GEOPHYSICAL BASIS AND CARTOGRAPHY OF THE COMPLETE BOUGUER GRAVITY ANOMALY MAP OF ARIZONA

by

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ABSTRACT

Computer-generated terrain corrections using Defense Mapping Agency digital terrain data have been successfully incorporated into an automated production system. Design and development of the Arizona Gravity Data Base were completed during 1974, and this data base constitutes the principal source from which information is obtained for gravitational research at The University of Arizona. A digital terrain data base consisting of 1-minute, 3-minute, and 208-foot square blocks has been established to fulfill the requirements of the terrain correction software. Development of this data collection into an operational data base system is continuing. Integration of the gravitational reduction process with terrain corrections and map production has proved to be feasible. The preparation of a complete Bouguer gravity anomaly map of Arizona was chosen to show the total capability of such a system; however, because of delays in data shipment and reduction of computer operation funding, only a test area 0.5-degree square was produced. The overall system design and operation were nonetheless proved. The final complete Bouguer gravity anomaly map of Arizona is to be produced at a 1:250,000 scale in one-degree square sheets using the Lambert conformal conic projection and a 5-mgal contour interval. The source datum for the final map will comprise approximately 22,000 gravity observations.

CHAPTER 1

INTRODUCTION

The thesis presented here represents nearly two years' work in the area of geophysical data processing. Designing the production process for the complete Bouguer gravity anomaly map of Arizona has provided the opportunity to approach several key problems in the handling and reduction of gravity observations. The most important of these problems is the calculation of a complete terrain correction through the use of a totally automated procedure using a digital terrain data base.

The nature of this thesis is one of a twofold task. The principal effort has been directed at developing the technology to obtain valid terrain effect values from a digital terrain data base. The second, though no less important, task has been to develop a workable system by which a geometrically accurate map could be produced from a collection of unprocessed gravity observations.

A major difficulty in the first task was a total lack of familiarity with the digital terrain data provided by the Defense Mapping Agency Topographic Command (DMATC), which were to be used to calculate the inner-zone terrain effect about each gravity station. In particular, the mapping transformation between the digitizer grid and geographic coordinates was not known until almost five months after the first data arrived from the Defense Mapping Agency Topographic Command. Slow and at times little progress was made in solving some of the logistical problems associated with such an immense volume of data. Such experience was essential to have since the development of procedures for obtaining and verifying the terrain effect calculations were intimately tied to the structure, accuracy, and completeness of the digital data.

Historical Background of Gravimetry

Understanding the earth and its environment has been the motivating force behind much of the scientific investigation performed since the times of Aristotle (384-322 B.C.) and before. Questions concerning the nature of the earth's surface and subsurface have been raised from these earliest times. Eratosthenes of Cyrene (276-196 B.C.) is often credited with the first and amazingly accurate measurement of the earth's circumference. His work can perhaps be called the first of many attempts to determine the figure of the earth in the field of geometrical geodesy. It was only since the time of Galileo Galilei (1564-1642) that observations concerning the gravitational attraction of the earth on falling bodies came to be used as a means of answering several of the fundamental questions about the earth. What is the shape of the earth? What is beneath the surface:

Although Galileo did not answer these questions, he did perform several of the first scientific (if not totally accurate) tests regarding acceleration of bodies drawn to earth in free fall. Because of his early work in this area of physics, the gravitational unit, the gal, is named in his honor. Most widely recognized as the fundamental investigator in the area of attracting masses is Sir Isaac Newton (1642-1727). In his mathematical and mechanical analysis of planetary and satellite orbits, Newton evolved the laws of gravitation and in so doing gave rise to the discipline of science known as gravimetry--the science of gravity fields and, in particular, terrestrial gravimetry.

Parallel growth in mathematics and physics during the 17th, 19th, and 19th centuries brought the calculus and the theory of the potential to bear on problems of gravimetry. Huygens, Clairaut, and Stokes are only a few of the many who pursued the determination of the shape of the earth. Much debate was generated over this problem, and its resolution had evaded researchers until this century. In quest of ascertaining the exact length of a degree of latitude and thereby confirming the then widely discussed "earth flattening" hypothesis, the French Academy of Sciences sent expeditions to Lapland and to the Peruvian territory, now Ecuador, in 1744. The results showed conclusively that the earth did indeed have an equatorial bulge and that polar flattening was a fact. In the resulting La Figure de la Terra, Pierre Bouguer (1749) discussed the need for considering the effect on a pendulum measurement of gravity of the masses between the observation point and the sea-level reference plane. Bouguer attempted several calculations of the effect, using an estimate of the attraction of the Andes around his station at Quito. Although he did not succeed in his calculations, he did call attention to the problem of being displaced from the reference plane of a survey and to the potential errors caused by local and regional terrain to gravity observations.

During the next century, measurements of absolute gravity predominated as efforts to define the shape of the earth gravimetrically continued. It was not until after World War I that subsurface or near-surface features of the crust began to be analyzed using gravimetric techniques. This was due primarily to the shift from pendulum measurements of absolute gravity to static and astatic gravimeter observations of relative gravity values (Pick, Picha, and Vyskocil, 1973). It should be pointed out that two distinct courses of applied gravimetry have developed. The first and oldest is the determination of the true shape and mass distribution of the earth at any given time--gravimetric geodesy. The second is exploration gravimetry or the search for anomalies in the earth's gravity field attributable to structural deformities or mass variations within the crust. To geologists and exploration geophysicists, the second course is of major importance, while the first lies in the area of physical geodesists.

Project Background

The Laboratory of Geophysics under the direction of John S. Sumner has vigorously pursued the gravimetric survey and analysis of Arizona data (Sumner and West, 1969). The work of West (1972) laid the essential framework of gravity stations over the state. Many other researchers in geology, hydrology, and geophysics have continued to add to the coverage in Arizona. Contributions of gravity observations from governmental agencies and industry have also added to the accumulating volume of data within the state.

The first Bouguer gravity anomaly map of Arizona (West and Sumner, 1973) incorporated all available data to that date. However, there was no economical means of performing terrain corrections available at that time, so the published map was that of a simple Bouguer anomaly. Because subsequent gravity investigations required a completely corrected anomaly value and the number of observations continued to grow, it was decided that an effort should be made to prepare a complete Bouguer anomaly map that would include the latest data using an automated production scheme. To reach this goal, two important problems required solution. First, an efficient, well-organized data handling process for gravity observations was needed, and second, some practical and accurate method of calculating terrain corrections had to be found. Corollary to this was the problem of obtaining and handling accurate terrain data compatible with the terrain correction process.

Development of the Arizona Gravity Data Base (AGDB) and acquisition of the U.S. Geological Survey's terrain correction software (Plouff, 1966) brought the goal into sight. The problem of a suitable digital terrain data source was solved when the Defense Mapping Agency Topographic Command (DMATC) made available its 1:250,000 scale digital terrain maps covering Arizona. In addition, coverage of the state in a 3-minute square grid was obtained in part from the U.S. Geological Survey and by manual digitization.

The many aspects of this project were then tied together in a systematic, computerized procedure, which has been shown to have applicability in other areas of geological, geophysical, and geomorphological investigations. This report describes the geophysical and cartographic background used in the preparation of a complete Bouguer gravity map of Arizona.

CHAPTER 2

GEOPHYSICAL BASIS FOR THE COMPLETE BOUGUER GRAVITY ANOMALY MAP OF ARIZONA

Gravitational Anomalies

In its simplest form, a gravitational anomaly is given by the difference between the observed value of gravity and the value of gravity for a reference surface of predetermined shape, density, and angular velocity--the normal gravity. Usually a reference spheroid is chosen with suitable dimensions, axial orientation, and velocity of rotation so as to be identical to those of the real earth. The formulation of γ, the normal gravity function, also assumes a density that does not vary laterally but is constant and equal to the average density of the earth.

The most often used value of γ in the United States is given by the so-called International Formula. This value is based on the Hayford ellipsoid as adopted in 1924 by the International Union of Geodesy and Geophysics (IUGG). Cassinis (1930) developed the final equation that was adopted by IUGG in 1930. The normal gravity at latitude ϕ is given by

$$\gamma = 978049\ (1 + .0052884 \sin^2\phi - .0000059 \sin^2 2\phi)\ \text{mgal}. \qquad (1)$$

Several other reference spheroids and constants have been developed over the years. IUGG accepted a revised set of parameters in 1964 that changed the normal gravity function to

$$\gamma = 978031.846\ (1 + .005278895 \sin^2\phi - .000023462 \sin^4\phi)\ \text{mgal}. \qquad (2)$$

Equation (2) will be recognized as the theoretical gravity formula of the International Gravity Standardization Network, 1971 (ISGN-71). E. J. Hauer (written commun. to A. G. Bittson, Department of Geosciences, The University of Arizona, 1975) describes the background of the ISGN-71 as follows:

> This net is a worldwide network, consisting of 24,000 gravimeter, 1,200 pendulum, and 10 absolute measurements collected over 20 years. These measurements have been adjusted by a Special Study Group of the International Association of Geodesy, discussed and approved within the same Association and adopted at the IV Assembly of the IUGG in Moscow, August 1971. The concept differs from that of earlier gravity reference systems in that datum is determined not by an adopted adopted value at a single station, but by the gravity values for 1,854 worldwide stations obtained from a single least square adjustment of absolute, pendulum, and gravimeter data. Standard errors for IGSN-71 gravity values are less than $\pm$ 0.1 mgal. The International Gravity Standardization Net, 1971 has been approved and adopted as the international gravity standard, replacing the Potsdam datum.

The Defense Mapping Agency converted its gravity library holdings to ISGN-71 datum in July 1973. The Arizona Gravity Data Base will convert its holdings to ISGN-71 during the compilation of the complete Bouguer gravity anomaly map of Arizona. However, the map will be computed using the Potsdam datum. Subsequent editions and revisions of the complete bouguer gravity anomaly map of Arizona will reference ISGN-71.

