SUPERFICIAL VERSUS DEEP-SEATED DENSITY ANOMALIES IN THE NORTHERN GREAT PLAINS

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THE STATEMENT has often been made that the Pratt-Hayford isostatic gravitational anomalies are due largely to differences in the density of rocks in the extreme outer part of the crust, and in some places even in the thin mantle of sedimentary beds very near the observation stations. The abrupt changes in the value of adjacent anomalies is the chief line of supporting evidence. Certain large areas in the United States have long been known, however, which in spite of these secondary abrupt changes have consistently yielded positive or negative anomalies. For example, there is the large area in the northern part of the Great Plains extending from the Black Hills northward into Canada. The Ridge and Valley Belt of the Appalachian Mountains is another example, as are the western Wisconsin-eastern Minnesota area, and a part of southern California. The attempt has more than once been made to explain even these large groups of positive and negative anomalies by shallow unevennesses of density. Various writers, on the other hand, have maintained that some of the gravity anomalies may at least partly be explained by relatively deep as well as by shallow density anomalies.[1,2] In fact, when the Pratt-Hayford isostatic anomalies of the northern Great Plains are corrected for the unusual lightness of the Cretaceous and early Cenozoic sedimentary rocks near the stations—assuming that their average density is less than the customary arbitrary crustal value of 2.67—a positive anomaly larger than before is the result.

The recent appearance of a paper by A. H. Miller[3] has made it possible to trace the outlines of this large positive area in the northern Great Plains much more completely than before.[4] Now, eighteen isostatic anomalies are found to be grouped in this area in Canada, and seventeen in the United States. Figure 1 shows the contour lines in western North America drawn with an interval of .010 dynes from all the available Pratt-Hayford isostatic anomalies (depth of compensation in all cases is 113.7 kilometers—computation of γ_0 for the Canadian stations was made with the U. S. Coast and Geodetic Survey 1917 formula, and for the United States stations with the same organization's 1912 formula[5]). The contours were drawn free-hand, as mechanically as possible, without regard to the geologic structure of the region except in a very general way. For example, in one or two minor cases a north-south trend was given to contours con-

[1]MacMillan, W. D. "On the Hypothesis of Isostasy." Jour. Geol. Vol. 25, pp. 105-111, 1917.

[2]Barrell, Joseph. "The Strength of the Earth's Crust." Parts III, IV, and V, Jour. Geol. Vols. 22 and 23, 1914-15.

[3]Miller, A. H. "Gravity in Western Canada." Transactions of the Royal Society of Canada, Third Series, Volume XXI, Section IV, pp. 175-187, 1927.

[4]Melton, F. A. "Interpretation of the Isostatic Anomaly." Amer. Jour. Science, Vol. X, pp. 166-174, 1925.

[5]Bowie, Wm. "Isostatic Investigations and Data for Gravity Stations in the United States Established since 1915." Special Publication No. 99, U. S. Coast and Geodetic Survey, pp. 8-9, 1924.

necting widely separated positive anomalies where an east west alignment of adjoining negative anomalies might have been shown. The chief example is the long north-south positive area in western Alberta and eastern British Columbia. These cases are of minor importance in all instances and are not in the large positive area under consideration. They are properly matters of interpretation since the measurements in regions of complex geology and rugged topography, such as one finds in general around the borders of this large area, do not show a high degree of self-consistency as regards size and sign. They do, of course, show a rather marked correlation with surface geologic structure and rock density but that is another story and is well known. The north-south trend of the large structural units of North America seem fully to justify the few liberties which were taken in drawing contours. Such liberties were carefully avoided, however, in the large positive area of the Black Hills and northern Great Plains, as the anomalies here are consistently of the same sign and, to a smaller extent, of similar size over a broad area. The large positive area is conspicuous. Areas of negative anomalies are ruled with diagonal lines.

Shallow irregularities of density exert a relatively great effect on the intensity of gravity compared to irregularities of similar size at greater depths. Density anomalies beneath the surface moreover manifest their greatest effect on the vertical component of gravity directly above their location. An anomalous mass five miles deep will affect the vertical component to a relatively great extent directly above, but only to a relatively slight extent a few miles to one side. The gravity stations in the United States and Canada are for the most part many tens of miles, and in some cases even hundreds of miles, apart. Only a few have been established very close together. Nevertheless, by comparing the neighboring stations on similar terranes and by leaving out of account the stations on dissimilar terranes it should be possible to obtain an estimate of the order of magnitude of the average effect which the less obvious but very common shallow density differences may have. We may thus eliminate the other kind of shallow density differences beneath stations—the obvious ones which arise from location on rocks of different geological age and history.

