United States Department of the Interior
Geological Survey

Maps of the Thickness of Cenozoic Deposits and the Isostatic Residual Gravity over Basement for Nevada

by

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Open-File Report 90-404
1990

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ABSTRACT

This study of gravity data from Nevada is part of a statewide analysis of mineral resources. The main objectives of the gravity study were: 1) to infer the structure and composition of the basement; and 2) to determine the thickness of Cenozoic deposits. An iterative procedure based on the gravity data, a knowledge of the surface geology, and an estimate of the density of Cenozoic deposits was used to separate the isostatic residual gravity field into two component parts, a "basement" component and a "cover thickness" component. The former component contains information about the basement whereas the latter yields an estimate of the thickness of Cenozoic deposits. All computations were performed with a rectangular grid having intersections spaced at 2 km. The results are presented as contours on two maps at a scale of 1:1,000,000. Sheet 1 represents the basement gravity and sheet 2 represents the inferred thickness of Cenozoic cover.

INTRODUCTION

In early 1988 a multidisciplinary group at the U.S. Geological Survey and the Nevada Bureau of Mines and Geology began an analysis of the mineral resources of Nevada (Cox and others, 1989; Jachens and others, 1989). Areas of expertise encompassed by the group include economic geology, Quaternary geology, mineral deposits, geochronology, geophysics, geochemistry, and igneous processes. Initially, a number of independent but related investigations were begun to provide the diverse information necessary for inclusion in a later integrated analysis covering the entire state.

One topic of particular interest concerns the nature of the basement (for the purposes of this report basement is defined as all pre-Tertiary rocks plus granitoids of Tertiary age), both in terms of shape and composition. Basement is exposed over only about 20 percent of Nevada but this exposed basement is host to about two-thirds of the base and precious metal deposits and prospects in the state. Assuming that the remaining 80 percent of the basement is similarly endowed, knowledge of its depth of burial and composition is crucial to any analysis of mineral resources. In this report, we present the results of a study of the concealed basement using gravity data.

GRAVITY ANALYSIS

Purpose

Analysis of the regional gravity data from Nevada was undertaken with two main objectives--to define the location and shape of the top surface of basement and to produce a gravity map that reflects only variations of density within the basement. Both objectives contribute directly to the analysis of the mineral resources of Nevada, the first by specifying the three-dimensional distribution of potential host rocks and the second by placing constraints on the density - and therefore the permissible lithology - of the concealed basement. Secondary information of potential importance to the mineral resource investigation, such as the location of faults, shear zones, calderas, concealed plutons, and other major crustal features, can come from analyses of these products alone and in combination with geological, geochemical, and other geophysical data.

Data Sources, Reductions, and Accuracies

Basic gravity data are from Saltus (1988a) and comprise approximately 71,000 point observations. These data are distributed unevenly over the state (fig. 1) with some areas (e.g. those surrounding the Nevada Test Site and those in the valleys in east-central Nevada) having observations at least every 1-2 km, whereas others (e.g. parts of northwest and northeast Nevada) are covered only by observations along profiles spaced tens of kilometers apart. Uncertainties in reduced gravity values resulting from errors in observed gravity, location, elevation, and terrain correction are estimated to be less than 1 mGal (1 mGal=10^{-5} m/s^2) for most stations, but uncertainties may be significantly greater for gravity values from stations in areas of rugged topography (Saltus, 1988a). The data have been used to produce a Bouguer gravity anomaly map with a reduction density of 2.67 g/cm^3 (Saltus, 1988b), an isostatic residual gravity map based on an Airy-Heiskanen model for buoyant support of topography, and various derivative gravity maps of Nevada (Saltus, 1988c).

We have chosen to use the isostatic residual gravity values (hereafter simply referred to as residual gravity values) as the starting point for our analysis because these data more clearly reflect shallow density distributions than the more commonly encountered Bouguer gravity values (Jachens and Griscom, 1985; Simpson and others, 1986). The Bouguer gravity anomaly map of Nevada (Saltus, 1988b) shows large amplitude, broad wavelength anomalies that inversely mimic the regional topography--low gravity over the high topography of east-central Nevada and high gravity over lower elevations in southern and northwestern Nevada. This inverse relationship between Bouguer gravity and topography is consistent with the principle of isostasy in which high topography is buoyantly supported by low-density material at depth. The broad gravity low in east-central Nevada is in part caused by such low-density material at depth. Broad gravity features related to isostasy can distort the narrower anomalies related to the geology of the upper crust, the anomalies of most interest in our study. The gravity anomalies shown on the isostatic residual gravity map (fig. 2) are relatively free of distortion from deep sources related to isostasy because a long-wavelength regional gravity field based on a quantitative model for isostatic support of topography has been removed from the data (Saltus, 1988c). The gravity features shown on figure 2 primarily reflect density distributions in the mid- to upper-crust.

