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ESTIMATING STORAGE CAPACITY IN DEEP ALLUVIUM BY GRAVITY-SEISMIC METHODS

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ABSTRACT

Large volumes of groundwater are contained in the deep intermontane valleys of Basin and Range regions. Determining the shape and storage capacity of these basins by drilling can be expensive and difficult because of the depth of alluvium and large areas involved. These difficulties can often be overcome by combining gravimetric and seismic refraction interpretations. The basin boundaries are determined by gravimetric methods, with bulk density samples taken of all representative formations. Density values can then be correlated with seismic velocities to estimate subsurface porosities. Studies indicate that seismic velocity varies inversely with porosity for the alluvial deposits. These values can be correlated with their respective formations in the basin from geologic sections derived from the seismic refraction survey. Thus, with volume and porosity of the alluvium known, storage capacity (both present and potential) can be computed.

RÉSUMÉ

De grands volumes d'eau souterraine se trouvent dans les bassins formés par de très profondes vallées entre montagnes et par de grandes étendues de terrain non délimitées. Le mode de détermination de la forme et de la capacité de ces bassins par la voie de sondages peut devenir très coûteuse et difficile, à cause de la profondeur de ces grands gisements alluviaux, et de l'étendue des terrains intervenant. Très souvent ces difficultés peuvent être surmontées en combinant les résultats gravimétriques et de réfraction sismiques. Les limites du bassin sont déterminées par des méthodes gravimétriques, avec des prélèvements de densité en masse pris sur toutes les formations représentatives. Ces valeurs de densité peuvent être alors mises en corrélation avec les vitesses de propagation sismiques pour estimer la porosité du sous-sol. Les expériences indiquent que la vitesse de propagation sismique varie inversement avec la porosité des gisements alluviaux. Ces valeurs peuvent être mises en corrélation avec les formations respectives, trouvées dans le bassin, et qui correspondent aux sections géologiques provenant du levé de réfraction sismique. C'est ainsi que la capacité de réservoirs (tant actuelle que potentielle) peut être calculée, si le volume et la porosité de l'alluvion sont connus.

INTRODUCTION

Much time and effort is being spent by various organizations in the search for and development of groundwater in the semiarid Southwest. Groundwater withdrawal is monitored in the heavy usage zones, such as the larger urban and agricultural areas, to prevent serious overdraft of available supplies, as well as to maintain quality control. Use has increased to the point where some basins are being declared "critical water shortage areas," and development and use of groundwater are restricted. Thus, these areas become increasingly important for future water needs.

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The deep, large volume basins, typical of Basin and Range provinces, are ideal for ground-water storage. The problem of evaporation, so critical with surface reservoirs in the Southwest, is practically eliminated. The depths to regional water table in most areas (ranging from 100 to 500 feet) minimize the possibility of contamination by surface sources. The sand and gravel that fill the basins act as an efficient natural filter for percolating water.

The ever-increasing problem of surface space available for development does not conflict with basin storage of large volumes of water. A local subsurface water source is more convenient to the user than a distant surface reservoir.

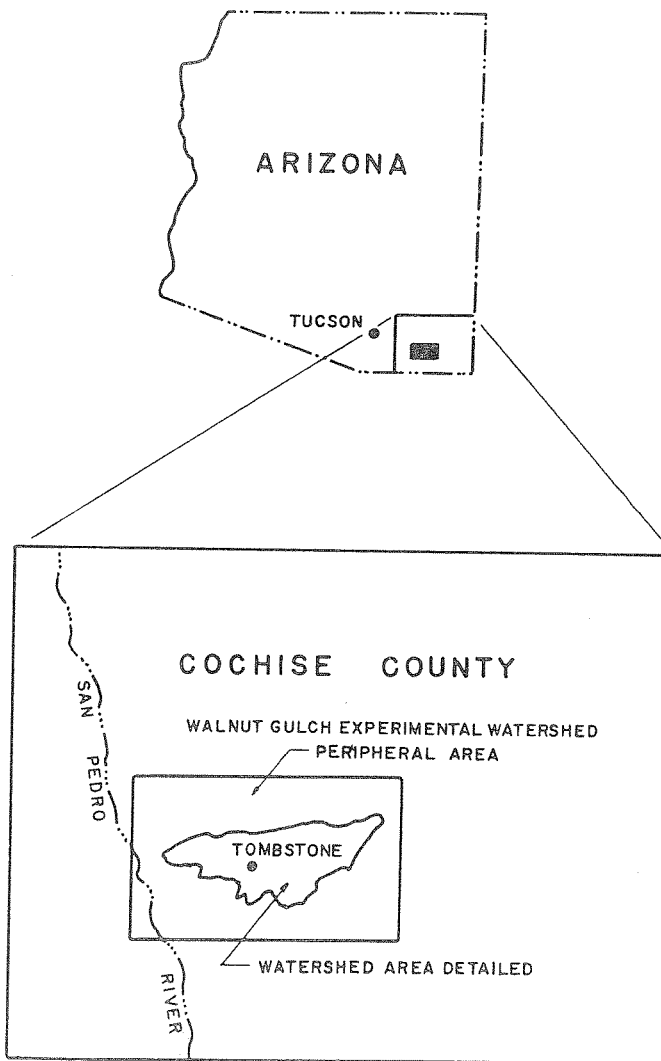


Fig. 1 — Location map of study area.