In the Soviet-block countries, the Krassovsky ellipsoid is used most frequently and yields the familiar Helmert's formula of normal gravity,

$$\gamma = 978030\ (1 + .005302 \sin^2\phi - .000007 \sin^2 2\phi)\ \text{mgal}.$$

It is clear that a very large number of different anomalies can be produced by simply changing the reference surface used for comparison of observations. All calculations for reductions in this project used the International Formula given in equation (1).

Anomalies vary in their nature according to the effect that they are tending to emphasize. The free-air (Faye) anomaly, for example, strongly reflects the local topographic features, while being little affected by anomalous geological masses. For this reason, the free-air anomaly is not often used in exploratory analysis of structural features or economic deposits. Conversely, the Bouguer anomaly is quite sensitive to lateral mass variations and is the most widely used gravitational anomaly in applied geophysics. Gravity anomalies also have numerical values of smaller magnitude than absolute gravity values and are therefore preferred in computational procedures that are always subject to numerical errors.

Observational Base Station Network

Because of the time, expense, and difficulty in obtaining a pendulum observation of absolute gravity, the relative gravity measurement has become the accepted form of measurement. A relative reference system also promotes the use of anomalous gravity fields in analysis, since the anomalies are determined with respect to a local rather than a remote standard. In Arizona there exists a network of 72 base stations (Fig. 1) established by The University of Arizona in 1964 and by the U.S. Army Topographic Command (TOPOCOM) during 1967-68 using gravimeters. All gravity observations made by University of Arizona personnel have been made with respect to this network. The Bouguer anomaly values derived from these observations are relative to the

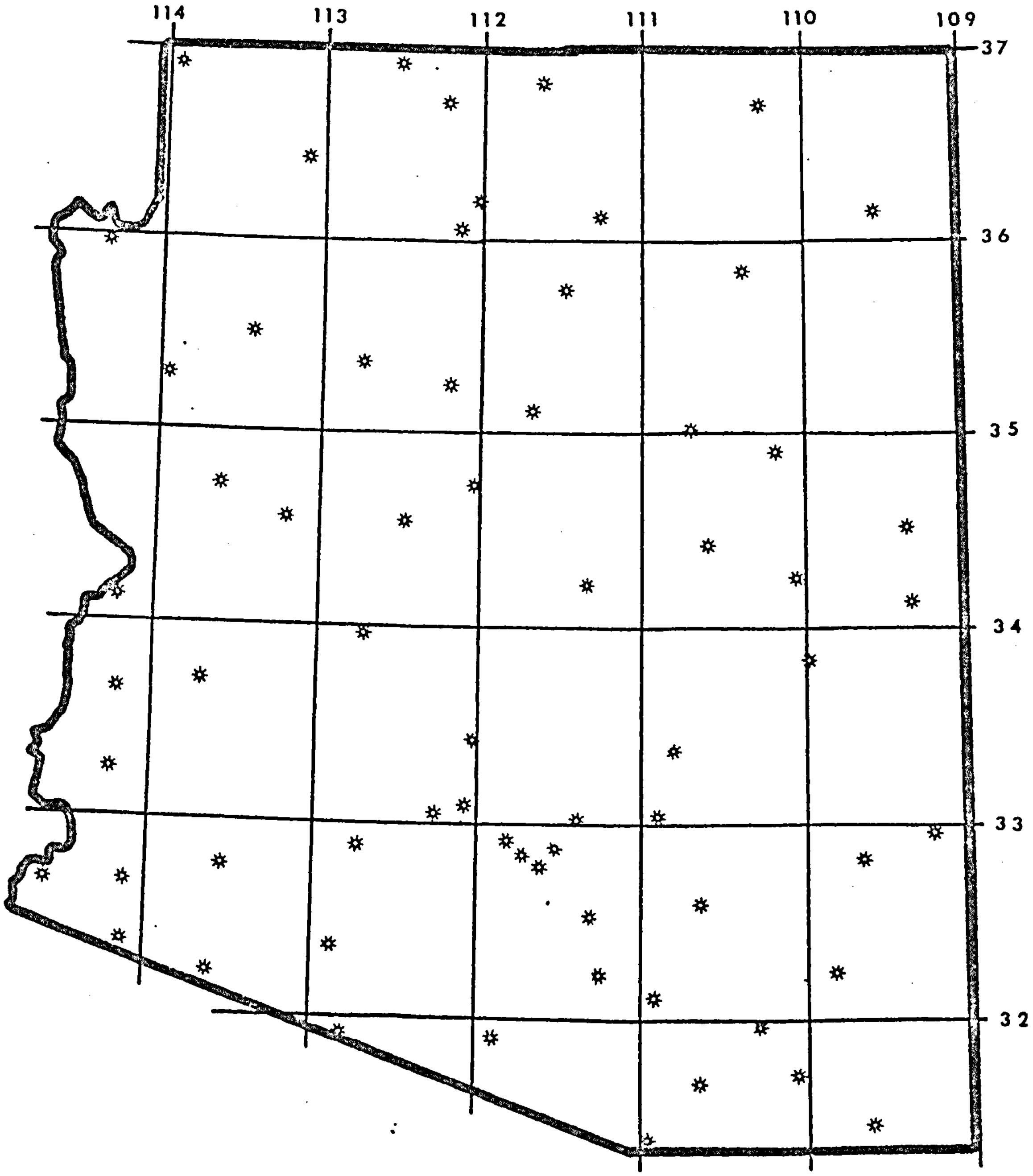

Figure 1. Arizona gravity base station network, 1967

network. Observations contributed to the Arizona Gravity Data Base have been re-reduced relative to the state network when necessary.

The Bouguer Reduction

To observe lateral mass variations in the near-surface crust due to anomalous geological masses, the observed gravity data must be reduced to a uniform (equipotential) surface and the distracting effects of irrelevant masses must be removed. The Bouguer reduction attempts to satisfy these requirements. Certain approximations will be made in order to do this. The first approximation made is inherent in the formulation of the normal gravity function. The mathematical ellipsoid is not everywhere coincident with the actual surface of the earth, and there thus exist discrepancies in elevation between the geoid, the actual surface, and the surface to which the normal gravity function is related. The variation in Arizona is on the order of only 3 meters and thus makes this approximation the least erroneous in the entire reduction process.

The free-air anomaly is calculated first by subtracting the normal gravity and the free-air correction from the observed gravity value. The free-air correction is given by

$$g_{FA} = .30855H - .00000072H^2 + .000219H\cos 2\phi \text{ mgal}, \qquad (3)$$

where the observation point is at latitude ϕ and H meters above mean sea level. The free-air anomaly is then given by

$$g_F = g_{obs} - \gamma - g_{FA} \text{ mgal}.$$

This procedure effectively takes care of the elevation difference between the geoid and the point of observation. The first term in equation (3) is often sufficent for heights below 6,100 meters (20,000 feet). The free-air anomaly does not take into account the attraction of the intervening mass. To do this, the assumption is made that the curved crust of the earth above mean sea level can be approximated by a horizontal plate of infinite extent and thickness equal to the distance H of equation (3). The density of this plate or slab is taken to be that of the average density of crustal material. A value for the density (ρ) of 2.67 g/cm^3 is most frequently used and is the value employed throughout this project. The simple Bouguer anomaly can now be found by subtracting the effect of this slab from the free-air anomaly,

$$g_B = g_F - 2\pi G \rho H,$$

where G = 6.673 x 10^{-8} cm/sec^2. The term "simple" is used here to indicate that the anomaly value uses only the slab approximation. Refinement of this value is possible by correcting for the curvature of the earth (Karl, 1971) and for the topographic relief that deviates above and below the slab surface (Fig. 2). The curvature correction is on the order of tenths of a milligal, while the terrain correction ranges from zero to tens of milligals in very mountainous environments.

The terrain correction is added to the simple Bouguer anomaly in all cases where the observation point is above sea level, subtracted when below. To illustrate the reason for adding the correction regardless of the type of deviation, consider Figure 3. The attraction of the mass centered about M+ tends to reduce the slab's effect. To compensate, the vertical component of attraction must be added. The lack of

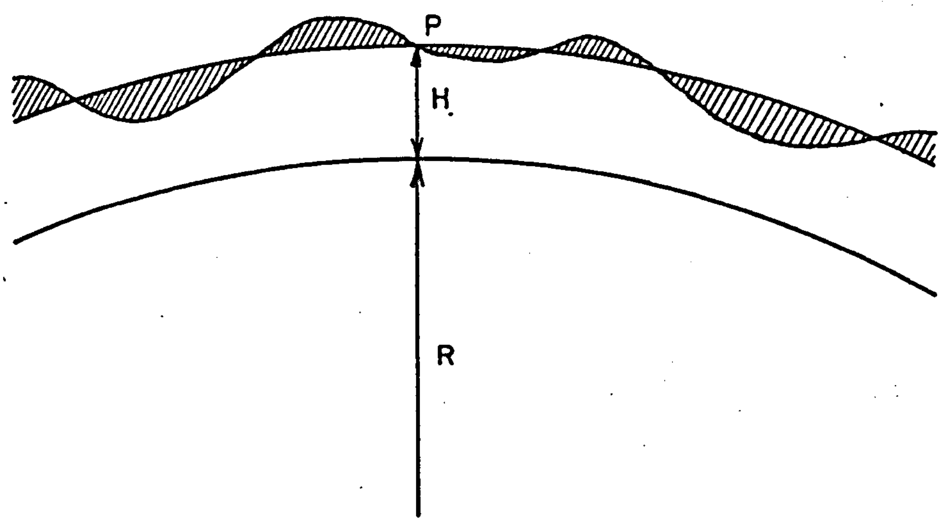

Figure 2. Deviation of topography on the spherical cap

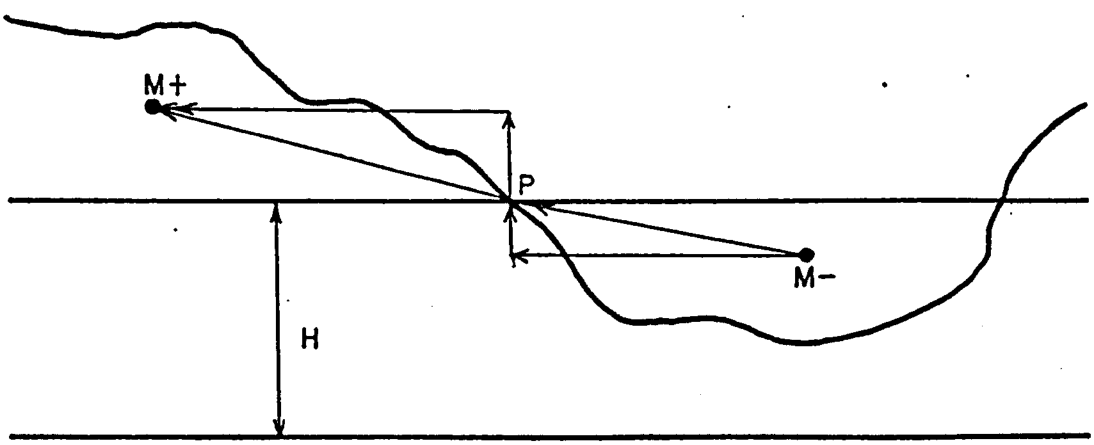

Figure 3. Demonstration of the accumulative nature of the terrain effect

attraction caused by the depression, M−, tends to reduce the attraction at P but has been erroneously removed in the slab approximation. To correct this error, the negative attraction of M− is algebraically added to the simple Bouguer anomaly.