Residual Gravity Field of Nevada

The most striking characteristic of the residual gravity map of Nevada (fig. 2) is the pervasive regional pattern of long, narrow gravity highs and lows. Individual anomalies are oriented generally north-south or northwest-southeast, have widths of 15-30 km, and have amplitudes of tens of mGal. This anomaly pattern is closely correlated with both the local topography and the near-surface geology--highs typically occur over ranges where basement rocks are either exposed or near the surface, and lows occur over intervening basins filled with young, low-density volcanic and sedimentary deposits. The dominant nature of this anomaly pattern reflects the strong difference in density between the basement rocks and the overlying Cenozoic deposits. The magnitudes of these narrow anomalies indicate the thickness of the low-density cover.

A longer wavelength, more subtle pattern of gravity variations also is apparent on the residual gravity map, perhaps most readily seen as broad regions of high gravity in the northern and southern parts of the state compared to generally lower values throughout the center. This broader pattern is not directly associated with the location or distribution of basins and ranges--some anomalies span many ranges. Rather, it is an expression of density variations within the basement.

The separation of sources of residual gravity anomalies into the two categories described above--density variations within the basement versus variations in thickness of young cover--suggests a natural separation of the residual gravity field into components that are well suited to the analysis of mineral resources. Separation of the gravity field into two components that correspond to the two source types given above, yields a "basement" gravity map from which to infer the relative density of various basement rock types and to identify large structural elements within the basement, and a "basin" gravity map from which to infer the thickness of Cenozoic cover and, therefore, the depth to basement. Both types of information are crucial to a successful analysis of mineral resources of Nevada and other areas covered by deposits that conceal the nature and location of the underlying rock.

Method of Separation

We have developed a method that, for the most part, succeeds in separating the gravity field of Nevada into its component parts. The method is based on a knowledge of the residual gravity field, of the exposed geology, and of the variation of density with increasing depth in the cover deposits. The process is an iterative one in which an inaccurate first approximation to the separation is refined during successive trials until the process converges to an acceptable solution. In principle, the method simply separates the actual gravity observations into two sets, one composed of all observations taken on outcrops of basement and the other composed of all observations made at stations on Cenozoic deposits. The second set is then inverted to yield the thickness of the Cenozoic deposits. The inversion is based on an assumed contrast in density between the Cenozoic deposits and the basement rocks they overlie. In practice, the method is somewhat more complicated for two main reasons--1) gravity measured at a site on basement will be influenced by the gravity anomaly caused by low density deposits in adjacent basins--the closer the basin, the greater the effect, and 2) the gravity field over the basement varies from place to place due to variations of density within the basement. These two effects make it difficult to isolate the gravity anomalies caused by the cover deposits.

The method we have used to overcome these difficulties is illustrated in figure 3 (for convenience, figure 3 shows the method in two dimensions, but all actual calculations were carried out in three dimensions). First, a smooth surface is interpolated through all gravity values obtained at sites on basement (shown by solid dots on figure 3b), yielding the curve labeled "Iteration 1" in the upper panel of figure 3b. This surface is the first approximation to the "Basement Gravity" field (fig. 3a), i.e. the field that would be measured if we could somehow replace all the low-density basin fill with rock having the density of the surrounding basement. The numerical difference between the observed gravity (lower solid curve of figure 3b) and "Iteration 1" is the first approximation to that part of the gravity field caused by the Cenozoic deposits alone ("Basin Gravity" curve of figure 3a).

The first approximation of the basin gravity is then used to calculate the first estimate of the depth to basement (i.e. the thickness of Cenozoic deposits) throughout the state (dashed curve in the lower panel of figure 3b). This estimate is made following the method of Bott (1960) by determining at each intersection of a regular 2- by 2-km grid the thickness of low density deposits needed to account for the gravity value at the corresponding grid intersection. For computational ease, the estimate at each grid intersection is made assuming that deposits of this thickness and density extend to infinity in all lateral directions, an extreme simplification but one which does not adversely affect the process. The thickness is forced to be zero at each grid intersection where the geologic map shows basement at the surface. At those grid intersections where Cenozoic deposits are found, two different density/depth functions are used depending on whether the exposed deposits are volcanic or sedimentary (figure 4). The two different density/depth functions used in this process are assumed to be applicable statewide and are based on data presented in the next section.

