH-26, delineating reflecting horizons such as the top of the Bouse Formation (at that time known as "estuarine sediments").

The General Atomic system used arrays of surface-mounted vibrating sources with controlled frequency and pulse width. In the survey, the source arrays were located at ½-mile intervals along the survey line, and geophones were placed midway between the array positions; frequencies used for the seismic signals ranged from 32.5 to 152.5 hertz (Herschel Snodgrass, written commun., 1965). This procedure was repeated until the entire survey line was covered.

Three contiguous or nearly contiguous lines were run southeast of Yuma, starting near well DH-26 (pls. 1, 3, 5). Unfortunately, this well penetrates only the top of the transition zone, not the top of the Bouse Formation nor deeper horizons (table 1). However, by using the observed velocity distribution recorded at well DH-17 (pl. 2) a synthesized seismogram was constructed which permitted a reasonable interpretation of the actual seismogram recorded near DH-26. The top of the Bouse Formation was inferred to be at a strong negative reflection (decrease in velocity below the reflecting interface) at a calculated depth of about 2,500 feet, about 200 feet below the bottom of the well.

Despite some difficulties during the trial survey, the results were encouraging; and in 1966 the U.S. Geological Survey, the U.S. Bureau of Reclamation, and the U.S. Section of the International Boundary and Water Commission recommended an additional seismic-reflection survey. The primary goals of the second survey were to define more adequately the configuration of the top of the Bouse Formation (the effective base of the main ground-water reservoir), the position and nature of the Algodones fault and other faults that might be hydrologically significant, and the configuration of the basement surface. The Bureau of Reclamation contracted with General Dynamics Corp., who then subcontracted with Rogers Explorations, Inc., to make the actual survey. Herschel Snodgrass of General Dynamics Corp., who was in charge of the 1965 survey, assisted with the 1966 survey, which used the same type of equipment and the same general field procedures as were used in the 1965 survey.

The 1966 survey, which was reported by R. D. Davis and Herschel Snodgrass (written communs., 1966), was generally successful, although at some places no usable data were obtained. Profiles were made west of Yuma from well DH-17 to well DH-19, east of Yuma from near well DH-26 to near well DH-2, and south of Yuma in the vicinity of the 1965 survey. As in the 1965 survey, relationships of time to depth were based on velocities observed at well DH-17 and interpolated to well DH-26; as a result, actual depths at locations away from those wells are somewhat uncertain. However, additional well control (such as at wells DH-8 and DH-19) was available at the time of the second survey, and therefore the identity and depth of the reflecting horizons are reasonably well known. The tops of the Bouse Formation, the transition zone, and several other reflecting horizons were successfully traced along the profiles, and the inferred Algodones fault and several other parallel(?) or en echelon(?) faults were identified (pl. 1).

INTERPRETATION OF STRUCTURAL FEATURES

GENERAL STRUCTURAL PATTERN

Major structural features of the Yuma area are delineated by the gravity and aeromagnetic data (pls. 1, 3). Gravity highs are associated with all known exposures of the pre-Tertiary basement complex, and gravity lows, with all areas known to be underlain by thick Cenozoic sedimentary fill. However, large variations in Bouguer anomaly values not related to the distribution of Cenozoic deposits are apparent and are attributed both to variations in the density of the basement rock and to a regional anomaly associated with the Salton Trough.

Bouguer anomaly values of −10 mgal occur at or near basement outcrops at Pilot Knob, at Yuma, and in the central Gila Mountains near the Fortuna mine, but values at other stations at or near basement outcrops (northern Gila Mountains, Muggins Mountains, and southern Gila Mountains) range from −18 to −30 mgal. This range of Bouguer anomaly values for stations over bedrock must reflect, at least in part, mass anomalies within the basement complex. For example, near the Fortuna mine, where the gravity values are about −10 mgal, presumably dense hornblende schist and gneiss are abundant; whereas farther south, less dense leucocratic granite is exposed, and the gravity values for stations near basement outcrops decrease to about −30 mgal.

Gravity surveys in the Colorado River delta region (Kovach and others, 1962; Biehler and others, 1964) have revealed a major regional gravity high presumably associated with a thinning of the crust under the Salton Trough. This regional gravity anomaly probably extends into the Yuma area and gives rise to an east-northeastward decrease in anomaly values across the surveyed area. The regional gradient however, does not appear to be significant, at least in comparison with the amplitudes of local anomalies in the Yuma area.

Superimposed upon the regional anomaly related to the Salton Trough and the gravity anomalies produced by variations in the density of the basement rock are anomalies produced by the density contrast between the Cenozoic sedimentary deposits and the denser, older rocks. In some parts of the area, however, the anomalies produced by Cenozoic rocks are difficult to distinguish from those reflecting intrabasement features, and this difficulty seriously limits the usefulness of the gravity data in studying the subsurface geology, particularly in making quantitative interpretations.

Within the study area the major gravity anomalies and associated structural features revealed by the gravity survey (pl. 1) consist of the following:

1. An elongate north-northwest-trending gravity high coextensive with the Gila, Laguna, and Chocolate Mountains, with a slight gravity saddle at the Gila River narrows and a more pronounced gravity saddle at the Colorado River narrows at Laguna Dam; these saddles reflect alluvial gaps through which ground water moves toward the Yuma area.
2. A pronounced gravity trough west of the Gila Mountains; the associated structural feature is designated the Fortuna basin.
3. An extension of the Fortuna basin anomaly, but of much smaller amplitude, that extends northwest between the Cargo Muchacho and Chocolate Mountains; the associated structural feature is designated the Picacho-Bard basin.
4. A gravity saddle between the Cargo Muchacho Mountains and Pilot Knob that reflects a significant alluvial gap through which ground water now moves westward from the Yuma area toward Imperial Valley.
5. A multiple-crested gravity high extending roughly southward from Yuma and comprising two main parts — the northern part, called the Yuma anomaly, and the southern part, called the Mesa anomaly; the overall associated structural feature is designated the Yuma basement high.
6. A gravity high centered on basement outcrops on the border with Sonora, Mexico, and separated from the Yuma basement high by a deep, broad gravity saddle; the associated structural feature is designated the Boundary basement high.
7. A gravity trough between Yuma and Pilot Knob; its associated structural feature is designated the Yuma trough.
8. A gravity low along the southerly international boundary 5-15 miles east-southeast of San Luis; its associated structural feature is designated the San Luis basin.

In the area covered, the aeromagnetic map (pl. 3) reveals the same major structural features as the gravity map. The Yuma basement high, the Fortuna basin, the Yuma trough, and the San Luis basin all are clearly shown by the magnetic data.

GILA, LAGUNA, AND CHOCOLATE MOUNTAINS

The east margin of the area of investigation is occupied by a mountain chain comprising, from south to north, the Gila, Laguna, and Chocolate Mountains. The Gila Mountains are formed chiefly of pre-Tertiary basement rock: granite in the southern and northern parts, gneiss and schist in the central part. Tertiary sedimentary rocks are exposed extensively in the Laguna Mountains. Tertiary volcanic rocks, of which basaltic andesite or basalt is most extensive, make up most of the exposures in the southern Chocolate Mountains (pl. 1).

The entire mountain chain is characterized by an elongate gravity high caused by a density contrast between the older rocks in the ranges and the less dense younger fill in the adjacent basins. At the few stations near the south end of the Chocolate Mountains, gravity values are lower than at stations farther south, probably owing, in part, to the presence of vesicular basaltic andesite flows overlying breccia and conglomerate in the Chocolate Mountains; both of these Tertiary units are less dense than the pre-Tertiary basement and the Tertiary sedimentary rocks. exposed farther south in the Laguna and Gila Mountains. The gravity high coextensive with the Gila, Laguna, and Chocolate Mountains is intersected at the Colorado River and Gila River gaps by gravity lows, of which the one on the Colorado River at Laguna Dam is the more prominent.

The northward decrease in gravity values at the northeast corner of the gravity coverage may reflect a basin under the Castle Dome Plain; if so, more extensive gravity coverage is needed to adequately define this basin.

Between the Laguna Mountains and the Muggins Mountains to the east a gravity low of about 6 mgal suggests a thickness of about 1,000 feet of Cenozoic deposits. This thickness is based on the density data of figure 4.

Irregularities in the gravity pattern over the area immediately adjacent to the Gila, Laguna, and Chocolate Mountains suggest a basement surface having considerable local relief.

The gap between basement outcrops in the Laguna Mountains and a southeasterly extension of the Chocolate Mountains was explored with seismic-refraction profile 1 (fig. 5). The profile lies about 1½ miles east of the Yuma Proving Ground Headquarters (labeled "Yuma Test Station" on pl. 1) and has a total length of 12,250 feet. The southwesternmost shotpoint is just northeast of an exposure of porphyritic quartz monzonite, and the northeasternmost shotpoint is about 350 feet southwest of an outcrop of gneiss. Gneiss similar to that near the northeast end of the profile crops out in a small hill near the center of the profile.

Two distinct velocity layers were recorded on profile 1; the average recorded velocity through the upper layer is about 5,500 fps between shotpoints 1 and 3, southwest of the central outcrop, and about 6,300 fps between shotpoints 4 and 6, northeast of the outcrop. The thickness of the upper layer is calculated to be about 540 feet near the center of the northeastern trough and about 400 feet near the center of the southwestern trough. The upper part of this 5,500- to 6,300-fps layer is unconsolidated alluvium, but the marine clay and silt of the Bouse Formation may be present in the lower part, as indicated by exposures of this unit about 1½ miles northwest of the profile, at the Yuma Proving Ground Headquarters.

The velocity of the underlying layer is computed to be 12,500 fps between shotpoints 1 and 2, 14,200 fps between 2 and 3, and 13,700 fps between 4 and 6. These velocities could represent either highly fractured or strongly weathered pre-Tertiary basement rocks or nonmarine sedimentary rocks of Tertiary age. Although the velocities are generally lower than those recorded for pre-Tertiary basement rocks elsewhere in the Yuma area, they are within or at least partly within the range of velocities for coarse-grained nonmarine sedimentary rocks of Tertiary age (breccia and conglomerate). Such Tertiary rocks are not exposed along the profile but do crop out less than a mile northwest of the northeast end of the profile (pl. 1). Fractured and brecciated basement does occur at several places within the Laguna Mountains.

Seismic-refraction profile 2 (fig. 6) extends across the Colorado River gap between the Laguna and Chocolate Mountains just upstream from Laguna Dam. Slightly to moderately fractured and weathered porphyritic quartz monzonite basement rock is exposed at both abutments of the dam, about a mile apart. Test well DH-1, drilled to a depth of 505 feet near the center of the profile, penetrated alluvium to a depth of 209 feet, Bouse Formation from 209 to 471 feet, and fanglomerate (Tertiary nonmarine unit) from 471 feet to the bottom of the hole.

Because shotpoints 1 and 2 are close to basement outcrops, all arrivals shown on the time-distance plot are assumed to represent basement refractions. A standard time-delay method was used to calculate the basement velocity and basement depth at each geophone (Hawkins, 1961). The basement velocity was calculated to be 15,700 fps, and a channel-fill velocity of 6,500 fps was measured near the center of the profile by means of an additional shotpoint not shown. The resultant cross section is shown in figure 6. The thickness of Cenozoic fill near the center of the alluvial gap is computed to be about 600 feet. An intermediate-velocity layer corresponding to the Tertiary nonmarine sedimentary rocks (fanglomerate) was not identified in the seismic data; therefore, the computed depths to basement, at least near the center of the profile, probably are too shallow. The small gravity low at the Colorado River gap between the Laguna and Chocolate Mountains (residual anomaly of about 3 mgal on pl. 1), however, is consistent with the 600-foot thickness of Cenozoic fill interpreted from the seismic data. There is no gravity evidence of a significantly greater thickness of fill in the area between Laguna Dam and Imperial Dam.

Seismic-refraction profile 3 (fig. 7) was recorded across the Gila River gap between the Gila and Laguna Moun-

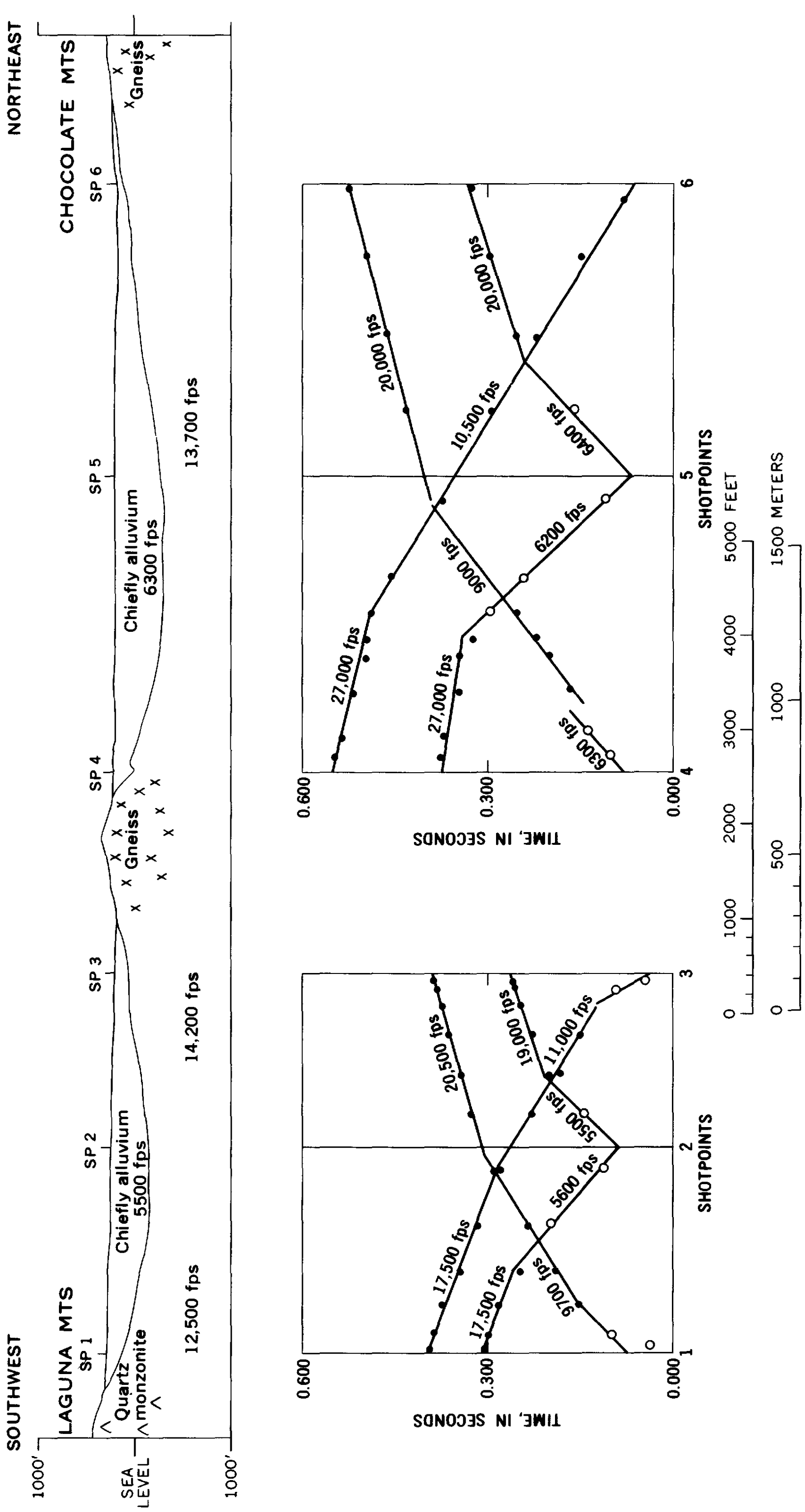


FIGURE 5. — Seismic-refraction profile 1 across gap between basement outcrops of the Chocolate and Laguna Mountains southeast of Yuma Proving Ground Headquarters. SP, shotpoint; circles, alluvium arrivals; dots, bedrock arrivals.