Bullard (1936) pointed out that the use of a spherical cap rather than the infinitely horizontal slab would be a more appropriate approximation. The curvature correction is given by the difference between the slab's effect and that of the cap, C_o, with inner and outer radii R and R + H, respectively. Bullard's term B is

$$B = C_o - 2\pi G\rho H.$$

Figure 4 from Pick and others (1973) illustrates the variation of B for $\rho = 2.67\ \mathrm{g/cm^3}$.

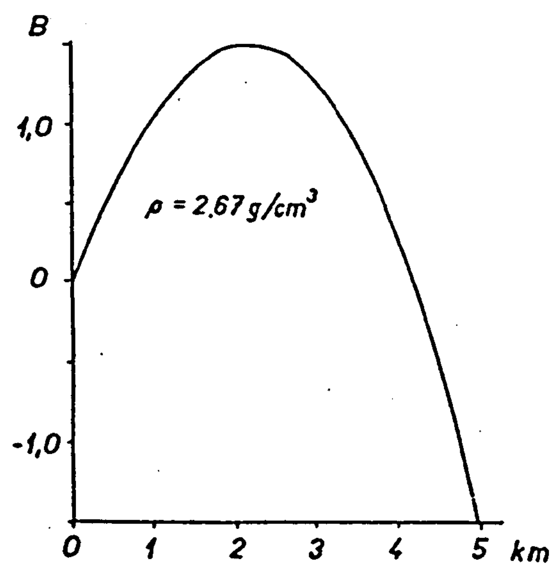

Figure 4. Bullard's term for curvature correction--After Pick and others (1973, p. 91)

The Terrain Effect

All the mass above and below the place of observation (considered to be an equipotential surface) must be accounted for in correcting the Bouguer slab approximation. To be completely correct, the deviating masses must be considered above the entire globe. Pick and others (1973) present a gravity topographic function that can, in theory, be applied over the entire earth. The topographic correction to the Bouguer slab is given by them as

$$\Delta g_c = G\iiint_t \rho \frac{\cos(n,r)}{r^2}\,dt, \tag{4}$$

where t is the region of volume to be corrected, n is the direction of the external normal to the equipotential surface at P, the point of observation, and r is the distance to dt, the elementary volume. G and ρ are as before. Equation (4) is the first derivative of the potential for a single layer (Pick and others, 1973) when the angle (n,r) is between the normal and dt.

The task now is to solve equation (4) in a manner consistent with the accuracy of the overall anomaly value thus far developed. The most widely used solution in this case has been the graphic integration of the surface topography as represented on an altitude map. The method calls for placing a clear template of a form similar to that of Figure 5 centered upon P, determining the effect of P of each compartment and then algebraically summing the individual effects.

Hayford and Bowie (1912) presented one of the most comprehensive tables of gravitational attraction of the topography about a point. However, the object in their work was computation of isostatic anomalies

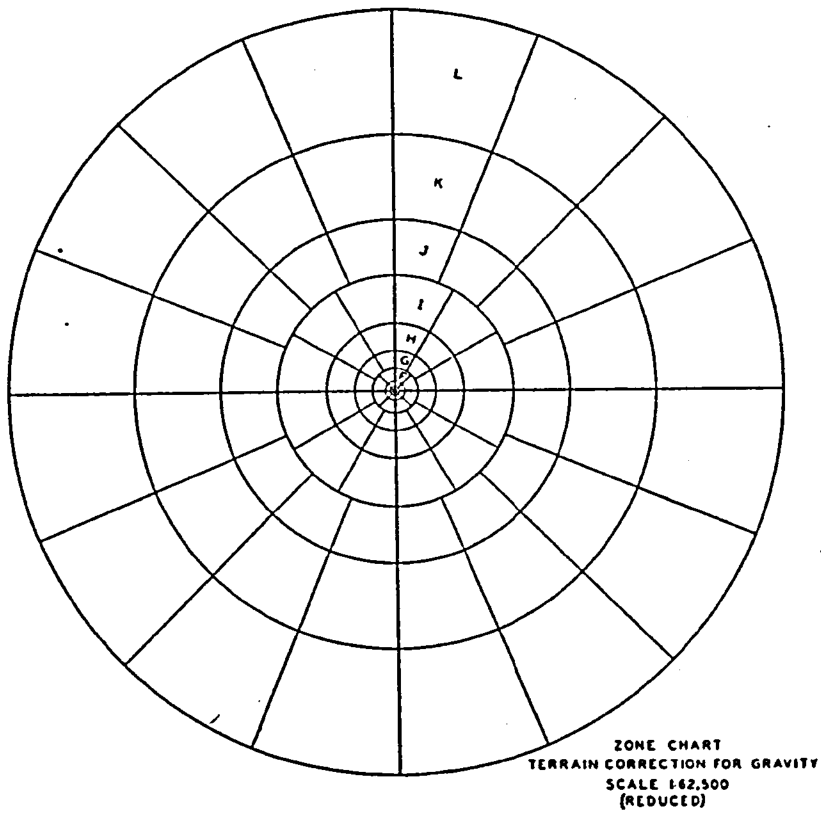

Figure 5. Zone chart for use in evaluating terrain corrections at gravity stations--From Hammer (1939, p. 188)

and they therefore used the entire mass above sea level in the construction of their table. Bullard (1936) improved the procedures of Hayford and Bowie by consolidating the numerous look-up operations in using the table into a three-term expression that includes the Bouguer slab, the curvature correction, and a terrain correction for the surface of the Bouguer slab. This procedure has been used since its presentation as the basis for terrain correction calculations. Bullard's form of the Bouguer anomaly is then

$$g_B = -1.118H + B + C$$

where C is the terrain correction to the Bouguer slab and H and B are as previously stated. The slab factor of -1.118 was found by assuming a ρ of 2.67 g/cm^3 for crustal rock and a ρ_e of 5.53 g/cm^3 for the average density of the earth.

Terrain Correction Calculation

There have been many contributions in the area of terrain correction methods. Of these, those by Hammer (1936), Sandberg (1958), Bott (1959), Kane (1962), and Takin and Talwani (1966) have described procedures that are in general use today. Most of the methods rely on finding the attraction of a segment of a hollow cylinder, a vertical prism, or the frustum of a cone as the figure that best fits the terrain configuration about a gravity station. The methods of Hammer and Sandberg were designed specifically for manual computation, using clear templates, as in Figure 5, by which the terrain heights are estimated. Bott, Kane, and more recent authors applied methods using rectangular prisms arranged on a regular grid to model the surrounding terrain. This modification was in response to the move toward computerized operations that could perform the terrain correction calculation much faster than the manual methods in previous schemes. Nagy (1966) developed the exact expression for the attraction of a right rectangular prism and applied it to the problem of terrain corrections with success. His computational algorithm is quite long and for a very large number of prisms (more than 1,000) it becomes uneconomic in typical usage environments.

Stacey and Stephens (1970) reviewed the essentials of these methods in an excellent publication of the Dominion Observatory at Ottawa. No further descriptions of these methods will be presented here except for those that pertain directly to the procedure used in the preparation of the complete Bouguer gravity anomaly map of Arizona. Heiskanen and Vening Meinesz (1958), Heiskanen and Moritz (1967), and other investigators have presented discussions covering the theoretical and geometrical developments of the attraction of the segment of a hollow cylinder.

The method employed in terrain correcting the Bouguer anomaly values for the complete Bouguer gravity anomaly map of Arizona is the line-mass approximation first described by Bott (1959) (Fig. 6) and reviewed by Plouff (1966). Terrain corrections were calculated for 3 x 3-minute blocks from 167 to 21 km and for 1 x 1-minute blocks from 21 to 7 km, using interpolated elevations derived from the average elevations of the 3-minute blocks. The DMATC 208-foot planar data were used for the local area within 7 km of each observation point. The programmed equations for the line-mass attraction without and with curvature correction are given in equations (5) and (6), respectively:

$$g_1 = G\rho A \frac{1}{(R^2 + H^2)^{1/2}} \tag{5}$$

and

$$g_{1c} = G\rho A \frac{1}{(R^2 + H^2)^{1/2}} - \frac{1}{\left[R^2 + (\frac{R^2}{2a} + H)^2\right]^{1/2}} . \tag{6}$$

G and ρ are as before, A is the area of the approximated block, R is the distance from P to the line mass, H is the difference between the station elevation and the top of the line mass, and a is the mean radius of the earth (6,371.2 km).