To secure such an estimate for the northern Great Plains was comparatively easy, since most of this area is underlaid by sedimentary rock of Cretaceous and to a small extent of early Cenozoic age. The strongly positive nucleus of the large area before mentioned is also, fortunately, situated mainly on stratified rocks of this age, excepting the two Black Hills stations at Hill City and Lead, South Dakota, which are located on Pre-Cambrian rocks. These, and a few other exceptions on the borders of the positive area were carefully eliminated; as before stated, the purpose being to reduce the obvious shallow inequalities of density to as small a role as possible in this investigation. Sixty-six algebraic differences were then read from the Pratt-Hayford isostatic anomaly map, using only the selected stations on stratified rocks of nearly the same age. The mean of the sixty-six algebraic differences amounts to .012 dynes. Extreme values were .039 and .000.

As a check on the reasonableness of this procedure, mean algebraic differences between the isostatic anomalies were determined for eleven other groups of (more or less) closely adjacent stations in the United States. The following table indicates the results. The value of .012 for the Cretaceous and early Cenozoic sedimentary rocks of the northern Great Plains area is close to the average value of the algebraic means in this table.

TABLE I

Station Group	Number of Stations	Mean Algebraic Difference Between Adjacent Isostatic Anomalies
Near Seattle	13	.042
Near Compton, Calif.	7	.017
Damon Mound, Texas	2	.022
In Wisconsin and Minnesota	17	.040
In Maryland and West Va.	6	.006
In New Jersey	3	.013
In southern Oklahoma	4	.013
Saline, Texas	4	.005
Austin, Texas	2	.004
Near Denver	5	.007
In N. E. Kansas	5	.017

The gravity stations in the region under consideration are not closely spaced in general and some of the pronounced minor flexures of the contour map (Figure 1) are due to a single anomaly of unusual value. If

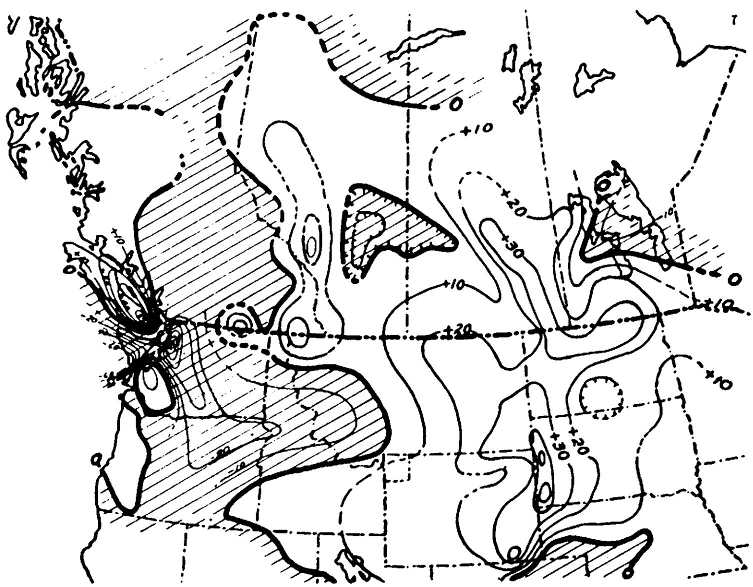

FIGURE I

A contour map of the Pratt-Hayford isostatic anomalies in part of western North America drawn with a contour interval of .010 dynes. Areas of negative anomalies are marked with diagonal lines. The large irregular positive area centering in the Black Hills and the northern Great Plains is of interest when compared with the same area in Figure II.

