Application of the Gravity Survey Method to Watershed Hydrology

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ABSTRACT

A gravity survey covering 250 square miles and including the Walnut Gulch watershed at Tombstone, Arizona has been conducted. The watershed is one of the experimental areas of the Southwest Watershed Research Center, Agricultural Research Service in Tucson, Arizona.

The gravity survey method was selected as the geophysical method that would give a regional picture of the subsurface geology before making extensive surveys by the seismic refraction method. Basically, the gravity survey method detects and measures variations in the earth's gravitational force. These variations are associated with changes in rock and alluvium density near the surface. Many geologic structures of interest in watershed ground-water hydrology cause disturbances in the normal density distribution which give rise to anomalies.

The geology of the watershed is typical of Basin and Range province and contains deep basin fill deposits surrounded on the east, south, and southwest by igneous intrusives, volcanics, and sedimentary rocks. Concealed border faults may have a decided effect on the hydrology of the watershed.

Four base stations were established and 360 gravity stations occupied by a Worden Educator* gravimeter loaned from the Geophysics Laboratory of the University of Arizona. Bench marks and large scale topographic maps served as control. Raw field data were reduced to the simple Bouguer anomaly values through the use of a computer program.

The gravity survey reveals a 16-mgal. gravity low over the east-central portion of the watershed. This low is interpreted as indicating that about 3200 feet of low density alluvium underlies the area at this point. Gravity highs are associated with mountain ranges and igneous plugs where the more dense rocks occur.

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* Reference to this manufactured product does not constitute endorsement by the government.

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INTRODUCTION

Purpose and Scope of Investigation

The Southwest Watershed Research Center of the Agricultural Research Service (ARS) is conducting a series of studies in semiarid rangeland watersheds of the Southwest to evaluate future water yield potential and sediment yield of semiarid rangeland watersheds as related to measures for their conservation and sustained production of forage. One of the research objectives is isolation and analysis of geologic factors operating in the ground-water system.

During these studies on the Walnut Gulch watershed near Tombstone, Arizona, it became evident that determination of hydrogeologic relationships could not be determined without detailed knowledge of the subsurface geology. Therefore, a complete geophysical survey was initiated in 1967.

The gravity survey method was subsequently selected to provide basic data on configuration of the basement complex and aid in directional control of planned seismic refraction profiles. In addition, alluvial depth approximations from the gravity data, along with water well and seismic data, will aid in construction of the geologic framework.

This report describes the principles of the gravity survey method, the field procedures and data reduction technique used, and some interpretations derived from a study on the Walnut Gulch watershed during 1967 and 1968.

GRAVITY SURVEY

Principles and Variations of Gravity

The theory of gravity surveying is directly dependent on Newton's law of gravity:

$$F = \frac{G\, M_1 M_2}{r^2} \qquad (1)$$

In the cgs system, F is force expressed in dynes or $\frac{\text{gm-cm}}{\text{sec}^2}$, G is the gravitational constant whose value is $6.670 \times 10^{-8}\ \frac{\text{cm}^3}{\text{gm-sec}^2}$, M_1 and M_2 are the mass of two respective spheres or particles expressed in grams, and r is the distance in centimeters between their centers of mass.

From Newton's second law of motion, the relation between force, mass, and acceleration is:

$$a = \frac{F}{M_2} \qquad \text{(2)}$$

The acceleration a of a mass M_2 due to the attraction of a mass M_1 is expressed as cm/sec^2. The symbol a is often referred to as g, the gravitational acceleration, with the gal as the unit of dimension.

The basic density-mass-volume relationship is:

$$D = \frac{M}{V} \qquad \text{(3)}$$

where D is density expressed in gm/cm^3. Equating (1) and (2) and substituting M = DV from (3):

$$g = G\,\frac{DV}{r^2} \qquad \text{(4)}$$

This basic relationship shows that the value of gravity is directly proportional to the density and volume of a mass (earth materials beneath the gravimeter) and inversely proportional to the square of the distance from the attractive body. As the earth is not perfectly homogeneous, spatial variations of gravity are also a function of latitude and the adjacent terrain.