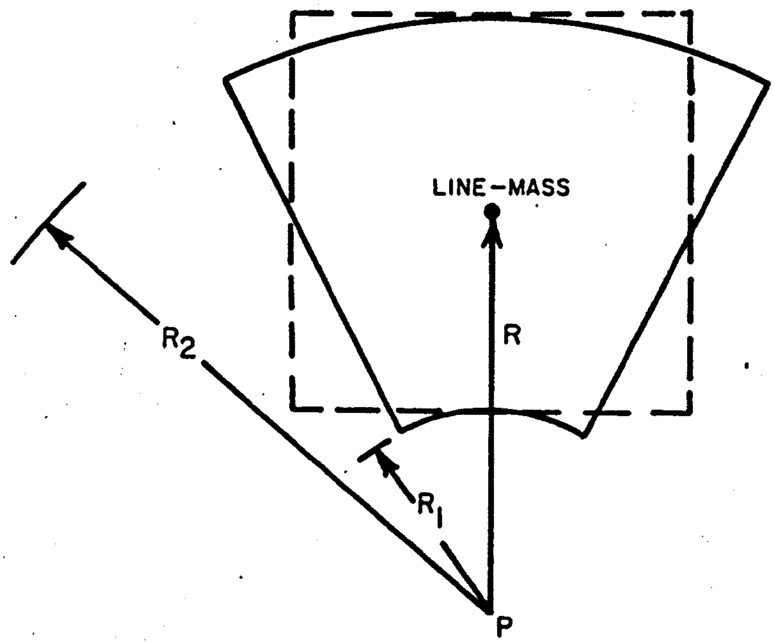

Figure 6. Correspondence between a sector of a cylinder, a prism, and line mass--After Bott (1959)

The determination of H within the 7-km radius requires a brief discussion. Because of the accuracy of the station location (0.01 minute), it is frequently possible to introduce an error of at least two seconds in either or both latitude and longitude. This will correspond to an error of one grid unit or more in the DMATC reference system and therefore cause an error in the elevation of the observation point. For the 167-km and 7-km corrections, the elevation recorded by the field operator is taken for the station height. M. F. Kane (oral commun., 1975) suggested using the digital map elevation instead of the (assumed) more accurate reported elevation. In this way, the overall accuracy of the inner zone correction is derivable from a single source, that is, the source of the digital map. The implemented procedure was to use the digital map elevation within the 7-km radius unless it was more than half of the 200-foot (60.96 m) contour interval different than the reported elevation, in which case the latter was used as the station height and the digital map elevation was taken as the top of the line mass. The terrain correction scheme assumes that the station location as well as the line mass is located at X_p, Y_p. The value Z_p is taken as the elevation of an observation point at the top of the approximating line mass.

The complete terrain correction process involved the terrain effect from 7 to 167 km, using the circular join feature of Plouff's (1966) program and then processing the planar data using a 7-km search radius. Any elevation point within the search radius was used as a line-mass location, and the sum of all line masses was added to the outer zone sum to obtain the total terrain correction. The 7-km radius was chosen as the minimum distance at which the 3-minute average elevation blocks could be accurately used.

CHAPTER 3

CARTOGRAPHY OF THE COMPLETE BOUGUER GRAVITY ANOMALY MAP OF ARIZONA

The process of producing any map is essentially done in four steps: (1) compilation of the data to be displayed, (2) selection of the projection to be used as the base map, (3) transformation of compiled data into mappable elements, and (4) final plotting. The preceding sections of this report have dealt with the first of the four steps. This section will cover the remaining three.

The method of choosing the base map projection requires an understanding of the nature of the data that are to be displayed and the use for which the map is intended. Gravity measurements are point information, that is, they are not two-dimensional in nature. As such, any projection would suffice for plotting as long as the map accurately reflected the geographic location of each observation point. On the other hand, the purpose of taking gravity readings over an area is to provide an array of points that can be used to infer the Bouguer anomaly at all points. The projection used must therefore be capable of representing the spatial relationships between observation points. Because the final map will consist of contours representing lines of constant Bouguer anomaly and making profiles generally perpendicular to such contours is an anticipated use of the map, the projection must also retain correct angular relationships between different lines drawn on the map. This is often overlooked in contour map production. It is necessary also to consider the overall shape of the final map. For geographic areas of predominantly east-west orientation, one type of projection may be more favorable than if the area being mapped is of predominantly north-south orientation. Arizona is slightly longer north-south than east-west; however, the difference is not significant and in this case the previously mentioned factors are of greater importance in selecting the proper projection. Comparison of areas within the map is also a potential function of the map. For this application, the map should show as little scalar distortion as possible.

It is clear that some type of conformal projection is needed to satisfy the above requirements and expected uses. The property of conformality is defined by Deetz (1936, p. 41) as follows:

> If at any point the scale along the meridian and the parallel is the same (not necessarily correct, but the same in both directions), and the meridians and parallels are at right angles to one another, then the shpaes of all elementary figures on the map are the same as their corresponding areas upon the earth.

Of the several types of conformal projections available, the Lambert conformal conic and the transverse Mercator projections are the most widely used. The U.S. Coast and Geodetic Survey (1951) state plane coordinate system for Arizona is a transverse Mercator projection. The digital terrain data from the DMATC are taken from maps plotted in transverse Mercator (Noma, 1974). The data are also directly referenced in the Universal Transverse Mercator reference system (U.S. Army Map Service, 1955).

Another important consideration in the production of a complete Bouguer gravity anomaly map of Arizona is its intended use in correlation with geological maps available over the state. The "Geologic Map of

Arizona" (Wilson, Moore, and Cooper, 1969) at 1:500,000 scale is plotted in the Lambert conformal conic projection using standard parallels of 33° N. and 45° N. The Lambert conformal conic projection is widely used in maps of the United States and of other areas having predominantly east-west dimensions (Adams, 1918). Computer programs are available for both the Universal Transverse Mercator and Lambert conformal conic projections.

It was decided that the accuracy and greater speed of computation of the Lambert conformal conic projection favored its selection. It should however be noted that, because both projections satisfy the conditions of conformality, a direct transformation between them exists and can be obtained if desired.

Lambert Conformal Conic Projection

The general configuration of the Lambert conformal conic reference system is shown in Figure 7. Among other things, the projection has the following important properties:

1. The longitude lines are straight and radiate from the cone's apex.
2. The parallels are concentric circles with their center at the apex point.
3. The meridians and parallels are everywhere perpendicular on the projection.
4. The scale distortion is greater than one north of 45° and south of 33°; it is less than one between 45° and 33° and exact along them (Fig. 8).

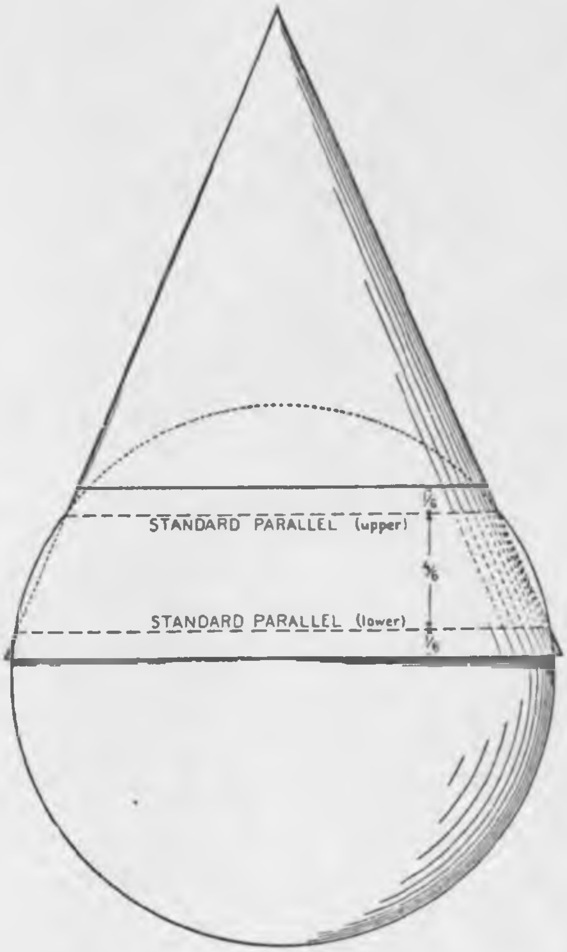

Figure 7. Intersection of a cone and sphere along two standard parallels--After Adams (1918)

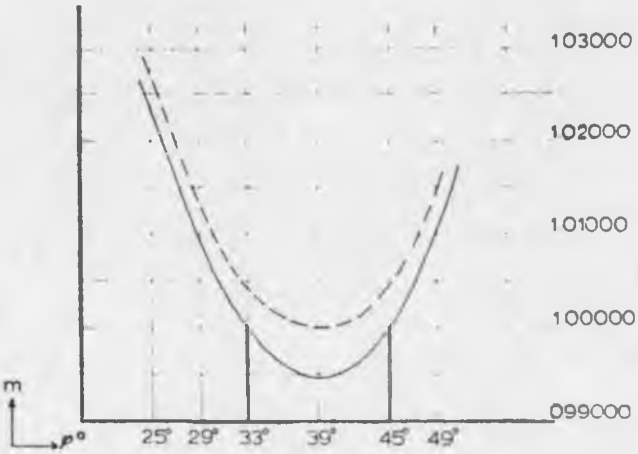

Figure 8. Lambert conformal conic scale distortions for standard parallels 33° N. and 45° N.--From Ricardus and Adler (1972, p. 95)

The parameters used for the reference spheroid calculations for Clark's 1866 spheroid are:

a = 6378206.4 meters

b = 6356583.8 meters (polar axis)

f = 1:295 (flattening)

The geographic and planar reference correspondence used to produce the plotting coordinates are shown in Figure 9.

Production Process

The production of a complete Bouguer gravity anomaly map of Arizona is to be carried out in three phases: (1) creation of the Arizona Gravity Data Base, (2) creation of the Arizona Digital Terrain Data Base, and (3) implementation of the terrain correction schema. Plotting of the final data will be done on an off-line plotter in 1x1 degree sections at a scale of 1:250,000, corresponding to the areas of coverage on each digital terrain data tape (Fig. 10). Gravity data in each one-degree area is retrieved, using the Arizona Gravity Data Base. The culmination of the terrain effect schema also involves updating the Arizona Gravity Data Base with the final Bouguer anomaly values. The terrain effect calculations will also be done using the same one-degree areas. Contouring is to be done by hand, using a 5-mgal interval. Each of these three phases will be discussed in the following sections. The first two constitute independent systems and as such will be given a broader treatment than the third, which is a functional user of the two systems. The base map chosen for the complete Bouguer gravity anomaly map of Arizona is the same as that of the "Geologic Map of Arizona"(Wilson and others, 1969).

