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Correlation of Gravity Observations with the Geology of the Coal Creek Serpentine Mass, Blanco and Gillespie Counties, Texas

By

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CORRELATION OF GRAVITY OBSERVATIONS WITH THE GEOLOGY OF THE COAL CREEK SERPENTINE MASS, BLANCO AND GILLESPIE COUNTIES, TEXAS*

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ABSTRACT

Gravitational observations were made of the pre-Cambrian Coal Creek serpentine mass in Blanco and Gillespie Counties, Texas, the geology of which had been mapped previously. The observed gravitational anomalies indicate roughly the depth of the serpentine mass below which it may possibly grade into its parent peridotitic rock. Probable correlation between the gravitational map and the other geologic features of the area is indicated.

INTRODUCTION

The investigation of the gravitational effects of a serpentine mass is one of several projects by the writers[1,2] in the application of gravitational observations to the prediction of the shape of rock masses in the basement. The Coal Creek serpentine mass is situated in central Texas, astride the Blanco-Gillespie County line a short distance south of the juncture of these counties with Llano County. The geology of the area, mapped by Barnes mostly in 1939 and 1940, is in part described by Barnes, Dawson, and Parkinson.[3] During 1942 and 1943 in connection with a detailed investigation of soapstone, some revisions were made of the mapping north of the serpentine mass.[4] Planetable-alidade traverses were made to obtain positions and elevations of the gravity stations, and with these data seven and one-half minute quadrangles have been compiled from which the generalized geologic map accompanying this paper was taken.

Observations were made with a portable gravity meter over the rough areas which include the serpentine mass and some adjacent territory. Along roads away from the serpentine mass, observations were made using a standard-sized gravity meter. Gravity observations and reduction of these observations were made by both writers; however, Romberg is responsible for the final gravity interpretations. Barnes is responsible for the geological observations and interpretations.

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[1] Frederick Romberg and V. E. Barnes, "Correlation of Gravity Observations with the Geology of the Smoothingiron Granite Mass, Llano County, Texas," *Geophysics,* IX (Jan., 1944), 79–93.

[2] V. E. Barnes and Frederick Romberg, "Gravity and Magnetic Observations on the Iron Mountain Magnetite Deposit, Llano County, Texas," *Geophysics,* VIII (Jan., 1943), 32–45.

[3] V. E. Barnes, R. F. Dawson, and G. A. Parkinson, "Building Stones of Central Texas," *Univ. Texas Pub. 4246* (1942), 90–91, 108–111, 113-114, Fig. 11.

[4] V. E. Barnes, "Soapstone and Serpentine in the Central Mineral Region of Texas," *Univ. Texas Pub. 4301* (1943), 47–80, Figs. 22–24.

At this point we wish to make it clear that the serpentine mass described in this paper is a part of the pre-Cambrian basement and is not related to the Cretaceous serpentine plugs of the Balcones fault zone. The conclusions in this paper cannot be applied to the Cretaceous serpentine plugs.

GEOLOGY

The Coal Creek serpentine mass takes its name from Coal Creek, a broad intermittent stream filled with granite wash, which crosses the western end of the serpentine outcrop. The mass is 3.7 miles long in an east-west direction and ranges from 0.3 to about 1.4 miles wide with important lobes at each end. The surface outcrop of the serpentine totals 2.54 square miles, of which 45 percent is in the attenuated 2.1 mile-long central part of the mass, 20 percent in the western end of the mass, and 35 percent in the eastern end. The widest part of the outcrop is at the eastern end of the serpentine mass.

The Coal Creek serpentine is derived from a basic igneous rock, and the abundant network structure seen in thin section indicates that the rock was originally mostly olivine. Another mineral, probably an amphibole, also has been replaced by serpentine. The presence of recognizable pseudomorphs shows that there has been little disturbance of the serpentine after its formation. The outcrop form and attitude of the serpentine suggest that it is essentially a thick sheet curved northward at each end, and such a sheet should extend, as a minimum, at least several miles in depth.