one assumes that these unusually high "erratic" anomalies are generally so by reason of a superficial density anomaly, and that the unusually low "erratic" anomalies are low for the same reason, Figure II may be drawn. This assumption is a fair statement of the position taken by those who advocate "nearly complete" isostatic balance within small areas. In other words anomalies which are much higher or much lower than their neighboring anomalies are probably due to relatively shallow density variations. Here the contour map of Figure I has been changed only in the positive area of the northern Great Plains. Unusually high anomalies have been lowered and unusually low places within the positive area have been raised by .010 dynes. This is the contour interval used and is also approximately the amount a single anomaly is apt to be influenced by the shallow less

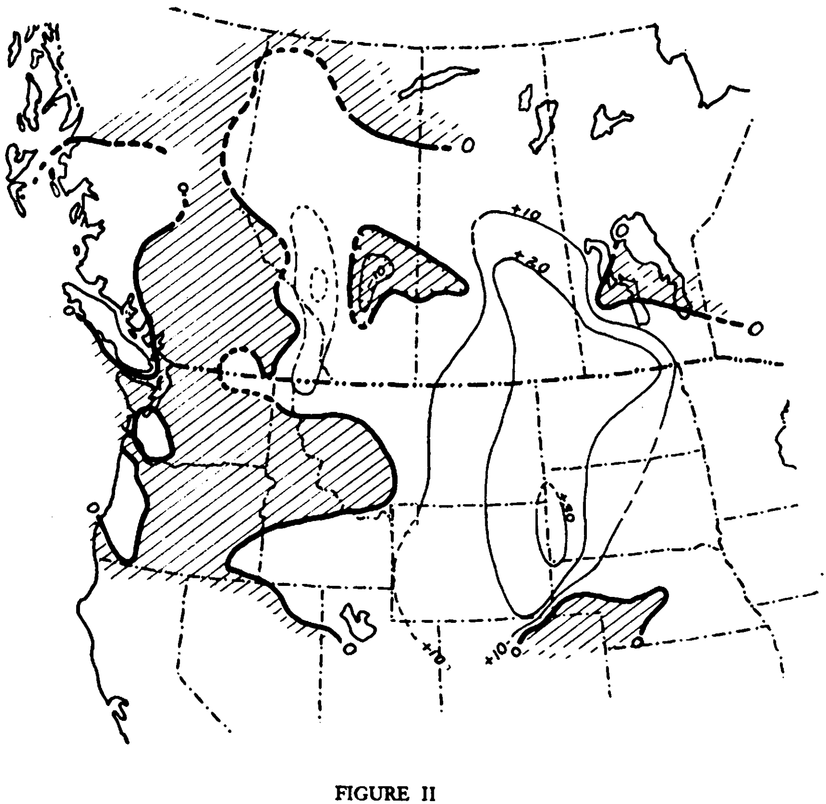

FIGURE II

The Pratt-Hayford isostatic anomaly contour map of Figure I has been simplified in the area of the Black Hills and northern Great Plains by smoothing out the large positive area. The correction was secured by averaging sixty-six algebraic differences between adjacent isostatic anomalies situated on Upper Cretaceous and early Cenozoic sedimentary rocks in this region. Assuming that this correction (.012 dynes) is the amount a single anomaly is apt to be influenced by the shallow less obvious density irregularities of these rocks, the unusually high places were lowered and the unusually low places were raised by a free application of the correction.

obvious density irregularities of this region, as assumed above.* It is obvious that a large positive area remains after lowering the highest spots by .010 dynes; and if this mean (.012 dynes) of the algebraic differences between adjacent Cretaceous and Cenozoic northern Great Plains anomalies is at all representative of the magnitude of the gravitational effect which the