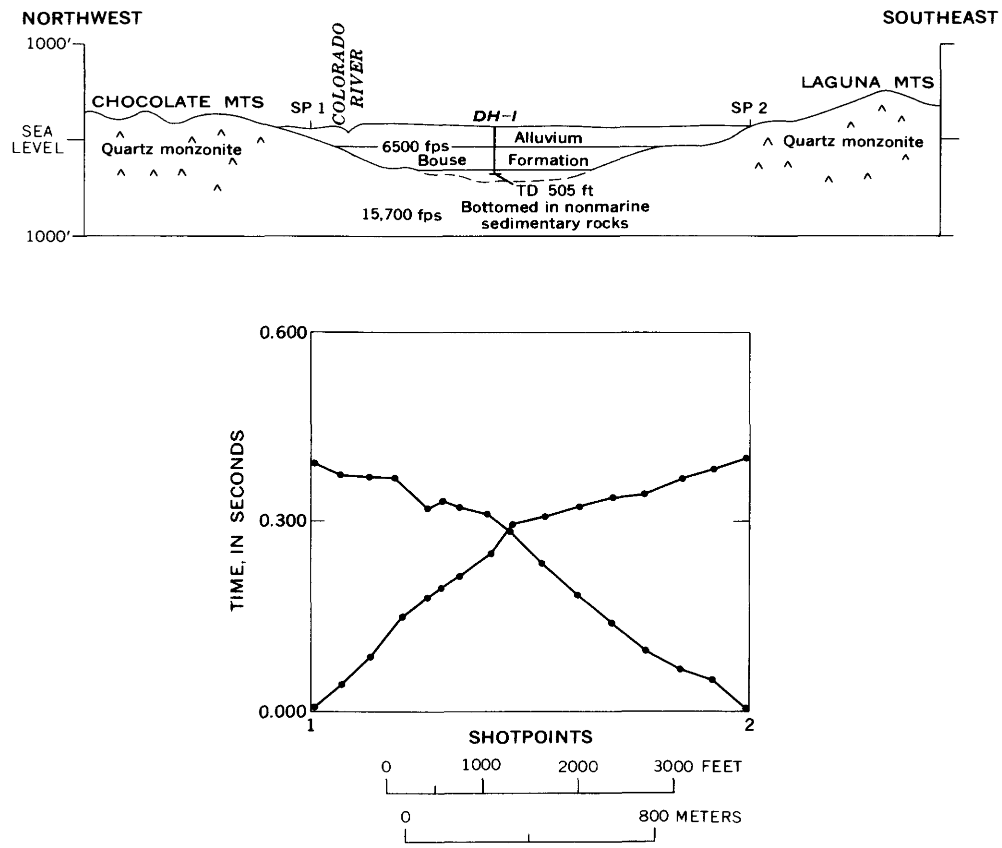


FIGURE 6. — Seismic-refraction profile 2 across the Colorado River gap between the Laguna and Chocolate Mountains just upstream from Laguna Dam. The contact between basement rock and overlying sedimentary rocks is dashed where seismic-refraction interpretation is doubtful. SP, shotpoint; TD, total depth; dots, bedrock arrivals.

tains. Megabreccia and boulder conglomerate (Tertiary nonmarine sedimentary rocks) are exposed at the west end of the profile; pre-Tertiary gneiss, schist, and migmatite are exposed near the east end. A low hill of porphyritic quartz monzonite lies near the center of the profile, on the east side of the Gila River flood plain. Dissected alluvial gravels of local derivation occupy the area between the quartz monzonite hill and the main mass of the Gila Mountains to the east; well DH-3 was drilled to a total depth of 396 feet in the western part of this area.

Beneath the Gila River flood plain, between shotpoints 1 and 2, the velocity of the alluvium is assumed to be about 6,000 fps; the velocity of the underlying refractor is computed to be about 12,000 fps. The maximum thickness of alluvium (which may include the Bouse Formation) between shotpoints 1 and 2 is computed to be about 320 feet. The 12,000-fps layer probably is the breccia and conglomerate exposed west of shotpoint 1. If this interpretation is correct, the contact of the breccia-conglomerate unit and the quartz monzonite must dip steeply and most likely is a fault, as shown in figure 7. The large amount of scatter about the average velocity lines on the time-distance plot (fig. 7) probably reflects a buried surface of Tertiary breccia and conglomerate that is highly irregular.

In the eastern part of the profile, between shotpoints 3 and 5, the near-surface velocity of 6,000 fps undoubtedly represents the exposed coarse alluvium. An underlying layer having a velocity of 10,700 fps probably represents semiconsolidated Tertiary nonmarine sedimentary rocks, which are exposed less than a mile north of the profile and are believed to have been penetrated in well DH-3 below a depth of about 207 feet (table 1).

The deepest refractor between shotpoints 3 and 5 has a calculated velocity of about 15,500 fps and a computed dip of about 12° SE. However, the calculated velocity and dip are based on an updip velocity of 22,400 fps recorded on only a very short segment of geophone spread; hence, the calculated velocity and dip may be erroneous. But even if this calculated velocity is erroneous, the 12,500-fps velocity recorded in the downdip direction is less than the velocity of either gneiss or quartz monzonite, and therefore the basement surface must dip eastward. Near the east end of the profile the eastward slope probably terminates against a steep fault that appears to be a continuation of a fault exposed to the northeast (pl. 1, fig. 7).

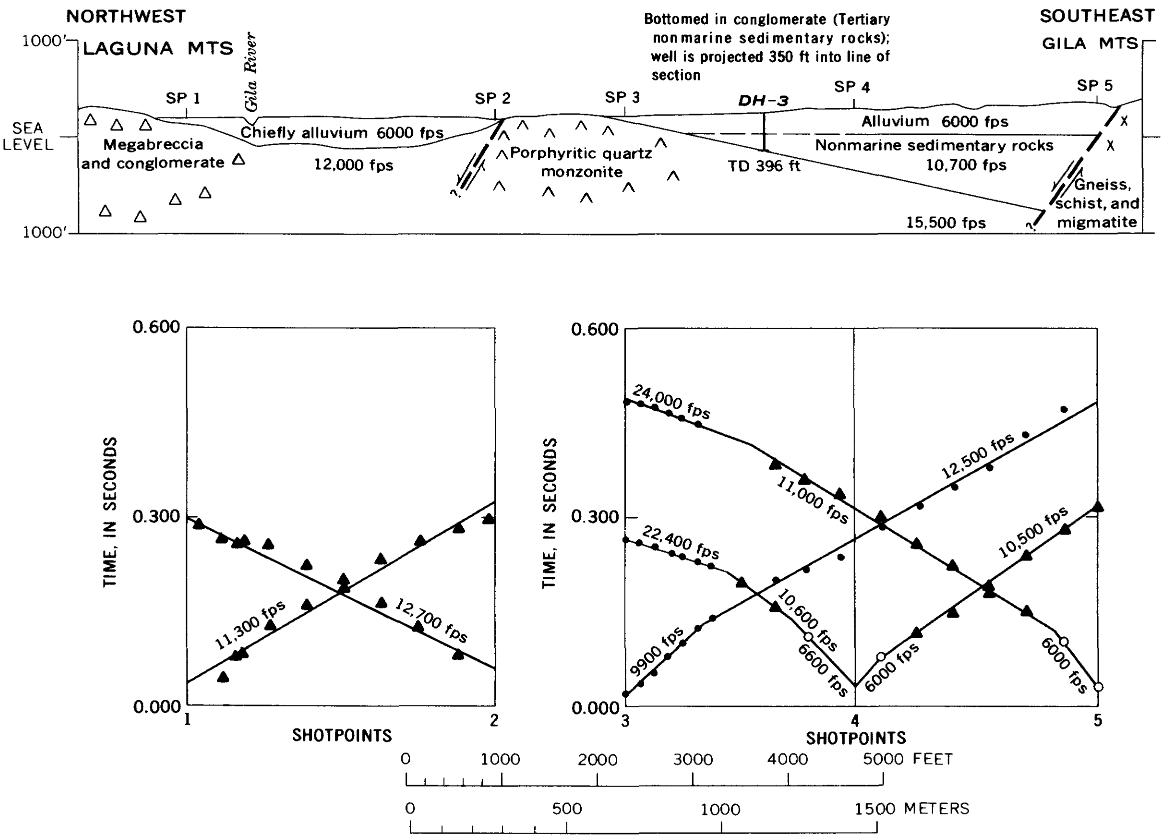


FIGURE 7. — Seismic-refraction profile 3 across the Gila River gap between the Gila and Laguna Mountains. The Gila River flood plain occupies the northwestern part of the profile. SP, shotpoint; TD, total depth; circles, alluvium arrivals; triangles, conglomerate or megabreccia arrivals; dots, porphyritic quartz monzonite arrivals.

FORTUNA BASIN

The most extensive and highest amplitude gravity anomaly within the surveyed area is an elongate low west of the Gila Mountains. This low extends south-southeast from U.S. Highway 80 to the international boundary (pl. 1) and appears to continue into Mexico. The gravity low is interpreted as reflecting a deep basin, here designated the Fortuna basin, which is filled with Cenozoic sedimentary rocks.

The Fortuna basin gravity low actually consists of two closed minimums separated by a northeast-trending saddle. Gravity profile *A-A'* (fig. 8) extends directly east from DH-25 on the Yuma basement high, crosses the north gravity low, and terminates in the Gila Mountains (pl. 1). The maximum amplitude is about −39 mgal. The maximum depth to basement along *A-A'* is computed to be 16,000 feet, assuming a density contrast between Cenozoic sediments and pre-Tertiary basement of 0.44, 0.30, 0.23, 0.20, and 0.19 g cm $^{-3}$ for depths of 0-1,000, 1,000-3,000, 4,000-8,000, 8,000-12,000, and>12,000 feet, respectively. (These assumed density contrasts agree with the data of fig. 4.) Similarly, the south gravity low, which has an amplitude of about −32 mgal relative to the gravity values over the boundary basement high to the west, probably reflects about 13,000 feet of Cenozoic fill. If the assumed density contrast is correct, the Fortuna basin contains the greatest thickness of Cenozoic fill within the area investigated. By comparison, the greatest depth to basement in the Salton Trough, west of the Yuma area, is estimated to be more than 20,000 feet (Biehler and others, 1964) — roughly 25 percent greater than the depth of the Fortuna basin. In the Salton Trough, however, the bulk of the overlying fill consists of alluvial and deltaic deposits of the Colorado River (Muffler and Doe, 1968), whereas in the Fortuna basin, as shown by DH-26 (table 1), only the upper one-eighth of the fill includes equivalent alluvial deposits — the lower seven-eighths consists of pre-Colorado River marine and non-marine deposits. The steep gravity gradients which bound the Fortuna basin anomaly to the east, west, southwest, and north probably reflect highly complex fault patterns in these areas. Over most of the Fortuna basin the gravity data are sparse (pl. 1). Only the approximate amplitude and configuration of the anomalies were recorded, and additional detailed observations would be required to define detailed structure of the basin.

Three lines of gravity stations, including the stations of *A-A'*, cross all or part of the east margin of the Fortuna basin (pl. 1). Faults are inferred by the local steepening of gradients, but continuity is doubtful because the profiles are too far apart. Probably one or more continuous fault zones occur within a few miles of the front of the Gila Mountains (pl. 1, fig. 8). The strike of the fault or fault zone shown on plate 1 is assumed to be north-northwest, the same direction as the trend of the steep gravity gradients and the strike of the nearby faults at the Fortuna mine. The exact location and nature of the faults bounding the Fortuna basin west of the Gila Mountains must remain speculative until more data are obtained.

The exceptionally steep gravity gradient directly west of the Fortuna mine is interpreted as reflecting a local area of high-density basement rock rather than a fault. A considerable amount of dark hornblende schist and gneiss exposed near the mine (Wilson, 1933, p. 189-193) may be the high-density rock causing the steep gradient.

Along the west margin of the Fortuna basin, in the vicinity of the basement outcrops of the northern part of the Yuma basement high, steep gravity and magnetic gradients imply a pattern of north- to north-northwest-trending faults (pls. 1, 3), whereas in the vicinity of the shallow basement rocks of the southern part of the Yuma basement high, gravity, magnetic, and seismic-reflection data suggest a pattern of northwest-trending faults (pls. 1, 3). These fault patterns are discussed further in the section on "Yuma Basement High." Two of these faults, which are associated with steep gravity gradients, are shown in figure 8.

The inferred Algodones fault (pl. 1), probably the major fault bounding the southwest margin of the Fortuna basin, is associated with an exceptionally steep gravity gradient in the vicinity of the Boundary basement high.

Because of the decrease in gravity values at the north end of the Fortuna basin, the basement is inferred to rise generally northward toward the Laguna Mountains and, to a lesser degree, toward the Picacho-Bard basin — a shallower continuation of the Fortuna basin. The sinuous gravity pattern at the north end of the Fortuna basin implies that the basement surface has considerable local relief in that area. The isolated outcrop of basement rock (porphyritic quartz monzonite) located on the prominent gravity nose south of the Gila River and enclosed by the −18-mgal contour appears from the gravity data (pl. 1) to be the high point on a mostly buried ridge of basement extending south from the Laguna Mountains to about the position of U.S. Highway 80.

A prominent magnetic high (pl. 3), a little more than a mile south of the porphyritic quartz monzonite outcrop (peak value 3196 γ), is only partly defined and could represent a body of more magnetic basement. Because of the proximity of this magnetic high to the gravity nose, they may be related to the same feature. An additional possibility is that this magnetic high and a second magnetic high 4½ miles farther west, just east of the confluence of the Gila and Colorado Rivers, reflect buried masses of volcanic rock — as was shown to be the source of the prominent magnetic high at DH-9 (pl. 4).

Seismic-reflection data (R. D. Davis and Herschel Snodgrass, written commun., 1966), together with information obtained from wells DH-4 through DH-8, show a fairly rapid shallowing of reflecting horizons toward the north and northeast sides of the Fortuna basin. The structure contours on the top of the Bouse Formation (fig. 3) illustrate this trend. Two faults were identified on a seismic-reflection profile about 1 and 2 miles south of test well DH-8. The data reveal downthrow to the south on both faults but do not show the strike of the faults; in the absence of other evidence, we assume that these are continuations of inferred range-front faults west of the Gila Mountains trending generally northwest or north-northwest (pl. 1, fig. 3).

In the vicinity of test well DH-26, the seismic-reflection survey recorded the top of the Bouse Formation at an approximate depth of 2,550-2,600 feet (about 2,400 ft below sea level). Farther south, at the international boundary, test well DH-31 penetrated the top of the transition zone at a depth of 1,285 feet (707 ft below sea level) — substantially shallower than it occurs at DH-26 (table 1). Near the east end of the seismic-reflection line, 4½ miles south of DH-26, R. D. Davis (written commun., 1966) reported westerly dips of reflecting horizons — in the opposite direction from the gravity gradient. We interpret these apparently anomalous conditions as indicating that the Tertiary sedimentary rocks older than the Bouse Formation thin rapidly westward against an east-dipping basement surface and that the center of the basin in Bouse and post-Bouse (alluvial) time was northwest of the basement trough. (Compare pl. 1 and fig. 3.)

An additional geophysical interpretation of the west margin of the Fortuna basin is shown by profile *a-a'* (fig. 9), constructed from four deep electrical soundings across the basin eastward from the Boundary basement high. Resistivity data reveal a highly conductive layer of about 3.6 ohm-m resistivity at a computed depth of about 1,200-1,300 feet (fig. 9). The top of this layer appears to be the top of the transition zone, penetrated at 1,285 feet in DH-31; the recorded value of 3.6 ohm-m is in good agreement with the average Bouse Formation resistivity of 3 ohm-m shown in table 2.

