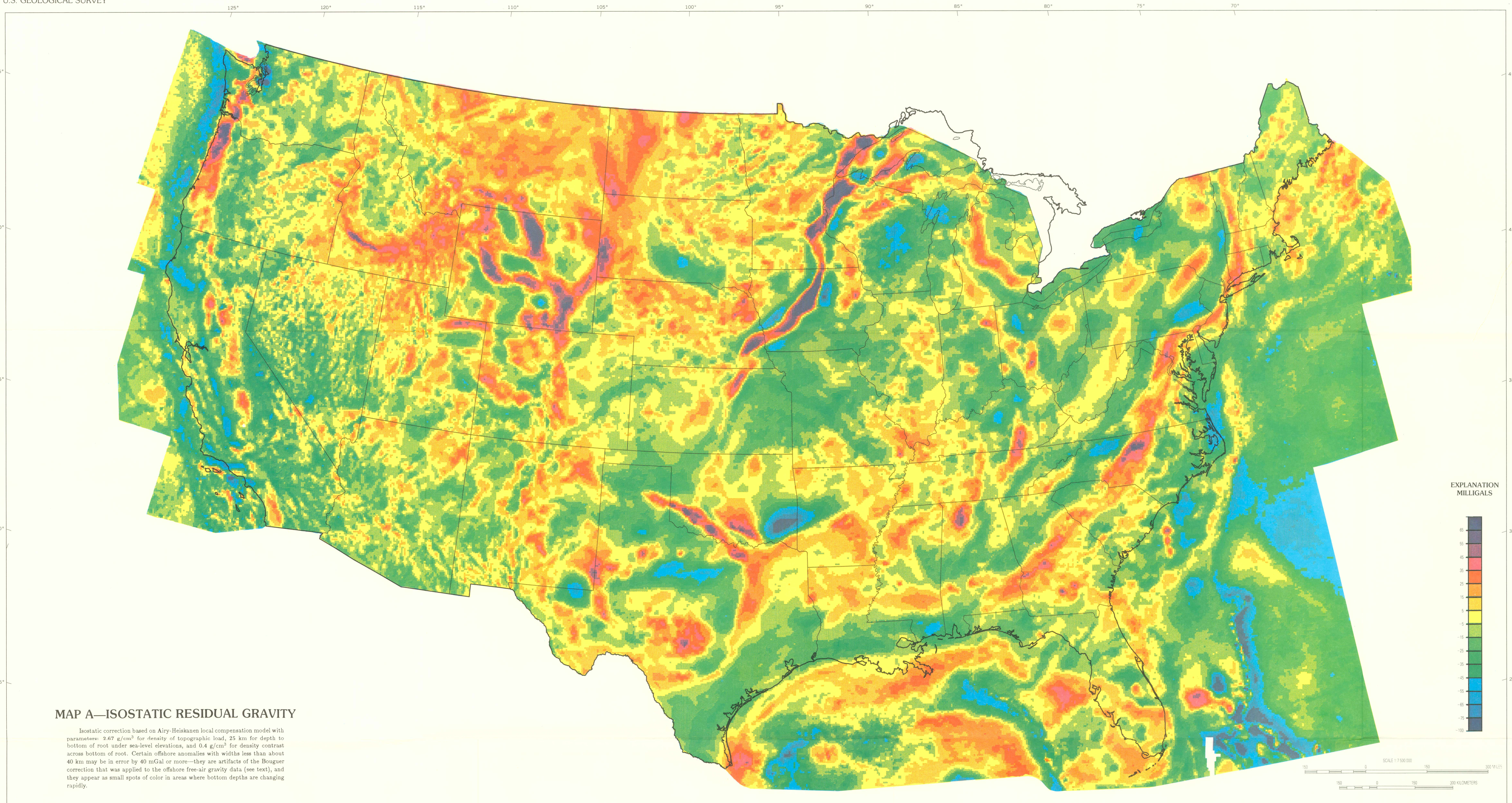
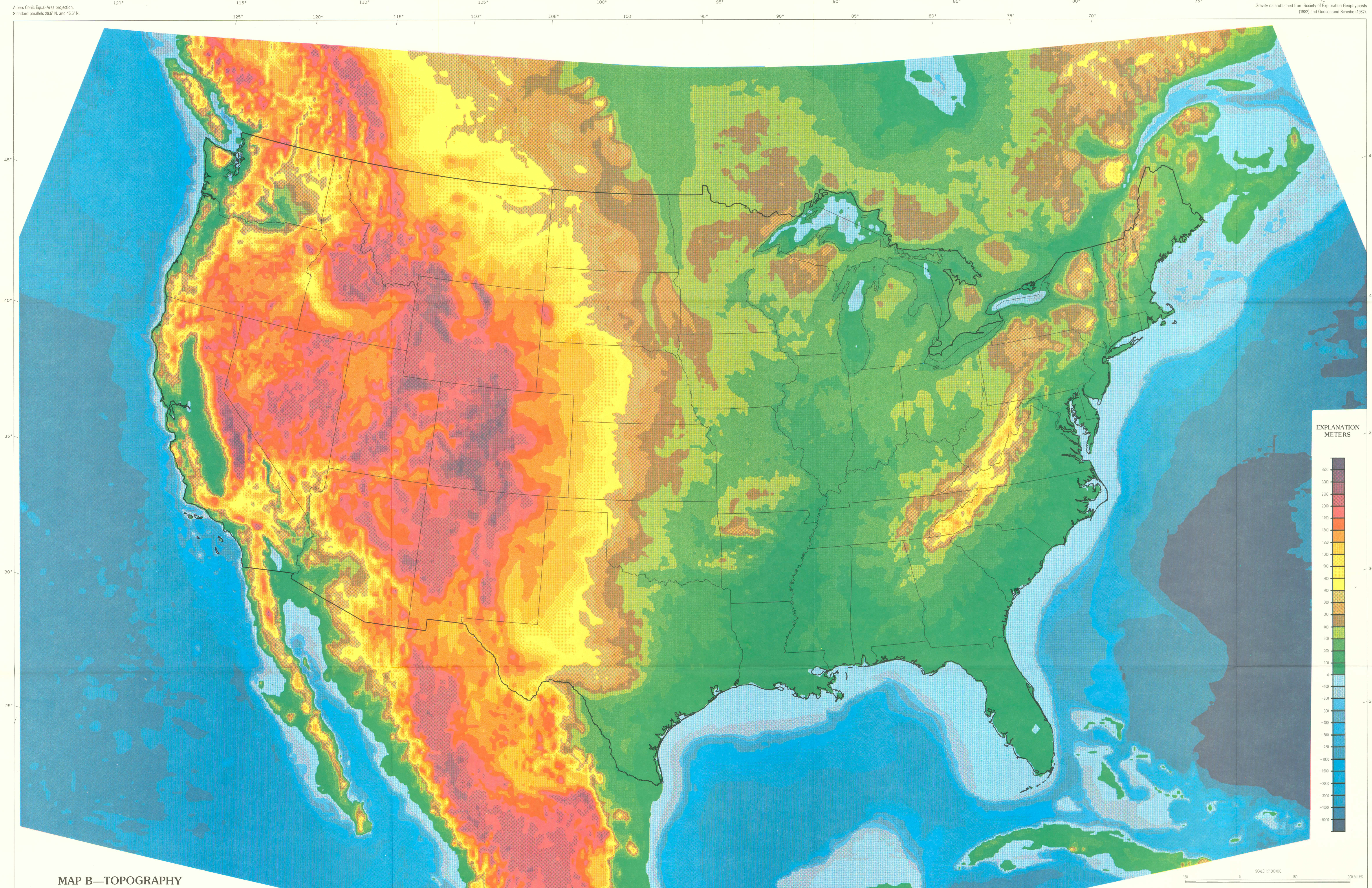