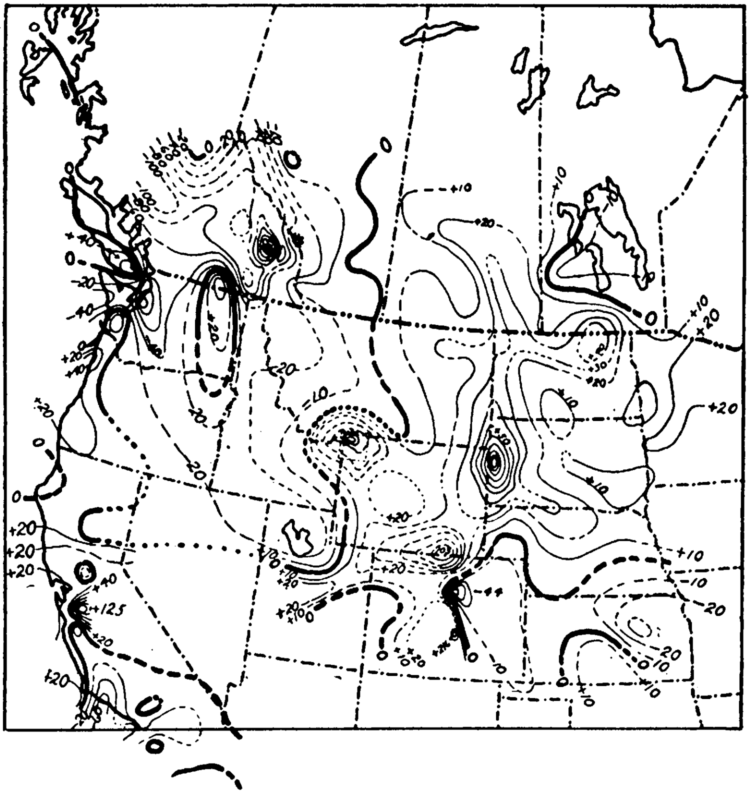

FIGURE III

A contour map of the "free-air" anomalies in part of western North America. East of the Rocky Mountains the contour interval is .010 dynes, while in the Cordilleran region it is .020 dynes. The large positive area in the Black Hills and northern Great Plains has nearly the same shape as the positive area of the same region as shown by the Pratt-Hayford isostatic anomalies in Figure I. Since the relief here is in general mild, this accords well with theory. The sudden extremes in the topographically rugged and geologically complex Cordilleran region seem to show that the net work of "free-air" anomalies here is much too coarse for the contours to show any appreciable correlation with either the topography or geological structure.

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*Whether one concludes that a given anomaly has been influenced to the value of .012 dynes, or half this amount—.006 dynes—by the very shallow density anomalies, depends largely on the size and self-consistency of the surrounding anomalies. For the sake of simplicity the intermediate correction of .010 dynes was used.

shallow density differences may cause, it seems clear that a deeper and more widespread density anomaly is revealed.

When the contours are drawn on the basis of the "free-air" anomalies, as in Figure III, the same positive area stands out with nearly the same outline as before, only more pronounced. Fifteen Canadian and eighteen United States free-air anomalies are located in this area. The free-air anomaly ($g^{\circ}-\gamma^{\circ}$) involves only the correction of "g" for the elevation of the observation station above sea-level. Corrections for topographic irregularities are neglected. This anomaly, hence, is unsuited for investigations of sub-surface density differences except in plain and plateau regions