A maximum depth to basement of perhaps 10,000 feet at a point about 1 mile west of DH-31 (fig. 9) is inferred from projection of the four electrical sounding depths. Comparison of this depth with the depth of 13,000 feet as calculated from the gravity data farther northeast and

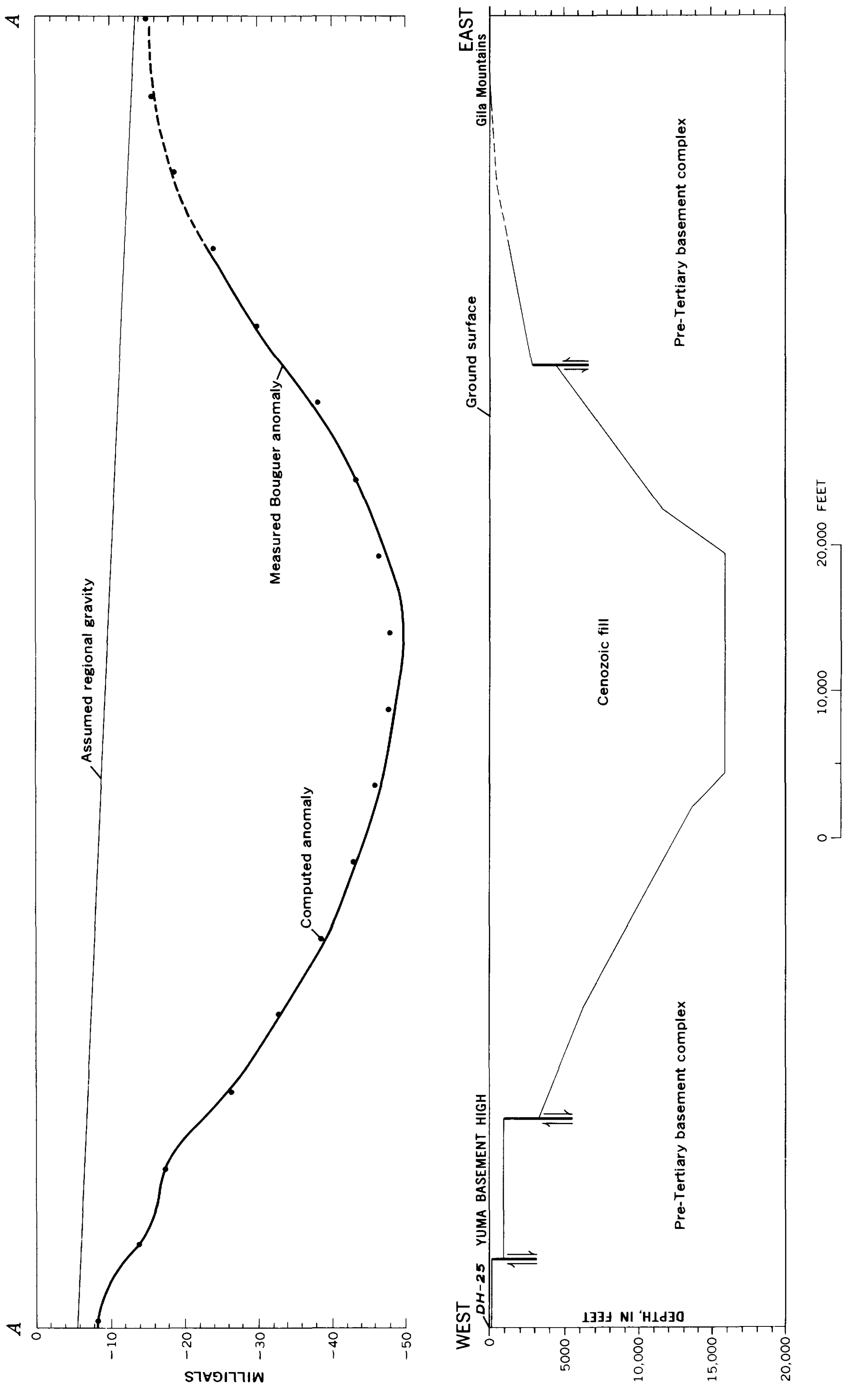


FIGURE 8. — Gravity profile *A-A′* across the Fortuna basin. Contact is dashed where interpretation is doubtful.

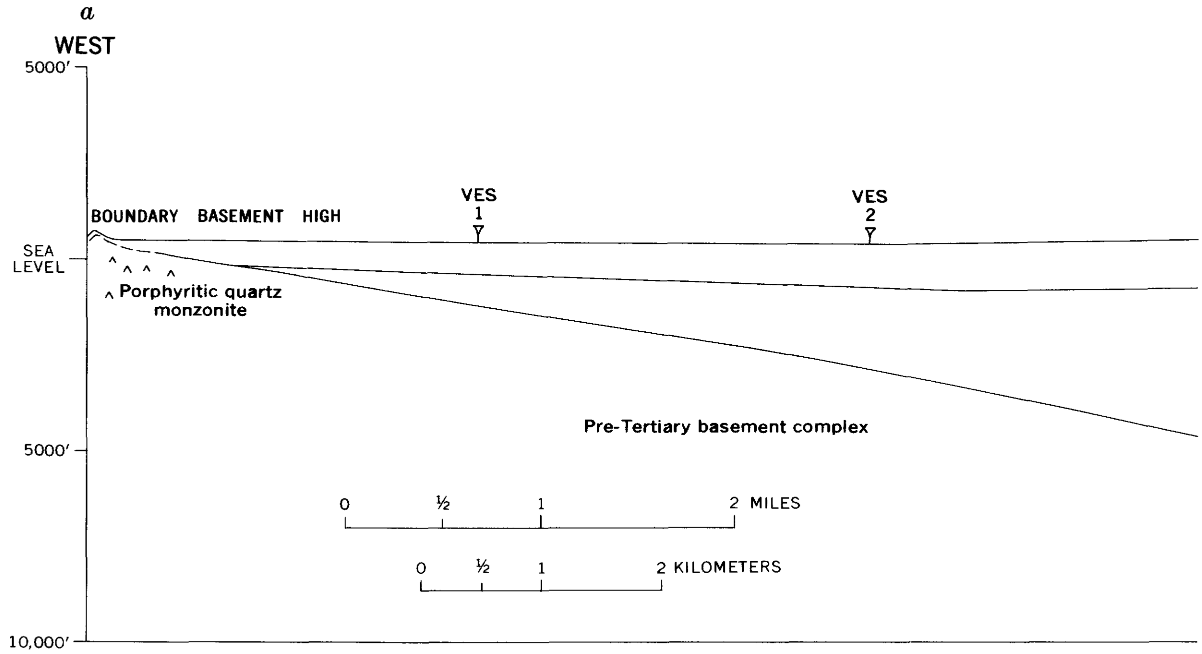


FIGURE 9. — Resistivity profile *a-a′* across the Fortuna basin along the border with Sonora, Mexico, showing interpreted results of four vertical electrical soundings (VES 1 through 4). These soundings were expanded along the line of profile, which is shown on plate 1. TD, total depth.

nearer the center of the gravity low gives reasonable depth agreement between the two geophysical methods.

PICACHO-BARD BASIN

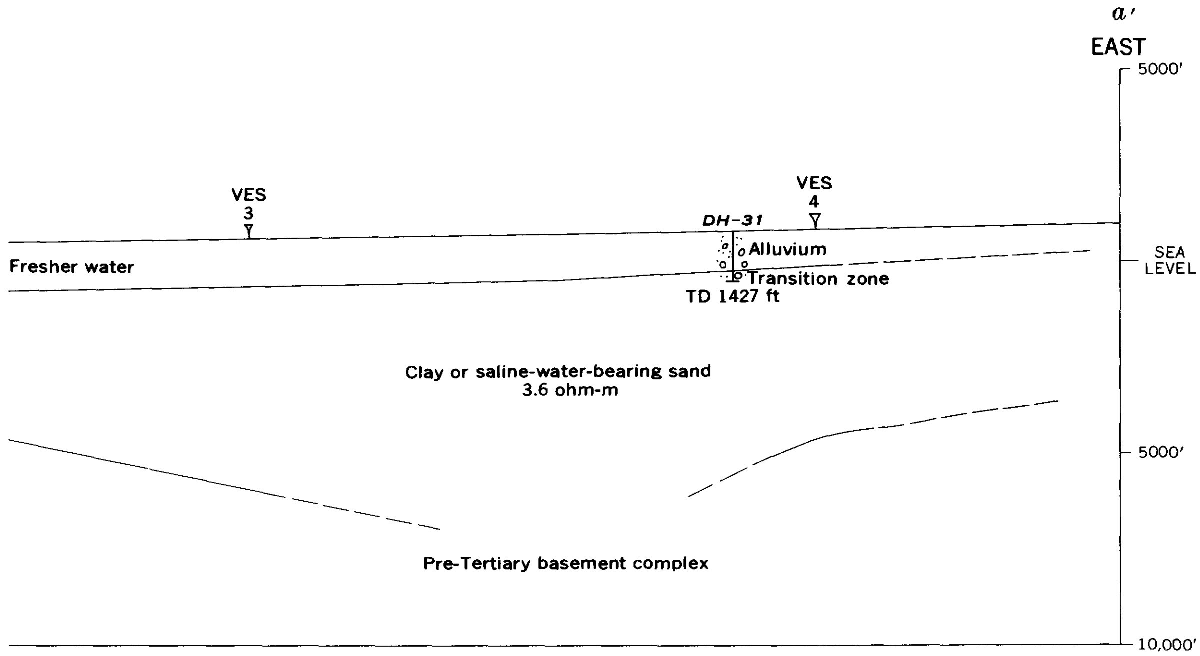
The shallower, northward continuation of the Fortuna basin is herein referred to as the Picacho-Bard basin. The Picacho-Bard basin is bordered on the southwest by the Yuma basement high and its northerly continuation and on the west by the Cargo Muchacho Mountains and their eastern outliers; the Laguna and Chocolate Mountains lie east of the basin.

As discussed in the preceding section, gravity, magnetic, and test-well data reveal a complex pattern of basement topography and rock type near the south margin of the Picacho-Bard basin. The major gravity expression over the basin is a sinuous gravity trough that extends northward and northwestward from the junction with the gravity low over the Fortuna basin. At the southeast end of the Picacho-Bard basin, near the confluence of the Colorado and Gila Rivers, the residual amplitude of the gravity low is about 16 mgal and near the north edge of the gravity coverage the residual amplitude decreases to about 7 mgal, implying that the thickness of Cenozoic fill decreases northward. Many more gravity observations would be required to define the details of the anomaly related to the trough but the general complexity of the gravity pattern suggests a basement surface having considerable relief.

The northwestern part of the Picacho-Bard basin and the northward continuation of the Yuma basement high were explored by means of seismic-refraction profile 4 (fig. 10). Profile 4 extends north-northwest from near the north end of the Yuma basement high, crosses test well DH-9 about 1½ miles north of the reservation, and terminates at an eastern outlier of the Cargo Muchacho Mountains (pl. 1). Test well DH-9 was drilled to a total depth of 360 feet. Alluvium was penetrated to a depth of 328 feet, and basalt, from 342 to 360 feet; the interval from 328 to 342 feet may be the Bouse Formation (table 1).

Granite breccia and conglomerate (Tertiary nonmarine sedimentary rocks) are exposed in a small hill at the south end of the profile, and granodiorite of the pre-Tertiary basement complex is exposed at the north end.

The *P*-wave velocity of the bedrock (fig. 10) ranges from 14,400 to 14,800 fps along the southern part of the profile and from 15,500 to 15,800 fps along the northern part. These velocity ranges probably represent different bedrock types beneath the respective parts of the profile — granite breccia and conglomerate (Tertiary nonmarine sedimentary rocks) to the south and granodiorite (pre-Tertiary basement complex) to the north — in agreement with the rock outcrops at the ends of the profile. Although the seismic data are inadequate for calculating the thickness of the Tertiary nonmarine sedimentary rocks along the southern part of the profile, a rough estimation of the thickness can be made from the gravity values. The residual gravity anomaly in the vicinity of DH-9 is about −10 mgal — equivalent to,

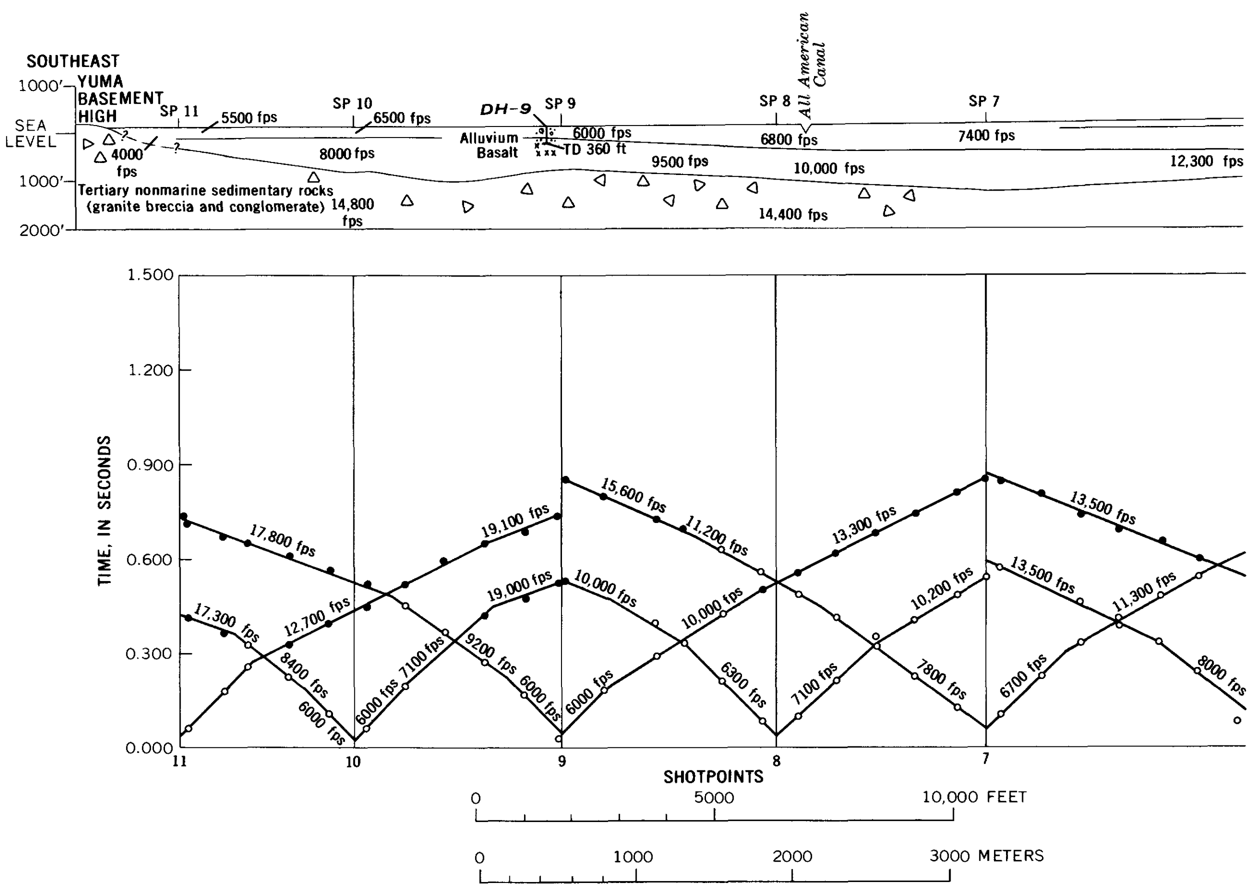


perhaps, 2,300 feet of Cenozoic sediments. This means that the Tertiary nonmarine sedimentary rocks in the vicinity of DH-9 are about 1,400 feet thick, inasmuch as the alluvium in that area is calculated from the seismic data to be about 900 feet thick.

Traveltime data show large lateral and vertical velocity variations in the material overlying bedrock. Along the south half of the profile two distinct layers appear within this material. The upper layer gradually increases in velocity from 4,000 fps near shotpoint 11 (where thickness is about 200 ft) to 8,000 fps near shotpoint 6 (where thickness is about 600 ft). The lower layer increases in velocity from about 8,000 fps near shotpoint 10 to about 12,300 fps near the center of the profile, at shotpoint 6. At DH-9 the upper layer has a velocity of 6,000 fps, and the lower layer, a velocity of 9,500 fps. According to the geologic log of DH-9, alluvial deposits and, possibly, thin Bouse Formation extend to a depth of 342 feet; therefore, the change in velocity recorded at a depth of 250 feet probably corresponds to a change in porosity within the alluvium (a greater porosity associated with the lesser velocity). Another possibility is that the seismic depth is in error and that the 9,500-fps velocity actually represents basalt. If this were so, however, the body of basalt would have to be of great areal extent since the nearby velocities of 10,000-12,300 fps, more than likely, would also represent basalt.

Similarly, two velocity layers overlie the bedrock along the north half of the profile. The upper layer, with a velocity of 3,000 fps, is interpreted as dry alluvium above the water table. The lower layer, which ranges in velocity from 8,000 fps near the center of the profile to 11,000 fps near the Cargo Muchacho Mountains, is interpreted as alluvium with decreasing porosity from south to north.