Observed time variations of gravity are primarily a function of earth tide fluctuations and instrument drift.

Establishing Base Stations

A base station is a point at which the observed value of gravity is accurately known, and it represents an extension of control from a point where the absolute value of gravity was determined. As modern gravimeters (Figure 1) do not measure absolute values of gravity, a gravity base station network is necessary throughout the area of interest. In establishing gravity base stations, one should consider the permanence of the site, its ease of identification, accessibility, and any extraneous terrain effects.

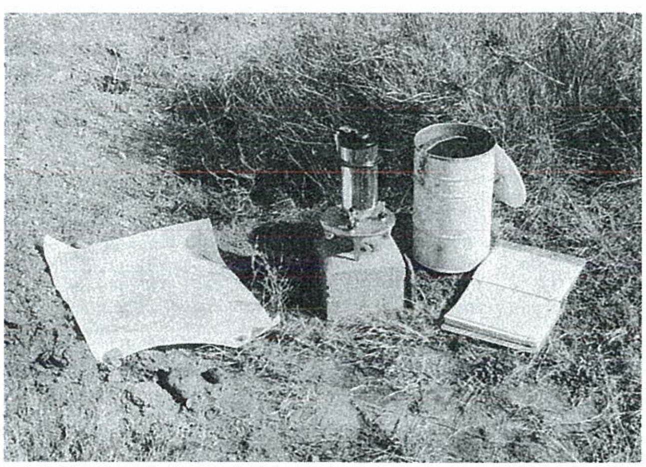

Fig. 1. A hand portable Worden Educator gravity meter placed on an elevation bench mark.

A new gravity base station is determined by making at least two traverses between it and a previously known base station. After corrections are made for earth tide and instrument drift, the instrument value is converted by a scale factor to milligals, and the difference is applied to the known gravity base station to obtain the observed gravity value of the new gravity base station.

The first gravity base station in the Walnut Gulch watershed was established at the ARS field office. The station was tied to the airport gravity base station at Benson, Arizona, 23 miles to the north. From the first station, a network of three other gravity base stations was established in the watershed (Figure 2).

Observation Stations

A total of 360 stations was observed on the watershed and surrounding area using a Worden Educator gravity meter. Station density averaged 1.4 per square mile. Some areas contained fewer than one station per three square miles, whereas other areas contained 8 stations per square mile. The frequency of sampling depended on detail desired, identification of station with respect to location and elevation, accessibility, and time available.

Short loops of two to three hours duration were made from a base station in order to minimize drift errors. When this was not possible and the loop was over four hours, earth tide corrections were applied.

Location and Elevation Determinations

The value of gravity decreases approximately 0.06 milligal per foot increase in elevation and increases approximately 0.1 milligal (middle latitudes) per 0.1 minute increase in latitude. Therefore, the most time-consuming element in field work of a gravity survey is determination of location and elevation of the station. Those areas having large numbers of well-distributed, accessible, and known bench marks are most desirable.

If a very precise survey (less than 1 milligal contour interval) is desired, transit, leveling, and chaining survey methods are necessary. For less detailed work, topographic maps referenced to mean sea level may be substituted. Davis (1967) concluded from a regional gravity survey in the Tucson Basin that topographic maps having less than a 40-foot contour interval were satisfactory for point elevation interpretation. Altimeter methods have been used as another alternative for elevation control, although their value is quite questionable, particularly during periods of rapidly changing barometric pressure or in rough topographic areas.

Density Determinations

As the value of gravity is directly proportional to the density of the adjacent materials (Equation 4), several surface samples of each rock type were analyzed by the volume-displacement method in compiling average densities for the rock units listed in Table 1.

The average for the igneous and sedimentary units combined was 2.66 gm/cm^3, a value in close agreement with the 2.67 gm/cm^3 commonly used in reducing gravity data. Sumner and Schnepfe (1966) found the density for a similar suite of rocks 24 miles south of Tombstone at Bisbee, Arizona to be fairly uniform, and in the range of 2.65 to 2.70 gm/cm^3.