General Geography

The area of study covered by this report includes a portion of the eastern flank of the Upper San Pedro River Valley near Tombstone, Arizona (fig. 1). The 290-square-mile study area includes Walnut Gulch Experimental Watershed, an Agricultural Research Service outdoor hydrologic laboratory. Elevation ranges from 3800 feet above sea level at the San Pedro River (the western boundary) to 6000 feet in the Dragoon Mountains (the eastern boundary). Land use is restricted mainly to cattle ranching, although some small-scale mining operations are present in the Tombstone Hills and Dragoon Mountains.

A broad alluvial pediment, bounded by fault-block mountains on the east, slopes westward to the San Pedro River, the axial stream of the valley. Igneous intrusions and complexly folded and faulted sediments interrupt the smooth downward slope of the alluvium in portions of the valley (fig. 2).

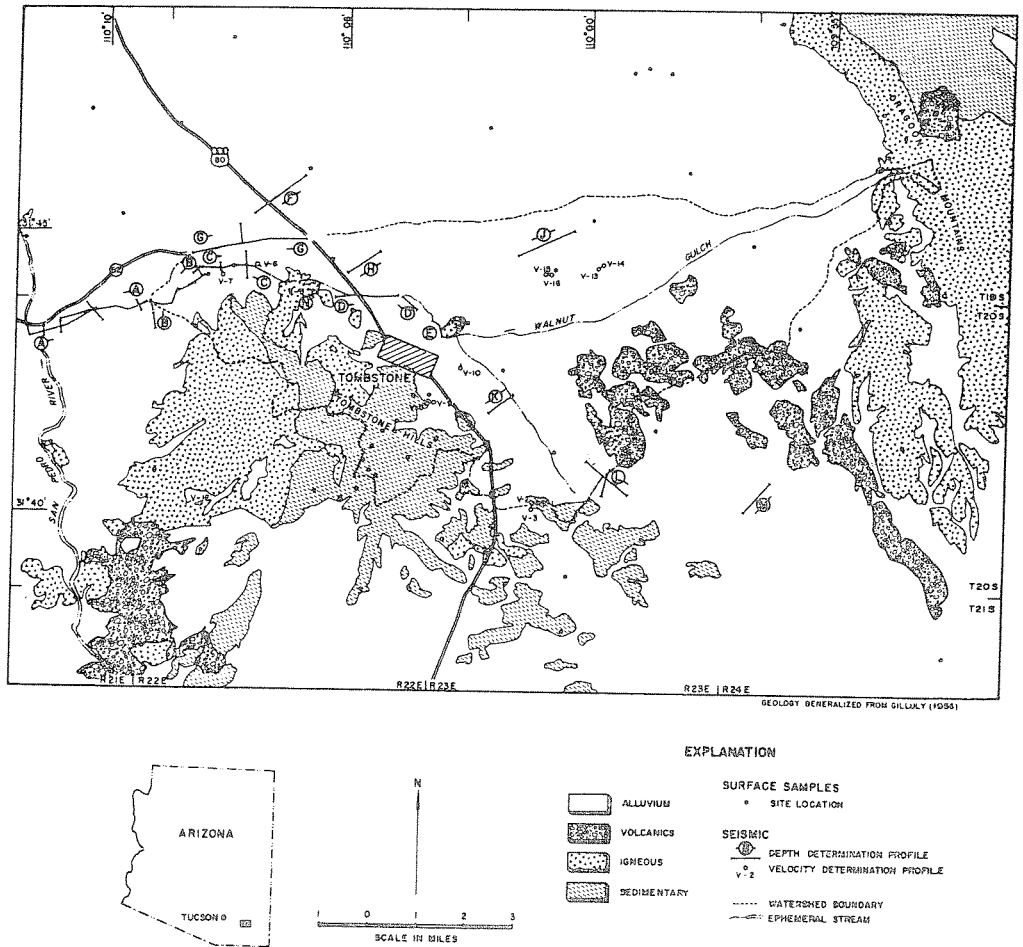


Fig. 2 — Generalized geologic map, showing location of seismic traverses and surface sampling stations.

Previous Work

Various mining companies have made exploratory surveys in the general location described here. Most of this work, however, was confined to the Tombstone Hills and Dragoon Mountains and did not extend to the deep alluvial areas. Consequently, the structural geology of these mining areas has been mapped in great detail, but has minimal value in this investigation because of the limited areal extent of the surveys. Geologic maps contained in a report by James Gilluly, *et al.*, (1956) serve as a base for this report.

A geohydrologic analysis of mine dewatering in the Tombstone Hills was made by Hollyday (1963). A gravimetric survey by Spangler and Libby (1968) and a seismic refraction survey by Libby, Wallace, and Spangler (1969) of the study area determined much of the subsurface structure of the valley and confirmed previous information on intrusive boundaries and depths to formations and water table.

