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AN ANALYSIS OF GRAVITY DATA FROM THE TUCSON BASIN, ARIZONA

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INTRODUCTION

The study described in this article was carried out by the Laboratory of Geophysics, Department of Geosciences, University of Arizona, during 1966 and 1967, and was financed by the Tucson Water Resources Research Center. The purpose of the study was to determine the major hydrologic boundaries of the Tucson Basin using geophysical methods, primarily through analysis of gravity data. The Tucson Basin is in south-central Arizona and is the site of the City of Tucson (Figure 1). This paper utilizes the data to speculate upon basin structure and history.

DATA ACCUMULATION

Gravity Data

Gravity station locations are shown in Figure 2. Circles indicate data collected during this survey; squares indicate data incorporated from Plouff (1962), Petersen (1965), and Abuajamieh (1966).

Over 75 percent of the gravity readings were taken on a LaCoste Romberg model G-49 instrument. The rest were either taken on a Worden Educator or on a Worden Prospector.

A nominal station spacing of one mile was used, this interval being shortened in a few areas of special interest. Readings taken south of T19S were supplementary to the main study and were taken only along easily accessible routes. The maximum estimated station-location error was $\pm$ 500 feet (approximately 0.1 minute of latitude or longitude). Locations were obtained from the largest scale U. S. Geological Survey topographic quadrangle sheets available. In the immediate vicinity of Tucson this scale was 1:24,000; elsewhere, 1:62,500.

Examination of gravity-station data revealed that the most critical parameter in Bouguer gravity computations would be elevation control. U. S. Geological Survey topographic quadrangle sheets were used for elevation determination. Their specified accuracy is plus or minus one-half contour interval for 90% of the points tested (U. S. Geological Survey, 1960). Contour intervals of the maps used varied from 10 to 80 feet. In terms of gravity this is equal to a range of Bouguer gravity accuracy from $\pm$0.61 to $\pm$4.88 mgals for 90% of the stations. As later discussed in

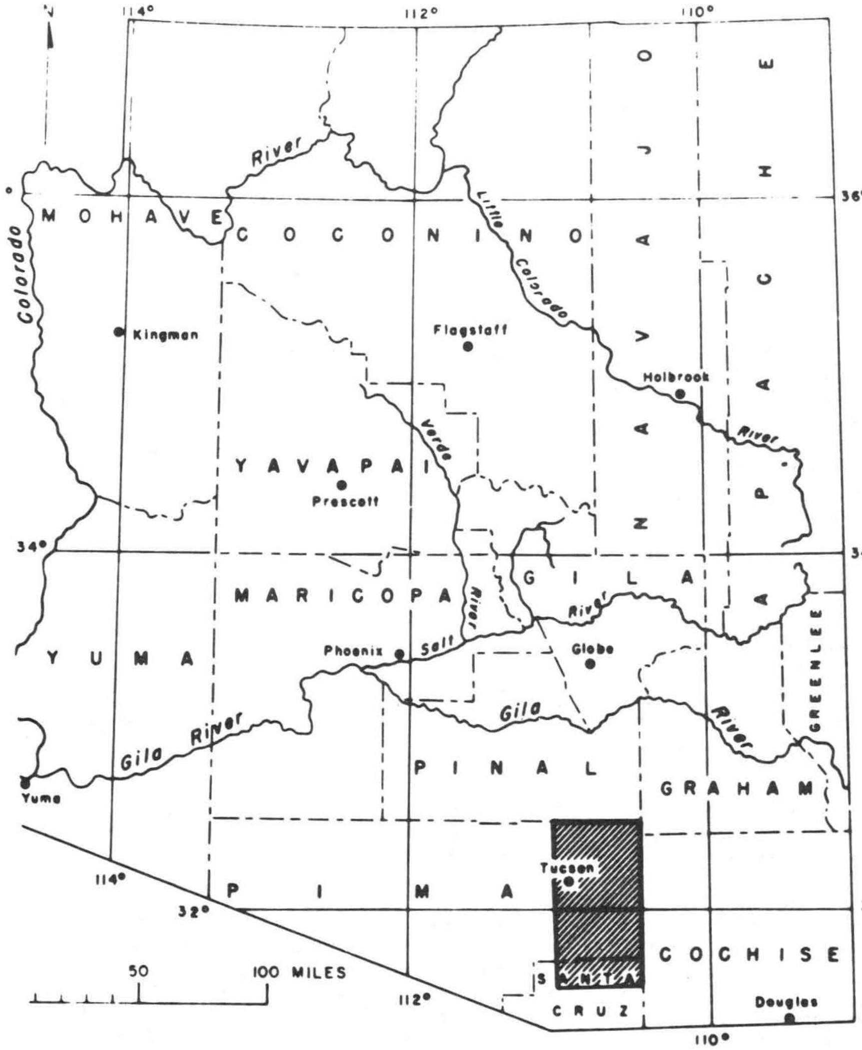

Figure 1.--Location of Tucson Basin.