The attitude of the main body of the serpentine, as determined from observations along its border and from observations of inclusions and alignments within the serpentine, suggests that it dips about 45 degrees to the south in its western part, steepening eastward to about 60 degrees where the mass curves northward and changes its dip to southeastward. The attitude of the serpentine beyond this point was not determined.

The serpentine is bordered along the south and for the western half of its distance along the north by Big Branch gneiss[5,6] of quartz diorite composition. The rest of the distance along its northern side is bordered by Packsaddle schist, which here is chiefly amphibole and mica schist containing numerous soapstone lenses. Valley Spring gneiss outcrops in the southwestern part of the map area, as well as Town Mountain granite which outcrops also in the southeastern part of the map area. Paige[7] has defined the Packsaddle schist and Valley Spring gneiss and Stenzel,[8] the Town Mountain granite. Other outcropping types of rock such as diorite and hornblendite are common, but the masses are not of sufficient size to alter noticeably the gravity map. Paleozoic sediments mask the pre-Cambrian

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[5] *Ibid.*, pp. 56–57.

[6] Barnes, Dawson, and Parkinson, *op. cit.*, Fig. 11.

[7] Sidney Paige, "Llano-Burnet, Texas, Folio of the Geologic Atlas of the United States," *U. S. Geol. Survey Folio 183* (1912), 3–4.

[8] H. B. Stenzel, "Pre-Cambrian Structural Conditions in the Llano Region," *Univ. Texas Bull. 3401* (1934), 75–79.

rocks both to the west and east. These areas stand high and are relatively inaccessible, limiting the area in which gravity observations can readily be obtained.

The Valley Spring gneiss and the Packsaddle schist are metasedimentary rocks, into which the Big Branch gneiss has been intruded. The formation of soapstone from calcareous rock in the Packsaddle schist apparently happened at this time and is not related to the later injection of peridotite from which the serpentine was formed. The essentially undeformed minerals of the serpentine and the presence of Packsaddle schist, soapstone, and Big Branch gneiss inclusions indicate that the peridotite emplacement postdates the period of metamorphism that accompanied the injection of the Big Branch gneiss. An aplite dike in the serpentine may be an offshoot of the Town Mountain granite, in which case the original emplacement of the serpentine would be earlier than that of the Town Mountain granite. The aplite, however, could possibly be interpreted as an inclusion, in which case the serpentine would be later.

The emplacement of the serpentine is definitely pre-Cambrian in age since it is overlapped by Cambrian sediments. The erosional surface upon which the Cambrian sandstone was deposited probably in no place was more than a few hundred feet above the present erosional surface. The Cambrian sediments were mostly stripped prior to the deposition of Cretaceous sediments, the base of which was only a few hundred feet above the present surface.

Some information on the density of the pre-Cambrian rocks follows:

	Density	*No. Determinations*
Serpentine	2.48	6 (Theoretical 2.55–2.58)
Big Branch gneiss	2.75	9
Packsaddle schist	2.95	8[9]
Valley Spring gneiss	2.64	25[9]
Town Mountain granite	2.62	7[9]

More detailed accounts of the geology are contained in the publications cited, and seven and one-half minute quadrangles of most of the area are being prepared showing more detail than does the map accompanying this paper.

Some generalizations on the time of formation of serpentine in relation to its emplacement are contained in geologic literature which do not seem to be supported by the Coal Creek serpentine mass. Hess[10] suggests that water may be picked up by peridotite to form serpentine from water-bearing geosynclinal sediments. The Coal Creek mass did not intrude geosynclinal sediments, not at least at the level now being observed. If geosynclinal sediments existed above this level, which is doubtful, their contained water would not have been available for serpentinization of this deeper portion of the mass. As pointed out by Bowen[11] it is unlikely that the water for serpentinization could be contained in the peridotite,

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[9] Romberg and Barnes, *op. cit.,* p. 80.