The Picacho-Bard basin was further explored with six electrical soundings spaced along profile *b-b′*. Profile *b-b′* extends from a point on the continuation of the Yuma basement high near the All American Canal, across the southern part of the Picacho-Bard basin, to the Colorado River one-half mile north of well DH-2 (fig.11). Three layers were detected on the sounding curves — an upper layer, a layer at intermediate depth, and a deep layer. The upper layer, which is interpreted to be alluvium, had a resistivity of 25 ohm-m at sites 3 and 4 and a resistivity of 36 ohm-m at the remaining sites. The more highly conductive intermediate layer was detected on all the sounding curves; the sounding-curve data, however, were inadequate to determine a unique value for the resistivity of the layer. Because of the high conductivity and the presence of Bouse Formation in DH-2 (table 1), this intermediate layer probably is Bouse Formation with a resistivity of about 3 ohm-m — in agreement with the average Bouse Formation resistivity measured on several electric logs of wells in the Yuma area (table 2). The computed depth (650 ft) to the top of the intermediate layer at *b′*, assuming a resistivity of 3 ohm-m, is in reasonable agreement with the depth (548 ft) to the top of the Bouse Formation in DH-2 (table 1) which is located about one-half mile south of *b′*. The third and deepest layer detected on the sounding curves was interpreted as either rocks of the basement complex or granite breccia (Tertiary nonmarine sedimentary rocks). In DH-2 (table 1) Tertiary nonmarine sedimentary rocks were penetrated at a depth of 687 feet, and either rocks of the



basement complex or granite breccia (Tertiary nonmarine sedimentary rocks) was penetrated at a depth of 703 feet.

The previously discussed results of seismic-refraction profile 4 suggest that the deep layer mapped by the resistivity survey beneath *b-b'* (fig. 11) is probably granite breccia (Tertiary nonmarine sedimentary rocks) rather than rocks of the basement complex. The inference that the basement surface is somewhat deeper than the bedrock surface shown in figure 11 and that Tertiary nonmarine sedimentary rocks underlie the Bouse Formation along at least part of the profile is supported by two additional kinds of evidence. Fresh-water-bearing conglomerate occurs in both the basal Bouse Formation and the underlying nonmarine sedimentary rocks in DH-2 (Olmsted and others, 1973). In addition, the seismic-reflection test by General Dynamics Corp. (Herschel Snodgrass, oral commun., 1965) indicates the presence of reflecting horizons significantly deeper than 703 feet near DH-2, although reflecting horizons would not be expected in the breccia either.

The shallow buried bedrock ridge near the west end of profile *b-b'* was inferred from equatorial data of sounding 2 and from sounding 4 (fig. 11). Both soundings were extended perpendicular to the axis of the ridge, so the effect of the ridge as a lateral inhomogeneity on the sounding curves was unequivocal. Although there is general agreement between the gravity profile and the bedrock configuration interpreted from the electrical soundings, the gravity data appear to reflect a ridge of larger amplitude and wavelength than indicated by the electrical soundings. This would be possible if the gravity is reflecting a ridge on the pre-Tertiary basement surface and the electrical soundings are reflecting a lesser ridge on the surface of the overlying Tertiary granite breccia.

The steep gravity gradient east of the ridge could be caused by a fault. Some support for inferring a fault is afforded by the presence of a zone of abnormally warm ground water at this location (Olmsted and others, 1973).

CARGO MUCHACHO MOUNTAINS

The Cargo Muchacho Mountains are an irregular, deeply embayed mass of pre-Tertiary granitic rocks and subordinate metamorphic rocks near the northwest corner of the investigated area. The relatively dense rocks of these mountains are the source of a gravity high, the details of which were not delineated in the present study. The pattern of outcrops, with several outliers of basement around the margins, suggests that near the mountains the buried topography is as rough as the exposed

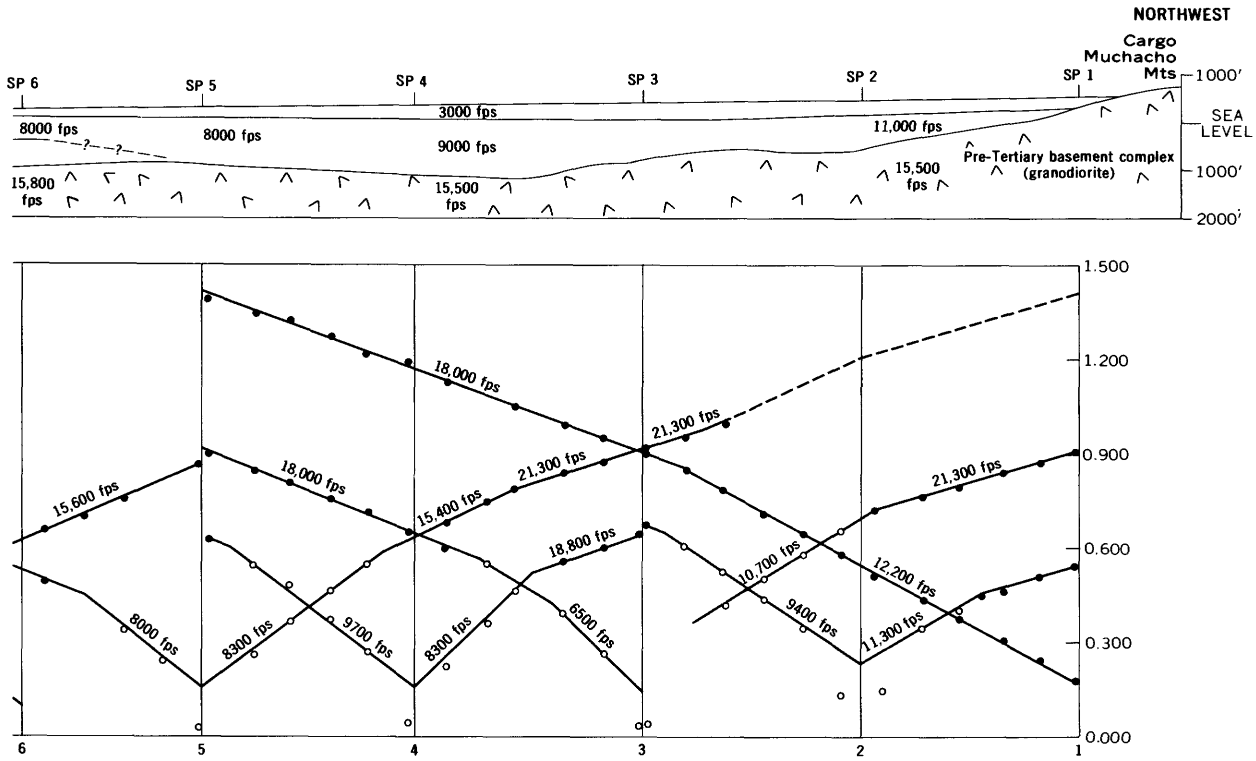


FIGURE 10. — Seismic-refraction profile 4 from near the north end of the Yuma basement high northwest to a basement outcrop east of the Cargo Muchacho Mountains. SP, shotpoint; TD, total depth; circles, alluvium arrivals; dots, bedrock arrivals (pre-Tertiary basement complex or Tertiary nonmarine sedimentary rocks); dashed lines, arrivals weak or inferred.

topography. One east-west line of small outcrops of granitic rock about 1½ miles south of the main mountain area probably represents a nearly buried ridge.

This ridge and the general configuration of the basement surface in the alluvial gap between the Cargo Muchacho Mountains and Pilot Knob, through which ground water moves westward from the Yuma area toward Imperial Valley, were explored by means of seismic-refraction profile 5 (fig. 12). Granitic rocks (chiefly granodiorite and quartz monzonite) are exposed in the Cargo Muchacho Mountains at the north end of the profile and in the nearly buried ridge which is bracketed by shotpoints 6 and 7; the southernmost shotpoint is about 350 feet north of an outcrop of gneiss at Pilot Knob.

The time-distance plot (fig. 12) appears to represent a simple two-layer problem. The upper layer, with an average velocity of 6,700 fps beneath the southern two-thirds of the profile and 5,600 fps along the remainder of the profile, is interpreted as unconsolidated alluvium. The alluvium is computed to be 1,350 feet thick at shotpoint 3 — near the center of a roughly symmetrical trough — and 620 feet thick at the north end of the smaller trough to the north. The somewhat higher alluvium velocity recorded beneath the southern trough probably reflects slightly greater compaction due to a greater thickness of alluvium.

Bedrock velocities of 15,700 and 15,200 fps were recorded between shotpoints 1 and 5 and shotpoints 7 and 9, respectively. Possibly the higher basement velocity of 15,700 fps represents gneiss, in contrast to quartz monzonite with a velocity of 15,200 fps. More likely, however, the higher velocity is simply the result of the greater shotpoint-to-geophone distance employed along the southern part of the profile.

At the north edge of both troughs, the basement arrivals from distant shotpoints are significantly early, and the average velocity lines for basement arrivals from shotpoints 6 and 9 show distinct offsets (fig. 12). These anomalous conditions must represent either steeply dipping depositional contacts or faults. Although the seismic data are insufficient to calculate a precise dip, the data must reflect a very steep slope — probably greater than 45° and possibly as much as 90°. The steepness of dip indicates that these contacts are probably fault planes rather than depositional contacts. The throw along these faults is computed assuming vertical fault planes. The northern inferred fault is about 1,000 feet south of the foot of a prominent steep escarpment along the south margin of the Cargo Muchacho Mountains; the intervening area is a narrow pediment cut on the basement rock, and the escarpment is interpreted as having retreated northward from its original position at the trace of the fault.

The gravity data along this profile, with residual anomalies of only several milligals over the two troughs, support the seismic interpretation of a shallow basement surface.

PILOT KNOB

Pilot Knob is an isolated hill of pre-Tertiary gneiss about 7 miles west of Yuma and 6 miles south of the Cargo Muchacho Mountains. It is the source of a pronounced gravity high that has a relatively steep gradient on the west side and has noses extending southeastward and northeastward (pl. 1). A steep gravity gradient probably also exists toward the southwest, in Mexico, but no observations were made to define this trend.

To delineate the basement slope toward the west, and possibly to determine the position of the Algodones fault, the area west of Pilot Knob was explored with seismic-refraction profile 6 (fig. 13).

Between shotpoints 1 and 2 the time-distance plot clearly represents a simple two-layer problem. The upper layer, interpreted as unconsolidated alluvium, has an average recorded velocity of 6,750 fps and is computed to be 850 feet thick; the lower layer, interpreted as more compacted alluvium, has a calculated velocity of about 8,200 fps. Between shotpoints 2 and 4 the near-surface unconsolidated alluvium has a recorded velocity of 6,750 fps, but the 8,200-fps layer is absent; rather, a deeper horizon with updip and downdip velocities of 10,000 and $>$ 50,000 fps, respectively, was recorded. The deeper velocity horizon, with a computed depth of 150 feet at shotpoint 4, is assumed to be the top of the basement complex. Its true velocity, therefore, is probably about 17,800 fps as measured on profile 9, which extends east from Pilot Knob (fig. 19).

The more compacted alluvial layer (velocity of 8,200 fps) probably continues beneath the entire profile even though it was not recorded between shotpoints 2 and 4; its absence can be explained by the particular geometry of the problem. Calculated arrivals from the assumed continuation of this layer are shown by a dotted line on the time-distance plot northeast of shotpoint 3. Apparently, energy arrivals from this layer would appear as second arrivals on all but one geophone. Inspection of the appropriate seismograms in the time zone calculated for these second arrivals, however, indicates that the energy level of the first arrivals is too high to distinguish possible second arrivals.

An alternative though less likely explanation for the absence of the 8,200-fps layer between shotpoints 2 and 4 is displacement along the Algodones fault. Reference to the geologic map (pl. 1) shows that the seismic profile crosses the projected strike of the Algodones fault at about shotpoint 2. This explanation is less probable because, if this were the case, the top of the 8,200-fps layer should be higher between shotpoints 2 and 4 than between shotpoints 1 and 2 and would distinctly appear on the time-distance plot. Although the major movement on the Algodones fault is horizontal, the upthrown side of the fault, at least near Pilot Knob, is to the east.

Assuming that the 8,200-fps layer continues across the profile, the apparent dip of the basement complex from Pilot Knob southwestward beneath the seismic profile is calculated to be about 27°.

YUMA BASEMENT HIGH

The highest Bouguer anomaly values and the highest magnetic intensity were observed in an area extending southward from Yuma for about 10 miles (pls. 1, 3). Outcrops of pre-Tertiary basement and numerous drill holes penetrating the basement at shallow depths clearly show that the high geophysical anomalies are caused by a basement high which is herein called the Yuma basement high.

The general correlation between the gravity and magnetic data over the Yuma basement high is well illustrated in profile *B-B'* (pl. 4). From low values over the southerly international boundary, both the gravity values and the magnetic intensity increase to a multicrested maximum over the Yuma basement high. The small southward displacements of the magnetic anomalies relative to the gravity anomalies are attributed to the inclination of earth's magnetic field (59° N. in the Yuma area); the magnetic data represent total magnetic field, whereas the gravity data represent only the vertical component of the total gravity field.

Both the gravity and the magnetic data reveal that the Yuma basement high anomaly includes two principal features: (1) a northern high, referred to as the Yuma anomaly and consisting of three maximums, is related to a row of basement outcrops; and (2) a southern high, referred to as the Mesa anomaly, is related to an area where holes drilled after the discovery of the feature by the gravity survey penetrated basement at depths of less than 100 feet. The two anomalies are separated by a gentle saddle, and as indicated on the gravity and magnetic maps (pls. 1, 3), they differ in the trend of their elongation.

The summits of the Yuma basement high — the present outcrops — are composed of the ubiquitous porphyritic quartz monzonite and are alined about N. 20° W., approximately parallel with the trend of the Yuma anomaly and with the northern Gila Mountains to the east. North of the quartz monzonite outcrops are two outcrops of Tertiary breccia and conglomerate, made up entirely of quartz monzonite detritus, between which the present channel of the Colorado River follows a superposed course.

Although several basement outcrops occur within the area of the Yuma anomaly (pl. 1), only two of these outcrops (the two southernmost) are associated with in-

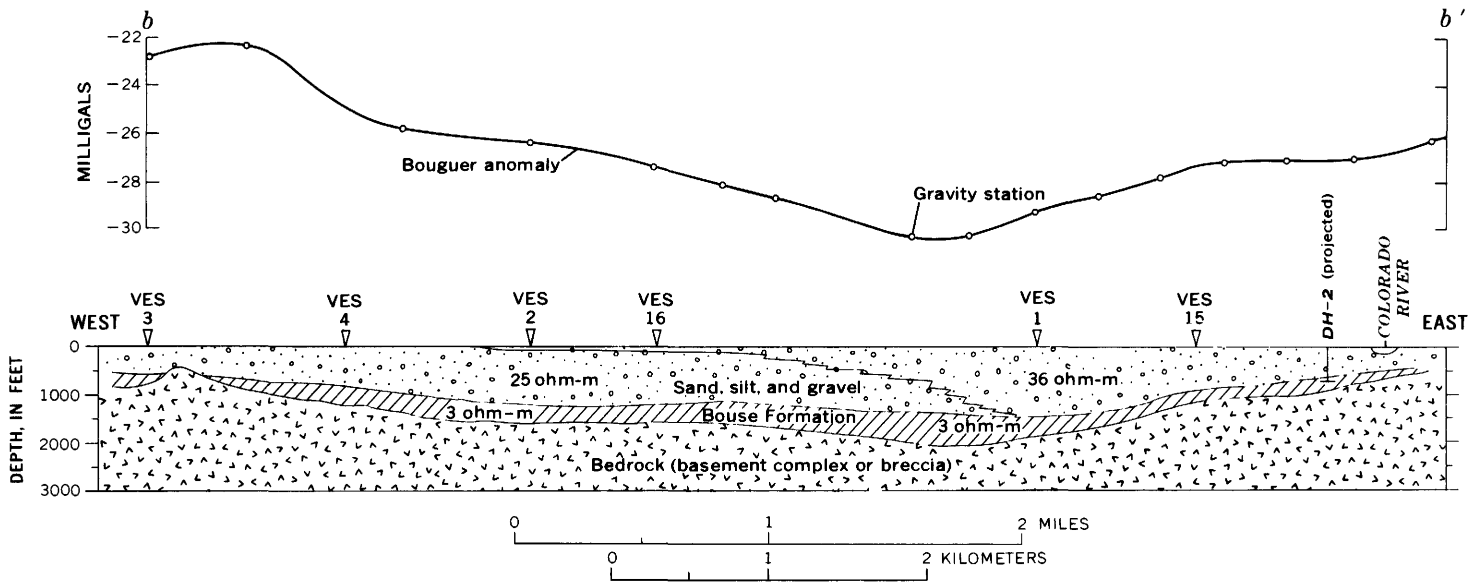


FIGURE 11.—Resistivity profile *b-b′* across part of the Picacho-Bard basin. For comparative purposes, a gravity profile is shown above the resistivity profile. VES, vertical electrical sounding. Well DH-2 has been projected about 3,000 feet into line of section. Line of profile shown on plate 1.