Once the approximate depth to basement has been specified everywhere, the gravity effect of the approximate distribution of Cenozoic deposits is calculated following the method of Parker (1972) as programmed by R. W. Simpson (written comm., 1988). In particular, the gravity effect of the young deposits is determined at each of the basement gravity observation sites used in the first step of this procedure and these calculated values are used to correct the basement observations for the effect of nearby Cenozoic deposits. The basement observations so corrected are not completely free of the actual effects of Cenozoic deposits because the original "basement" gravity field is only a first approximation to the actual "basement" gravity field. This first approximation is probably too low over the basins (see figure 3b) due to the proximity of the basement observation sites to the thick, low density deposits, thus causing the first estimates of the anomaly from the Cenozoic deposits (and their inferred thickness) to be too small. Note that the corrected basement gravity observations are closer to being free of the effects of nearby Cenozoic deposits than the uncorrected ones and should therefore yield a better approximation to the "basement" gravity field in the next step.

Following this reasoning, a smooth surface is interpolated through the corrected basement gravity observations to produce a second approximation to the "basement" gravity field which then leads to improved estimates of the "basin" gravity, the depth to basement, and a new correction to the basement gravity observations. The whole procedure is repeated until successive iterations produce no substantial changes in the "basement" gravity field, usually between 6 and 10 iterations.

A commercially available routine from Dynamic Graphics, Inc., and based on the principle of a minimum curvature (Briggs, 1974) was used to interpolate basement gravity values at the grid intersections from the irregularly distributed gravity observations taken on basement outcrop. Simple application of this routine worked well in areas where gravity observations were relatively closely spaced (at least every 10 km) but the routine showed evidence of unstable behavior in areas where outcrops were more widely spaced. To overcome this difficulty, the following procedure was adopted. Initially, basement gravity values were determined at the intersections of a coarse grid 40 km on a side. The locations of the intersections were then tested for proximity to actual basement gravity observations and for any that were located more than 20 km from an observation location, the interpolated grid value was designated a "synthetic" basement gravity observation. The basement gravity data augmented by the "synthetic" observations then served as the basis for interpolating gravity values at the intersections of a new grid 20 km on a side. This procedure was repeated for progressively finer grids until a final grid of the desired spacing was obtained.

The interpolation procedure described above appears to have worked well in all parts of Nevada except in the northwest corner. There a large area is not only lacking in outcrops of basement rock within the state but also is lacking such outcrops in adjacent Oregon and California. A constant basement gravity value for that region was specified for all iterations based on the value of gravity over basement outcrops located along the southeastern margin of the area.

Density Data

The success of the separation procedure described above is critically dependent on accurate knowledge of the density of the Cenozoic deposits and of the basement. Density information about the Cenozoic deposits came mainly from borehole gravity meter studies and borehole density logs from deep holes in central Nevada (Healey, 1968; 1970; Ponce and Hanna, 1982; Healey and others, 1984), and from similar data from boreholes in other parts of the Basin and Range (Oppenheimer, 1980; Tucci and others, 1983) supplemented by densities inferred from seismic wave velocities (Zbur, 1963; Okaya and Thompson, 1985). Densities of Cenozoic volcanic rocks also were determined from measurements of hand-samples (Healey, 1970; Ponce, 1981; Snyder, 1983; Snyder and Healey, 1983; Snyder and Carr, 1984; Okaya and Thompson, 1985). Density data on the basement rocks were limited, scattered, and, in our opinion, not adequate to define a reliable representative density so, for the purposes of this work, the basement was assumed to have a representative density of 2.67 g/cm^3--the density used for the Bouguer and isostatic reductions. Locally, this density undoubtedly is incorrect, but tests of results based on this assumption discussed in the following section suggest that, state-wide, this is a reasonable average density for the basement.