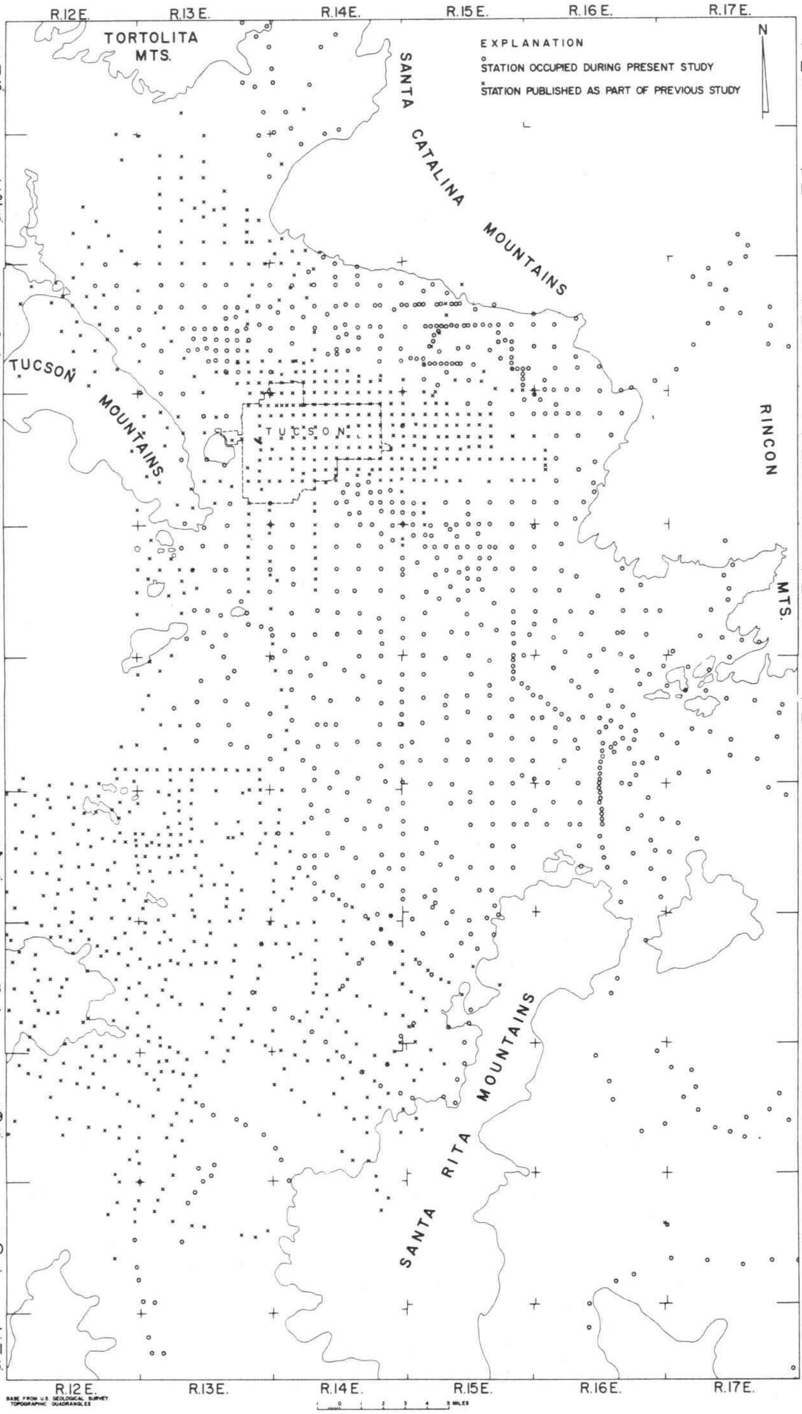

Figure 2.--Gravity Station Location Map of the Tucson Basin.

this report, this is by far the greatest possible source of error. An American Paulin model M-1 barometric altimeter was used to check elevations at some stations, especially those in areas of high topographic gradient. The results suggest that the topographic contours are probably accurate to ± 0.4 contour interval for 90% of the points checked on maps with contour intervals of 40 feet or greater. The internal consistency of the gravity net also indicates that the maps were probably more accurate than U. S. Geological Survey specifications. Elevation accuracy also depended upon horizontal control. Assuming a maximum station location error of 500 feet, sampling of 10 per cent of the data points occupied during this survey indicated that the maximum possible Bouguer gravity error due to elevation errors from this discrepancy would be less than 0.73 mgals (12 feet) for 90% of the stations occupied. Most of the data points were from maps with a scale of 1:62,500. Horizontal location accuracy would be much better on the maps with a 1:24,000 scale.

Base station readings were taken at least once every four hours when possible. When this was not feasible, a correction for earth tides was made using tables published by the European Association of Exploration Geophysicists (1965). Several new base stations were established for this survey.

It was necessary to determine corrections for terrain effects for a few stations. Such corrections were made with a Hammer graticule (Dobrin, 1960, p. 230) out to the M ring. An average upper crustal density of 2.67 gm/cm^3 was assumed. Determination of this value is discussed later.

To correct Bouguer gravity values for the regional gradient, representative values for Bouguer gravity in broad areas of granitic or metamorphic outcrop were chosen and corrected for terrain effects. The regional gradient across the basin appears to be a plane dipping south twenty degrees east at 1.0 mgal per mile.

Simple Bouguer anomalies can result both from density variations of material within the basement and variations in alluvial fill thicknesses. No drill holes reach the basement except around the basin margins so there is no way to resolve the question of cause over most of the area. Assuming a laterally homogeneous basement, removing the regional gradient from simple Bouguer gravity data (Figure 3) yields a map (Figure 4) which shows only anomalies due to variations in thickness and density of alluvial sediments. Using profiles selected from the residual gravity map, cross sectional interpretations were made. These interpretations were then used to construct a basement depth contour map (Figure 5).

A gravity graticule similar to those shown by Dobrin (1960, p. 256-258) was constructed for the profile analyses. Infinite length in the third dimension was assumed when using the graticule. In an area as intruded and apparently structurally broken as the Tucson Basin, anomalies due to intrabasement features of secondary interest and "end effects" due to features not having infinitely long third dimensions present interpretational problems. In the present analyses, gravity contours were straightened and smoothed to eliminate these problems where necessary. Interfaces were assumed to be either horizontal or vertical unless the gravity profile strongly suggested a different slope. A basement-alluvium density difference of 0.40 gm/cm^3 was used. Determination of this density value is discussed in later sections of this paper.