TABLE 1. ROCK DENSITY DATA

Rock units	*No. samples*	*Range (gm/cm^3)*	*Average (gm/cm^3)*
Alluvium	4	2.05–2.40	2.22
Volcanics	6	2.23–2.57	2.40
Igneous	15	2.52–2.93	2.63
Sedimentary	18	2.61–2.83	2.69

Density determinations of the alluvium noted in Table 1 compare with the average densities of 2.2 to 2.3 gm/cm^3 reported by Mabey (1966) for major basins in the Basin and Range province. Actual density distribution within the alluvium may deviate substantially due to lateral variations and compaction at depth.

Reduction of Data

For gravity data to be most useful, Dobrin (1960) notes that observed gravity values should be corrected for latitude, station elevation, and the influence of the nearby topography. In general, the values are all reduced to a common datum in order to show anomalous areas.

As previously noted, the observed value of gravity is a function of latitude because the earth is neither spherical nor at rest. The rate of change of gravity with latitude in milligals per mile is 1.307 sin 2 ϕ where ϕ is latitude. A step in data reduction was eliminated by determining latitude and longitude for each of the gravity stations to the nearest 0.1 minute from field maps, using an analog to digital converter at the Southwest Watershed Research Center in Tucson, Arizona.

The elevation correction contains two parts: (1) the free air correction, and (2) the Bouguer correction. From Equation 4, it was noted that the gravity value was inversely proportional to the square of the distance. Therefore, the free air correction accounts for the difference in the distance between the datum chosen (sea level in this report) and the station elevation. The free air correction for a datum of sea level is approximately -0.094 mgal/ft. The Bouguer correction accounts for the attraction of a presumed flat infinite slab of rock material between the sea level datum and a horizontal plane passing through the station. If the density is taken as 2.67 gm/cm^3, this correction is approximately $+0.034$ mgal/ft. The combined elevation correction for a gravity station is therefore -0.060 mgal/ft. If only the latitude and the elevation corrections are applied to the observed gravity values, the result then is simple Bouguer values.

Rough topography violates the assumption of a flat slab made in the Bouguer correction to some degree and, therefore, may dictate that terrain corrections be applied to the simple Bouguer values to give complete Bouguer gravity values. Terrain corrections were not applied in the compilation of Figure 2. A few selected stations were analyzed, and their values varied according to the type of terrain from 0.2 to 2.0 milligals. The percent error in depth calculations by not applying terrain corrections depends on the amplitude of the anomaly in question. In Figure 3 this error may amount to 10 percent of the depth shown in the large negative anomaly.

The Walnut Gulch watershed gravity data were reduced through the use of a computer program written by Davis (1967). Input for the computer program consisted of station number, latitude and longitude, elevation, time of reading, instrument value, the base station reading before and after a loop, and the base station's observed value of gravity. The program output was simple Bouguer gravity values.

Regional Gradient

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 out so as to leave the residual gravity. The process of determining the plane of regional gradient is often a tedious one. In many cases, as noted by Dobrin (1960), the gravity cross section is drawn through the center of the anomaly, and the best straight line connecting the maxima is assumed to approximate the regional gradient. This procedure was used recently by Cook, Berg, and Lum (1967) in discussing a gravity profile across the Northern Wasatch Trench in Utah. In Figure 3, the relationship between the observed simple Bouguer anomaly, the assumed regional gradient, and the residual gravity was derived similarly.

GEOLOGY AND INTERPRETATION

Geologic Setting

The survey area is typical of Basin and Range physiography, with isolated mountain blocks separated by broad alluvium-filled basins.

Deep-seated igneous intrusions and accompanying high-angle reverse faulting are responsible for the high relief areas that comprise the Tombstone Hills on the west and lower Dragoon Mountains on the east (Figure 2). Great thicknesses of sedimentary rocks, mostly limestone, make up the topographic relief of the Tombstone Hills which are underlain by and adjacent to large igneous bodies of Tertiary age. The igneous lower Dragoon Mountains of Triassic-Jurassic age are without caprock; the only residual limestones in this area are small drag blocks along fault zones.