MAP A—ISOSTATIC RESIDUAL GRAVITY

Isostatic correction based on Airy-Heiskanen local compensation model with parameters: 2.67 g/cm³ for density of topographic load, 25 km for depth to bottom of root under sea-level elevations, and 0.4 g/cm³ for density contrast across bottom of root. Certain offshore anomalies with widths less than about 40 km may be in error by 40 mGal or more—they are artifacts of the Bouguer correction that was applied to the offshore free-air gravity data (see text), and they appear as small spots of color in areas where bottom depths change rapidly.

Albers Conic Equal-Area projection. Standard parallels 29.5° N. and 45.5° N.

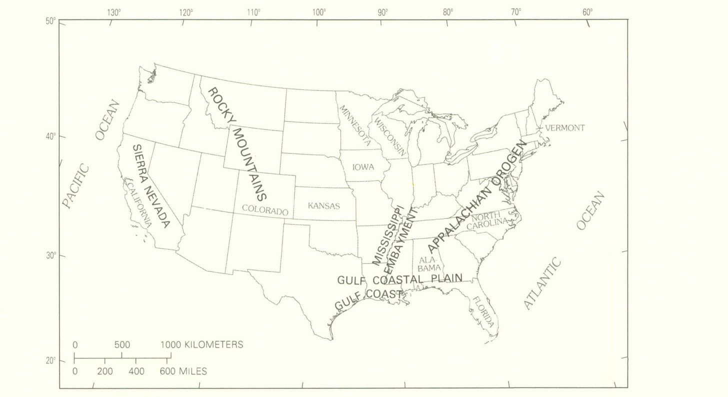
Gravity data obtained from Society of Exploration Geophysicists (1982) and Godson and Scheibe (1982)



MAP B—TOPOGRAPHY

Albers Conic Equal-Area projection. Standard parallels 29.5° N. and 45.5° N.