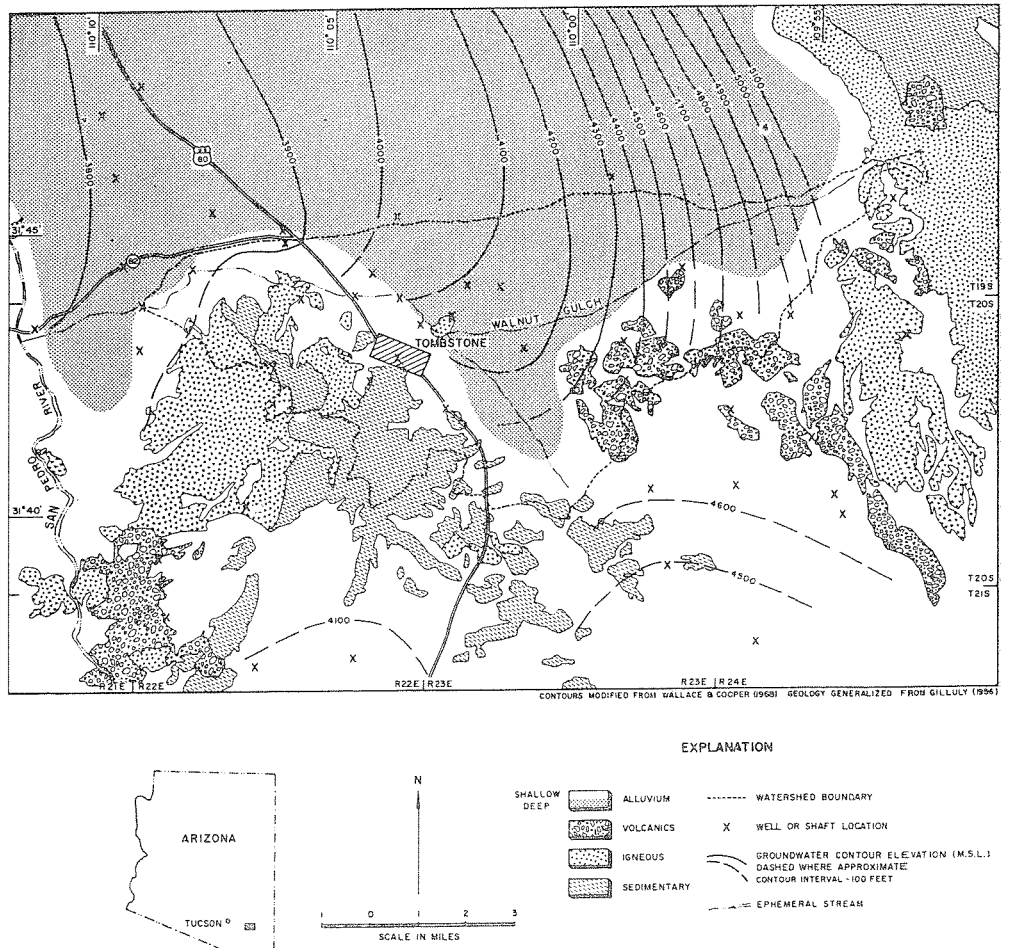


Fig. 3 — Generalized groundwater contour map, showing the extent of deeper alluvium in the basin.

In preparation for this study, we collected all available well logs from the area. This includes all available U.S. Geological Survey logs, logs contributed by the various mining companies and local water well drillers, and logs of numerous wells drilled for the Agricultural Research Service. These data helped to correlate seismic velocities with representative formations and to analyze and interpret the subsurface data. The groundwater contour map of the study area (fig. 3) was compiled from the well logs, in conjunction with data from a study by Wallace and Cooper (1968) on natural ion dispersion in groundwater.

HYDROGEOLOGY

The deep alluvial fill areas of the basin are treated as the most important storage areas for groundwater, although the mountainous areas must not be overlooked. Highly-shattered limestones and quartzite beds in the Tombstone Hills hold much promise as potential storage areas, but are not discussed in detail in this report.

The alluvial area is divided into two pediments, the Tombstone pediment (upper) and the Whetstone pediment (lower), in addition to the present-day flood plain of the river (Gilluly, 1956). The majority of the investigation reported here was done in an area classified as undifferentiated alluvium (Gilluly after K. Bryan), with portions of the Tombstone pediment south of Walnut Gulch also included. The only differentiation of units in the alluvium, as far as storage capacities are concerned, is between the uncemented sand and gravels and the various conglomerates. The hydrologic characteristics of the Tombstone and Whetstone pediments and their contained units are believed not to differ significantly, although each has varying density relationships with increasing depth. Thus, the generalized units within the alluvium are considered homogeneous, but they are actually a mass of individual beds, isolated lenses, buried channels, and faults. However, for a study of this magnitude, any effect of these factors must be considered insignificant when analyzing the total alluvial area.

Alluvial Aquifers

This study revealed three major units are dominant within the alluvium: recent channel fill unconsolidated alluvium, and conglomerate.

Recent Channel Fill. The recent channel fill is the material that fills the present-day channel system. It varies from very fine eolian dune deposits to large cobbles and boulders. According to Renard and Keppel (1966), the particles exhibit a logarithmic normal distribution having a geometric mean particle size of 2.3 mm. with 54% in the gravel range (2.0 mm). Depths of the channel fill vary, depending on the presence and degree of consolidation of underlying conglomerate. Measured depths range from less than 10 feet in upland areas to more than 100 feet near the axis of the valley. The material is uncemented, and the uppermost surface is reworked by each flow of water in the ephemeral channels. Channel widths increase greatly as the slope of the alluvial aprons decreases in the central portion of the valley, and the wide areas and older meanders promote more recharge to regional groundwater from transmission losses (Wallace and Renard, 1967).

Unconsolidated Alluvium. This formation underlies the recent channel fill in some areas and also underlies most of the surface area outside the channel. It varies greatly in thickness throughout the area. Although it contains many layers and discontinuous lenses of conglomerate, it is differentiated from the deeper conglomerate unit by its predominance of loose, stratified sand and gravel beds. Conglomerate beds within this formation vary widely in the degree of cementation, ranging from very weakly-cemented sand-matrix units to sandy clay beds with gravel. The more highly resistant, cemented beds are equivalent to the higher velocity conglomerate in the deeper unit, although they are much thinner and less widely distributed.