Late Tertiary volcanics in the southeast portion of the study area are relatively thin beds of flows and tuffs and are in overthrust position. Minor amounts of late Tertiary and early Quaternary rhyolite and basalt occur as intrusive dikes, sills, and plugs in the south and central portions of the study area. A basalt plug, lying on a concealed fault alignment in the central portion of the study area, occupies a relatively small percentage of the surface but may be quite extensive along this fault.

The alluvium filling the intermontane basin consists of very deep Quaternary and Tertiary sand, gravel, clay, and well-cemented caliche conglomerate. From well data, it is known to be over 1,200 feet deep in places and contains a large volume of ground water in storage. A great deal of the conglomerate in the alluvium is extremely well cemented approaching the strength and appearance of a high grade structural concrete. These conglomerates act as rock units and exert much structural control on surface stream channels and the flow of ground water.

Interpretation

The gravity low noted in Figures 2 and 3 is produced by a thick accumulation of low-density alluvium and volcanic rocks of Cenozoic age. Because the gravity anomaly is several times longer than the thickness of the low-density units producing the anomaly, a profile across the watershed, approximately normal to the axis of the gravity low and well removed from the ends, has been analyzed as a two-dimensional feature.

The only geologic controls available in the vicinity of the profile are: (1) The surface position of the rock units and their contact with the alluvium; (2) Well A in Figure 4 showing a depth of 575 feet to sedimentary rock; (3) Well B in Figure 4 showing that at least 600 feet of alluvium have been penetrated;