Compiled from 5-minute topographic and bathymetric data from National Oceanic and Atmospheric Administration (NOAA) Data Center



INDEX MAP OF UNITED STATES SHOWING GEOGRAPHIC LOCALITIES REFERENCED IN TEXT

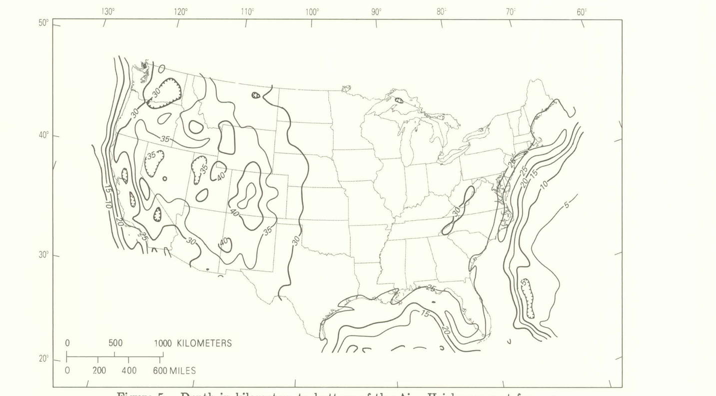


Figure 5.—Depth in kilometers to bottom of the Airy-Heiskanen root for $\rho_t = 2.67$ g/cm³, $\Delta\rho = 0.4$ g/cm³, and $d_s = 25$ km. Contour interval is 5 km. Map has been smoothed by low-pass wavelength filtering with a cutoff at 200 km in the Fourier transform domain. Hachures on closed contours point toward small depth values.

SUMMARY

Two isostatic residual gravity maps of the conterminous United States have been prepared to better display gravity anomalies caused by bodies of geologic interest in the upper portions of the crust and to illustrate the insensitivity of isostatic residual maps to the choice of model parameters. The maps are based on Airy-Heiskanen local compensation models with reasonable parameters selected for the State of California (map A) and the Eastern United States (map C). Gravity data were taken from the grid used to prepare the Gravity Anomaly Map of the United States (Society of Exploration Geophysicists, 1982). The surface load requiring compensation was defined by topographic and bathymetric data averaged over 5- by 5-minute compartments (map B). A first-vertical-derivative map (map D) of the isostatic residual gravity further enhances the short-wavelength anomalies produced by bodies at or near the surface and emphasizes regional fabrics and trends in the gravity field.

INTRODUCTION

Hayford and Bowie published the first isostatic gravity anomaly map of the United States in color in 1912. This first map, showing "lines of equal anomaly for [the] new method of reduction," was based on 89 pendulum gravity observations collected at various sites around the country. Remarkably, the 89 observations sampled nearly every major anomaly in the isostatic gravity field of the conterminous United States.

Subsequent isostatic maps (table 1) have considerably refined the shapes of anomalies, and digital computers have eased the enormous task of calculation, but our understanding of the significance of isostatic anomalies has not changed greatly since the pioneering efforts of Hayford and Bowie. Their early work was ably summarized by Daly (1940), who offered an insightful critique into the problems of isostatic corrections and argued for the importance of integrating additional geologic and geophysical information into isostatic models.

Table 1.—*Isostatic gravity maps of the United States*

Observations	Scale	Reference
89	1 : 7,000,000	Hayford and Bowie (1912)
124	1 : 7,000,000	Bowie (1912), Gilbert (1913)
219	1 : 7,000,000	Bowie (1917)
296	1 : 22,000,000	Bowie (1924)
~ 1,000	1 : 14,600,000	Woollard (1936)
~ 200,000	1 : 14,200,000	Woollard (1966)
80,000	1 : 41,300,000	Lewis and Dorman (1970)
unknown	1 : 20,300,000	McNutt (1980)
1,800,000	1 : 2,500,000	Jachens and others (1985)
1,800,000	1 : 7,500,000	This report

[illegible]