Older buried stream channels filled with coarse stream gravel are common in this unit and provide excellent avenues for subsurface water movement. Some clay beds have been encoun-

tered in the alluvium during drilling, but no regional or large-scale continuity could be established.

Conglomerate. These beds are composed almost exclusively of well-cemented conglomerate, with very little structural discontinuity. Possible exceptions such as highly-compacted clay lenses were not discernible from the seismic survey.

In many cases resistant conglomerate controls the course of streams, and many sharp deviations occur from encounters with thick beds or cliffs of the well-cemented material.

Carbonates (mainly CaCO_3) are the major cementing agents for the conglomerate, with some beds approaching the strength of structural concrete. The conglomerate beds were divided into two major units based on seismic velocities, with lower velocities (6000-10,000 feet per second) representing a weakly-cemented unit and higher velocities (10,000-12,500 feet per second) representing a more strongly-cemented unit. The conglomerate beds make up the thick section between the unconsolidated alluvium and basement or bedrock in the valley and are by far the thickest of the various units described here. The distinguishing characteristics of the conglomerate formations are their great volume and seeming continuity. Within the deeper alluvium (fig. 3), depth to the low-velocity conglomerate units averaged 175 feet, and depth to velocity the high-velocity conglomerate units averaged 494 feet. The conglomerate beds are exposed along portions of the stream channels within the shallow alluvium.

Groundwater Contour Map

The map of groundwater elevations within the area studied shows the natural flow pattern away from the higher areas toward the San Pedro River (fig. 3). Gradients are steeper near the Dragoon Mountains and reduce somewhat as the axis of the valley is approached. The major deviation in the central portion of the map near Tombstone is due to a granitic intrusion and the Tombstone Hills sedimentary complex. These formations cause the normal downslope pattern to deviate and flow northwestward around the perimeter of the mass. Once around this obstruction, the normal flow pattern again continues toward the center of the valley.

A groundwater divide is apparent in the southeastern portion of the map. Here, massive limestones and rhyolite—andesite volcanics lie at shallow depths below the alluvial cover and cause the anomaly. Groundwater north of the divide flows northward around the Tombstone Hills, while groundwater south of the divide flows southwest toward the San Pedro River.

The depth to regional groundwater within the area ranges from less than 100 feet near the axis of the valley to more than 400 feet in the deep alluvial areas.

ANALYSIS AND APPLICATION OF DATA

Density Sampling

An important parameter in conducting geophysical surveys (gravity in particular) is density. In areas where a good representation of either well cores and density logs, or both, are available, accurate estimates of the densities of the different rock types and the overlying alluvium can be made. As this was not the case in this study area, one of the first objectives was to initiate an extensive surface sampling program.

Density within a particular formation may vary widely. Therefore, where feasible, samples should be taken from several sites. Samples of common rock types were collected at 58 sites, and samples of the alluvium and its conglomerate units were collected at 17 sites (fig. 2).

To achieve wet bulk density values as suggested by Grant and West (1965), the consolidated rock samples were subjected to saturation in the laboratory for at least 24 hours prior to density determinations by the volume displacement method. Wet bulk density values for the alluvium were determined in the field through a technique originated by the authors and later used and described by Hench (1968). The range and average values of density and the number of samples are shown in table 1.

From a study of the density data in Table 1 and the generalized geologic map in figure 2, it was concluded that the igneous and sedimentary units comprising the basement have the higher densities and occur in the Tombstone Hills on the southwest and the Dragoon Mountains on the northeast. The alluvium and conglomerate units have the lower densities and occur in the valley or midportion of the study area. Assuming the basement beneath the alluvial or low-density units is representative of the present exposures around the margins, any observed gravity anomalies would be produced by the density contrasts between them. Weighting the average densities of each unit by the number of samples taken, the density contrast between the basement and the alluvium is approximately 0.4 gm/cm³.

TABLE 1

Range and average of density values for generalized rock types of the study area

Rock units	No. samples	Range (gm/cm ³)	Average (gm/cm ³)
<i>Alluvium</i>			
Unconsolidated	10	1.77-2.20	2.02
Conglomerates	25	2.22-2.47	2.34
<i>Basement</i>			
Sedimentary	36	2.52-2.83	2.65
Igneous	37	2.39-2.84	2.62

Gravity Interpretation

A gravity survey covering 290 square miles (fig. 4) was conducted for the following reasons: (1) to evaluate structural trends; (2) to approximate the alluvium thickness; and (3) to determine the basement rock configuration.

The first gravity base station was established at the Agricultural Research Service field office and was tied to the airport gravity base station at Benson, Arizona, 23 miles to the north. Three additional base stations were then established and 360 observation stations occupied (fig. 4). Station density averaged 1.2 per square mile, with areas of special interest receiving more detailed treatment. The gravity data were reduced through the use of a computer program written by Davis (1967). The computer output was simple Bouguer gravity values, which were contoured on a two-milligal interval (fig. 4).

Gravity highs occur over all the exposures of basement-type igneous and sedimentary rocks; values in the Dragoon Mountains are generally nine milligals lower than those in the Tombstone Hills. The decrease of approximately one milligal per mile is related to an increase in regional elevation in the eastern portion of the watershed. This example of the inverse relationship between Bouguer anomaly values and regional elevation characterizes much of the Basin and Range province.

The dominant feature of the gravity map is an asymmetrical gravity low with an amplitude of 24 milligals over the alluvial fill. The anomaly has a northwest-opening similar to the surface expression of the Tombstone Hills and the Dragoon Mountains; the minimum values of gravity are east of the geographic center between them. Northwest of the Tombstone Hills, a gravity low with an amplitude of seven milligals indicates an alluvium-filled trough deepening to the north and northeast. At the extreme eastern edge of the map in T20S, the gravity values are decreasing toward a low in Sulphur Springs Valley, an adjoining northwest-trending alluvial valley east of the Dragoon Mountains.