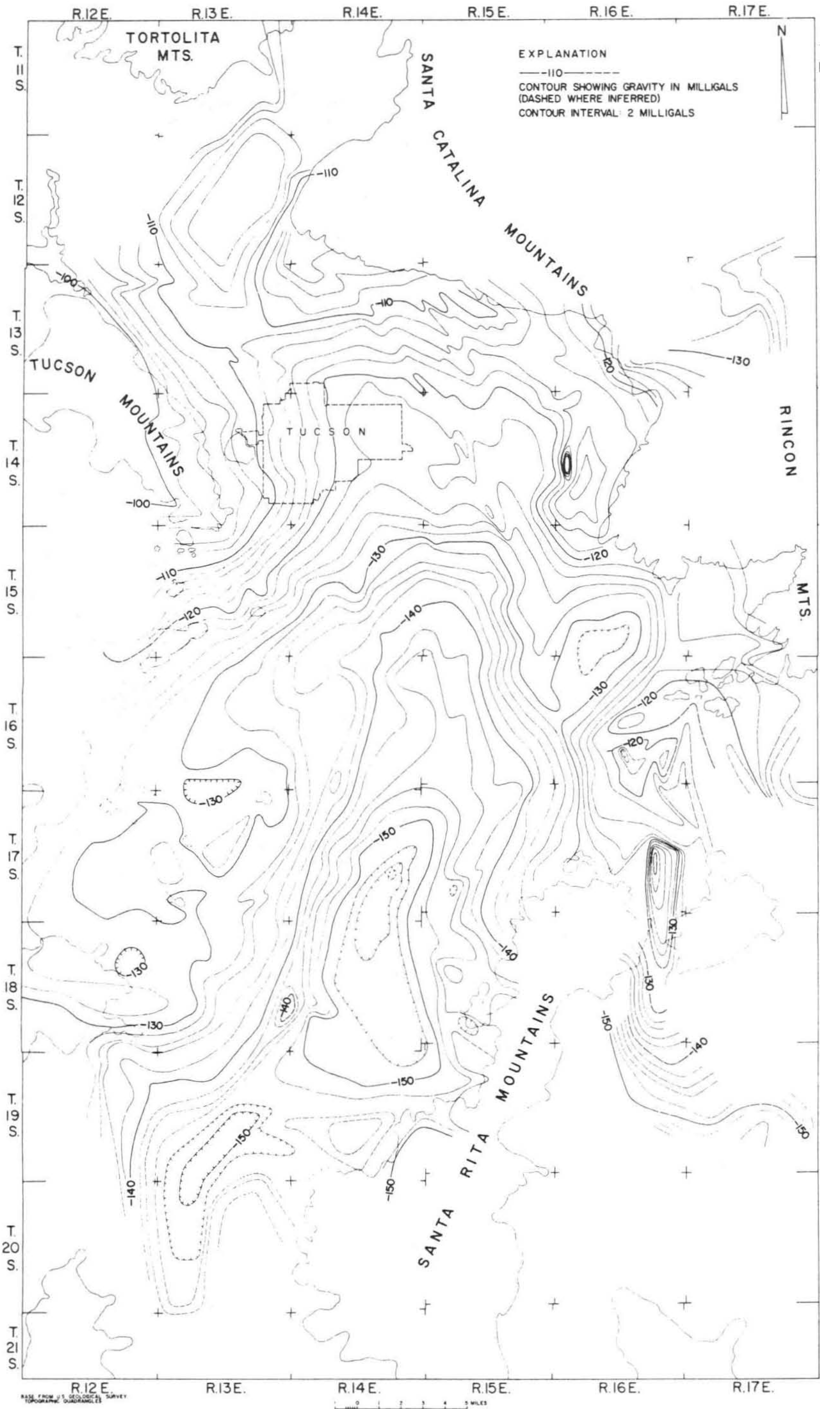

Figure 3.--Simple Bouguer Gravity Map of the Tucson Basin.

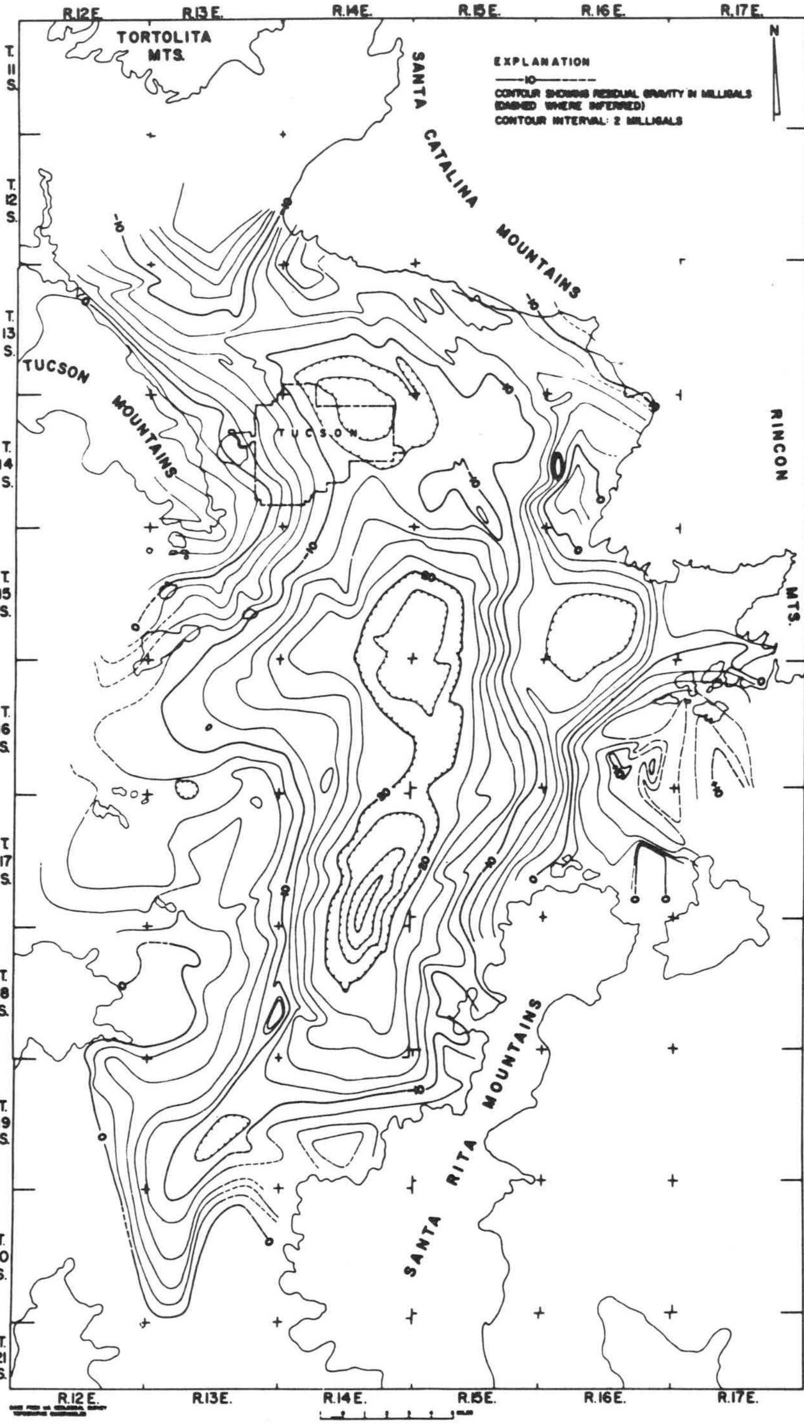

Figure 4.--Residual Gravity Map of the Tucson Basin.