REASONS FOR MAKING ISOSTATIC GRAVITY MAPS

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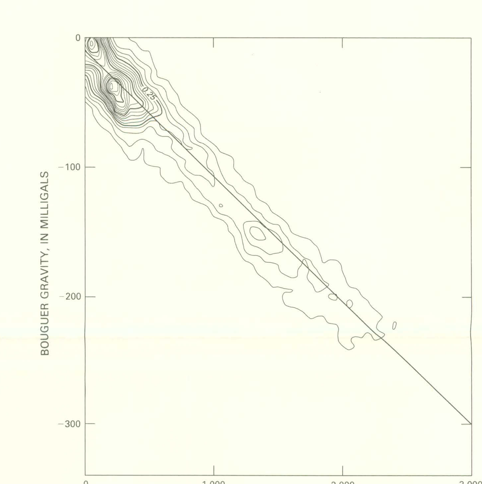

Figure 1.—Inverse correlation of on-land Bouguer gravity anomaly values with elevation for the conterminous United States. The Bouguer gravity and topography grids described in the text were sampled at 20-km intervals to obtain the values for this two-dimensional histogram. The number of grid points falling into 5-mGal tall by 50-m wide cells was counted, this number was normalized to the largest number in any one cell, and the results were contoured at 0.05 interval after a small amount of smoothing. The closed high at about 250 m, which falls slightly below the main trend, is caused by broad areas of low Bouguer value in the midcontinent, which can also be seen on the isostatic residual map (map A). A regression line, $y' = a + bx$, is shown, for which $a = -11.5$ and $b = -0.0942$. Standard error of estimate is 24.0, and correlation coefficient is −0.942.

The principle of isostasy offers an explanation for this inverse correlation: loads at the Earth's surface in the form of topographic features are supported at depth by deficiencies in mass as if the Earth's crust were floating on a denser substratum (Dutton, 1889; Daly, 1940; Woollard, 1966; Heiskanen and Moritz, 1967). These deficiencies in mass under topographic loads are often called *compensating masses* or *roots*. Because the Bouguer reduction process removes the gravitational attraction of topographic masses (usually out to a radius of 166.7 km), the compensating masses—which have not been accounted for in the Bouguer reduction—will appear as Bouguer gravity anomaly lows over mountainous areas. Analogous Bouguer gravity highs appear over oceanic areas, because the Bouguer reduction corrects for the deficiency of mass near the Earth's surface caused by the presence of water, yet this deficiency is compensated at depth by a mass excess or antiroot.

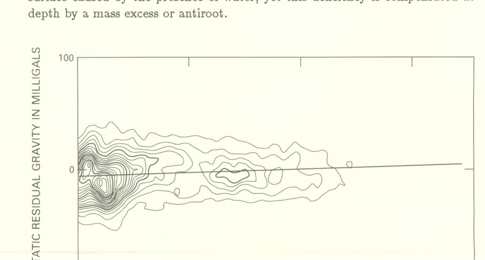

Figure 2.—Relation between isostatic residual gravity values and elevations for the conterminous United States shown as a two-dimensional histogram. Constructed as in figure 1. A regression line, $y' = a + bx$, is shown, for which $a = -6.7$ and $b = 0.0039$. Standard error of estimate is 18.5, and correlation coefficient is 0.148.

While the Bouguer correction attempts to remove the attractions of topography onshore and bathymetric variations offshore, the isostatic correction goes one step farther and attempts to remove the attractions of the compensating masses. Figure 2 shows the lack of correspondence between gravity anomalies and topographic elevations after an isostatic correction has been applied. In the process of removing the strong inverse correlation with regional topography, Bouguer gravity values spanning a range of more than 300 milligals (mGal) have been reduced to isostatic residual gravity values spanning 100 mGal (fig. 3).

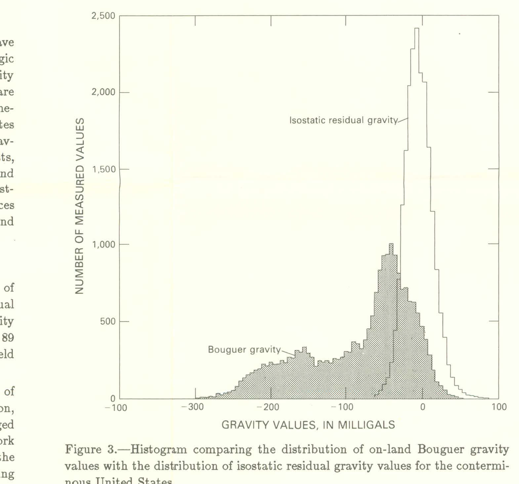

Figure 3.—Histogram comparing the distribution of on-land Bouguer gravity values with the distribution of isostatic residual gravity values for the conterminous United States.