[10] H. H. Hess, "Serpentinization: Origin of Certain Asbestos, Talc and Soapstone Deposits," *Economic Geology, 28* (1939), 643–657.

[11] N. L. Bowen, "Magmas," *Geol. Soc. Am. Bull., 58* (1947), 263–280.

and for the Coal Creek mass, it looks equally impossible for sufficient water to have been picked up during the emplacement of the peridotite to form the serpentine.

The Town Mountain granite, as pointed out above, is probably later than the serpentine and could possibly have furnished the solution for serpentinization of the peridotite. However, the intervening rock shows little if any granitization and few aplites, pegmatites, and quartz veins come near to the serpentine. At least half of the serpentine is more than 2 miles from the nearest outcropping granite mass, and a regional gravity survey indicates that there is little probability of granite being as near beneath the serpentine. It, therefore, seems unlikely that serpentinization was influenced by the granite.

The production of serpentine within the zone of ground-water circulation has been little considered, except for serpentine of the type found along the Balcones fault zone.[12] If the Coal Creek mass is a result of ground-water alteration, then there should be a limit to the depth to which the serpentine extends. The depth to which the serpentine extends cannot be observed directly, but an examination of the gravity field indicates that it is bottomed at a relatively shallow depth. When peridotite changes to serpentine, a large volume increase theoretically takes place, and in many deposits there is little evidence of the deformation that should accompany such a change. However, where serpentinization is a near-surface phenomenon, there is little confining pressure and the serpentine could expand upward with a minimum of shearing.

GRAVITY OBSERVATIONS

The gravity observations were corrected in the usual manner, and a contour map was drawn from them (Fig. 2). The expected error in the observations is less than one-tenth milligal, so that whatever errors are in the map are due to sparseness of data and to the contouring rather than instrumental errors. No terrain corrections were made; since the anomalies observed were of the order of several milligals, it was not considered that errors due to terrain would affect the conclusions.

Qualitative Interpretation of Gravity Data.—The first feature to be noticed on the map is a fairly strong gradient rising to the north and east. The geological map (Fig. I) shows granite and various Cambrian sedimentary rocks southwest of the serpentine mass; and beyond the map to the south and west, granite is dominant. The granite and the sediments are lighter than the schist and gneiss, and this may account for the lower values of gravity to the south and west. No regional gradient has been subtracted from the values used in making the contour map, even though a fairly well-defined regional gradient appears.

The most obvious anomaly on the map is the strong positive closure north of

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[12] J. T. Lonsdale, "Igneous Rocks of the Balcones Fault Region of Texas," *Univ. Texas Bull, 2744* (1927), 139–141.