Regional gradients in gravity caused by large, deep-seated, structural features often distort or obscure local anomalies. For this reason regional gravity is often subtracted to leave the residual gravity. A method suggested by Dobrin (1960) for gravity profiles drawn perpendicular to the isogal lines and through the gravity anomaly, connects the gravity maxima on either side of the enclosed minima by a straight line. This line is then assumed as the regional gradient, and the observed Bouguer gravity profile is subtracted from it to give the residual gravity profile. In figures 5 and 6, the relationship between the observed simple Bouguer gravity, the assumed regional gradient, and the residual gravity is shown for three profiles taken across the northwest-trending anomaly noted in figure 4.

Parameters for the construction of interpretational subsurface models were established by using the relationship:

$$g_z = .01277 \sigma t \quad (1)$$

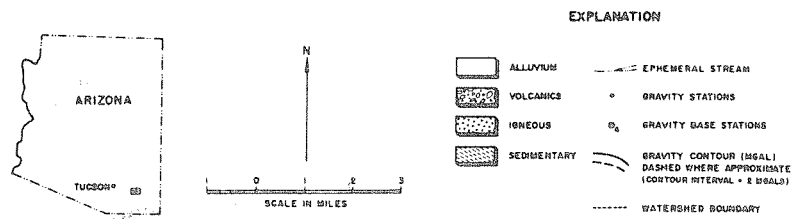
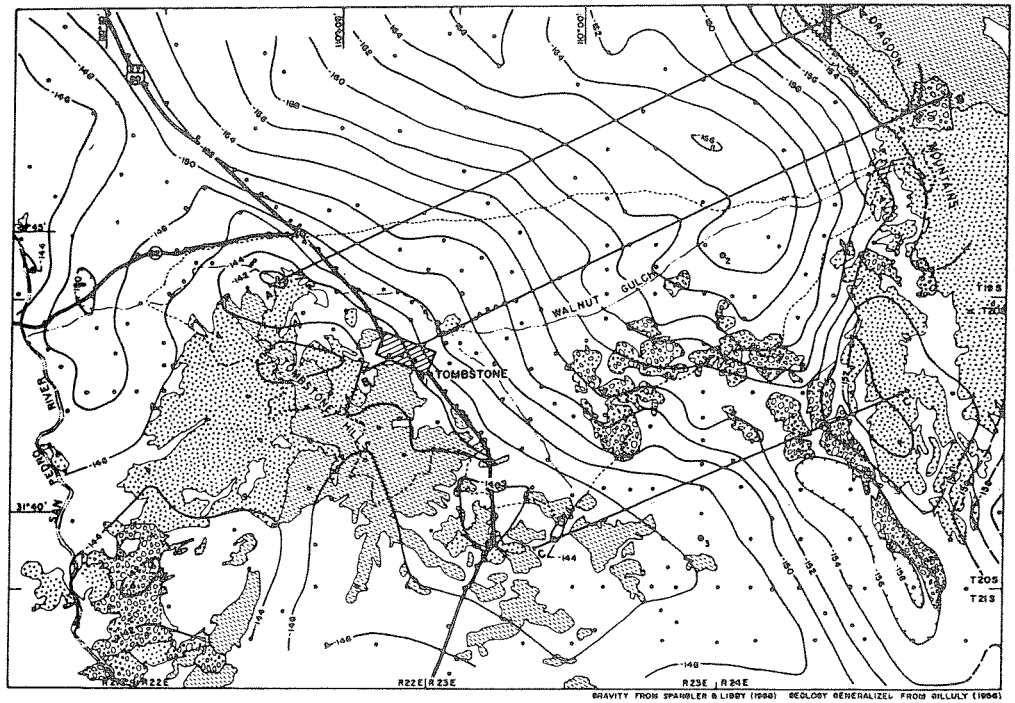


Fig. 4 — Simple Bouguer gravity map, showing location of gravity stations.

where, g_z the amplitude of the residual anomaly at any selected point, is expressed in milligals; σ , the density contrast, is expressed in gm/cm^3 ; and t , the thickness of the lower-density medium, is expressed in feet. A two-dimensional gravity graticule, similar to that described by Grant and West (1965) and Davis (1967), was used to calculate the gravity effect of the models for comparison with the residual gravity anomaly. The final models or geologic cross sections for these profiles are shown in figures 5 and 6, with the calculated gravity effect from each model noted on the residual gravity curves.

Gravity lows indicated in the profiles are produced by a thick accumulation of low-density alluvium. Steep slopes on the east and west segments of the residual gravity profiles $A-A'$ and $B-B'$, and on the east segments of profile $C-C'$, have been interpreted as indicative of Basin and Range-type faults. The graben structure shown in cross section $A-A'$ reveals a wedge of