Most isostatic corrections are based on simple models for the geometry of the compensating masses, and such models are of necessity highly idealized representations of the real-world geometries. Nonetheless, for the enhancement of those gravity anomalies related to mapped and near-surface geologic features, the application of an isostatic correction of some sort is of greater importance than the exact details of the model used. In the discussion that follows, *isostatic regional* refers to the gravity field produced by the attractions of the compensating masses. *Isostatic residual* refers to the gravity anomalies that remain after the isostatic regional field has been subtracted from the Bouguer gravity anomaly field—that is, after the isostatic correction has been applied.

THE UTILITY OF ISOSTATIC RESIDUAL ANOMALIES

One isostatic residual anomaly associated with a first-order geologic feature is the remarkable linear gravity high extending along the length of the Appalachian orogen from central Vermont in the north to southeast Alabama, a distance of more than 1,500 km. Although the specific source of this anomaly is not well established (Hutchinson and others, 1983), it undoubtedly reflects some fundamental aspect of the evolution of the orogen. The Appalachians disappear beneath Gulf Coastal Plain sediments in Alabama, but it appears that this anomaly continues with progressively reduced amplitude as far as the Gulf Coast near the west edge of Florida. Thus, the gravity data suggest that the Appalachian system may continue on a southwesterly trend beneath the Gulf Coastal Plain for a distance of about 250 km. The isostatic residual gravity map allows this important anomaly to be compared along its entire length with all topographic-related influences removed at least to first order.

A second example showing the utility of isostatic residual gravity maps is found in the apparent change of base level that exists across the southern part of the midcontinent gravity high (MGH). The MGH is the prominent linear high that extends from Minnesota and Wisconsin in the north to Iowa and Kansas in the south. This high is attributed to mafic igneous rocks emplaced in a Precambrian rifting event (Craddock and others, 1963; King and Zietz, 1971; Ocola and Meyer, 1973; Green, 1983). Gravity values over a large region to the west of the MGH average 20-30 mGal higher than those over regions to the east. The step between these base levels coincides with the MGH in the south, but diverges to the east of the MGH in its northern part. The width of the step, though obscured by the presence of the MGH along part of its length, appears to be sufficiently narrow that the causative density contrast are, at least in part, likely to be shallower than 50 km. The coincidence of the gravity step with a first-order geologic feature is probably not entirely fortuitous. Because rifting frequently occurs along or near old sutures, which apparently persist as zones of weakness in the crust, we speculate that the MGH may mark a rift that started to open along an old suture between two Precambrian terranes that had been rafted together at an earlier time. In any case, the gravity step which requires explanation is not so obvious on Bouguer maps because the large range of Bouguer values makes it more difficult to display lower amplitude features, and because a broad gravity gradient caused by the compensating masses under the Rocky Mountains extends eastward from the Rockies almost to the MGH, obscuring the regional extent of the changes in gravity base level.

The usefulness of isostatic maps becomes most apparent in mountainous terranes, such as most of the Western United States, where large regional gradients caused by the compensating masses distort or completely obscure the smaller anomalies caused by near surface features. Examples of the interpretation of such anomalies aided by the isostatic correction are given in Jachens and Griscom (1982, 1983).

INSENSITIVITY OF RESIDUAL TO CHOICE OF MODEL

A variety of isostatic models have been tried over the years, including statistical approaches which infer the best isostatic response function from the data themselves (Neidell, 1963; Dorman and Lewis, 1970; McNutt, 1980). No single model or response function is likely to be appropriate for an entire continental area, given the typical diversity of tectonic environments found on most continents. Yet, almost all reasonable isostatic models will yield very similar appearing isostatic residual maps. The reason is that the total mass of compensating materials for all models will be very nearly the same, and the compensating masses are usually sufficiently deep that their gravitational effects observed at the Earth's surface are smoothed by distance. Thus, the differences in the isostatic corrections caused by variations in the geometry of the compensating masses will tend to be a small percent of the total correction (Jachens and Griscom, 1982; Saltus, 1984).

To make the same point more mathematically, for most isostatic models the isostatic correction, to first approximation, is equivalent to spreading the compensating masses on a sheet at some depth d. The isostatic regional field produced by this mass distribution is proportional to the field obtained by the upward continuation of the topography to a height d as if it were a potential field. (See McNutt (1980) for the equation for *linear Airy* compensation.) Other approaches such as the Faye anomaly (Putnam, 1894, 1895; Mabey, 1966), the Graaff-Hunter reduction (Graaff-Hunter, 1958), and the residual Bouguer correction method (Aiken, 1976; Aiken and others, 1981), which all correct for isostasy induced anomalies by using averaged topography rather than an isostatic model, will produce very similar results because these methods also suppress short wavelengths in the topography as does the upward continuation filter. Distributing the compensating masses (Vening Meinesz, 1939; McNutt, 1980) rather than having them entirely local (that is, directly under the load) also has a smoothing effect similar to additional upward continuation of the topography. These considerations explain why it is so difficult to determine the actual isostatic mechanism operating in the Earth from the gravity evidence alone, and why all of the various reasonable isostatic models give results that are so similar to first order.