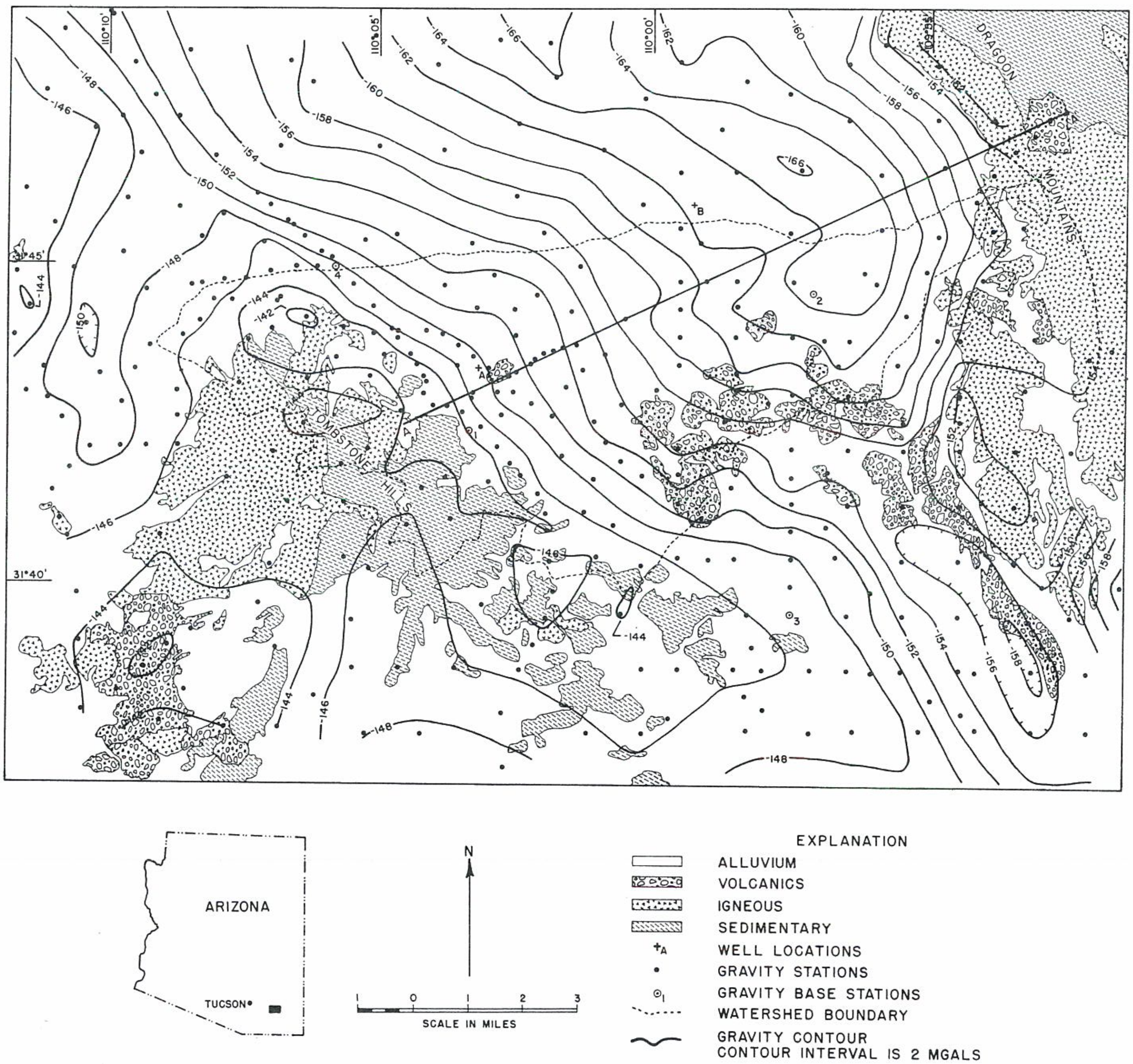

Fig. 2. Simple Bouguer gravity map and generalized geologic map. Geology modified from Gilluly (1956).