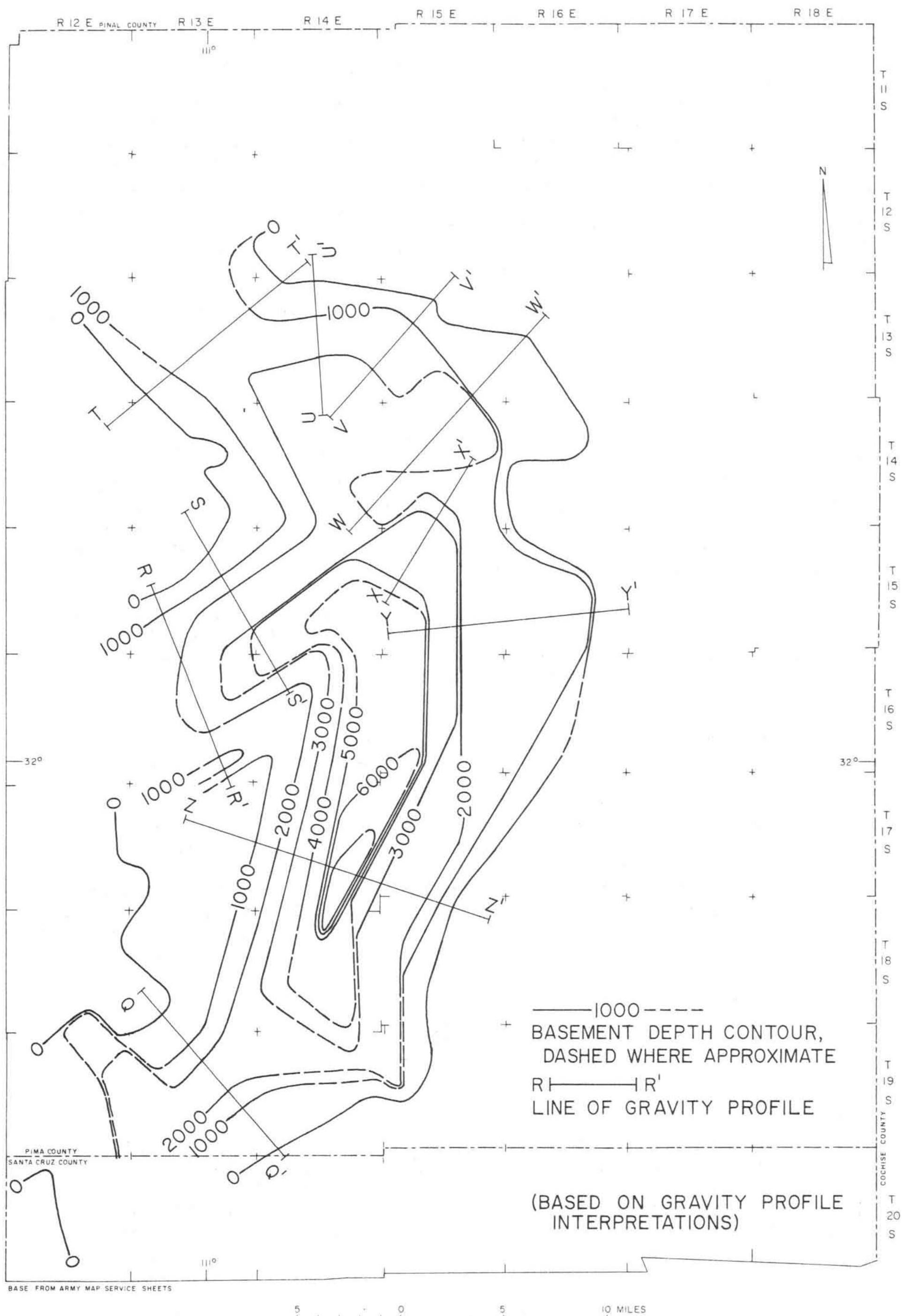

Figure 5.--Generalized Basement Depth Contour Map of the Tucson Basin.

Subsurface Data

During 1966 the U. S. Geological Survey and the City of Tucson drilled six exploratory holes in the basin (Figure 6). Because the primary purpose of the drilling programs was to obtain information on the basin aquifers, they were extensively cored and logged. Figures 7 and 8 show some of the logs obtained. Lithologic logs were also compiled by the U. S. Geological Survey. Those shown here were obtained by sieve analysis of cuttings samples taken every 10 feet. Per cent fines refers to material which would pass a 0.061 millimeter mesh screen. All of the logs obtained, plus cores and core descriptions, are in U. S. Geological Survey open files. A great deal of unpublished subsurface data were also obtained from the open files of the U. S. Geological Survey (USGS) and the University of Arizona Agricultural Engineering Department.

Density Data

A critical value necessary for any interpretation of gravity data is the difference in density of subsurface materials involved. Three primary sources of data were used to determine densities. The first source was from surface samples collected by Abuajamieh (1966) and later by the writer for this study at locations shown on Figure 6. A second source was laboratory density measurements from well core samples.

Four or five samples of material from surface exposures were taken at each site shown on Figure 6. These samples were immersed in water for at least 24 hours and then their densities were determined by the volume-displacement method. The average density at each site is given in Table 1.

The wells drilled by the USGS and the City of Tucson were cored at intervals. The Laboratory of Geophysics was able to obtain samples of the core material for density measurements. Densities were determined by the volume-displacement method. Several problems other than disaggregation were encountered in obtaining the density values (Figure 9), but the most serious ones were caused by the finer material. Some of the clays in Well No. 3 had hardened and become so impermeable during drying that they would not resaturate even after three weeks of soaking. Most of the cores from this well which did resaturate swelled so much that the density determinations were deemed spurious and are not used here.

DISCUSSION & INTERPRETATION

Stratigraphy

The Tucson Basin is a typical Basin and Range structural feature being an alluvium-filled valley surrounded by mountain blocks. These consist mostly of plutonic igneous and metamorphic lithologies mantled in places by a thin veneer of sedimentary rocks. One exception is the Tucson Mountains on the northwestern edge of the basin. These mountains are for the most part volcanic in origin.

The alluviated portion of the Tucson Basin contains three known sedimentary units above the pre-Tertiary basement material.