It would be highly desirable to be able to incorporate additional geophysical data into the construction of an isostatic model, but it does not appear to us that either the quality or quantity of such data is yet adequate to warrant such an application on a continent-wide scale. The flexibility of digital data sets will undoubtedly encourage such integrations in areas where good geophysical information, such as seismic velocities and depths to the Mohorovičić (M-) discontinuity, are available (Sprenke and Kanasewich, 1982; Gettings, 1984).

THE AIRY-HEISKANEN LOCAL COMPENSATION MODEL

To prepare the isostatic residual maps (maps A and C), we chose to use an Airy-Heiskanen model using local compensation (fig. 4). The calculation of an isostatic regional in the local Airy-Heiskanen model of compensation requires a choice of values for three parameters: the density ρ_t of the topographic load, the depth d_s of compensation for areas at sea-level elevation, and the density contrast $\Delta\rho$ across the bottom of the root. These parameters determine the depth d to the bottom of the root under land areas by the relation

$$d = d_s + e\,(\rho_t/\Delta\rho) \tag{1}$$

where e is the elevation of the topographic surface above sea level (e is negative for onland areas below sea level). For the Great Lakes region, the weight of the water in the lakes was added to the topographic load in the calculation of the root.

In the Airy-Heiskanen formalism, oceanic crustal columns with water depth d_w (taken to be positive here) have a negative load (weight deficiency) at the top caused by the presence of water of density ρ_w rather than rock (Heiskanen and Moritz, 1967). Negative compensation is provided by an antiroot of denser material that has its top at a depth given by

$$d = d_s - d_w(\rho_t - \rho_w)/(\Delta\rho). \tag{2}$$

The density of the crust above the bottom of the root is frequently assumed to be constant in presentations of the Airy-Heiskanen model, but no such restriction is required by the equations—the density of the model crust below sea level may change with depth provided only that the density contrast across the bottom of the root remains constant at all depths.

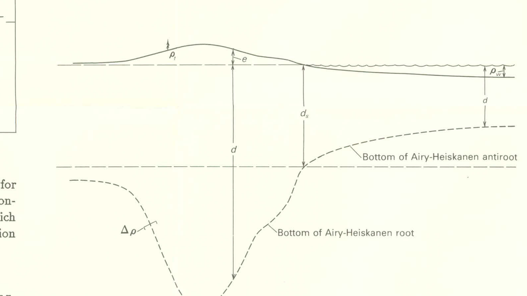

Figure 4.—Geometry of compensating masses in the Airy-Heiskanen local compensation model: e, elevation of topographic surface above sea level; d, depth to bottom of root; d_s, depth to bottom of root for sea-level elevation; ρ_t, density of topography; d_w, depth of water in ocean areas; ρ_w, density of water; $\Delta\rho$, density contrast at depth across bottom of root.

For map A, the density of the surface load was 2.67 g/cm³, the depth to the bottom of the root for sea-level elevations was 25 km, and the density contrast at the bottom of the root was 0.4 g/cm³. These three parameters completely specify the geometry of the compensation model (fig. 5). These parameters were originally chosen for the preparation of an isostatic residual map of California (Roberts and others, 1981). They result in root depths along the coast and under the Sierra Nevada which agree reasonably well with seismic refraction determinations of depth to the M-discontinuity. The M-discontinuity is probably an appropriate depth for the bottom of the Airy-Heiskanen root because it is likely to be a major density discontinuity within the lithosphere.

To prepare the second isostatic residual map (map C), we used as parameters a surface load density of 2.67 g/cm³, a depth to the bottom of the root of 31.7 km for sea-level elevations, and a density contrast at depth of 0.385 g/cm³. The density differential of 0.385 g/cm³ was suggested by Woollard (1966, p. 562) and the root depth at sea-level of 31.7 km was obtained from the relation $M = -(31.7 + 7.5h)$, between depth M to the M-discontinuity and surface elevation h in km, that best fit the seismic refraction data for the United States for areas with isostatic anomalies less than 10 mGal (Woollard, 1968, p. 313). This choice of Airy-Heiskanen parameters, however, implies a constant of 6.94 rather than 7.5 in the above seismic relation. The reason for the discrepancy is that Woollard assumed a topographic load density of about 2.89 g/cm³ (closer to an average crustal density) and the value of 7.5 in order to arrive at the density contrast at depth of 0.385 g/cm³. Given the uncertainties in all of the values, we decided to let the result stand although it had originally been our intention to match the Airy-Heiskanen root (equation 1) to Woollard's M versus h relation. We have in subsequent maps (e.g., Jachens and others, 1985) used parameters of 2.67 g/cm³, 30 km, and 0.35 g/cm³ which imply a constant of 7.6 that is closer to the value of 7.5 in the M versus h relation. As can be seen from table 2, only small differences result in the isostatic correction because of the insensitivity of the isostatic regional to changes in the parameters.