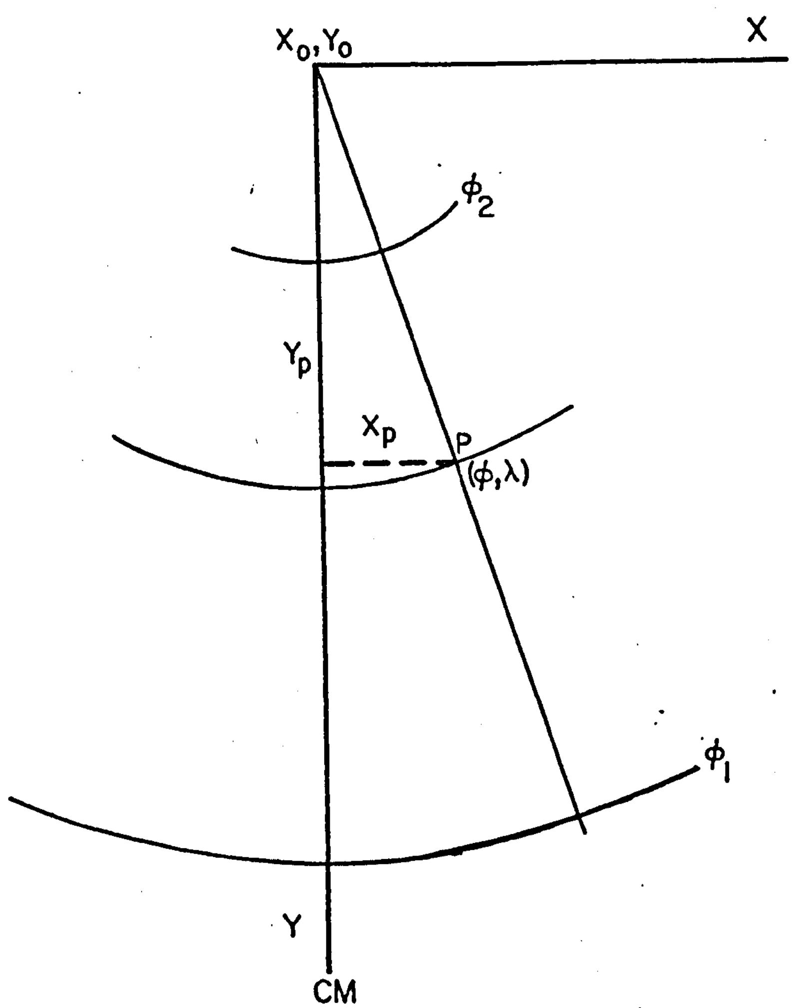

Figure 9. General form of the Lambert grid with standard parallels ϕ_1 and ϕ_2 and central meridian

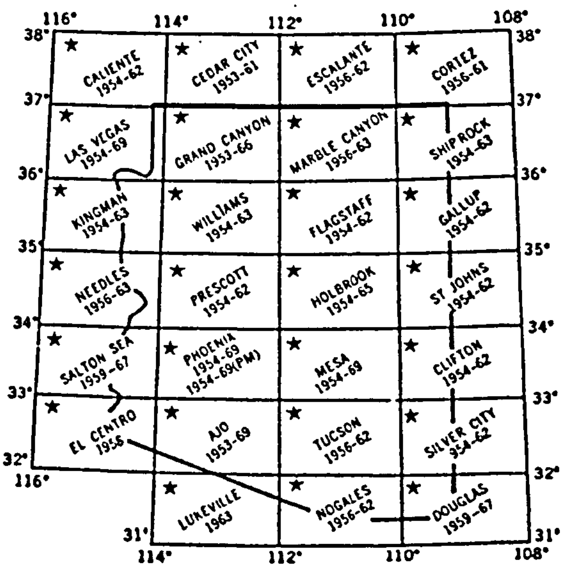

Figure 10. Index map for digital terrain coverage for planar compaction and 3-minute data

<u>Arizona Gravity Data Base</u>

Schmidt, Aiken, and Sumner (1973) describe the initial concept and structure of the Arizona Gravity Data Base as first implemented. Later developments in file organization and record structure have caused several important changes, including consolidation of the data base into a single file and the addition of terrain correction and geologic information in each observation record. Appendix B includes a more complete breakdown of the record structure currently being used. The overall organization of the Arizona Gravity Data Base will be discussed with an emphasis on its functional characteristics.

The Arizona Gravity Data Base was designed to be a stand-alone system for maintaining the gravity data accumulated by the Laboratory of Geophysics, The University of Arizona, over the past several years. Many of the observations in the data base were made during the work of West (1972) in preparation of the regional Bouguer gravity anomaly map of Arizona. Sumner and West (1969) describe the gravity observation program to that time. Continuing work by students within the Laboratory of Geophysics and the Department of Geosciences have also contributed to the growth of the data collection as it now stands. Considerable numbers of observations have also been generously donated by commercial mining companies over the years. Approximately 22,000 gravity observations are presently contained in the Arizona Gravity Data Base.

The Arizona Gravity Data Base concept defined two distinct areas. The first is the data-record collection comprising the data bank, their content and format. The second is the data management system that performs the clerical operations of the data base. The management system consists of the file structuring and manipulation software and user interface software. The system was required to meet five criteria:

1. The system must be compatible with the University of Arizona CDC 6400 computer.
2. It must provide security against data loss or unauthorized access.
3. The system should be generally applicable to other types of geophysical data.
4. The system should be easily interfaced with existing software systems used for gravity analysis.
5. The cost of operation must be economical as compared with manual filing and retrieval systems.

After nearly two years of operation, the Arizona Gravity Data Base has been found to have met these criteria.

File, Index, and Key Structures. Data records are stored and recovered, using an index sequential file structure. The data are initially sorted on latitude and longitude in ascending order. The sorted records are then used to create the index sequential file (IS file). Once the original index is built, succeeding records may be added without prior sorting. The coverage over the entire state is contained in a single IS file.

The index contains information concerning the exact location of each record within the storage medium (random disk pack). The same principle is used here as represented by the familiar card catalog of any library. By knowing the title of a book, for example, the location within the library can be obtained by entering the card catalog (a sequential file in alphabetical order) with the title and obtaining the shelf number, a Dewey decimal number perhaps, where the book may be found. If the book is not in the library, no entry in the catalog will match the search key--the book title. This is clearly easier than beginning with the first book in the library and searching sequentially until the sought-after item is found or otherwise determined to be missing. Although the filing systems of most libraries are considerably more complex than that employed by the Arizona Gravity Data Base, the similarities of the two systems are quite close.

The search key used in the Arizona Gravity Data Base serves for both the initial sorting operation and all references to records within the data base. The key is a unique combination of characters associated with a particular record. A key is said to belong to a record and vice versa. In the Arizona Gravity Data Base, the key for each gravity observation is made up of the latitude and longitude of the point of measurement and also a special code assigned by the data base administrator. In all, 15 characters constitute a search key. The symbolic structure of a data base key is

DDMMHHLLLMMHHTT

where
DD is the degrees latitude
MM is the minutes latitude
HH is the hundredths of minutes latitude
LLL is the degrees longitude
MM is the minutes longitude
HH is the hundredths of minutes longitude
TT is the assigned special code.

The sequentiality of the file structure comes from the sorted nature of the record arrangement during file creation. By having at least one data element of a group of elements in a predetermined order, retrieval of consecutive records is greatly facilitated. Sequential organization also permits a convenient method by which the IS file can be grouped into sections, for example, latitude bands.

Arizona Digital Terrain Data Base

Gravity analysis in Arizona necessitated the application of terrain corrections to observed gravity data. To accomplish this, it was necessary to establish a source of terrain data compatible with the terrain correction process. Because the entire gravity reduction process was being computerized and the terrain correction program required elevation data prepared on a geographically delimited square grid, the initial data base was confined to elevations representing rather large areas. Even with the addition of data digitized on a smaller size grid, the terrain data base did not completely satisfy all requirements for a uniformly accurate data source. Point elevations, such as bench marks, were not considered as an adequate data source because of the irregular spacing encountered between points.

The geographic extent of the Arizona Digital Terrain Data Base is currently limited to that shown in Figure 10 because it was not necessary to calculate terrain effects for topography at any greater distance for stations located within Arizona. The subdivision of the data base is a 1x2 degree area as defined by the 1:250,000 scale Defense Mapping Agency (formerly, Army Map Service) topographic map series. This provided a convenient means of identifying blocks of terrain data and a suitably large area so that there were only 23 area identifiers to keep track of while processing.

A variety of reference systems can be used with the Arizona Digital Terrain Data Base; however, all systems must be transformable in some well-defined manner into geographic coordinates. The geographic reference system is the basic system of all geophysical data collections held by the Laboratory of Geophysics. The problems associated with transformation to the geographic system are not necessarily trivial as will be pointed out later in this section.

Depending on the type of data being used, there are several rectangular reference systems available, the most frequently used of which is the Universal Transverse Mercator grid (Fig. 11). Direct conversion from the Universal Transverse Mercator to geographic coordinates and back are available in the Arizona Digital Terrain Data Base program library. A second system is based on the Lambert conformal conic projection (Fig. 8).

Defense Mapping Agency Digital Terrain Data. The digital terrain data used in calculating the terrain corrections were obtained from the Defense Mapping Agency Topographic Command on 7-track magnetic tape in the planar compaction format (Appendix C). Noma (1974) describes the entire system by which the Defense Mapping Agency Topographic Command has produced the digital terrain library of over 1,600 tapes covering North America in 1x1 degree areas. The source maps from which the Arizona data were obtained are the 1:250,000 scale topographic maps. Each map covers a 1x2 degree area in latitude and longitude, respectively, and meets class A national map accuracy standards (Marsden, 1960).