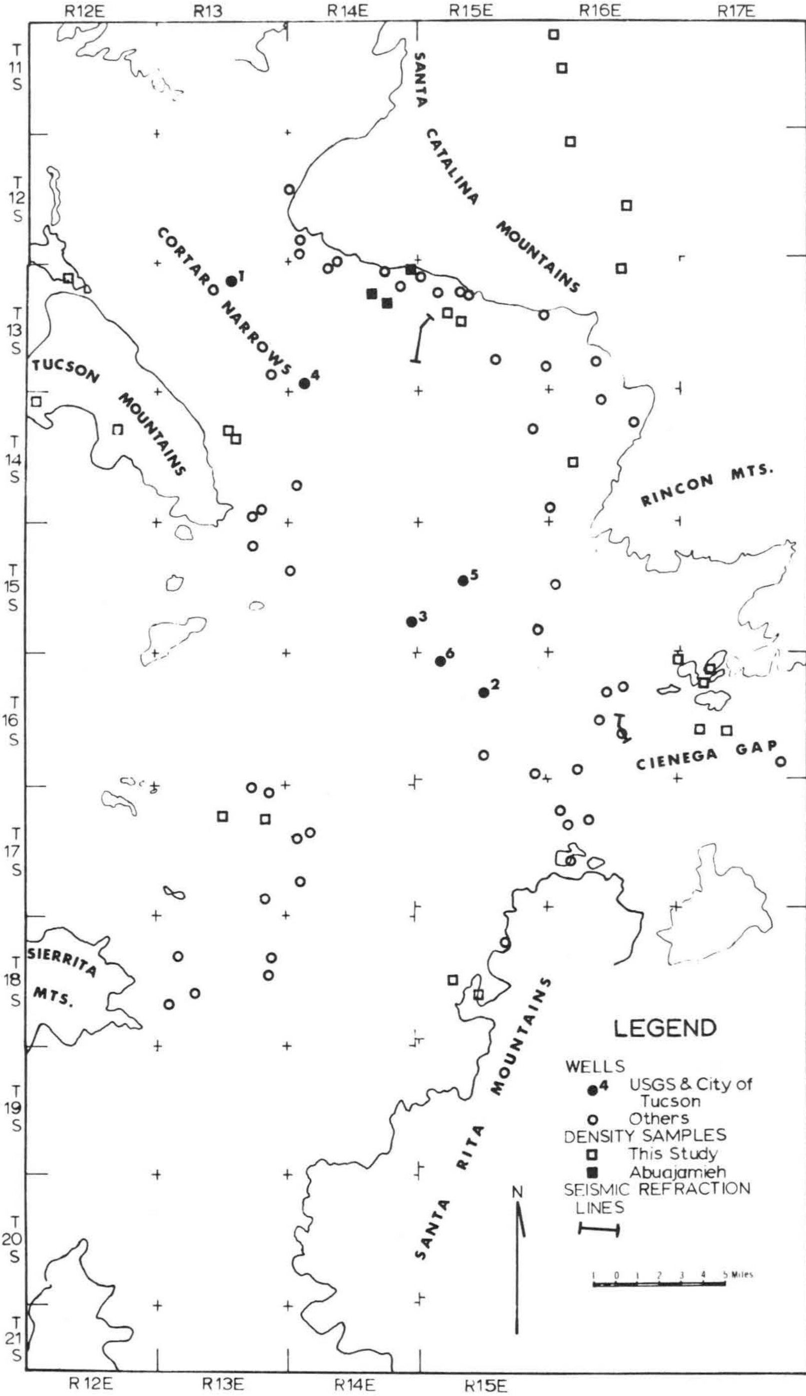

Figure 6.--Data Collection Points in the Tucson Basin.

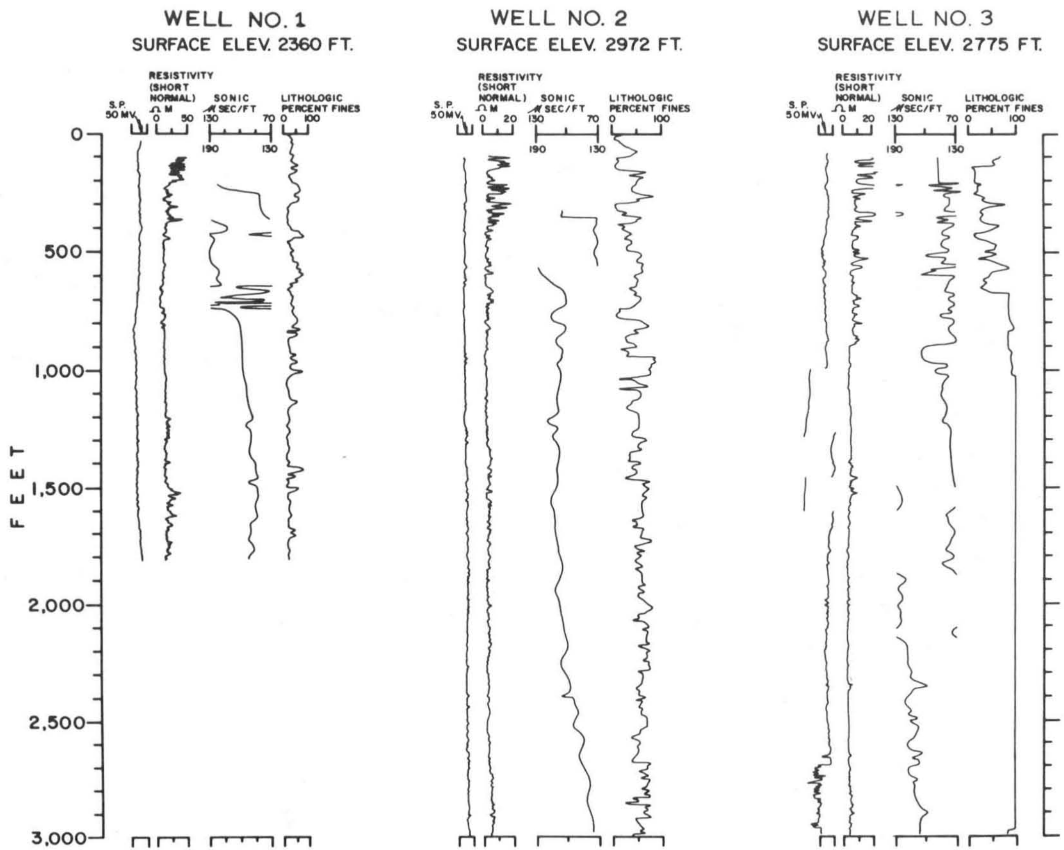

Figure 7.--Borehole Logs from the Tucson Basin.