Table 2.—*Comparisons of various Airy-Heiskanen isostatic regionals out to 166.7 km*

d_s (km)	$\Delta\rho$ (g/cm³)	Maximum Difference (mGal)	Average Difference (mGal)	Standard Deviation (mGal)	Percent of Difference <10 mGal
30[1]	0.35[1]	(1)	(1)	(1)	(1)
25	0.2	−31.7	−0.7	1.3	99.9
25	0.3	−15.9	−2.1	1.7	99.9
25[2]	0.4	−15.8	−2.7	2.8	98.0
25	0.5	−22.2	−3.2	3.5	93.6
25	0.6	−26.7	−3.4	3.9	90.8
30[3]	0.6	−13.8	−1.0	1.7	99.8
31.7[4]	0.385	4.9	0.6	0.5	100.0
35	0.2	−29.7	4.1	4.5	86.3
35	0.3	15.4	2.7	2.8	98.0
35	0.4	10.4	2.1	1.8	99.9
35	0.5	13.1	1.7	1.2	99.9
35	0.6	14.7	1.4	0.9	99.9
45	0.2	47.6	8.6	5.6	68.9
45	0.3	35.0	7.3	5.3	71.1
45	0.4	28.2	6.7	5.3	72.7
45	0.5	24.0	6.3	5.2	74.2
45	0.6	23.3	6.0	4.9	75.5

[1] All comparisons are for onland areas relative to this regional.
[2] Map A, this report.
[3] Woollard (1966), Kärki and others (1961).
[4] Map C, this report.

The limitations of the Airy-Heiskanen model as an accurate description of the true density contrasts in the crust and upper mantle are quite apparent. Parameters for both maps A and C define roots that disagree rather seriously with M-discontinuity depths in certain parts of the country (compare fig. 5 with Allenby and Schnetzer, 1983). What makes the Airy-Heiskanen model a useful and usable model is its simplicity and the relative insensitivity of isostatic corrections to the exact geometries and depths of the compensating masses. Any isostatic model consistently applied will serve the primary goal of illuminating density contrasts of geologic importance. Future gravity modeling of these anomalies will ultimately require the incorporation of all available geologic and geophysical data and a reevaluation of the isostatic model.

DATA SETS USED

The preparation of an isostatic residual map requires two data sets: (1) Bouguer gravity values to define the gravity field and (2) topographic elevations to define the surface load and the geometry of the compensating masses in the chosen model.

1. Gravity data

The gravity values used came from the gridded data set described by Godson and Scheibe (1982), which was assembled to prepare the Gravity Anomaly Map of the United States (Society of Exploration Geophysicists, 1982). The distribution of the 1 million onshore gravity observations and 0.8 million offshore observations is shown as an inset map on the Gravity Anomaly Map of the United States (Society of Exploration Geophysicists, 1982). For onshore areas, approximately 95 percent of all 5- by 5-minute cells have at least one gravity observation available.

Onshore, the gridded data set contains Bouguer gravity values calculated using a reduction density of 2.67 g/cm³ and terrain corrected by computer for topography between 0.895 to 166.7 km from a given station. Offshore, the grid contains free-air gravity values. The coordinates of observation locations were projected before gridding with an Albers equal-area conic projection (Snyder, 1982) having its central meridian at 96° W. and standard parallels at 29.5° and 45.5° N. The grid interval is 4- by 4-km in the projected coordinate system. In the gridding process, data within a 40-km search radius of a grid point were averaged, after being weighted by distance from the grid point, to aid interpolation in areas of sparse data coverage (Godson and Scheibe, 1982).

For land areas, Bouguer gravity values are subject to errors caused by uncertainties in the elevation of the observation, in the calculated terrain correction, and in the gravity measurement itself which probably combine to an uncertainty that is less than 2 mGal for most observations. Additional error is introduced by ignoring the correction for terrain within 0.895 km of the site of observation (probably less than 1 mGal for most stations but tens of mGal for a few stations). Offshore, the free-air values are generally more accurate than 10-20 mGal.