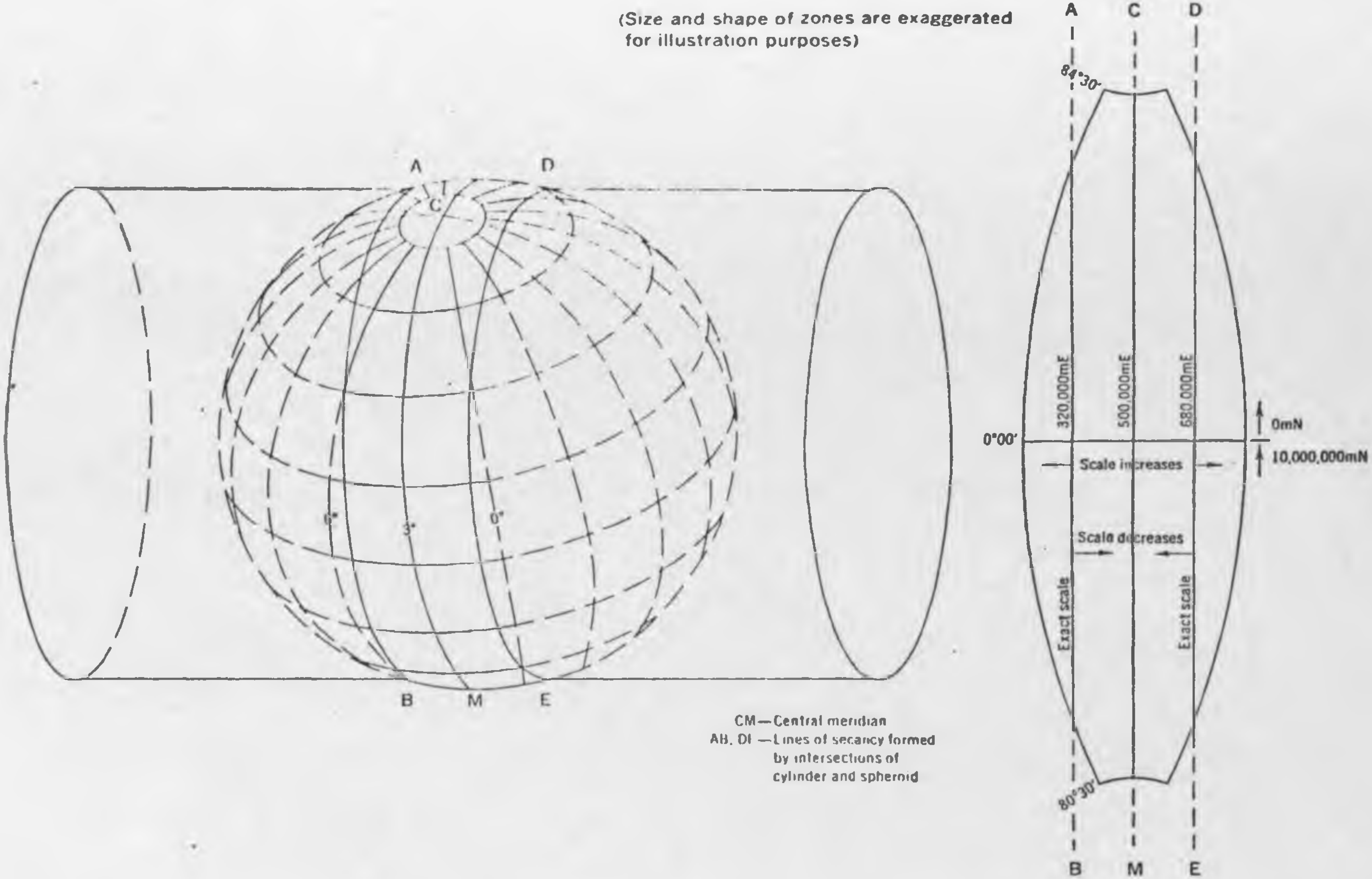

Figure 11. Universal Transverse Mercator grid for a typical 6-degree zone--After Department of the Army (1967)

Digitizing a single map produces two so-called planar compaction tapes each covering a one-degree square. The general method employed to produce these data is as follows:

1. The contours of the original maps are digitized, replotted, and verified.
2. The digital contour data are sorted in X and Y, and a linear planar interpolation scheme is carried out that eventually produces an elevation value at every (X,Y) position within the map boundaries.
3. The planar interpolation output is sorted again and stored as vertical raster lines or profiles, one profile for each X coordinate computed during interpolation. Prior to writing the final magnetic tape, the data are compressed to 18 bits per elevation, each raster being written as a single physical record.

The digitization process has a resolution of 0.01 inch or 10,000 elevations per square inch. The typical one-degree map area is 17.5 minutes north-south and 14.5 minutes east-west. Such a map would contain 2,537,500 point elevations after the planar interpolation process. Roughly 150 million elevations are involved in the coverage of Arizona.

The digital terrain data represents discrete areas of approximately 208 feet on a side derived as follows: original map scale = 1:250,000 or 1 cm = 2,500 meters; digitizing at a 0.01-inch grid interval produces a grid distance of

2500 m/cm x 2.54 cm/in. x .01 in./grid unit x 3.28 ft/m

= 208.3 ft/grid unit = 63.5 m/grid unit.

Therefore, each elevation represents a square area 208 feet (63.5 m or 0.0635 km) on a side. The correspondence between the digital model of terrain and the actual surface is illustrated in Figure 12 from Biggin (1971).

Implementation of the Terrain Correction Scheme

Terrain corrections are computed using a two-phase approach. The first phase consists of obtaining the uncorrected gravity data for up to 500 stations and computing the terrain effect of the outer zones from 3 or 7 km to 167 km. The choice of either a 3- or 7-km starting radius is governed by the availability of one-minute digital terrain data. The outer zone terrain effect is found using the U.S. Geological Survey's program (Plouff, 1966) as modified for use with the Arizona Gravity Data Base record format.

Phase two of the terrain correction scheme uses the Arizona Gravity Data Base format records as input. Six major steps are carried out in this phase:

1. Transforming station latitude and longitude coordinates into the coordinate system of the digital terrain data.
2. Computing search limits for each station based on the selected outer zone radius (usually 3 or 7 km).
3. Sorting stations on their x-coordinate to facilitate sequential searching of the digital terrain data tapes.
4. Obtaining and checking reported station elevation with the elevation found at the station coordinates within the digital terrain data. If the digital terrain elevation is within ± 100 feet

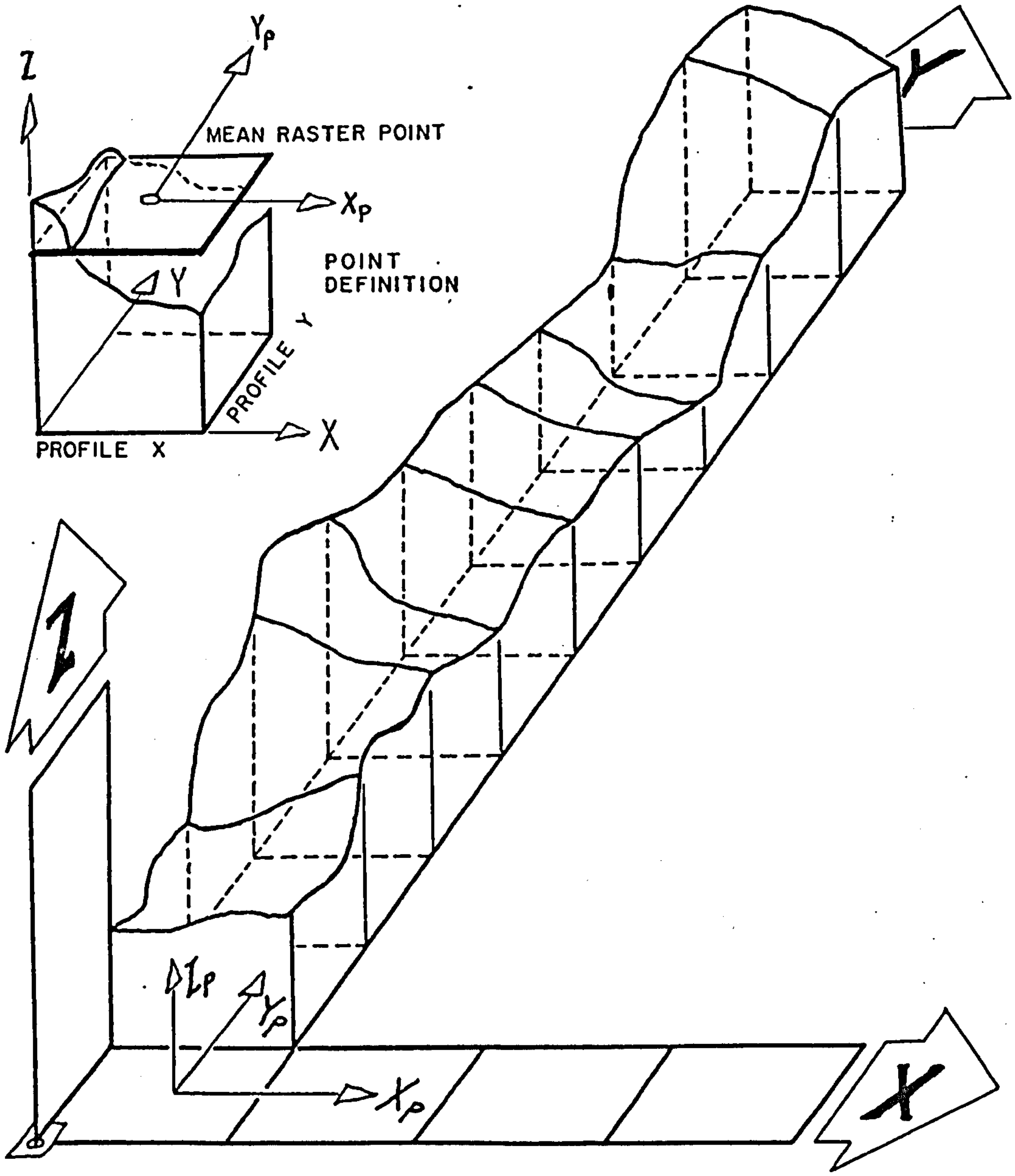

Figure 12. The digital terrain model--From Biggin (1971)

(30.48 m) of the reported station elevation, the digital terrain elevation is used as the station elevation; otherwise the reported value is used.