The subsurface density data show that densities of the Cenozoic deposits generally increase with increasing depth. To accomodate this fact in the separation procedure, a layered density model was assummed for all Cenozoic deposits (figure 4). In the calculations, a density/depth model was assigned to each grid intersection, with different models assigned based on the type of deposit exposed at the surface--sedimentary or volcanic. The layered model for Cenozoic sedimentary deposits at the surface (left side of figure 4) is based on a composite of the subsurface density data. In this model, all deposits deeper than 1.2 km are assumed to have a constant density, an assumption that undoubtedly is in error. However, subsurface density data are too limited for the region below 1.2 km to warrant a more precise definition of the density structure statewide, and, furthermore, our primary interest is in the region above a depth of 1.0 km so that precise knowledge of the deeper density structure is not crucial. Subsurface density data from areas where Cenozoic volcanic rocks are exposed are too limited to define a density/depth model but measurements of 471 samples of Cenozoic rocks (average density 2.25 g/cm^3) indicate that, at least in the shallow subsurface, any such model should be denser than its sedimentary counterpart. Based on these sample measurements and other considerations such as possible biases in the sampling and fractures that tend to close with increasing depth of burial, we selected a density/depth model for volcanic deposits that has a higher density in the upper 600 m compared to the model for sedimentary deposits (right side of figure 3). This model is most appropriate for volcanic rocks that are felsic in composition but is less so for volcanic rocks of andesitic to basaltic composition that may have densities approaching those of the basement rocks.

RESULTS AND LIMITATIONS

The primary products of the separation procedure described above are shown on sheets 1 and 2. The basement gravity (sheet 1) is shown at a contour interval of 5 mGal. On sheet 2 contours of the thickness of Cenozoic deposits corresponding to 0.5 km and 1.0 km are labeled and the remaining unlabeled contours are presented to show the geometric form of the deposits rather than actual thicknesses. The unlabeled contours correspond to depth intervals of 1 km for a constant density contrast of -0.25 g/cm^3. This presentation can be viewed as the gravity equivalent of a seismic reflection time section which shows the geometry of the reflectors but not calibrated depths. Also on this sheet, the basement geology (equivalent to the "zero" contour) from Stewart and Carlson (1978) is screened.

The separation procedure appears to have been successful although testing the veracity of the basement gravity map against other data is more difficult than establishing the uncertainties associated with the cover thickness map. For the basement gravity map, comparison of sheet 1 with the original residual gravity map (figure 2) shows that the major long-wavelength features are present on both and that the procedure has not generated new anomalies on the basement gravity map that cannot be found by close inspection of figure 2. What has been accomplished is that the pervasive short-wavelength grain of figure 2 is absent from sheet 1.

To test the accuracy of the thickness map, the predicted values of cover thickness were compared to values of depth to basement contained in logs of wells drilled through Cenozoic deposits. Oil well data are from Garside and others (1988) and water well data are from U.S. Geological Survey internal files. The results of this comparison for 225 wells are shown as a histogram in figure 5. Only wells that were interpreted by the drillers to have penetrated basement in the top 1.2 km and have sufficient gravity coverage to constrain the calculation (generally gravity stations within 2-3 km of the well site) are shown. For this set of wells, observed and predicted depths to basement agreed to better than ±200 m in about 70% of the cases and to better than ±300 m in about 85% of the cases. Agreement was much poorer for wells that penetrated basement deeper than 1.2 km, most likely because of the unrealistic model density distribution below this depth.

Although the results of the comparisons discussed above suggest that the basement gravity and cover thickness information portrayed on sheets 1 and 2 is reasonably reliable, the method that was used to generate this information has certain unavoidable limitations that must be understood by anyone attempting to use the results. The sources of these limitations and a brief discussion of their effects are given below.

a) Gravity Station Distribution

Gravity data are distributed unevenly over Nevada and, as a result, the reliability of the predicted cover thickness, and to a lesser extent the basement gravity, varies from place to place. Ideally, for maps at the scale of sheets 1 and 2, gravity data points are needed every 2-3 km in the covered areas and at somewhat wider spacing over the areas of basement outcrop. These conditions are met in some areas (figure 1) but are not satisfied in others. For specific areas of interest, the user is advised to check the gravity station plot at 1:750,000 given by Saltus (1988b) to determine local coverage.

b) Computational Grid Spacing

All computations were performed with a grid of 2 km spacing. Thus, even in areas where the gravity data are spaced closer than 2 km, features with characteristic dimensions less than a few grid dimensions (i.e. about 6 km) are not faithfully portrayed. One effect of the finite grid spacing is that steep slopes, such as the sides of valleys bounded by near-vertical faults, appear more gentle on the cover thickness map. Also, outcrops of basement narrower than 2 km may appear to lie in areas of substantial cover thickness if the outcrop happens to fall between grid intersections.