The grid of Godson and Scheibe (1982) contains free-air gravity values offshore. We wished to continue the Airy-Heiskanen model offshore, so a Bouguer correction was applied to the offshore data by using the 5- by 5-minute bathymetric data set to determine water depths. Because of the averaging inherent in this bathymetric data set and because of the 40-km search radius used in the preparation of the Godson and Scheibe grid, the location mismatch between the site of the gravity observation and its Bouguer correction is potentially quite large. We estimate that in areas of extreme sea bottom relief, this mismatch could result in short wavelength errors as large as 40 mGal, that would appear as small spots of color at a scale of 1:7,500,000. No offshore anomalies with widths greater than about 40 km are likely to disappear if a better Bouguer correction were to be applied. For most oceanic areas, our Bouguer correction probably results in errors less than 10 mGal or one color interval. We think that the patterns in the offshore data are of sufficient interest to warrant keeping these data on the isostatic residual map—the user should, however, be aware of this Bouguer correction problem, especially for places where the bottom depth changes rapidly.

2. Topographic data

Bathymetric and topographic data sets (map B) were obtained from the National Oceanic and Atmospheric Administration (NOAA) Data Center (National Geophysical and Solar-Terrestrial Data Center, NOAA, Boulder, CO 80303). Offshore, the 5- by 5-minute Synthetic Bathymetric Profiling System (SYNBAPS) data were used (NOAA announcement 81-MGG-14). Onshore, the 5- by 5-minute North American data set was used (NOAA announcement 1980 SE-V). Details on the process of combining these data sets can be found in Simpson and others (1983b). The lake bottom elevations for the Great Lakes in the North American 5- by 5-minute data appear to be in error; apparently because of a problem with units. An adjustment was made to correct these lake bottom elevations.

The 5- by 5-minute data were projected using an Albers projection to match the coordinate system of the gravity data grid. In the projection process, the 5- by 5-minute unprojected data grid was converted by linear interpolations to an 8- by 8-km rectilinear projected grid.

CALCULATION OF THE ISOSTATIC REGIONAL

The geometry of the root that results for our first choice of parameters is shown in figure 5. Calculation at a point on the Earth's surface of the attraction of this root was done in two steps. The attraction on a flat Earth out to a distance of 166.7 km was computed using a program (Simpson and others, 1983a) based on the fast Fourier transform algorithm developed by Parker (1972). This result was combined with a published regional field for the attraction of both topography and root beyond 166.7 km (Kärki and others, 1961) to a distance of 180° on a spherical Earth. Although a mismatch exists between the model parameters for the published result of Kärki and others (sea level compensation depth = 30 km, density contrast = 0.6 g/cm³) and those used by us for the calculation of the root attraction inside 166.7 km (25 km and 0.4 g/cm³ for map A, 31.7 km and 0.385 g/cm³ for map C), simple calculations with flat geometries suggest that this mismatch causes long wavelength errors of less than 5 mGal for most of the onshore conterminous United States. (A mismatch of up to 10 mGal may occur in western Colorado where a broad area attains an average elevation of almost 3 km.) Offshore, the maximum mismatch for the deepest ocean areas on our maps remains about 5 mGal for map C, but could reach 18 mGal for map A.

The isostatic regional gravity field obtained by this procedure is the gravitational attraction of the root system that would be measured at sea level (fig. 6). Because most gravity stations are collected at elevations above sea level, the sea-level result must be upward continued to yield the proper isostatic correction at the observation elevation. The upward continuation adjustment is usually not very large given the depth to the bottom of the root and the consequent smoothness of the isostatic regional—even in areas of extreme topographic relief such as the Sierra Nevada of California, the adjustment seldom exceeds 5 mGal. Such an upward continuation has been applied to the isostatic regional and details of the correction method can be found in Simpson and others (1983a).

The final step in the production of the isostatic residual map is the subtraction of the isostatic regional field from the Bouguer gravity field. We expect that onland, with all errors combined, most (probably 95 percent) of the isostatic residual gravity values on maps A and C are accurate to better than 5 mGal or one-half of a color interval. In a few areas of extreme topographic relief, errors may reach 10 mGal. Offshore, residual values are probably more accurate than 10-20 mGal in most cases, although short-wavelength anomalies over areas of rapidly changing bottom depths could be in error by as much as 40 mGal as explained above in the data section.

Text continued on sheet 2 of 2.

ISOSTATIC RESIDUAL GRAVITY, TOPOGRAPHIC, AND FIRST-VERTICAL-DERIVATIVE GRAVITY MAPS OF THE CONTERMINOUS UNITED STATES

By
R.W. Simpson, R.C. Jachens, R.W. Saltus, and R.J. Blakely

1986