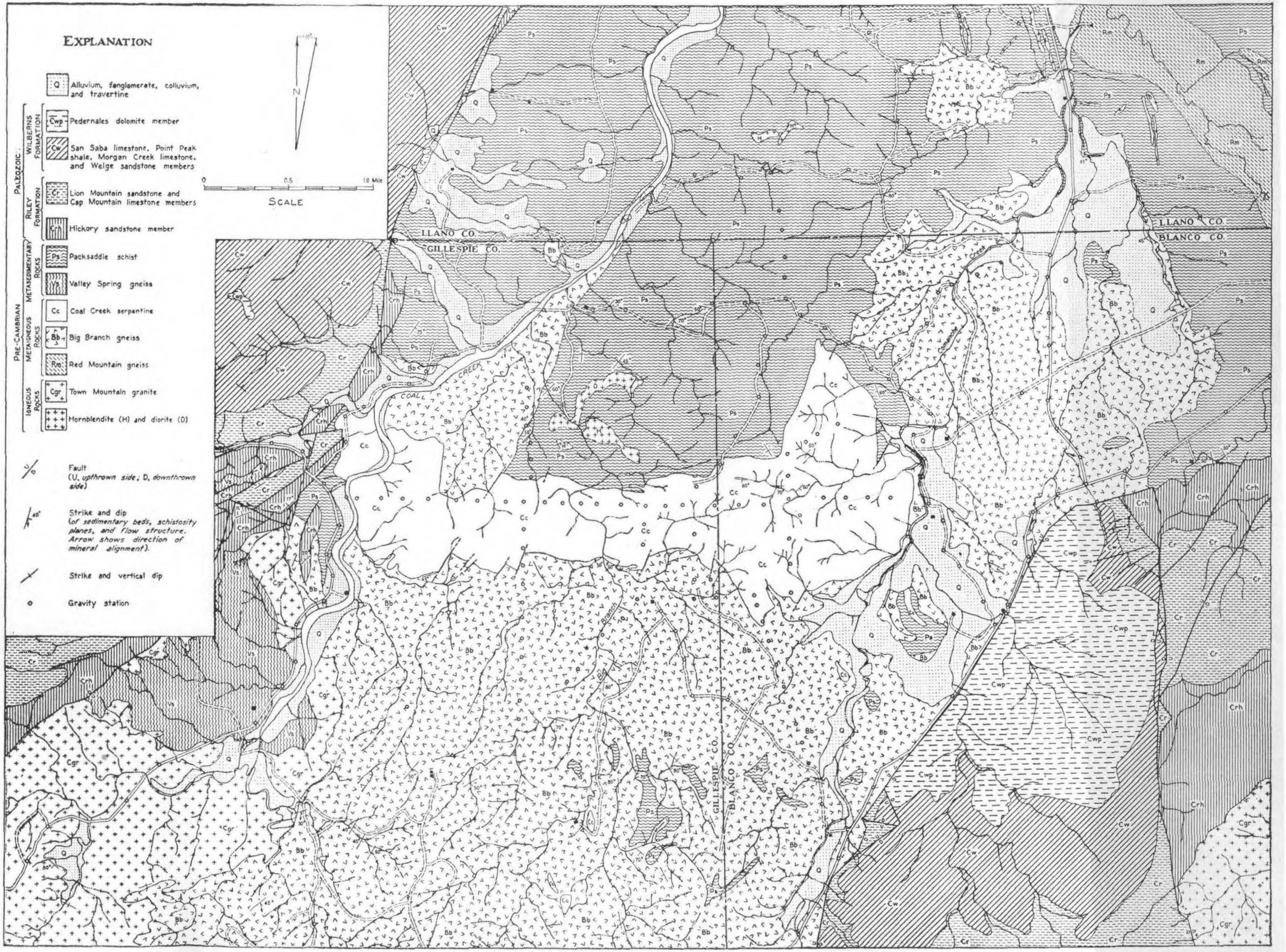

FIG. 1. Geologic map, Coal Creek serpentine, Gillespie and Blanco Counties, Texas.

the serpentine mass. The position of this closure corresponds to the position of the Packsaddle schist, as shown on Figure I. As the schist is more dense than either the gneiss or the serpentine, it is normal for it to cause a positive gravity anomaly.

The serpentine mass appears in turn to be associated with a negative anomaly, contrasting sharply with the schist anomaly to the north and less sharply with the gravity values to the south over the gneiss. This is natural because the gneiss, while heavier than the serpentine, is lighter than the schist.