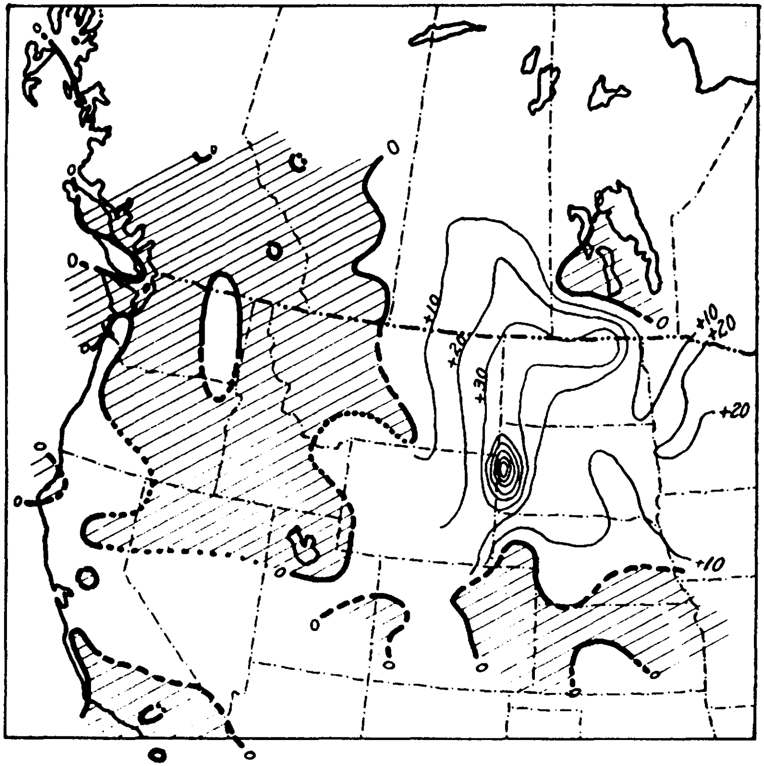

FIGURE IV

The "free-air" anomaly contour map of Figure III has been simplified in the area of the Black Hills and northern Great Plains by smoothing out the large positive area. A correction of .015 dynes—which is believed to represent the amount a single "free-air" anomaly is apt to be influenced by the shallow, less-obvious density irregularities of this terrane—was freely applied, the unusually high places being lowered and the unusually low places being raised by this amount.

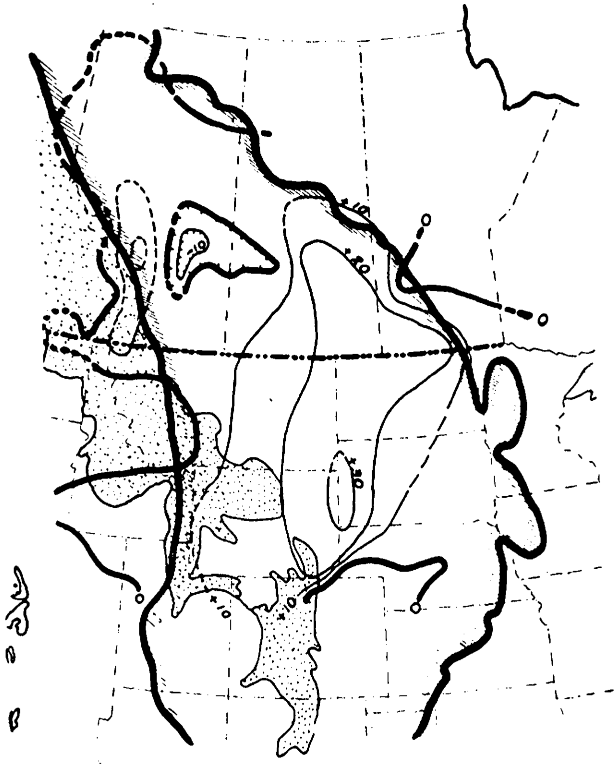

FIGURE V

The approximate area of the Cretaceous geosyncline, which underwent marked sedimentation, as well as the Southern and Northern Rocky Mountains are shown here in relation to the large, positive, *simplified,* isostatic anomaly area of the Black Hills and northern Great Plains. If the Airy explanation of isostatic balance is correct, and if there was an upward protuberance of relatively dense sub-crustal "sima" here in Upper Cretaceous time, it is suggested that this positive area may correspond to a "relic" of this protuberance.

where the immediate relief is small. In such flat lands as these the free-air anomaly may be very advantageously used. The unfitness of this anomaly in the rugged Cordilleran region seems to be indicated by the great irregularity of the contour lines in this region. On the other hand, the close resemblance between the free-air and the Pratt-Hayford isostatic anomaly contours in the Great Plains region lends added weight to the assertion that in flat lands the former is also suitable for density studies.

The mean of the algebraic differences between adjacent free-air anomalies on sedimentary Cretaceous and early Cenozoic rock in the northern Great Plains region is .015 dynes. When the large positive area in question, as shown by the free air contours, is again rounded off and smoothed as much as possible by freely applying a correction of .010 dynes, a large positive area stands out more clearly than in Figure II, where the isostatic anomaly was used (Figure IV).

Figure V shows the relations of the large positive area to the region which underwent such marked sedimentation in the Upper Cretaceous period, and which is still largely underlaid by these thick sedimentary deposits. The Rocky Mountains are dotted. The positive area is thus rather centrally located in the Cretaceous geogyncline. If the Airy explanation of isostatic balance is correct, the explanation is at once suggested that a relic, so to speak, of the upward protuberance of relatively dense sub-crustal "sima" beneath the bottom of the geosyncline may still exist and may be responsible for the large area of positive anomalies. Gravitational data are still very scattered in the western United States, however, and any speculation concerning the gravitational effect of the growth of the Rocky Mountains, would be quite insecure.