5. Sequentially passing through the digital terrain data tape calculating the terrain effect for each station.
6. Preparing the updated gravity data file for insertion into the Arizona Gravity Data Base.

Because both phases use the Arizona Gravity Data Base format records as initial input, either phase can occur first. Operational programs detect and take into account which phase of terrain correction each gravity station is undergoing. The final updated station records are manually screened and made available for insertion into the Arizona Gravity Data Base.

CHAPTER 4

SUMMARY

Creation of an operating Arizona Gravity Data Base has been a reality since 1974. Establishment of the Arizona Digital Terrain Data Base has been successfully carried out during 1975. Supporting software and administrative mechanisms for operating these data bases has been implemented with the underlying concept of generality of function and broadest application. Both data bases constitute a significant advance in making gravity reduction and analysis in Arizona a more accurate and better organized method of geophysical research. Development of the Arizona Digital Terrain Data Base will be a continuing program.

The essential cartographic procedures have been completed for this project with the successful implementation of the Lambert conformal conic projection transform operation as integrated into the Arizona Gravity Data Base system. The result being an effective method for generating Lambert conformal conic projection maps of any or all of the state using data held in the Arizona Gravity Data Base. Additional results in this vein include creation of a back-up data base using the Lambert conformal conic reference system centered on long 112° W., the creation of an independent data base for bedrock stations, the establishment of a uniform record format for recording gravity observations, and the implementation of cross transforms between the Lambert conformal conic, the Universal Transverse Mercator, and geographic coordinate systems.

The major technical problem encountered in this effort was developing an accurate method by which the relative grid positions of the digital terrain data provided by the Defense Mapping Agency Topographic Command could be transformed into geographic coordinates. The values provided by DMATC on each data tape proved insufficient to produce the required one-second accuracy needed to distinguish two adjacent points. Only after discussion with DMATC personnel and their providing additional positioning data for the Arizona area maps was a sufficiently accurate method developed.

Once accurate geographical positioning was available, programs to find the location of observation points within the terrain data tapes and to determine possible line-mass locations within a stated radius of each station were implemented. This then lead to the successful completion of the inner zone terrain correction calculation algorithm. Refinement of the complete data reduction system is continuing. Calculation of terrain corrections and updating of the Arizona Gravity Data Base are ongoing functions. Budget limitations involving computer operations have limited this effort to producing only a test area 0.5-degree square (Fig. 13). Delays in data shipments and tape copying errórs have also forced completion of the entire complete Bouguer gravity anomaly map of Arizona to a future date. The operating procedures and functional units composing the total system have nonetheless been proved during the test area production runs.

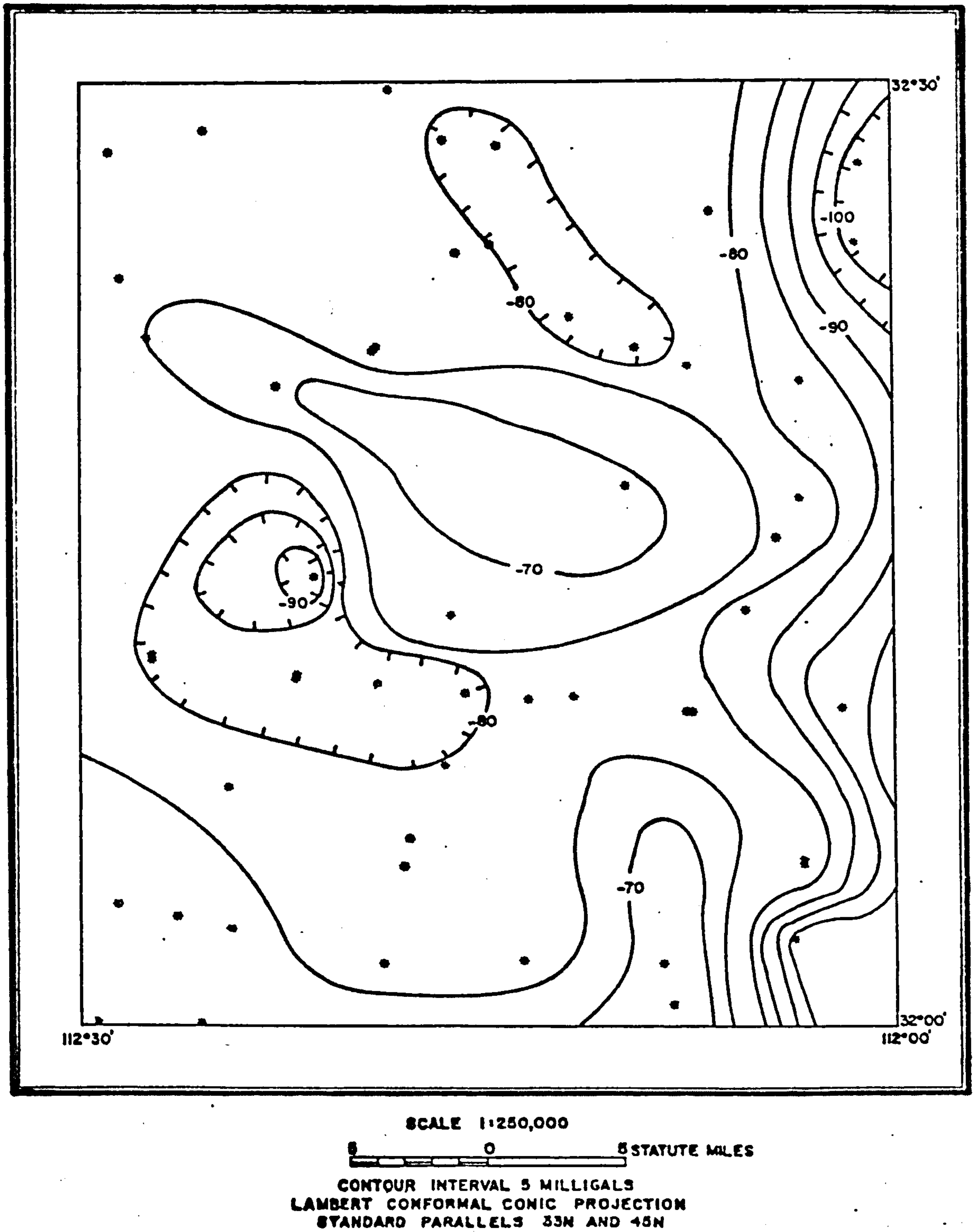

Figure 13. A complete Bouguer gravity map of a 0.5-degree square area in the northwestern part of the Papago Indian Reservation, southern Arizona

APPENDIX A

MAPPING EQUATIONS FOR THE LAMBERT CONFORMAL CONIC PROJECTION

Standard parallels: 33° N. $= \phi_1$; 45° N. $= \phi_2$

Central meridian (CM): 112° W.

Scale of projection: scale

Semimajor axis: a

Semiminor axis: b

Station coordinates: ϕ = latitude, $\Phi = 90 - \phi$, λ = longitude

$E = (1 - (b^2/a^2))^{1/2}$

$N_1 = a/(1 - E^2 \sin \phi_1{}^2)$

$N_2 = a/(1 - E^2 \sin \phi_2{}^2)$

Δ = sine of 1 sec $= 4.84814 \cdot 10^{-6}$

$\sigma_1 = 1/\Delta N_1$

$\sigma_2 = 1/\Delta N_2$

$\Phi_1 = 90 - \phi_1$

$\Phi_2 = 90 - \phi_2$

$$Q_1 = \tan\left[\frac{1/2\Phi_1(1 + E\cos\Phi_1)}{1 - E\cos\Phi_1}\right]^{E/2}$$

$$Q_2 = \tan\left[\frac{1/2\Phi_1(1 + E\cos\Phi_2)}{1 - E\cos\Phi_2}\right]^{E/2}$$

$$\alpha = \log\left[\Delta^2 N_1 N_2(\cos\phi_1/\cos\phi_2) - (Q_1/Q_2)\right]$$

$$\beta = \cos\phi_1/\alpha N_1 Q_1{}^{\alpha}$$

$$B = (CM - \lambda)\alpha$$

$$X = \left[-b\left(\frac{1 + E\cos\Phi}{1 - E\cos\Phi}\right)^{E/2} \sin B\right] / \text{scale}$$

$$Y = \left[b\left(\frac{1 + E\cos\Phi}{1 - E\cos\Phi}\right)^{E/2} \cos B\right] / \text{scale}$$

APPENDIX B

RECORD FORMAT OF THE ARIZONA GRAVITY DATA BASE

The record format currently used in the Arizona Gravity Data Base has been derived from that originally described by Schmidt, Aiken, and Sumner (1973). Each record is 136 ASCII characters long with all records in the data base being fixed in length. Each record occupies fourteen 60-bit words on the CDC 6400 computer. Figure B-1 illustrates the format of a record as described under data element symbol in Table B-1. Records are entered and retrieved by keys made up of the latitude, longitude, and special code (UU). The format for a search key is also shown in Figure B-1. A decimal point appearing in the symbols also appears on each data record. The format shown in Figure B-1 is broken into lines because of the space limitations in the figure.