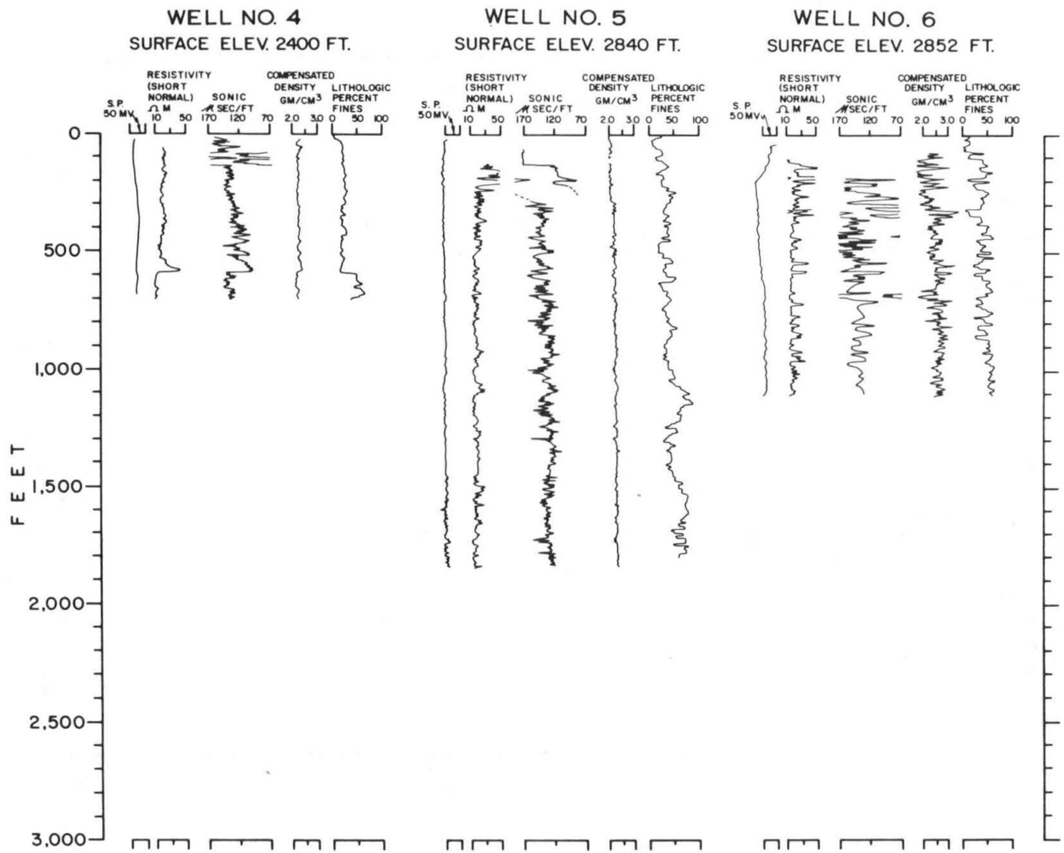

Figure 8.--Borehole Logs from the Tucson Basin.

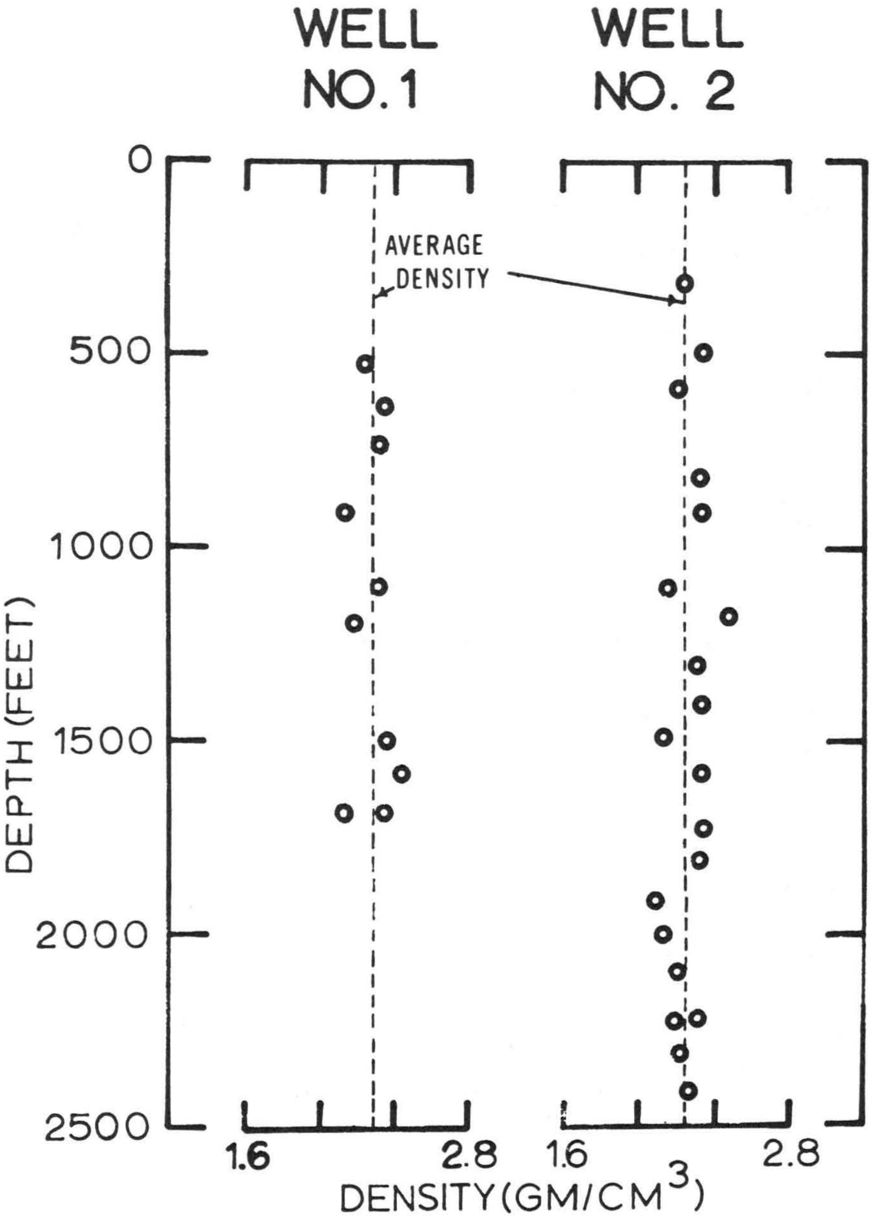

Figure 9.--Densities of Core Samples from Tucson Basin Wells.

The oldest is a mid-Tertiary sequence of sediments represented in Cienega Gap by almost 14,000 feet of clastic continental deposits, some of fluvial origin, which were named the Pantano formation and described by Brennan (1962). Potassium-argon dating of a rhyolite ash flow in the sequence (Damon and Bikerman, 1964) gave an age between 30 and 38 million years. Cooper (1960) measured about 10,500 feet of an incomplete section of clastic continental material called the Helmet fanglomerate on the east flank of the Sierritas and correlated it with the Pantano formation. Damon and Bikerman obtained a date of 24 million years on dikes intruding the Helmet. In neither area was there sufficient depth to basement to accommodate more than a small fraction of these thicknesses. Thrust faulting was called upon as a mechanism for truncating and emplacing the units. Pashley (1966) and Drewes (1966) correlated the Rillito formation north of Tucson and the Nogales formation in the southern part of the basin, respectively, with the Pantano formation. Heindl (1959) did the same with the San Xavier formation in T15S,R13E. In this paper all of these units will be referred to collectively as mid-Tertiary sediments, with time of deposition being assumed to have extended from late Oligocene through early Pliocene as suggested by Pashley (1966).

Above the mid-Tertiary sediments is a unit commonly designated Basin Fill, which is of probable late Pliocene to early Pleistocene age. The third, youngest unit is the late Pleistocene to recent alluvium. This latter material is found as inner valley fill along streams or as alluvial fans along the present mountain fronts.