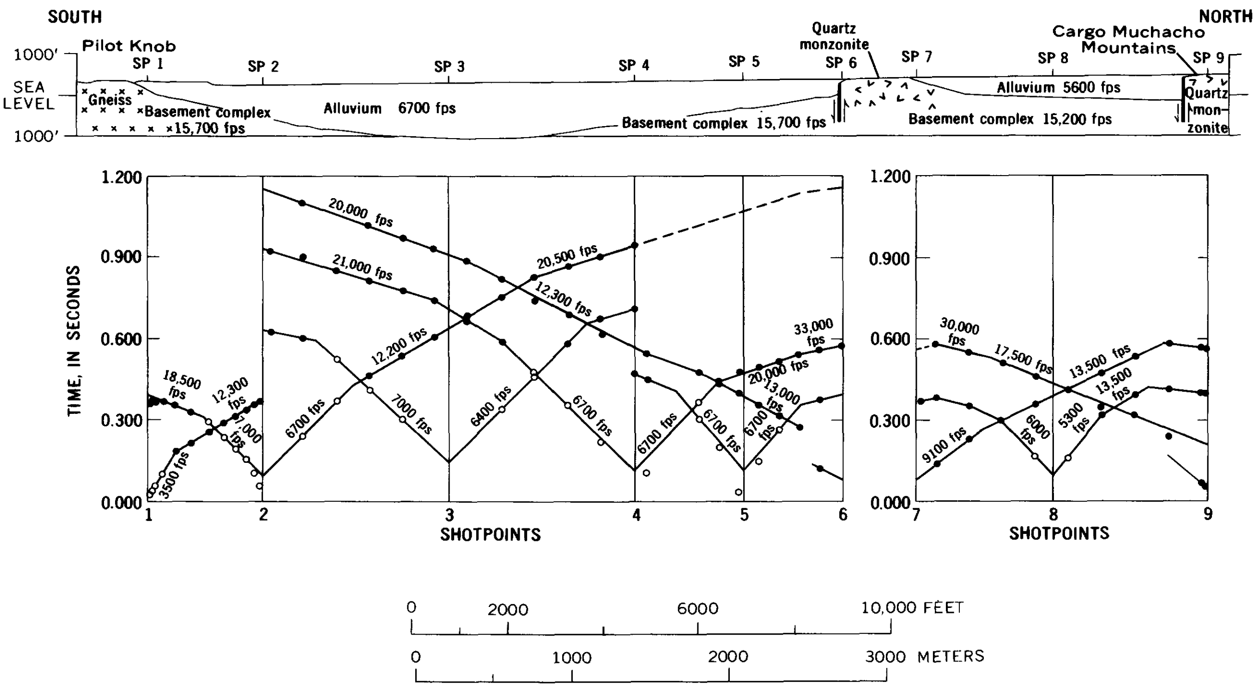


FIGURE 12. — Seismic-refraction profile 5 from Pilot Knob to the Cargo Muchacho Mountains. The higher basement velocity recorded along the southern two-thirds of the profile may represent gneiss, in contrast to quartz monzonite beneath the northern one-third of the profile. The higher velocity, however, more likely reflects the greater shotpoint-to-geophone distance employed along the southern part of the profile. SP, shotpoint; circles, alluvium arrivals; dots, basement arrivals; dashed lines, arrivals weak or inferred.

dividual gravity closures. Similar closed highs possibly occur over the remaining outcrops, but the station density was insufficient to differentiate individual closures. Bouguer anomaly values are decidedly lower on the outcrops of breccia and conglomerate than on the outcrops of quartz monzonite, a fact which reflects the lower density of these Tertiary nonmarine sedimentary rocks as compared with the quartz monzonite basement.

Although the magnetic data reveal a general high associated with the Yuma anomaly, the details are different from those of the gravity pattern. Instead of the elongate high oriented about north-northwest as indicated by both gravity and outcrop patterns, the magnetic high is more nearly equidimensional and is centered on a point slightly east of the quartz monzonite outcrop traversed by U.S. Highway 95 in Yuma. The reason for the difference in pattern is not known; however, it may be caused by a local mass of more magnetic basement east of the porphyritic quartz monzonite outcrop.

The Yuma anomaly is separated from the Mesa anomaly to the south by a gravity saddle and a magnetic saddle (pls. 1, 3). Although no basement rock is exposed within the area of the Mesa anomaly, the gravity and magnetic values suggested a shallow depth to basement on the crest of the Mesa anomaly, and subsequent drilling confirmed the presence of basement rock near the surface. A detailed gravity map of the Mesa anomaly at a contour interval of 1 mgal (pl. 5) reveals three closed highs which apparently represent buried basement peaks. Test wells DH-25 and DH-24, drilled at the two highest Bouguer anomaly values, penetrated porphyritic quartz monzonite at depths of 47 and 79 feet, respectively. Two other test wells (DH-23 and DH-22), drilled at gravity stations having Bouguer anomaly values 0.7 mgal lower than those at the previous two sites, penetrated similar rock at depths of 90 and 267 feet, respectively. Additional information is provided by two oil test wells on the flanks of the basement ridge: DH-20, 2 miles northwest of the high at DH-22, penetrated granitic basement (probably the quartz monzonite) at a depth of 1,431 feet; and DH-21, an old well reported by Kovach, Allen, and Press (1962), penetrated granitic rock at a depth of 730 feet (table 1). In all these wells alluvium appears to directly overlie porphyritic quartz monzonite basement.

Both gravity and magnetic patterns imply that the buried basement ridge causing the Mesa anomaly has a more northwesterly trend than the ridge responsible for the Yuma anomaly.

The general subsurface configuration of the Yuma basement high is shown on profile *B-B'* (pl. 4), which extends from DH-30 near the international boundary, across the Yuma basement high, to an outlier of the

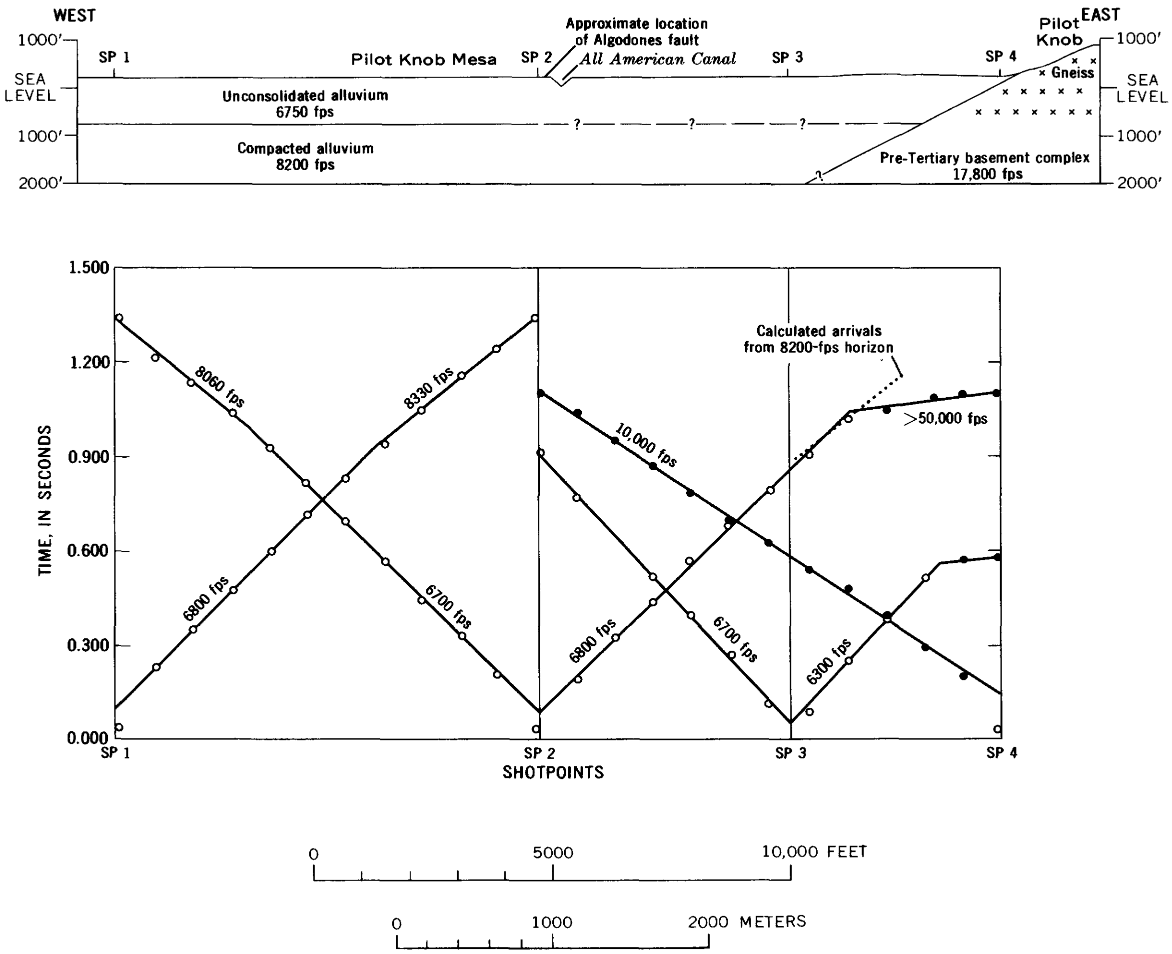


FIGURE 13. — Seismic-refraction profile 6 from Pilot Knob west across Pilot Knob Mesa. The basement velocity is assumed to be 17,800 fps as measured on profile 9, which extends east from Pilot Knob. SP, shotpoint; circles, alluvium arrivals; dots, basement arrivals.

Cargo Muchacho Mountains. The subsurface geology in the vicinity of the San Luis basin was constructed from gravity data and the data of wells DH-27 and DH-30 (table 1). The interpretation in the vicinity of the Picacho-Bard basin is based on the previously discussed data of seismic-refraction profile 4 (fig. 10) and the gravity data of plate 1. The interpretation in the central part of plate 4, in the vicinity of the Yuma basement high, is based on the following seismic-refraction surveys, detailed gravity surveys, and resistivity surveys: (1) Seismic-refraction profile 7 (fig. 14), extending between two of the quartz monzonite outcrops in the area of the Yuma anomaly; (2) gravity profile *C-C'* (fig. 15), extending across the gravity saddle between the Yuma and Mesa anomalies; (3) a detailed resistivity survey in the area of the Mesa anomaly (fig. 16); and (4) seismic-refraction profile 8 (fig. 17), on the south flank of the Yuma basement high. These four surveys are discussed in detail in the following paragraphs.

The depth and configuration of the basement surface between two of the quartz monzonite outcrops associated with the Yuma anomaly were determined by seismic-refraction profile 7 along Pacific Avenue in Yuma (fig. 14); the location of profile 7 is shown on plate 5. The time-distance plot shows two distinct layers: the upper layer is correlated with alluvium, and the lower layer is correlated with the quartz monzonite basement exposed beyond the two ends of the seismic spread. The *P*-wave velocity in the alluvium is about 5,200 fps — indicative of unconsolidated deposits. The greatest thickness of alluvium, about 620 feet, is near the center of the profile. The downdip and updip velocities of the basement are about 10,000 fps and 22,500-35,500 fps, respectively, and the true velocity is calculated to be about 14,900 fps, about average for granitic rocks in the Yuma area. The seismic data do not show any evidence of Tertiary nonmarine deposits beneath the alluvium.

Well data confirm the seismic-refraction results; semiconsolidated to consolidated Tertiary nonmarine deposits are absent except on the lower flanks and in the northern part of the Yuma anomaly. Wells DH-12 through DH-16, drilled in the vicinity of the Yuma

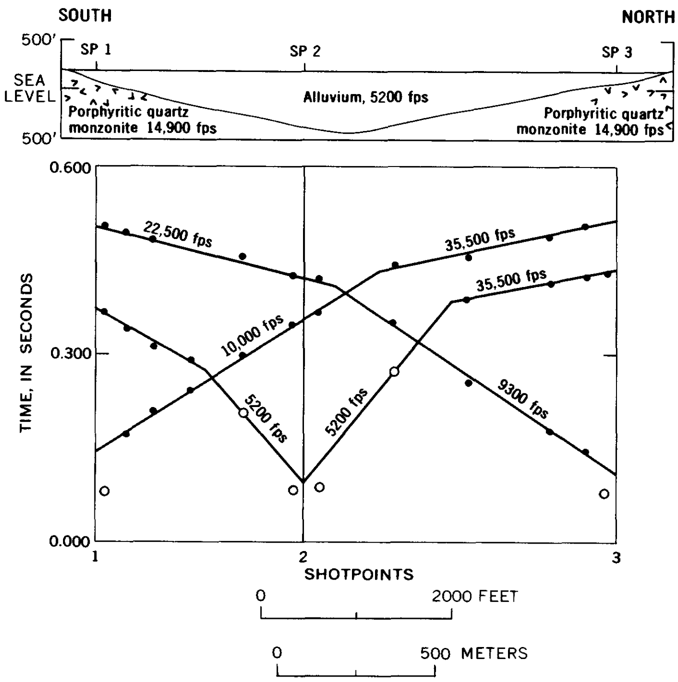


FIGURE 14. — Seismic-refraction profile 7 along Pacific Avenue in Yuma between two basement outcrops. SP, shotpoint; circles, alluvium arrivals; dots, basement arrivals.

anomaly, all bottomed in granitic basement rock — probably the porphyritic quartz monzonite exposed in the area (table 1). Of these wells, only possibly DH-12, which is near the exposures of Tertiary breccia and conglomerate (pl. 1), and DH-15 penetrated the Tertiary nonmarine sedimentary rocks between the alluvium and the basement complex. Well DH-14 penetrated "granite" (probably porphyritic quartz monzonite) at a depth of 1,085 feet beneath predominantly fine-grained alluvium. Well DH-15, farther down the western flank of the basement high from DH-14, appears to have penetrated the Bouse Formation and about 155 feet of underlying Tertiary fanglomerate between the alluvium and the basement complex, which was penetrated at a depth of 1,398 feet (table 1).