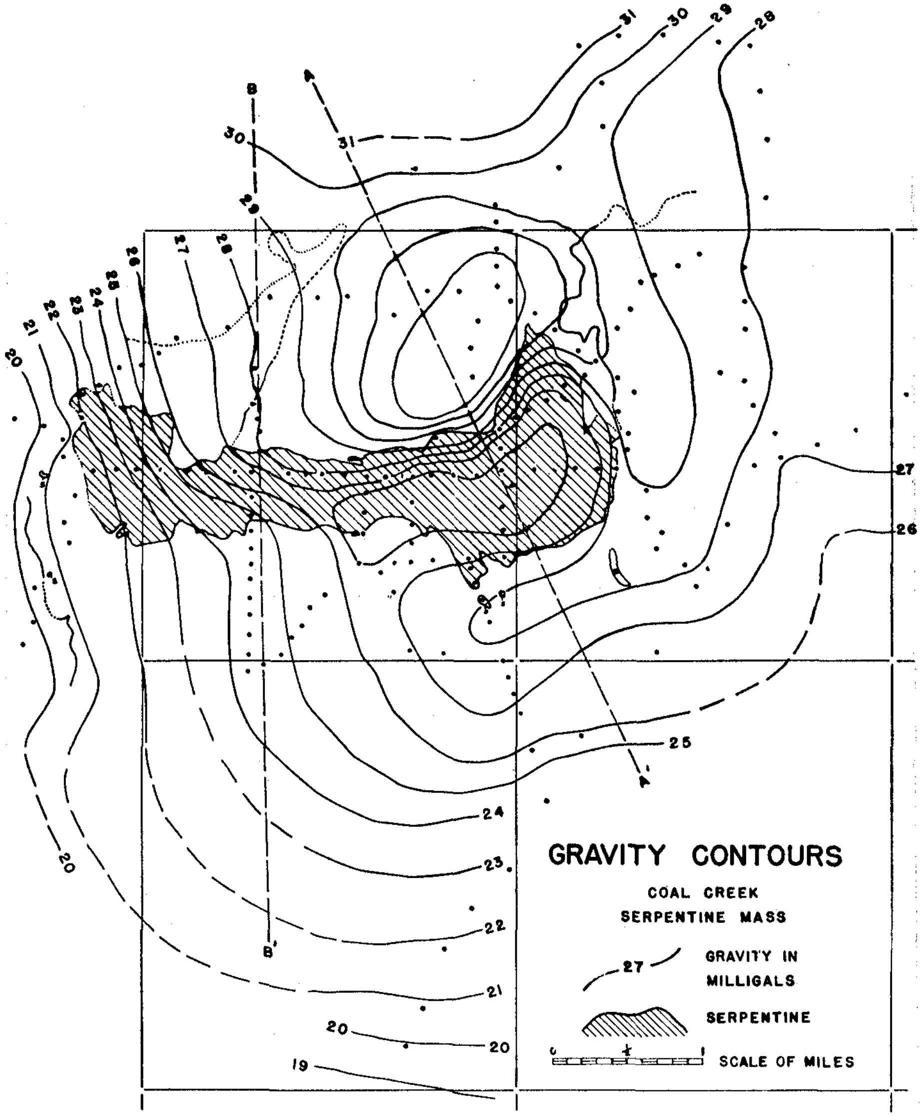

FIG. 2. Gravity map, Coal Creek serpentine, Gillespie and Blanco Counties, Texas.

The gravitational effects of schist and serpentine can be seen in Figure 3, which shows two north-south profiles of the observed field through the east and the west ends of the serpentine mass. (The locations of these profiles are shown as the lines *AA'* and *BB'* in Figure 2.) The profiles show a general slope to the south, so that a regional gradient may be assumed for the purpose of measuring the magnitude of the anomalies more accurately. The assumed gradient is shown by dotted lines and is roughly the same on both profiles.

It is to be noted that the gravitational anomalies at the west end of the serpentine mass are less than half as large as those at the east end. This indicates that the serpentine probably extends to less than half the depth at the west end