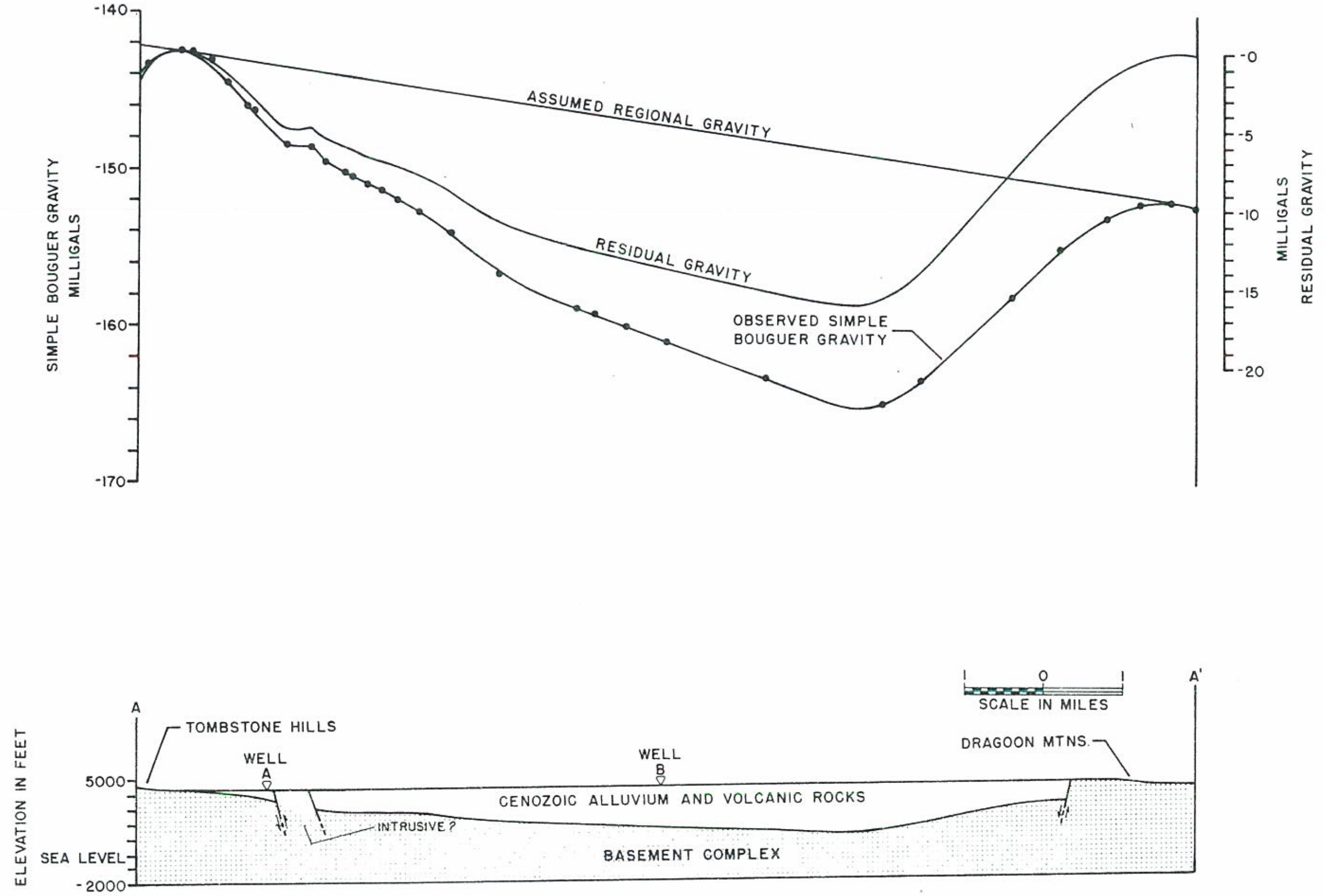

Fig. 3. Profile A-A' across Walnut Gulch watershed, illustrating observed simple Bouguer gravity, assumed regional gravity, and residual gravity (in milligals), and interpretive geologic cross section along gravity profile.

and (4) the approximate density of the major units throughout the watershed.

From density data in Table 1, the density contrast between the alluvium and its enclosing units (igneous and sedimentary) is approximately 0.4 gm/cm^3. With this density contrast, the measured gravity anomaly in the watershed could be produced by the 3,200-foot thick prism of alluvium shown in Figure 3.

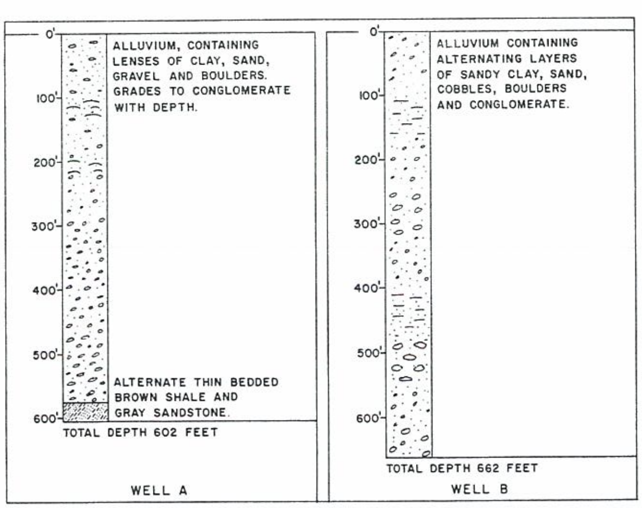

Fig. 4. Sample well logs from study area.

The steep slopes on the east and west segments of the residual gravity profile in Figure 3 have been interpreted as indicative of Basin and Range faults. Their actual form and location will demand more extensive study. A change in slope in the west segment of the residual gravity profile corresponds to a surface outcrop of intrusive basalt. The lineation and trend of the contours in Figure 2 in a predominantly NW-SE direction suggests structural control of ground-water movement.

SUMMARY AND CONCLUSIONS

It has been shown that the gravity survey method can be applied to watershed ground-water hydrology. The field techniques are simple, and one man can collect all field data. The time involved for a gravity survey will depend directly on the vertical and horizontal control available and the ease of access to the desired stations. Actual reading time once the station is occupied is less than 3 minutes.

Reduction of data is relatively straightforward if a computer program is available. Reduction time per station will average about 10 minutes when manual calculating machines are used.

Gravity surveys are sometimes performed on a contract basis for about \$6 per station. This survey has cost ARS approximately \$1,500, which is considerably less than a contract because of student support and free use of a gravity meter loaned by the Geophysics Laboratory of the University of Arizona. This amount is equivalent to the cost of one water well drilled to a depth of 400 feet.

The gravity survey method will not replace other geophysical or bore-hole studies, but it can reduce the amount of time and expense in watershed ground-water hydrology studies by pointing out those areas needing additional detailed work.

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