INTERPRETATION OF DENSITY DATA

The ambiguities of gravity interpretation should be borne in mind throughout the following discussion. Geological data place limits on the number of possible pre-Tertiary basement configurations, but still leave a problem in interpretation. Because of these ambiguities the writer has attempted, in this paper, to give the location of all new, unpublished basic data on which interpretations have been based so that the reader may reinterpret if he chooses. It should be noted that many of the field notes, maps, computer output, and seismic records are on file in the Laboratory of Geophysics.

The commonly used figure for an average upper crustal density is 2.67 gm/cm^3. Surface samples (Table 1) from outcrops around the basin margin apparently confirm this as a reasonable value for basement material in the Tucson Basin. In this paper, the term "basement" refers to Pre-Tertiary units and to Cenozoic crystalline units. One of the major assumptions made in accepting this density value is that buried basement rock types are adequately represented by the presently exposed material. There is probably some degree of deviation from this assumption in certain areas. Erosion may not have removed Cretaceous sedimentary units, for instance, from the topographically low areas of the basement surface as completely as from present topographic highs. Secondly, the Mesozoic sediments, where exposed, show some degree of metamorphism. It is, therefore, difficult to assess an average metamorphism density for these rocks. Finally, it is generally assumed that the whole Tertiary sedimentary section in mid-basin is as devoid of intrusive and extrusive material as that part so far penetrated by drilling.

Data from cores from wells shown in Figure 9 indicate that an approximate density of 2.27 gm/cm^3 fits the upper portion of the unconsolidated mid-Tertiary formations. In order to check the

TABLE 1

SURFACE SAMPLE DENSITIES
(Site locations shown on Plate 6)

Site No.	Formation Name and/or Rock Type	Average Density of 4-5 samples (gm/cm3)
1	Leatherwood diorite	2.86
2	Apache group (phyllite)	2.82
3	Catalina granite (Quartz monzonite)	2.58
4	Catalina gneiss	2.59
5	Catalina gneiss	2.73
6	Catalina gneiss	2.65
7	Amole (?) formation (metasedimentary siltstone)	2.77
8	Rincon granite (quartz monzonite)	2.69
9	Escabrosa limestone	2.77
10	Bolsa quarzite	2.69
11	(Granitic)	2.62
12	Naco Group (limestone)	2.70
13a	(Granitic)	2.56
13b	(Granitic)	2.62
14	(Aplite Dike)	2.58
15	Tertiary volcanics (Welded Tuff)	2.35
16	Tertiary volcanics (Vesicular Basalt)	2.68
17	Rincon gneiss	2.60
18	Rincon gneiss	2.70
19	Pantano volcanics (Andesite porphyry)	2.52
20	Pantano formation (silty sandstone)	2.40
21	Tucson Mtn. Chaos (breccia ?)	2.62
22	Recreation redbeds (Cretaceous mudstone)	2.76
23	(Andesite Porphyry)	2.63

laboratory data, velocities and densities from geophysical logs of basin wells (Figures 7 and 8) were examined. These wells all penetrated at least the upper portion of the mid-Tertiary sequence. The density logs in Figure 8 indicate that densities between 2.20 and 2.25 gm/cm^3 are most common. A plot of velocity versus density was made (Figure 10) using the logs in Figure 8. This plot shows that a definite velocity-density relationship exists, although it is not the same as some others previously published. The velocity logs in Figure 7, interpreted in the light of velocity-density relationships, also imply that mid-Tertiary sediment densities of at least 2.5 gm/cm^3 exist at depth.

Turning to surface evidence, Abuajamieh's (1966) density samples came from mid-Tertiary sediments in the Catalina foothills area (Figure 3). He measured values in the laboratory between 2.34 and 2.51 gm/cm^3. Samples from Pantano units in Cienega Gap (Table 1, Site 20) had an average density of 2.40 gm/cm^3. Seismic refraction velocities in Cienega Gap ranged from about 9,000 to 11,000 ft/sec. in Pantano units. This correlates well with the velocity-density relationships in Figure 10.

Summing up, Cenozoic sediment densities over most of the basin appear to vary from about 2.0 gm/cm^3 at the surface to at least 2.5 gm/cm^3 at the greatest depths reached. The velocity and density data also show that densities in some of the foothill areas at specific depths are much higher than average, while those in the fine-grained sediments at the same depths near basin center are much lower than average. A density of 2.27 gm/cm^3 for the Cenozoic sediments was selected as the best average for gravity interpretations. No attempt was made to correct for the lateral density variations.

The Tucson Mountains pose a complex problem in density determinations. Their lithology includes basalts, rhyolitic tuffs, and alluvial material in unknown ratios. It was estimated that 2.67 gm/cm^3 or less would be a good average density. Assuming the regional gradient to be correct, there should be no residual Bouguer anomaly over the range. Yet, one does exist as can be noted on Plate 5. Another, similar, positive anomaly occurs in Cienega Gap where there is again little surface evidence of high densities, although a well in the gap penetrated between 100 and 300 feet of volcanic material. Its density is unknown. Basic volcanics at depth are possibly the explanation for the positive anomaly in both areas. Before an adequate interpretation can be made of gravity data in the Tucson Mountains, it will be necessary to conduct an extensive sampling program to evaluate the average density of the surface material.

Gravity Maps

Plouff (1961, p. D-258) noted the linearity of gravity patterns in the Tucson and Sierrita Mountains. Figure 5 shows that this type of pattern prevails across the whole Tucson basin. There appear to be three major directions of linearity: north-northeast, northeast, and northwest. The latter two directions are in agreement with Mayo (1958). Within the basin, northwest trends appear to offset or terminate other trends. Northeast trends, in turn, generally terminate or offset north-northeast alignments.