The area between the Mesa and Yuma anomalies was explored by gravity profile *C-C'* (fig. 15). *C-C'* extends north-northeastward from DH-24, across the gravity saddle between the Yuma and the Mesa anomalies, to the southernmost basement outcrop on the Yuma anomaly (pl. 5). If we assume a variable density contrast in accord with the data of figure 4 (0.44 g cm^{-3} for depths of 0-1,000 ft and 0.30 g cm^{-3} for depths greater than 1,000 ft), the computed model has a maximum

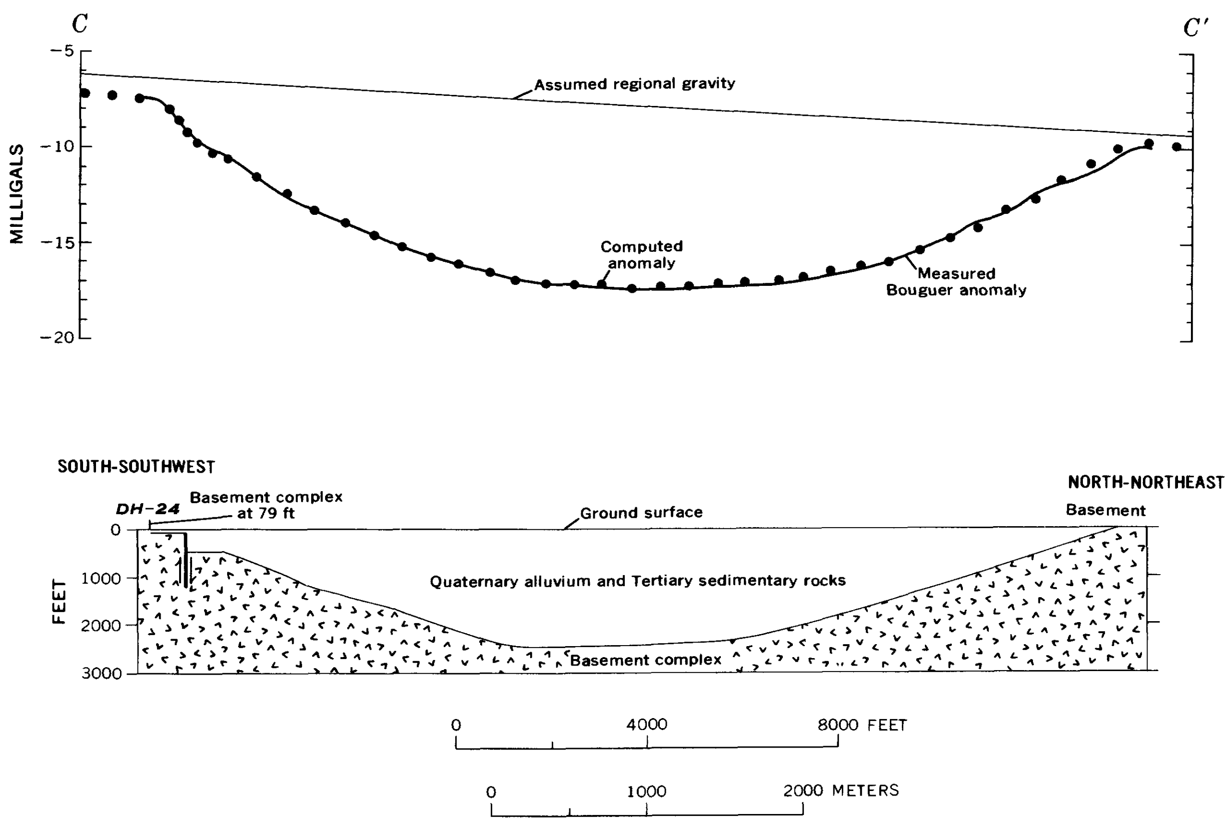


FIGURE 15. — Observed and computed gravity anomaly on profile *C-C'* across the gravity saddle between the Yuma and Mesa anomalies. Maximum sediment thickness is about 2,600 feet near the center of the trough.

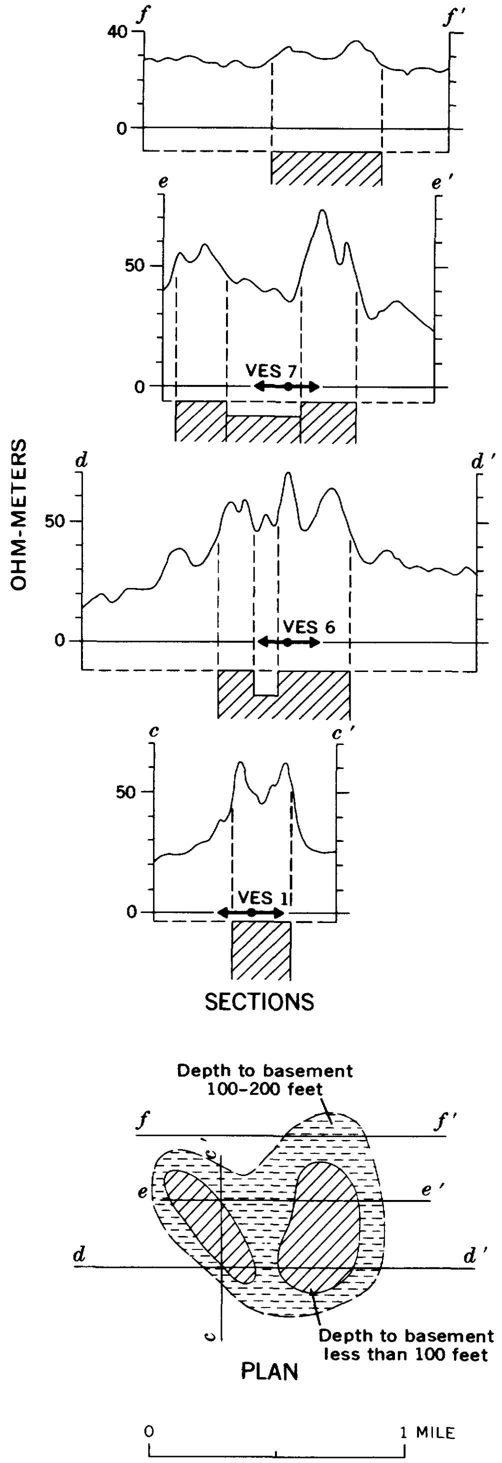


FIGURE 16. — Resistivity profiles c-c′ through f-f′ across the Mesa anomaly. Sections show a qualitative interpretation of the resistivity profiles assuming a basement composed of vertical blocks (crosshatched); dashed lines show boundaries of blocks in which basement rock is interpreted to be shallow. VES, location of vertical electrical sounding. Lines of profiles shown on plate 5.

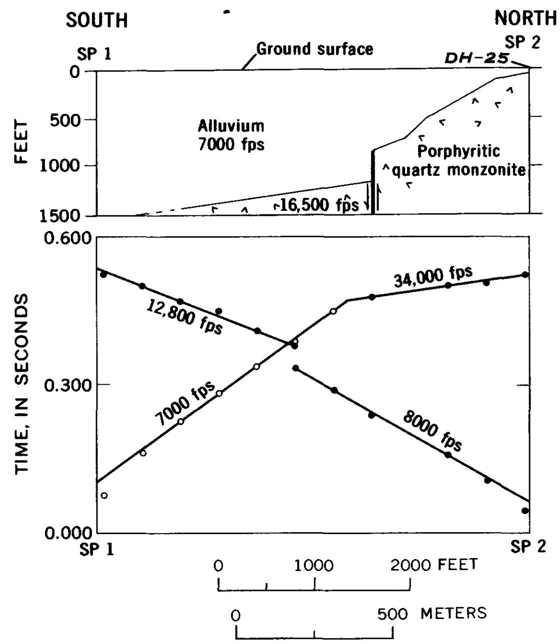


FIGURE 17. — Seismic-refraction profile 8 on the south flank of the Yuma basement high. SP, shotpoint; circles, alluvium arrivals; dots, porphyritic quartz monzonite arrivals.

sediment thickness of about 2,600 feet; this thickness probably includes some relatively dense Tertiary sedimentary rocks (both marine and nonmarine?) in the basal part of the fill overlying the basement. The steep gravity gradient about 700 feet northeast of DH-24 suggests a basement fault; the computed model, which assumes a vertical fault with about 400 feet throw, gives a good fit to the observed anomaly. Note that this model was computed using two-dimensional analysis, but the actual layout of profile *C-C′* (pl. 5) indicates that a two-dimensional analysis is not completely justified. The results, therefore, should be considered approximate.

The area of the Mesa anomaly was surveyed with four resistivity profiles, and depth information along these profiles was provided by three electrical soundings (fig. 16, pl. 5). The data reveal the general complexity of this area. A simple qualitative interpretation assuming a basement composed of vertical blocks is shown in figure 16. At VES (vertical electrical sounding) 6, which is about 1,450 feet S. 64° E. from the basement high at DH-25, the depth to basement is computed to be about 115 feet. In addition, by matching the recorded sounding curve with a set of theoretical VES curves over a dipping contact (Dakhnov, 1953), we estimated that the basement surface dips about 40° S. This slope is in reasonable agreement with the slope of 30° estimated from seismic-refraction profile 8 (fig. 17) described next.

The area of steep magnetic and gravity gradients on the southwest flank of the Mesa anomaly was explored with seismic-refraction profile 8 (fig. 17). The north end of profile 8 is at the center of the southernmost gravity closure of the Mesa anomaly, where test well DH-25 penetrated porphyritic quartz monzonite at 47 feet, the highest known point on the buried basement ridge. In the computed model, the basement surface dips about 30° S. along the line of profile. About 1,600 feet south of DH-25, a significant offset on the time-distance plot probably reflects a steeply dipping fault which offsets the basement surface. Assuming the fault to be vertical or nearly vertical, we computed a throw of about 350 feet.

The considerable relief associated with the Yuma basement high probably results from a complex fault pattern traversing a buried erosion surface as rugged and complex as the slopes in the exposures of basement rock in the Yuma area. Although the general fault pattern can be delineated from the geophysical data (pl. 1), the exact location and nature of these faults must remain speculative, at least until more data are obtained.

Along the east flank of the Yuma anomaly the gravity and magnetic gradients imply a complex pattern of faults that probably trend north (fig. 8); in contrast, along the northeast side of the Yuma anomaly, at the north end of the Yuma basement high, gravity and magnetic gradients suggest a northwest-trending fault or faults. The gravity gradients on the northwest side of the Yuma anomaly suggest north-northeast- to northeast-trending faults; one such fault, as indicated by the alinement of fault intercepts on seismic-refraction profile 9 (fig. 19) and gravity profile *D-D′* (fig. 18), may bound the Yuma basement high on the northwest (pl. 1). The gradients on the west and northwest flanks of the Yuma anomaly are less pronounced than those on the east flank, presumably because the bordering west basin (Yuma trough) is shallower than the Fortuna basin to the east. On the west flank of the Yuma anomaly, close to the northern basement outcrops of the Yuma basement high, the gravity gradients suggest a north-northwest-trending fault or faults, as shown on plate 1 for the easternmost fault recorded on gravity profile *D-D′*.

Southwest of the Yuma basement high, the seismic-refraction data recorded a fault with about 350 feet of throw (fig. 17). This fault is interpreted as the Algodones fault (Olmsted and others, 1973). About 4,000 feet farther south, down the flank of the Yuma basement high, the steep gravity gradient indicates an additional 1,000 feet of throw on a parallel fault (pl. 4, fig. 20). The magnetic and resistivity data are consistent with these results insofar as they confirm that the south flank of the Yuma basement high dips steeply into the San Luis basin, and the linearity of the southwest sides of the gravity and magnetic anomalies associated with the high implies that the faults or fault zone trends northwest.

Along the northeast flank of the Mesa anomaly the trend of the gravity and magnetic gradients probably reflects a northwest-trending fault, as does the alinement of fault intercepts on profiles *C-C′* (fig. 15) and *A-A′* (fig. 8). An additional fault to the east, recorded during the seismic-reflection survey and inferred from gravity data of profile *A-A′* (fig. 8), was assumed to strike northwest. This interpretation is supported by seismic-reflection data to the south, where two seismic-reflection profiles revealed several faults (Herschel Snodgrass and R. D. Davis, written communs., 1966). These faults were interpreted on the basis of offset reflectors, local steep dips, and zones of missing record. Although strike was not determined, the faults are inferred to strike northwest because of the alinement of fault intercepts on mutually perpendicular profiles. One of these faults appears to be along the trace of the Algodones fault, and the other are parallel or en echelon to the Algodones fault (pl. 1).

The complex structure inferred for the Yuma basement high relative to other areas of the survey probably reflects the greater abundance of geophysical data in this area of near-surface basement rather than anomalously complex structure.

BOUNDARY BASEMENT HIGH

A pronounced gravity high is centered on a line of outcrops of porphyritic quartz monzonite that straddles the southerly international boundary (pl. 1). This gravity high is interpreted as reflecting a basement ridge, which is herein called the Boundary basement high. The outcrops (most are located south of the border in Mexico and are not shown on pl. 1), which are the summits of this mostly buried basement ridge, trend about N. 45° W. As seen on the gravity map (pl. 1), the gravity high is elongated in the same direction and is separated from the Yuma basement high 20 miles to the northwest by a broad saddle about midway between the two highs. The maximum Bouguer value is −20.0 mgal on the northernmost basement outcrop, on the United States side of the border; the Bouguer anomaly in the saddle is not well defined, owing to sparse control, but appears to be about −37 mgal. Using the density data shown in figure 4, the difference in gravity values reflects a depth to basement of 4,000-5,000 feet in the saddle.

The gravity data (pl. 1) indicate that from the Boundary basement high the basement surface slopes steeply into the Fortuna basin and somewhat more gently into the San Luis basin.

Basement outcrops to the southeast, in Sonora, Mexico, imply that the Boundary basement high continues in that direction.

YUMA TROUGH

The Yuma trough is a north-northeast-trending trough between the Pilot Knob basement high on the west and the Yuma basement high on the east. The gravity data (pl. 1) indicate that the axis of the trough is about midway between the basement outcrop at Pilot Knob and the one in Yuma and that a gentle saddle crosses the trough west of Yuma. Bouguer gravity values decrease north-northeastward and south-southwestward from this saddle.

As a first approximation, an idealized model was computed from the gravity data of profile *D-D'*, which extends from Pilot Knob to Yuma across the saddle (fig. 18). Near the west-central part of the profile the depth to basement is about 2,700 feet, as estimated from the magnetic data by using the method described by Vacquier, Steenland, Henderson, and Zietz (1951). Additional basement control was available from well DH-15, which penetrated the basement complex at a depth of 1,398 feet (table 1). On the basis of the preceding depth information and the density data of figure 4, we computed an idealized gravity model — a nearly symmetrical trough with about 3,500 feet of Cenozoic sediments at the center (fig. 18). Two faults near the east end of the profile were required to give a reasonably good fit to the observed gravity data.

Seismic-refraction profile 9 (fig. 19) extends across the Yuma trough approximately along the west-flowing reach of the Colorado River from Yuma to Pilot Knob. Pre-Tertiary gneiss of the basement complex is exposed at Pilot Knob, near the west end of the profile, and Tertiary breccia and conglomerate composed of porphyritic quartz monzonite detritus forms the outcrop near the north end of the Yuma basement high, just east of the profile (pl. 1). Subsurface control is provided by wells DH-10, DH-17, and DH-18, all near the profile.

The time-distance plot for profile 9 (fig. 19) reveals a simple two-layer configuration. The *P*-wave velocity recorded in the upper layer ranges from about 6,500 to 7,000 fps and averages about 6,700 fps. In the western part of the profile, between shotpoints 1 and 4, the velocity of the lower layer is calculated to be 17,800 fps. In the eastern part, between shotpoints 4 and 8, however, the velocity of the lower layer is only 12,800 fps.