c) Density/Depth Model

The general agreement between the predicted thickness of Cenozoic deposits and the depth to basement determined by drilling indicates that the density/depth model used in the computations is reasonably accurate statewide in the depth range between 0 and 1.2 km. This is particularly true for areas with sedimentary deposits at the surface, but less so for areas with exposed Cenozoic volcanic rocks because both the density information and the well control are poorer there. Locally, these models may be in error because the subsurface density data are not adequate to permit specifying unique density/depth models for individual basins or parts of basins. Uncertainties in the local density/depth model should primarily affect the predicted cover thickness, but the basement gravity map should be relatively insensitive to them.

d) Scale of Concealed Anomaly Sources

The primary function of the separation procedure is to partition the gravity field into a component reflecting density variations within the basement and a component indicative of the thickness of cover deposits. The method used appears to be effective for basement gravity anomalies with characteristic dimensions greater than the separation between basement outcrops. However, the procedure breaks down for those cases where the gravity anomaly from a basement source is completely contained within an area where the basement is covered (e.g. the anomaly from a small, low-density intrusion contained within the basement and concealed beneath a broad alluvial plain). In such cases, the "basement" anomaly will be falsely interpreted to reflect a change in thickness of the Cenozoic cover. The northwest corner of Nevada is particularly susceptible to problems of this kind because there over 6000 km^2 are covered by Cenozoic deposits with no basement exposures in the area. Only with significantly improved well control or other information on the depth to basement could these problems be avoided.

e) High-Density Volcanic Deposits

The separation procedure is dependent on the contrast in density between the basement rocks and the overlying Cenozoic deposits. Most of Cenozoic deposits are significantly lower in density than the underlying basement, but a few rock types may be quite dense. Mafic volcanic rocks such as basalts or basaltic andesites may have densities approaching those of the basement rocks, and the estimates of thickness for them will be too small. Fortunately, Cenozoic mafic volcanic rocks are not volumetrically important in most areas of Nevada.

f) Detached Basement Blocks

Large slide-blocks of basement rock completely engulfed by younger materials occur in some places in Nevada, especially near large calderas. If these blocks are not recognized as slide-blocks and are treated as outcrops of in-place basement, both the basement gravity map and the predicted Cenozoic cover thickness will be in error. In general, the basement gravity will be too low and the estimate of cover thickness will be too small.

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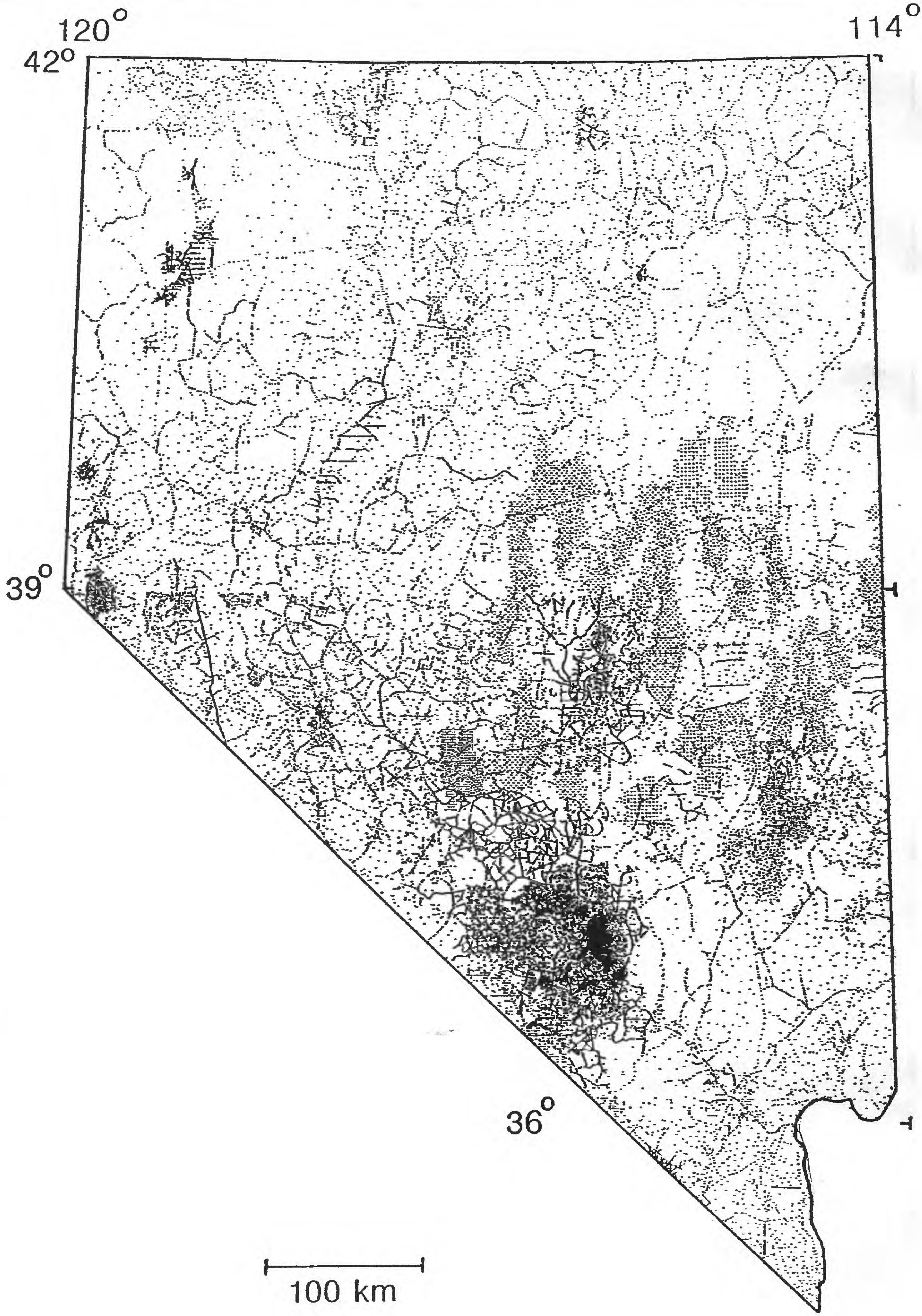