Gravity data show a number of northwest trending highs in the northeast quarter of the basin from the area west of the Rincons northward to the western end of the Santa Catalina Mountains. Because of strong parallelism with magnetic data, the highs are

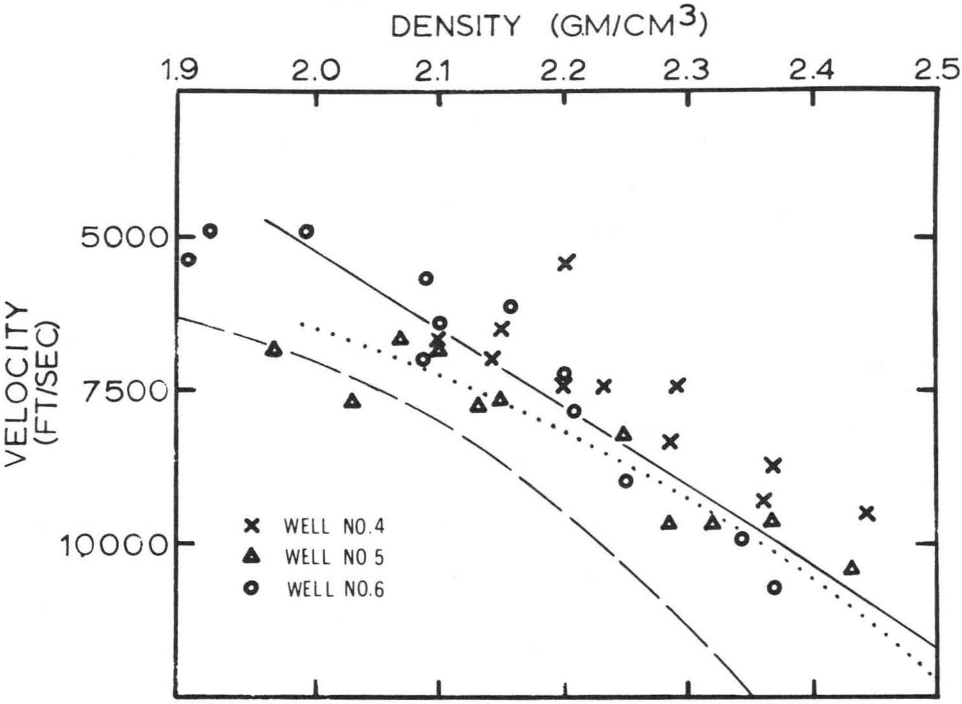

Figure 10.--Density versus velocity plot of Tucson Basin Sediments. Data Points are from well logs. The solid line is a fourth order polynomial fit to the data. Data from other sources is shown for comparison. The dashed line is from Grant and West (1965, Fig. 7-7) for sediments in the Gulf Coast. The dotted line is from Clark (1966, Fig. 9-3) for ocean bottom sediments.

interpreted as dikes. If they are dikes, the half-widths of both gravity and magnetic profiles indicate that they penetrate to within 1000 feet of the surface. Their exact depths cannot be calculated without a denser station spacing along profile lines. This would be within the upper portion of mid-Tertiary units implying a post-lower Pliocene intrusive. No intrusives of such a late date have been noted on the surface around the basin margins.

Basin Structure and History

Given the present status of knowledge, Figure 6 is necessarily a generalized picture of the depth to the base of the Tertiary sediments, but it serves as a very useful working model. Several interesting features emerge from the contour map. Broad slopes fronting the Sierrita, Santa Rita, Rincon, and Catalina Mountains are interpreted as pediments cut on metamorphic or igneous material. Along the southwest margin of the Santa Catalinas, this pediment is obviously older than the overlying mid-Tertiary sediments. Whether or not the basement pediments are older than the entire mid-Tertiary section is not certain. Assuming they are erosional surfaces, they would certainly signify that a long or intense period of erosion preceded or accompanied deposition of mid-Tertiary sediments. Basement pediments would also signify that uplift preceded or accompanied deposition of mid-Tertiary sediments and would correlate with Damon's (1966) post-Laramide erosion surface of mid-Tertiary age.

Rather than a pediment. the smooth gravity gradient on the east side of the Tucson Mountains has been interpreted as due to the base of a spreading volcanic pile interbedded with more and more alluvial materials as one proceeds toward the basin. It could be a combination of both pediment and interbedded volcanics.

Cortaro Narrows at the northern end of the Tucson Basin takes the form of a relatively shallow swale sloping gently into the basin and dropping abruptly to the northwest. The northwest end of the swale is probably terminated by an extension of a fault system which bounds the northwest margin of the Santa Catalina Mountains.

Figure 6 shows the basin divided into three major portions. Beneath the City of Tucson alluvial deposits are on the order of 3,000 feet thick. The south edge of this portion is marked by a basement scarp trending northeast through T14S, R13E. South of this scarp alluvial thicknesses increase to over 5,000 feet. This depth prevails south to T18S where an extension of a northwest trending fault zone in T19S, R15E probably cuts the basin floor again. South of the extension the basin floor rises to 2,000 or 3,000 feet below the surface.

The large graben in T14S, R13E has been discussed in previous studies (Heindl, 1959: Sumner, 1965: Lacy and Morrison, 1966). Its northern margin was referred to by Sumner as the Black Mountain fault zone. Heindl noted that the graben may be filled with pre-Tertiary sediments. Lacy and Morrison state that it is filled with volcanic material. There is evidence of volcanic activity in the area. The heterogeneity of such a basement complicates gravity interpretations. Consequently, depths to basement derived from gravity data are not too reliable. A coincidence of magnetic, gravity, and geologic data do define the graben margins very closely and these appear to extend into the center basin as fault zones.

Considered in the light of Basin and Range tectonics, most of the high, linear gravity gradients could be interpreted as normal faults. Evidence presented earlier suggesting buried pediments implies that they may have been initiated prior to the mid-Tertiary.

Most of the mid-Tertiary surface exposures are dominantly fluvial with minor lacustrine deposits. However, wells in the center of the basin penetrate great thicknesses of siltstone, claystone, and evaporites below Basin Fill units. Well No. 3 passed through approximately two thousand feet of such material. This implies that fluvial deposits around basin margins grade laterally into lacustrine material in the central basin. Gamma-ray logs from Wells 1, 2, and 3 are notable for their low response. The source of such radiation is usually organic material which is apparently lacking throughout the central basin sections that have been logged to date. Lack of organic material and the presence of evaporites are strongly indicative of playa lake deposits. This, in turn, suggests an arid climate, much like the present, and mountain barriers which prevented drainage from the basin. Mid-Tertiary deposition probably ended when streams were provided a means of egress from the basin. It should be noted that this analysis suggests the inception of arid conditions in the Southwest earlier than Anderson's (1962) date of the late-Tertiary.

Both Brennan and Cooper called upon thrusting to explain the presence of over ten thousand measured feet of Pantano section in Cienega Gap in areas of shallow basement. Where did this thickness accumulate? First, it is doubtful, from these gravity results, that Brennan's thirteen thousand feet of sediment could be accommodated in the central basin. Second, because tension, not compression, has been the stress regimen of the Southwest since the Oligocene Epoch, it is difficult to find a mechanism to thrust the sediments out of the central basin even if they could be accommodated. Third, even if gravity gliding is suggested as a mechanism to emplace the sediments, it is illogical to put the required thickness of alluvial material over rising mountain blocks when it cannot be accommodated in the neighboring basin. Either the depositional dip was greater than suspected or there is repetition of beds.

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