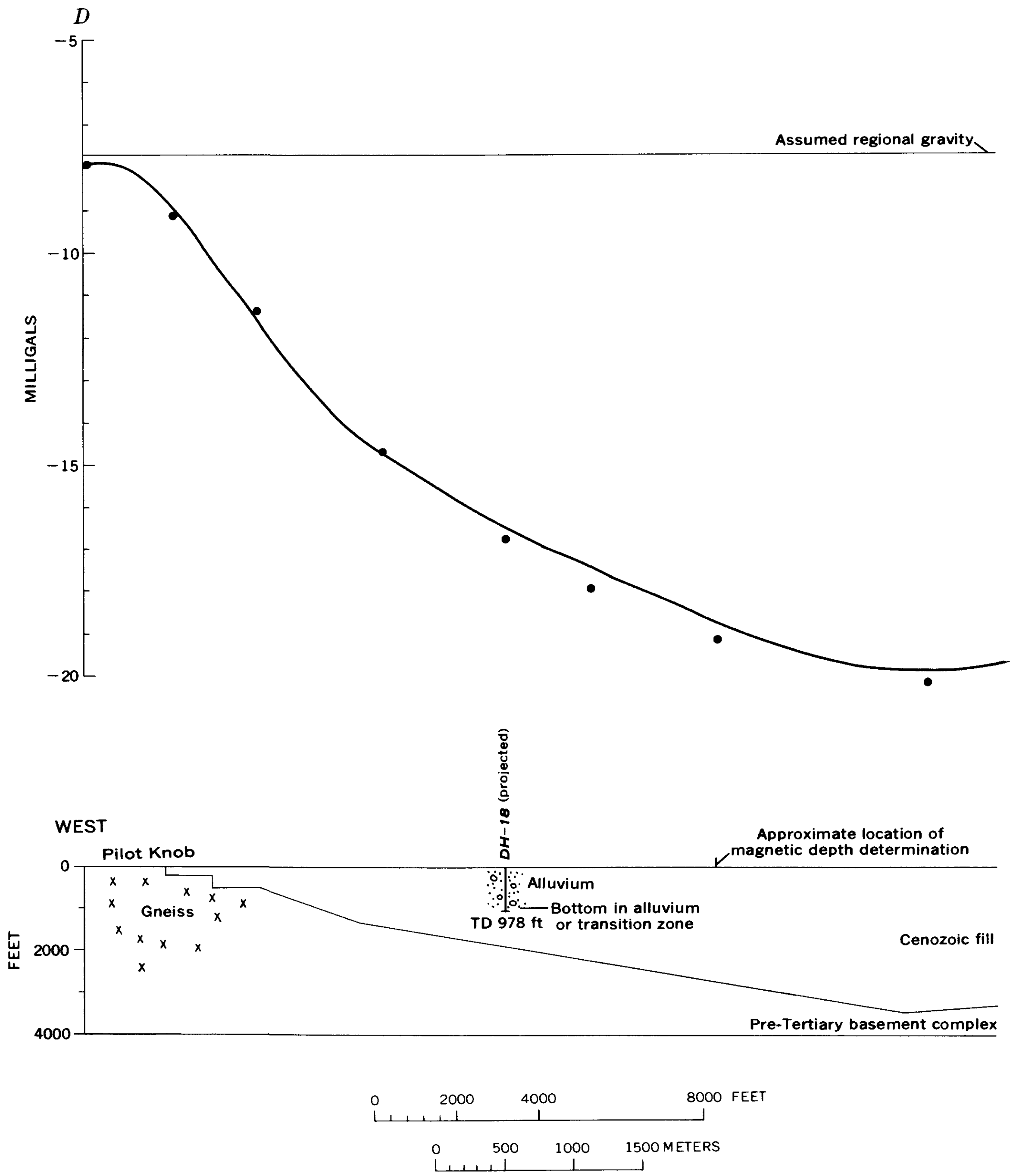
Interpretation of these velocities is facilitated by the acoustic-velocity and lithologic logs of DH-17, about one-half mile north of the profile. (See pl. 2 and table 2.) These logs recorded three distinct seismic layers (a fourth, deeper layer — the basement — was not penetrated by the well): (1) alluvium (including the underlying transition zone); (2) Bouse Formation (the clay, silt, and sand part); and (3) nonmarine sedimentary rocks (including the tuff(?) and limestone at the base of the Bouse Formation). According to the acoustic log, the recorded velocities for these layers are about 7,500, 6,500, and 13,000 fps, respectively.

Comparison of these velocities with the seismic-refraction data reveals the following: (1) The velocity of the upper layer as measured by seismic refraction is about 10 percent less than the weighted-average velocity of the equivalent alluvium, transition zone, and major part of the Bouse Formation recorded by the acoustic-velocity log; (2) seismic-refraction methods cannot differentiate the lower velocity Bouse Formation from the overlying higher velocity alluvium and transition zone; and (3) the lower layer along the east half of the seismic-refraction profile corresponds to the fanglomerate (Tertiary nonmarine sedimentary rocks unit), and the velocities recorded by the two methods for this unit agree closely. (The top of the fanglomerate probably dips south between well DH-17 and the seismic profile, as shown by the fact that this horizon was penetrated at a depth of 1,380 ft in the well and that, at a point on the seismic profile directly south of the well, the computed depth to the top of the fanglomerate is 1,550 ft.)

The discrepancy between the velocities measured in the upper layer by the two methods probably can be explained by anisotropy; the velocity is measured vertically by the acoustic log and horizontally by the seismic-refraction technique. In the seismic computations, if an average velocity of 7,500 fps is used, instead of 6,700 fps, the computed thickness of the upper layer is increased by about 10 percent.

Between Pilot Knob and shotpoint 3 the 17,800-fps layer is assumed to be gneiss like that exposed at Pilot Knob, and its surface is computed to dip west 6½°. Well DH-18, less than one-half mile south of the profile, bottomed in alluvium (or possibly in the transition zone) at a depth of 978 feet, suggesting that the Cenozoic fill overlying the basement, at least near the west end of the profile, is chiefly or entirely unconsolidated alluvium. At shotpoint 5, about 0.6 mile southeast of DH-17, the top of the Tertiary fanglomerate is computed to dip east about 2¼°. Projection of the dips of the pre-Tertiary basement and Tertiary fanglomerate surfaces implies that the Tertiary fanglomerate overlaps the basement and pinches out near shotpoint 4, as shown by the dashed lines in figure 19.

The seismograms recorded between shotpoints 4 and 6 were studied for later arrivals that could reveal the attitude of the basement complex beneath the Tertiary fanglomerate, but any possible later arrivals were masked by the high energy level of the first arriving waves. A raypath analysis on the computed cross section, however, indicates that east of shotpoint 5 the basement surface must lie at a depth of at least 1,000 feet



below the top of the Tertiary fanglomerate; otherwise, the first arrivals recorded between shotpoints 5 and 6 and shot from shotpoint 3 would have been basement arrivals. Possibly, the contact between the Tertiary fanglomerate and basement complex is actually a fault plane; however, because of the lack of gravity or magnetic expression, this alternative interpretation is unlikely.

The shelf of Tertiary nonmarine sedimentary rocks extending west from the Yuma basement high to about shotpoint 6 (fig. 19) is probably associated with the Yuma basement high. The fault shown on the cross section just west of shotpoint 6 is required to explain the discrepancy in depth to the top of the Tertiary rocks as computed in shooting east and west from shotpoint 6. As shown on plate 1, this fault may be a continuation of a fault that intercepts gravity profile *D-D'* (fig. 18). If so, the fault strikes north-northeast and bounds the northwest side of the Yuma basement high.

At the south end of the Yuma trough the gravity and magnetic data (pls. 1, 3) suggest that the depth to basement increases southward toward the San Luis basin.

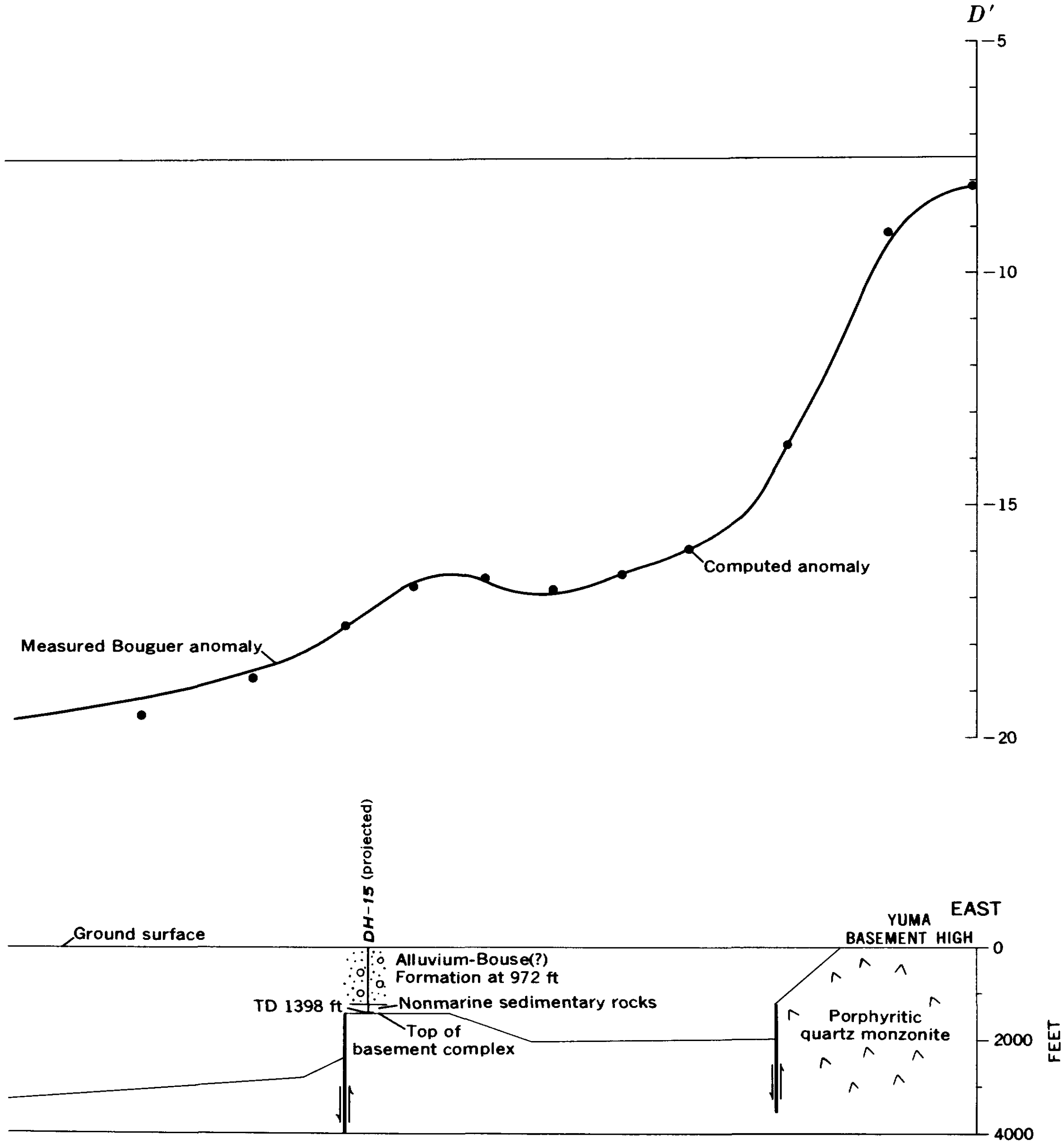


FIGURE 18. — Observed and computed gravity anomaly on profile *D-D′* across the Yuma trough. The idealized model was computed on the basis of the density data of figure 4, test well DH-15 (projected 3,000 ft), and a magnetic depth determination. TD, total depth.

SAN LUIS BASIN

From the extreme southwest corner of Arizona both magnetic intensity and Bouguer anomaly values rise toward the north-northeast, and a resulting zone of low magnetic and gravity values trends east-southeastward along the border with Sonora, Mexico. This magnetic and gravity low is interpreted as reflecting a low on the basement surface, which is herein called the San Luis basin. The San Luis basin is bounded on the northeast by a largely buried ridge that includes the Yuma basement high and the Boundary basement high. Although the magnetic coverage is incomplete near the international border, the center of the basin appears to straddle the border about 11 miles west-northwest of the Boundary basement high.

Although no wells south of the Yuma basement high have penetrated the pre-Tertiary basement, three oil tests — DH-27, DH-28, and DH-30 (pl. 1) — provide minimum depths to basement which are significant to the geophysical interpretation (table 1). DH-27, the deepest drill hole in the Yuma area, bottomed in Tertiary nonmarine sedimentary rocks at a depth of 6,007 feet (5,837 ft below sea level); DH-28 and DH-30 were drilled to depths of 3,660 and 4,868 feet, respectively, without reaching the Tertiary nonmarine sedimentary rocks.

Figure 20 shows a model computed from the gravity data along profile *E-E'* from well DH-25, at the south end of the Yuma basement high, to the center of the San Luis basin, at the international border. The depths to basement at the extreme north end of this profile (including the northernmost fault) are based on the results of seismic-refraction profile 8 (fig. 17). A second fault, about 4,000 feet down the flank of the Yuma basement high from the prior fault, is based on a local steepening of the gravity gradient; the throw of this fault is estimated to be about 1,000 feet. The trend of the gravity and magnetic gradients at the south end of the Yuma basement high (pls. 1, 3) suggests that these faults probably strike northwest. If the computed model is correct, the basin fill — including alluvium, rocks of the transition zone, Bouse Formation, and Tertiary nonmarine sedimentary rocks — is about 13,500 feet thick at the border with Sonora, Mexico. The model was computed using the density contrasts shown in figure 4.

ALGODONES FAULT AND RELATED FAULTS

A principal branch of the San Andreas fault system extends along the northeast side of the Salton Trough to a point near the southeast shore of Salton Sea, southeast of which it is concealed by apparently unaffected alluvium and windblown sand. This branch has been identified as the Banning-Mission Creek fault (Allen, 1957) or as the San Andreas fault (Dibblee, 1954). Biehler (1964; oral commun., 1967) inferred that the trace of the fault, which is indicated by a strong alinement of gravity lows, extends from the Salton Sea southeastward beneath the Sand Hills on the East Mesa of Imperial Valley to the Colorado River south of Pilot Knob. The gravity data are supported by information from seismic-refraction profiles (Kovach and others, 1962), which indicate downthrow of the basement surface southwest of the fault.

A continuation of this fault (or possibly a parallel fault) which extends southeastward across the Yuma area from a point on the Colorado River about 2 miles south of Pilot Knob to the southerly international boundary 26 miles east of the Colorado River (pl. 1) was named the Algodones fault by Olmsted, Loeltz, and Irelan (1973). Those authors presented five kinds of evidence for this fault, which may be summarized as follows:

1. *Anomalous topography on the "Upper Mesa."* Exposures of older alluvial deposits in the so-called "Upper Mesa" in the south-central part of the area of investigation contain an anomalous northwest-trending drainage approximately perpendicular to the normal, consequent drainage from the Gila Mountains. The inferred trace of the fault is along the anomalous drainage at the foot of an eroded northeast-facing alluvial escarpment; the mesa surface southwest of the escarpment is elevated 30-60 feet relative to the northeast side. Lineaments apparent on aerial photographs suggest that the fault trace has a branching pattern near the middle of the area, as shown on plate 1.

2. *Ground-water-barrier effect and displacement of the water table.* Shallow test wells drilled in the area of the "Upper Mesa" indicate a sharp displacement in the water table along the inferred fault trace. Water levels northeast of the fault are more than 30 feet higher than those southwest of the fault (near the northwest edge of the "Upper Mesa") and are about 7-8 feet higher near the southerly international boundary. Measurements in private irrigation wells and government observation wells in the southeastern part of the Yuma Mesa show that the water-table offset continues about 3 miles northwest of the edge of the "Upper Mesa," although this part of the fault trace is concealed. The displacement of the water table may be caused by the fault acting as a barrier to ground-water movement. Electrical-analog data indicate that observed changes in water level on both sides of the fault are best modeled by assuming that the transmissivity of the fault barrier is less than one one-thousandth that of the alluvial deposits on either side.

3. *Magnetic gradients.* A steep magnetic gradient along the southwest flank of the Mesa anomaly and extending across Yuma Valley to the Colorado River somewhere between 1½ and 4 miles south of Pilot Knob (pl. 3) suggests a northwest-trending fault or series of faults along which the basement is downthrown to the southwest.

4. *Gravity patterns.* Gravity data along the southwest flank of the Mesa anomaly indicate a steep gradient at about the same position as the magnetic one. In addition, the gravity map (pl. 1) shows a very steep gradient on the northeast flank of the Boundary basement high, which suggests downthrow of the basement surface toward Fortuna basin along a fault about in the position of the fault inferred from topographic and hydrologic evidence.

5. *Ground-water-temperature anomalies.* Although the fault is concealed beneath Yuma Mesa and Yuma Valley, its position throughout much of its extent across these features is revealed by an elongate body of anomalously warm ground water, mostly on the northeast side of the inferred fault trace. Similar temperature anomalies farther southwest probably reflect parallel or subparallel faults. The higher temperatures in these areas probably result from upward movement of deep warm water induced by the barrier effects of the faults. However, the effect of the buried basement ridge at the Mesa anomaly may in part account for the temperature anomaly along the Algodones fault.