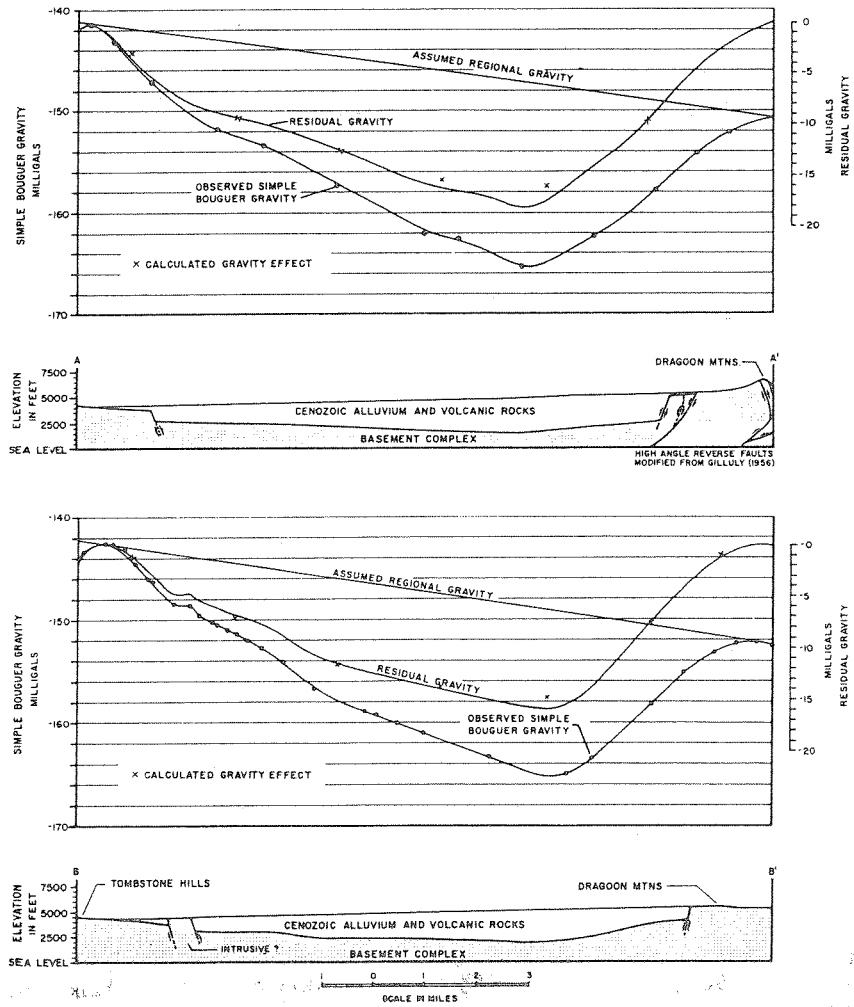


Fig. 5 — Cross sections through central portion of study basin, as derived from gravity profiles.

alluvium 10 miles wide with a maximum thickness of 3500 feet. Cross section $C-C'$ illustrates that the graben diminishes in width and depth to the southeast toward the volcanics.

Seismic interpretation

A total of 54 seismic profiles, aggregating a length of 120,000 feet of in-line seismic profiling was accomplished in 13 areas within the study basin (fig. 2). The seismic refraction profiles provided data from which geologic sections were constructed. These sections revealed: the depth, attitude, and extent of subsurface units within the alluvium; structural features such as faults, buried ridges and channels; the depth of the basement complex in some locations; and the presence, depth, and attitude of the regional water table.

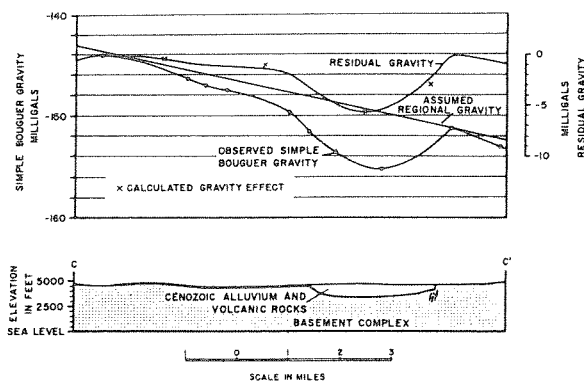


Fig. 6 — Cross section through southern portion of study basin, as derived from a gravity profile.

In areas where borehole or sonic logs are not available, the velocities must be determined by measurements made along the surface (Grant and West, 1965). As a means of extrapolating useful relationships to density, several velocity determinations (locations shown in figure 2) were conducted on surface exposures. Locations giving 250 feet or more of fresh in-line exposure on a rather level surface were selected. Problems were encountered with some areas where rock fracturing and weathering were believed to have influenced the arrival times. In these cases the highest value derived from the time-distance graph was chosen. Additional velocities were taken from the reversed seismic profile records where nearby exposures or well control data justified a direct identification of rock type. Data from the seismic records were taken to compile a range and average of velocities for the channel and alluvial deposits.

Velocities averaged 2200 feet per second for channel fill, 5000 feet per second for unconsolidated alluvial deposits, 10,700 feet per second for conglomerate and depending on the particular unit, 12,300 to 15,600 feet per second for basement type rocks. The range of velocities compared favorably with histograms of seismic-wave velocities for various classes of rocks as presented by Grant and West (1965).

Integration of Geophysical Methods

Plots of velocity versus density, from field studies by Davis (1967) and evidence cited by Grant and West (1965), indicate a tendency of seismic wave velocities and bulk densities to increase simultaneously. These relationships have been described as a function of lithification accompanying age and compaction.

The method of predicting bulk densities from seismic velocities in this study has certain qualifications: (1) density is not a function of velocity in the true physical meaning, but is used in the sense of integrating the parameters connecting them and allowing a prediction Y (density) to be made from a measurement X (seismic velocity); (2) normal distribution of the data is assumed; (3) departures from the assumption of homogeneous and isotropic conditions would be greatest where a horizontal separation existed between a match pair of observations; and (4) a small quantity of variation in either density or velocity (without a corresponding variation in the other) may be a function of measurement errors in either density or velocity.