A station is considered to be on bedrock (B_r = B) when the following definition applies: the observation point lies on

1. Low-density rocks ($\leq$ 2.4 g/cm^3), or
2. Intrusive rocks of any age, or
3. Any pre-Cenozoic material.

The inner and outer ring indicators refer to the terrain effect value that they follow. Table B-2 gives the distances in kilometers by which the ring designators are to be determined. The quality of reading (Q) indicator is a subjective measure made by the field operator and is not an

$\mathrm{SSSSSSSS}\ D_1D_1\ \ M_1M_1.M_1M_1\ \ -D_1D_1D_1\ \ M_2M_2.M_2M_2\mathrm{EEEEE.EEEE}_tO_gO_gO_gO_gO_gO_g.O_gO_gO_gB_4$

$\mathrm{FFFF.FFF}B_gB_gB_gB_gB_gB_g.B_gB_gB_g\mathrm{TTTTTTT.TTTUU}\,H_1H_2H_3H_4H_5I_hO_hT_1T_1(.)T_1T_1T_1T_1I_1O_1$

$T_2T_2(.)T_2T_2T_2I_2O_2T_cT_c(.)T_cT_cT_cI_cO_cS_tS_tC_oC_oQE_cG_1G_1G_1G_2G_2G_2G_3G_3G_3\mathrm{PPPPPPPP}$

Record Format

$D_1D_1M_1M_1M_1M_1D_2D_2D_2M_2M_2M_2M_2M_2\mathrm{UU}$

Search Key Format

Figure B-1. Formats for an Arizona Gravity Data Base record and a search key indication of the accuracy of the observation but rather a statement as to measuring conditions at the time of observation. A blank is permitted. The elevation control indicator (E_c) is determined from the topographic map, survey sheet, or other documentation used in determining the elevation value EEEEE.EEE.

The geology of the area about the station ($G_1G_1G_1, G_2G_2G_2, G_3G_3G_3$) is optional. The choices are to be made from an examination of the station location as plotted on the "Geologic Map of Arizona" (Wilson and others, 1969), and the appropriate symbols as described in the map's explanation representing the surrounding geology are entered in the observation record.

The project identification indicator (PPPPPPPP) is an alphanumeric string of characters that identifies the project, program, or supporting organization or person that caused the observation to be made. Such identification includes observations made as part of a thesis or dissertation or as part of a regional survey for course work. Contributions from agencies other than The University of Arizona are to be identified in this position.

Table B-1. Symbolic record description for the Arizona Gravity Data Base

Data Element Symbol	Character From	Character To	Description
SSSSSSSS	1	8	Alphanumeric station identification
	9	10	Blank
D_1D_1	11	12	Degrees latitude
	13		Blank
$M_1M_1.M_1M_1$	14	18	Minutes latitude to nearest .01 minute
	19	20	Blank
$-D_1D_1D_1$	21	23	Degrees longitude (always negative for Western Hemisphere
	24		Blank
$M_2M_2.M_2M_2$	25	29	Minutes longitude to nearest .01 minute
EEEEE.EEE	30	38	Elevation of observation point
E_t	39		Elevation units: blank or 0--meters, F--feet
$O_gO_gO_gO_gO_gO_g.O_gO_gO_g$	40	49	Observed gravity in mgal
B_r	50		Bedrock indicator: blank--nonbedrock; B--station on bedrock
FFFF.FFF	51	58	Free-air anomaly in mgal
$B_gB_gB_gB_gB_g.B_gB_gB_g$	59	67	Bouguer anomaly in mgal for $\rho = 2.67$ g/cm^3
TTTTTTT.TTT	68	78	Normal gravity in mgal using International Formula

Table B-1. Symbolic record description--Continued

Data Element Symbol	Character From	Character To	Description
UU	79	80	Special code assigned by the data base administrator
$H_1H_2H_3H_4H_5$	81	85	Hand or innermost terrain correction from ring I_h to O_h with decimal point assumed between H_2 and H_3
I_h	86		Innermost ring
O_h	87		Outer ring
$T_1T_1(.)T_1T_1T_1$	88	92	Terrain correction for I_1 to O_1
I_1	93		Inner ring
O_1	94		Outer ring
$T_2T_2(.)T_2T_2T_2$	95	99	Terrain correction for rings I_2 O_2
I_2	100		Inner ring
O_2	101		Outer ring
$T_cT_c(.)T_cT_cT_c$	102	106	Total terrain correction for all rings
I_c	107		Innermost ring contributing to T_c
O_c	108		Outermost ring contributing to T_c
S_tS_t	109	110	State abbreviations: AZ--Arizona (or blank) CA--California NV--Nevada UT--Utah CO--Colorado NM--New Mexico MX--Old Mexico

Table B-1. Symbolic record description--Continued

Data Element Symbol	Character From	Character To	Description
C_oC_o	111	112	Arizona county: MV--Mohave SC--Santa Cruz YM--Yuma NJ--Navajo CN--Coconino GA--Gila YI--Yavapai GM--Graham MP--Maricopa GL--Greenlee PN--Pinal CH--Cochise PM--Pima AP--Apache
Q	113		Quality of gravity reading: E--excellent G--good F--fair P--poor
E_c	114		Elevation control: A--triangulation B--bench mark C--checked spot D--spot elevation E--altimeter F--survey point (manual) G--contour pick H--photo control
$G_1G_1G_1$	115	117	Geology of area about station--first choice
$G_2G_2G_2$	118	120	Geology of area about station--second choice
$G_3G_3G_3$	121	123	Geology of area about station--third choice
PPPPPPPP	124	130	Project identification
	131	136	Blank

Table B-2. Ring designators and outer limits used for Arizona Gravity Data Base Records

Ring Designator[a]	Outer Limit, km[b]
A	0.0024
B	0.01664
C	0.05334
D	0.17008
E	0.39014
F	0.89489
G	1.15295
H	2.61457
I	4.46897
J	6.65255
K	9.90294
L	10.74162
M	21.94434
W	40.0
X	60.0
Y	100.0
Z	167.0

a. Rings A to M as defined in Hammer (1939).

b. Inner limit given by previous ring boundary.

APPENDIX C

DMATC PLANAR COMPACTION DATA FORMAT

The planar compaction data distributed by the Defense Mapping Agency Topographic Command (DMATC) is built on a UNIVAC 1108, 36-bit word size computer. The format of the data tapes as provided by DMATC follows.

1. General Specifications
   a. Recorded on one-half-inch 7-track IBM compatible tape.
   b. All records are recorded in odd parity, binary mode.
   c. Density 800 BPI, Interrecord gap 0.75".
   d. Physical records are variable in length but will be a multiple of six (6) characters from 18-6912.
   e. Each character is 6 bits in length.
      (1) First two records are identification records.
      (2) Records 3 to N are data records.
         (a) Characters 1-6--binary record count.
         (b) Characters 7-6912--data quantities.
      (3) End-of-file record.
   f. Data is sorted on X direction and then on Y.
   (i.e., $X_1, Y_1, X_1, Y_2, X_1, Y_3, \ldots X_1, Y_n, X_2, Y_n, \ldots X_2, Y_n, \ldots X_n, Y_n$)

2. Identification Records

a. Tape identification (78 characters)

Frame	Contents	Explanation
1-6	000000000020	Tape ID indicator
7-18	(e.g., NI 12-10W)	Sheet number (ALFANUMERIC)
19-24	X sw	
25-30	Y sw	
31-36	X nw	
37-42	Y nw	Sheet corners (binary position of digitizing instrument)
43-48	X ne	
49-54	Y ne	
55-60	X se	
61-66	Y se	
67-72	Series	
73-78	Edition	

b. File identification (78 characters)

Frame	Contents	Explanation
1-6	000000000120_8	File ID indicator
7-18		Sheet number
19-24	ø sw	
25-30	λ sw	
31-36	ø nw	Sheet corners--word format
37-42	λ nw	
43-48	ø ne	
49-54	λ ne	
55-60	ø se	
61-66	λ se	
67-72	Series	
73-78	Edition	

Bits	Contents
1	sign
2-24	degrees (binary)
25-30	minutes (binary)
31-36	seconds (binary)

3. Data Records (variable length)

Character	Contents	Explanation
1-6	$410000RRRRRR_8$	41--data record indicator R--binary record count
7-10	$xxxxyyyy_8$	X--coordinate of scanline Y--coordinate of scanline
11-13	$zzzzzz_8$	Z_1--coordinate associated with first y-coordinate of scanline
N-(N+2)	$zzzzzz_8$	Z_n--coordinate associated with last y-coordinate of line
(N+3)-(N+5)	777777_8	Sentinel to terminate scanline

4. End-of-File Record (78 characters)

Character	Contents	Explanation
1-6	012546261500_8	End-of-file indicator
7-18		Sheet number (ALFANUMERIC)
19-24		Record count (binary)
25-30		Number input control points (binary)
31-36		Total points on tape (binary)
37-78		Irrelevant

5. End-of-Information Record (78 characters)

Character	Contents	Explanation
1-6	012551311500_8	End-of-information indicator
7-78		Irrelevant

6. Notes on Data Records

Where

XXXX (OCTAL) = X-coordinate of scanline. X = unsigned binary integer from 0.00" to 40.95" (actual size of map).

YYYY (OCTAL) = First Y-coordinate of scanline. Y = unsigned binary integer from 0.00" to 40.95' (actual size of map).

ZZZZZZ (OCTAL) = Z-coordinate (elevation) of point within scanline. Z = signed integer from -32,767 to +32,767 (true elevation in feet).

Z-Coordinate (bit 1 equals high-order bit).

Bit	Explanation
1-2	00 = computed point 01 = internal contour (fixed) point
3	0 = positive elevation 1 = negative elevation
4-18	Binary integer value

7. Example: consider a scanline consisting of five points:

Point	Coordinates
1	X = 1.00" Y = .50" Z = 495 ft
2	X = 1.00" Y = .51" Z = 499 ft
3	X = 1.00" Y = .52" Z = 504 ft
4	X = 1.00" Y = .53" Z = 510 ft
5	X = 1.00" Y = .54" Z = 518 ft

These five points would be represented in a physical record as:

Character	Contents	Explanation
1	41_8	Data record indicator
2-6	0000000001_8	Record count in binary
7-8	0144_8	X-coordinate of scanline
9-10	0062_8	First Y-coordinate of scanline
11-13	000757_8	Z-coordinate associated with first Y-coordinate of scanline
14-16	000763_8	Z-coordinate associated with second Y-coordinate of scanline
17-19	000770_8	Z-coordinate associated with third Y-coordinate of scanline
20-22	000776_8	Z-coordinate associated with fourth Y-coordinate of scanline
23-25	001006_8	Z-coordinate associated with last Y-coordinate of scanline
26-28	777777_8	Sentinel for this scanline
29-30	7777_8	Sentinel to fill word

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