Figure 1)--Map showing distribution of gravity observations in Nevada.

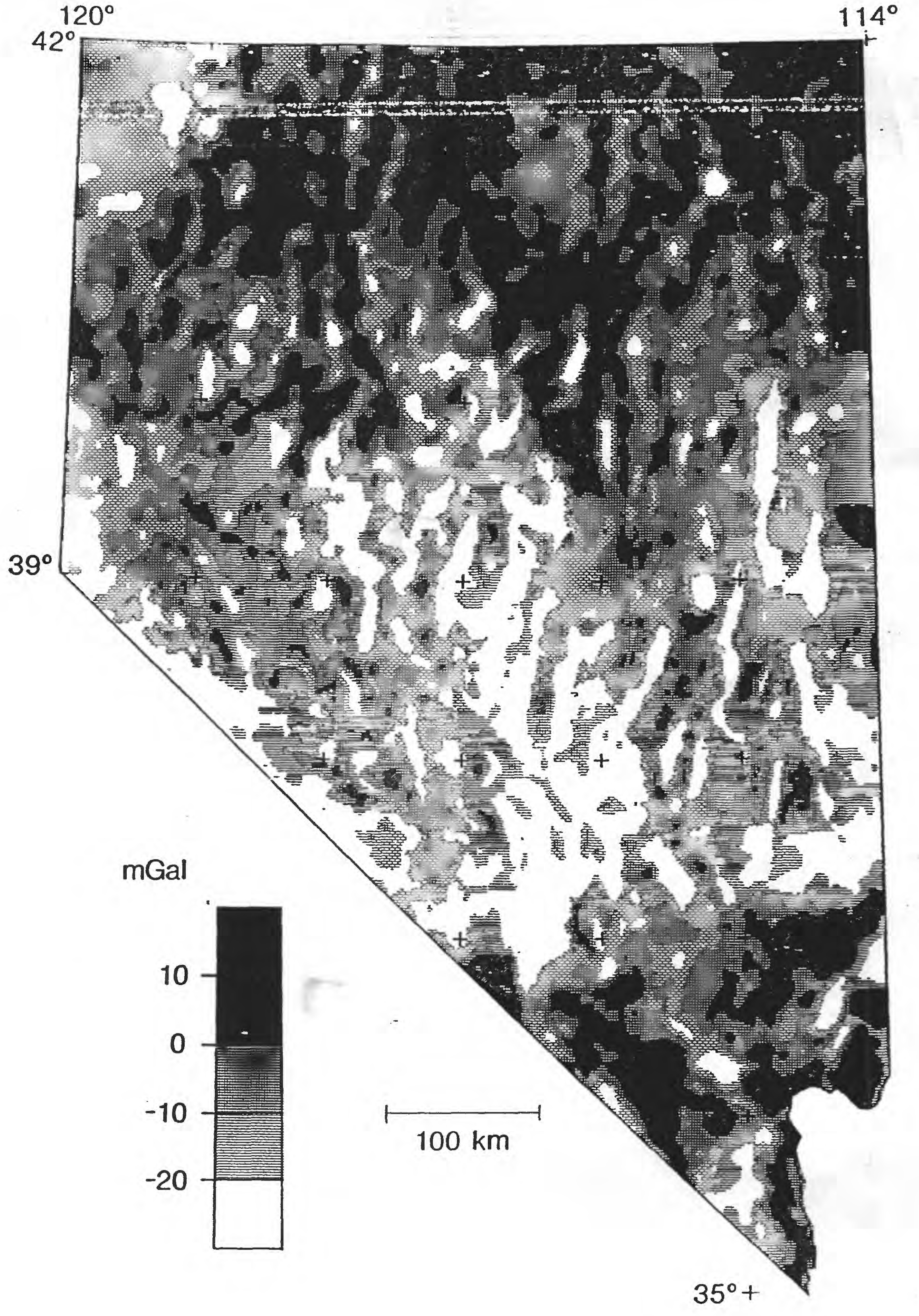

Figure 2)--Isostatic residual gravity map of Nevada from Saltus (1988c). Isostatic correction based on an Airy-Heiskanen model for isostatic compensation of topography. Model parameters: crustal thickness at sea level 25 km; density of topography 2.67 g/cm^3; density contrast across the base of the model crust 0.4 g/cm^3. Contour interval 10 mGal.