Twenty matched pairs of bulk density and seismic velocity were analyzed for a least squares fit by a regression analysis program written by Huszar (1966) for an IBM 7072 computer and modified for a CDC 6400 computer. The regression or prediction line and equation are shown in figure 7. Using this relationship between density and velocity and the relationship discussed by Krynine and Judd (1957) between porosity and density:

$$n = 1 - \frac{D_b}{D_g} \quad (2)$$

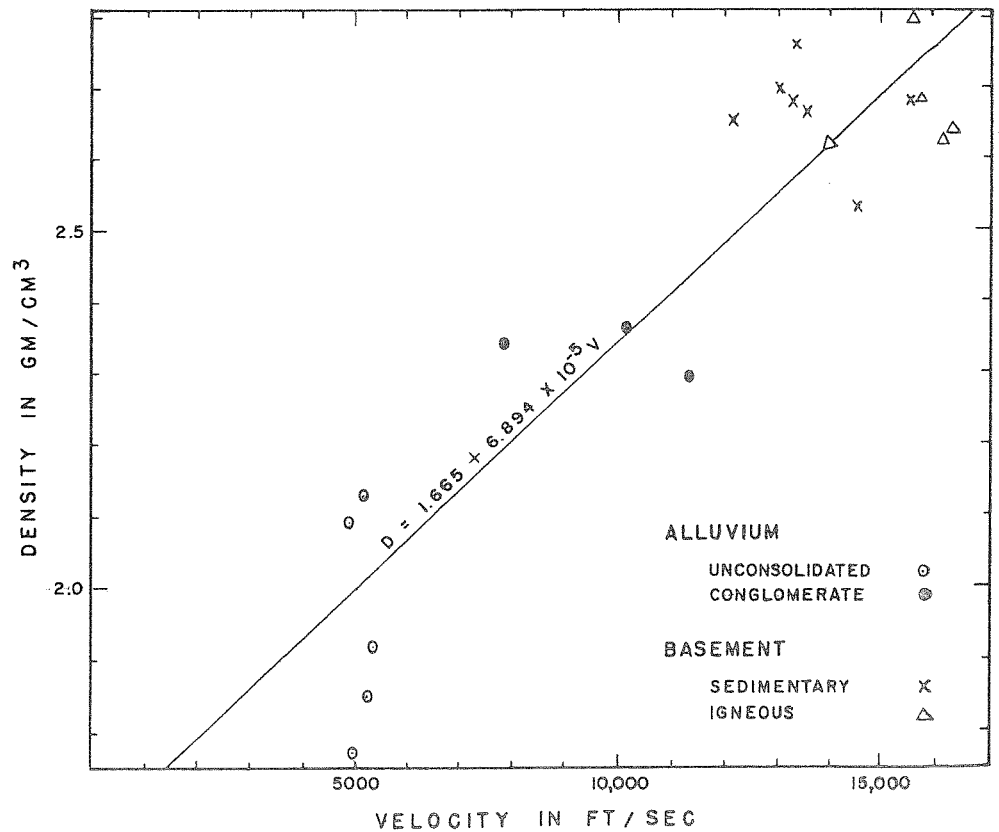


Fig. 7 — Graph showing density-velocity relationship.

where n is porosity, D_b is bulk density, and D_g is grain density, a value of porosity for the alluvium can be derived from a determination of its seismic velocity. Assuming porosity becomes negligible as the bulk density approaches 2.67 gm/cm^3 (average density of common rock forming minerals), porosities for a typical range of velocities in the study area have been calculated and are shown in table 2.

TABLE 2
Table illustrating seismic velocity-rock density-porosity relationships

Velocity (V) (ft/sec)	Density (D) (gm/cm^3)	% Porosity (n)
2000	1.80	32
3000	1.87	29
4000	1.94	27
5000	2.01	24
6000	2.08	22
7000	2.15	19
8000	2.22	16
9000	2.29	14
10000	2.35	11
11000	2.42	9
12000	2.49	6
13000	2.56	3

Groundwater Volume Determination. A total of 103 square miles of deep alluvium was used when computing volume and storage capacity (fig. 2). This area was determined from a combination of the gravity, seismic, and well log data, plus a thorough surface investigation of the area. The depth to basement in the central portion of the basin is approximately 3500 feet (from gravity data), with peripheral areas having less than 200 feet of alluvial cover in some places. Thus, an average depth to basement must evolve from integrating depth determinations along selected profiles. Depth-to-bedrock data were taken from all available well logs in the deep alluvial area and combined with the gravimetric data to give an average depth of alluvium of 2060 feet by the Thiessen method. Depths to water level were taken from these same wells and averaged by the Thiessen method to give a 277-foot depth throughout the alluvium for the regional water table.

A definite break, or change in seismic velocity was noted from 60 to 310 feet in depth throughout the alluvial area and averaged 175 feet in depth. This horizon, when correlated with well logs from the area, was interpreted as the interface or transition zone between unconsolidated alluvium and the underlying conglomerate (fig. 8). Using the velocity-density-porosity relationship derived earlier, the unconsolidated alluvium was determined to have a porosity ranging from 11.8 to 24 percent.

Compaction due to depth, as well as degree of cementation, is a contributing factor to the higher velocities encountered in the deeper areas. The low-velocity conglomerate extends below the water table for an average depth of 217 feet. This unit was calculated to have a porosity of 11.8 percent. Directly beneath the low-velocity conglomerate is 1565 feet of high-velocity conglomerate having a computed porosity of 7.0 percent.