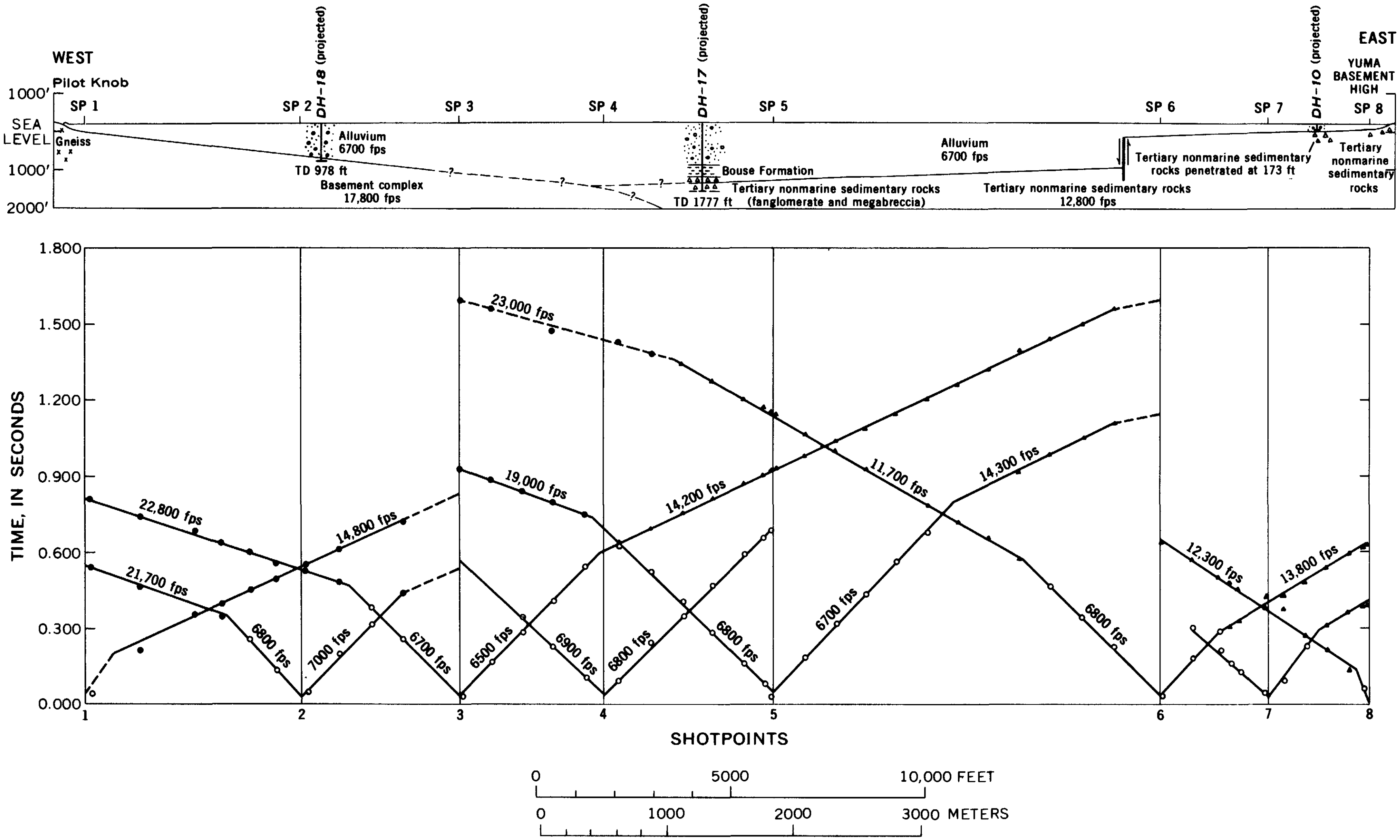


FIGURE 19. — Seismic-refraction profile 9 from Pilot Knob eastward to near the north end of the Yuma basement high. The velocity of 17,800 fps probably represents gneiss like that exposed at Pilot Knob. The velocity of 12,800 fps is interpreted as Tertiary nonmarine sedimentary rocks. Seismic-refraction data are inadequate to define the contact between the gneiss and the nonmarine Tertiary sedimentary rocks. SP, shotpoint; TD, total depth; circles, alluvium arrivals; triangles, Tertiary nonmarine sedimentary arrivals; dots, basement arrivals; dashed line, arrivals weak or inferred.

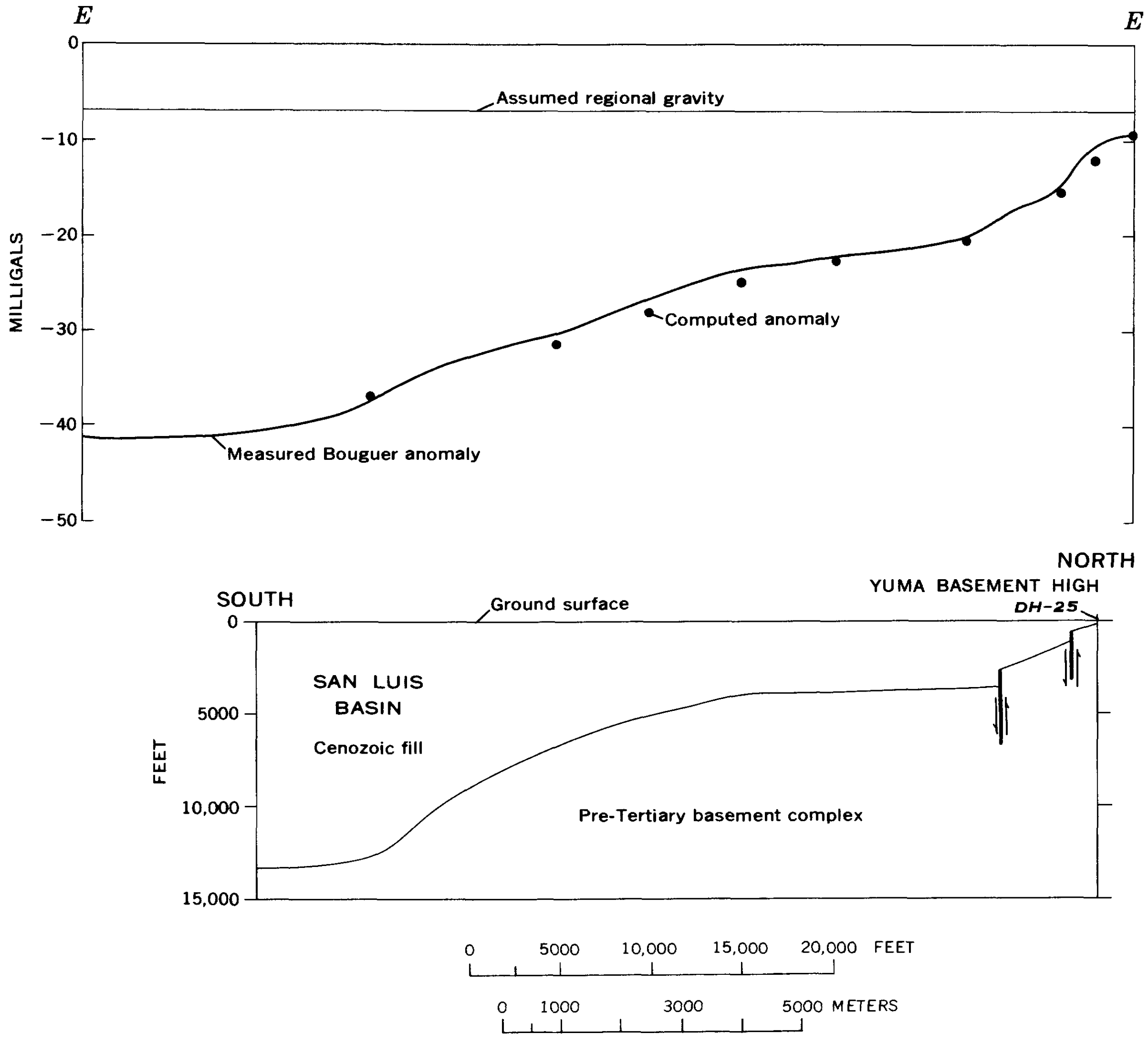


FIGURE 20. — Observed and computed gravity anomaly on profile *E-E′* from well DH-25, at the south end of the Yuma basement high, to the center of the San Luis basin, at the international border. The depths to basement at the extreme north end of the profile (including the northernmost fault) are based on the results of seismic-refraction profile 8 (fig. 17).

To further define the location and nature of the Algodones fault and possible parallel or en echelon faults, the postulated trace of the fault zone was crossed at several places by seismic and resistivity profiles (pl. 1).

Several faults, including the probable Algodones fault, were delineated in the seismic-reflection survey of 1966; the following interpretations are summarized from Herschel Snodgrass (written commun., 1966). A seismic-reflection profile along the Colorado River southeast of Pilot Knob indicated a steeply dipping fault along the east bank of the river about 2½ miles south of Pilot Knob — within the zone indicated by the magnetic data and about in alinement with the fault to the northwest postulated by Biehler (1964; oral commun., 1967). The top of the Bouse Formation was estimated to be downthrown 500 feet to the south or southwest. Throw on the basement surface was not determined but is estimated to be even greater. An area of shallow basement believed to be a southeasterly nose of Pilot Knob was found about 1-2 miles north of the fault. Southeast of the Mesa anomaly two seismic-reflection profiles revealed several faults. These faults were inferred from offset reflectors, local steep dips, and zones of missing record. Although strike was not determined, alinement of fault intercepts on mutually perpendicular profiles suggests that the faults strike generally northwest. One of these faults appears to be along the trace of the Algodones fault inferred from water-level data; the others apparently are en echelon or parallel faults.

Five resistivity profiles across the inferred trace of the Algodones fault southeast of the Mesa anomaly (pl. 5, fig. 21) failed to yield near-surface direct evidence for the fault. The large anomalies on profiles *g-g′* and *h-h′*, which could be explained by the presence of highly resistive fault gouge, are interpreted instead as represen-

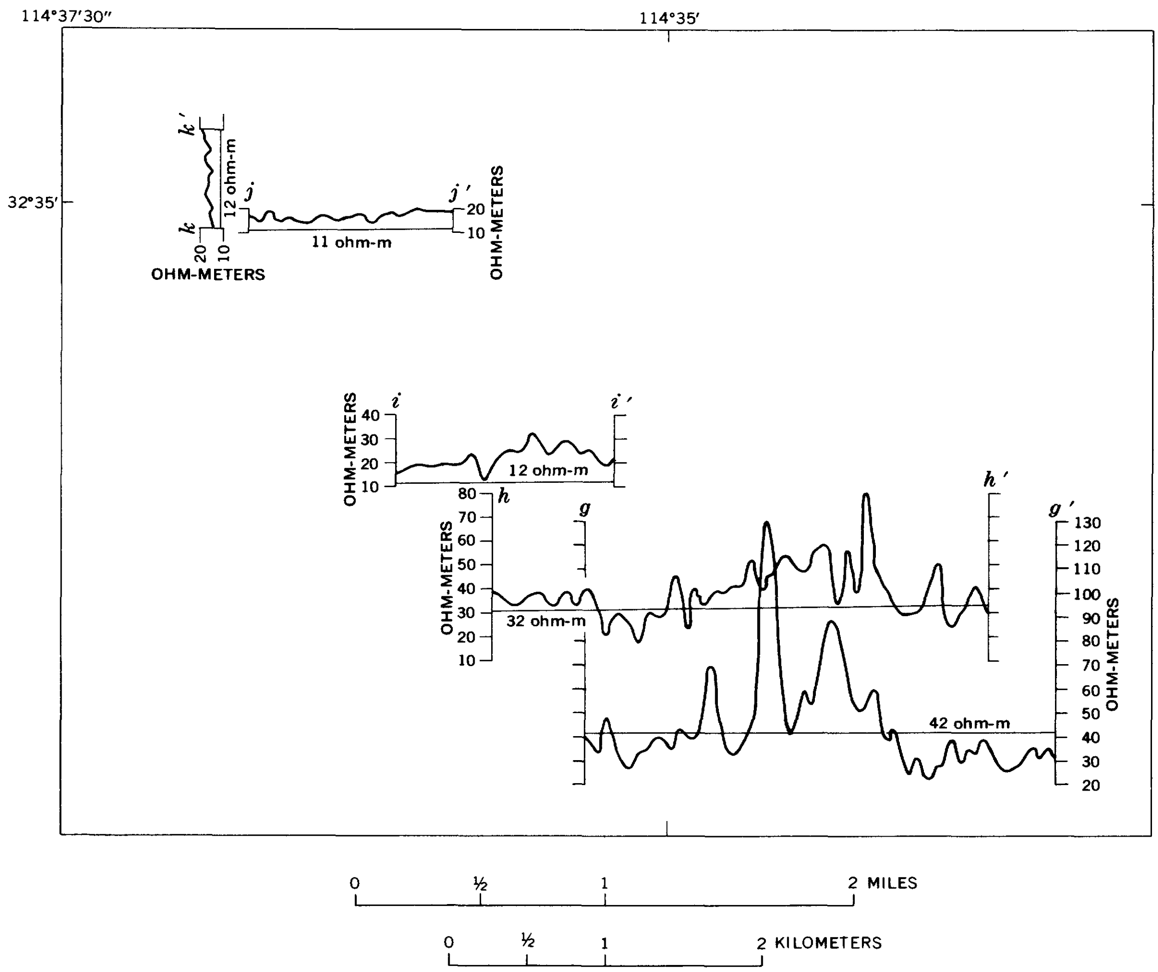


FIGURE 21. — Resistivity profiles *g-g'* through *k-k'* across the inferred trace of the Algodones fault southeast of the Yuma basement high. Lines of profiles shown on plate 5.

ting strongly cemented gravel tongues with a high resistivity (about 1,000 ohm-m). Evidence for this interpretation is the fact that these large anomalies do not appear on profiles *i-i'*, *j-j'*, and *k-k'*, along the presumed trace of the fault; rather, the anomalies are oriented northeast, parallel to known trends of gravel tongues in the area (Olmsted and others, 1973), instead of northwest, along the inferred fault.

Although the resistivity surveys did not yield anticipated information about the position and nature of the fault or fault zone, the hydrologic data obtained later in the same area delineated the trace of the concealed barrier within narrow limits but did not provide information about its precise attitude and nature. Interpretations of the barrier's dip, width, and cause must await detailed exploration by means of test drilling or excavation.

Unequivocal data on the direction and amount of movement on the Algodones fault are likewise difficult to obtain. Until it can be shown that several features along the trace of the proposed fault all are offset, we can only speculate about the amount and type of movement. By analogy with other faults in the San Andreas system, the movement probably has been chiefly right lateral. The gravity nose north of Somerton (pl. 1) may reflect a part of the Yuma basement high displaced northwestward by right-lateral movement. The westward offset of the Mesa anomaly relative to the northern part of the Yuma basement high (the Yuma anomaly) could also be explained by right-lateral movement, on a parallel fault to the northeast.

Vertical components of displacement on the Algodones fault are more apparent. In the northwestern part of the area near the Colorado River, seismic-reflection data indicate that the top of the Bouse Formation is downthrown 500 feet on the southwest side of the fault. Seismic-refraction data along the southwest flank of the Mesa anomaly (fig. 17) indicate that the basement is downthrown 350 feet on the southwest side of the fault, and gravity data 4,000 feet farther south suggest an additional 1,000 feet of throw (fig. 20). Farther southeast, however, geophysical information suggests throw in the opposite sense — the Fortuna basin northeast of the fault is downthrown relative to the boundary basement high southwest of the fault. In the same area the topographic offset of the "Upper Mesa" surface also suggests downthrow to the northeast. Similar reversals in throw along the strike of the fault are common along other faults in the San Andreas system which have had predominantly strike-slip movements.

Time of the last significant movement on the Algodones fault can be established qualitatively from geologic and topographic evidence. The near-surface alluvial deposits beneath both the Holocene flood plain of the Colorado River (Yuma Valley) and a river terrace of probable late Pleistocene age (Yuma Mesa) are unaffected, but the fault is clearly exposed across the older alluvial surface of the "Upper Mesa" farther southeast. The age of the "Upper Mesa" surface has not been established but is almost certainly older than latest Pleistocene. Significant movement on the Algodones fault therefore ceased sometime during the Pleistocene. The parallel or en echelon faults are inferred to be even older, owing to the apparent absence of significant hydrologic effects (other than thermal effects) caused by these faults. By contrast, most of the faults crossing the Salton Trough farther west are still active, reflecting the much more recent deformational activity of that region as compared with the Sonoran Desert.

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