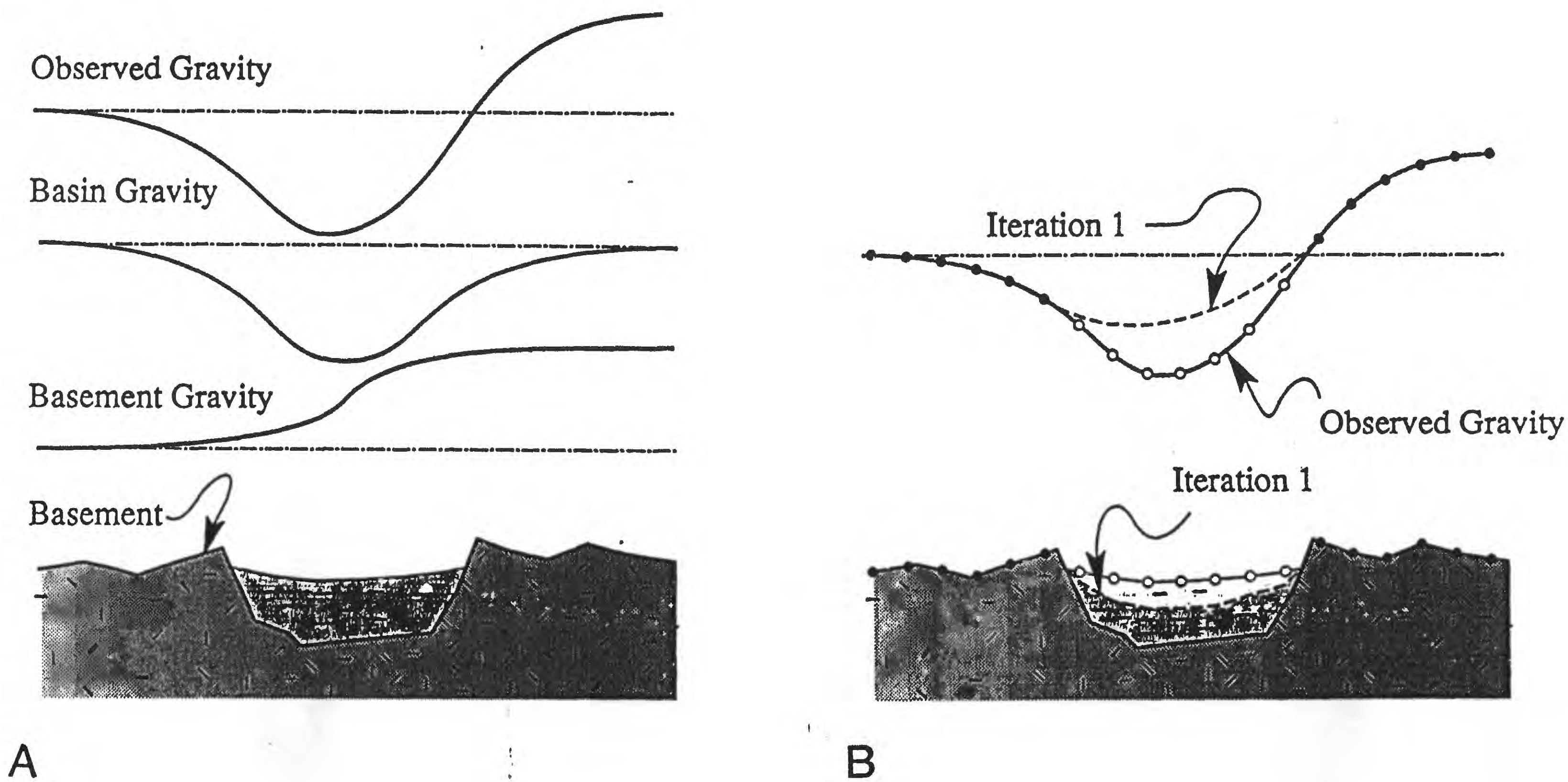

Figure 3)--Schematic representation of gravity separation procedure.

DEPTH BELOW SURFACE (m)	DEPOSIT TYPE VOLCANIC	SEDIMENTARY
0		
	2.22 g/cm^3	2.02 g/cm^3
200		
	2.27	2.12
600		
	2.32	2.32
1200		
	2.42	2.42

Figure 4)--Layered density models used to invert the "basin gravity" component.