Based on 103 mi^2 of deep alluvium, with a 2060-foot average depth, a total volume of alluvium of 40.16 mi^3 in the basin was computed. Of this volume, 34.77 mi^3 were saturated. Based on velocity-density-porosity relationship, a total of 2.64 mi^3 (8,900,000 acre-feet) of groundwater was determined to exist in the basin. Of this 2.64 mi^3 of water in storage, 0.50 mi^3 were in the saturated portion of the low-velocity conglomerate beds, and 2.14 mi^3 were in the high-velocity conglomerate beds. These data are presented in tabular form in figure 9.

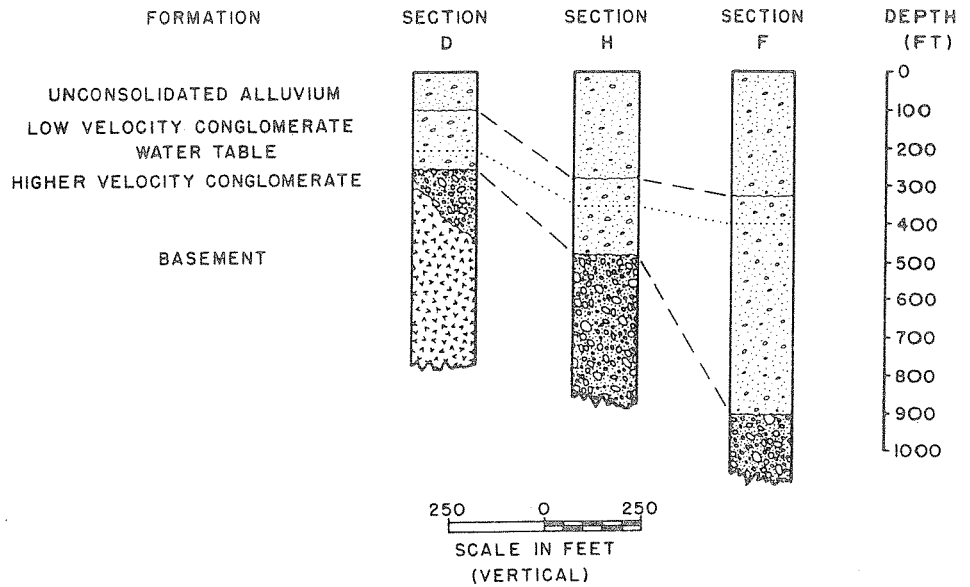


Fig. 8 — Section showing stratigraphic relationship of formation within the alluvial basin.

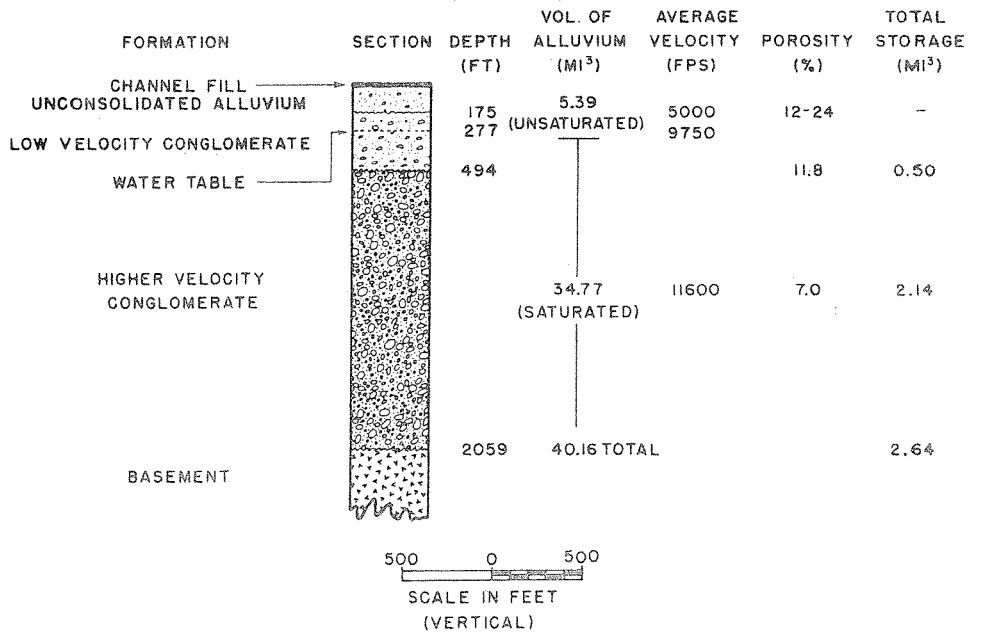


Fig. 9 — Average section of basin showing average depths, volume of alluvium, velocity, porosity, and total storage.

CONCLUDING REMARKS

The gravity-seismic method of basin analysis provides useful numerical data in arriving at a groundwater storage capacity estimate. The basin configuration can be obtained from profiles taken across the gravity contour map. Average depth to basement is noted from the gravity profiles. From this depth and the surface area, a total volume of alluvium can be established.

Seismic refraction traverses completed as an integral part of the exploration will provide or confirm stratigraphic sequence of the units and determine seismic velocities of the various rock types. In many cases, depth to groundwater may be determined. With water table depth, volume and porosity of alluvium known, present storage of groundwater can be estimated, and future storage or recharge areas can be delineated.

The gravity-seismic method of estimating storage capacity in deep alluvium is best adapted to regional surveys, although it may be altered to include smaller areas. The regional approach is especially valuable in areas of limited prior work and may be used effectively as a basic survey from which future research may be initiated.

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