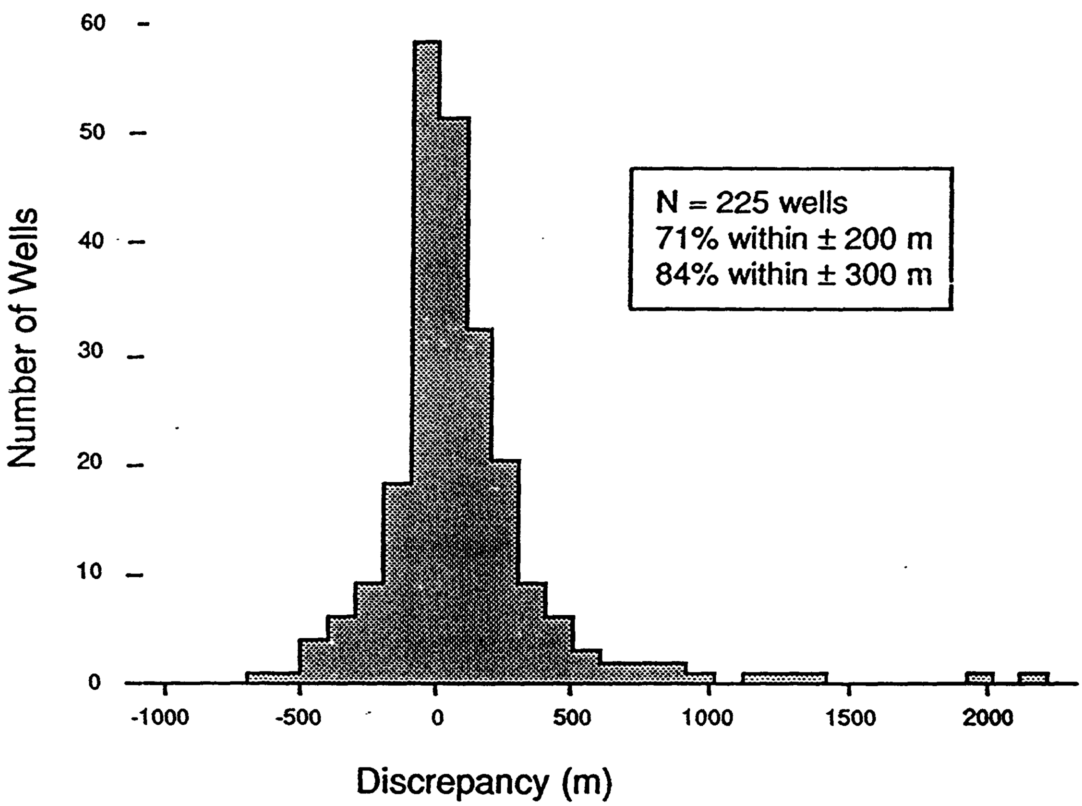

Figure 5)--Comparison of measured depth of basement from drill holes to inferred depth to basement based on gravity data, for wells that penetrated basement before exceeding 1200 m in depth. (predicted - measured)