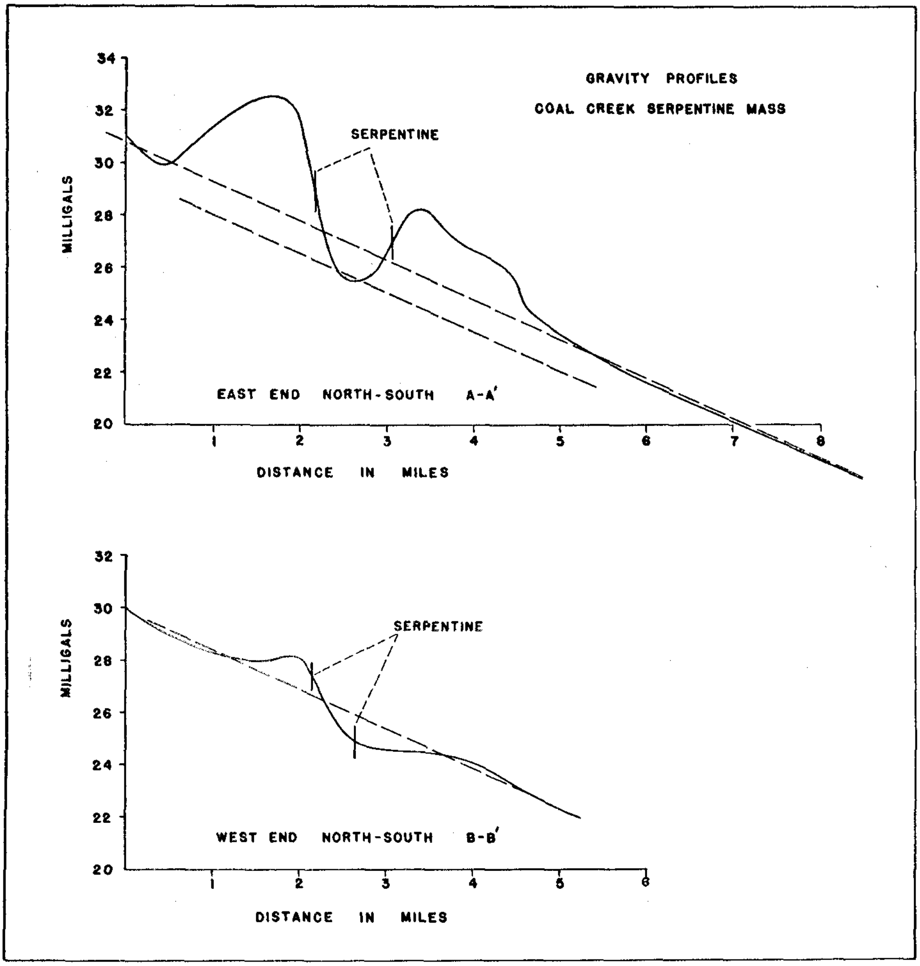

FIG. 3. Gravity profiles, Coal Creek serpentine, Gillespie and Blanco Counties, Texas.

of the mass than at the east. The smallness of the positive anomaly suggests that the schist is almost gone; this is confirmed by the geological map. In addition, the position of outcrop of the serpentine is offset from the middle of the negative anomaly, suggesting that the serpentine present dips southward. The same thing is true of the schist anomaly. On the cross section *AA'*, over the main part of the structure, the center of the anomaly and the center of the outcrop coincide; this throws doubt on the possibility that the east end of the serpentine may be dipping.

Two-Dimensional Assumption.—As a first step toward a quantitative interpretation of the gravity data, let us assume that the contact between the gneiss and the serpentine is straight and extends infinitely east and west. If this is true, the depth to which the serpentine extends can be computed from the change in the observed values of gravity, assuming that the density difference between the two substances is known. The density difference is 2.75 - 2.55 = 0.20 gm/cm^3, and the gravitational anomaly (Fig. 3) is about 3.5 milligals. When these data are used in the Bouguer equation

$$\Delta g = 2\pi ksz$$

for the attraction of an infinite, uniform, horizontal layer (Δg = gravitational acceleration, s = density difference, z = depth, and k is the gravitational constant), they yield z = 1,400 feet.

Since the dimensions of the serpentine are not infinite, this depth is, of course, too small, and we shall consider a better assumption later. If the density used for the serpentine is too large (six surface samples average 2.48 instead of 2.55 gm/cm^3), the computed depth is too great.

A second estimate for the depth of the serpentine may be made by using the gravity difference between the schist and the serpentine, which is 5.5 milligals. Used in the Bouguer equation, this value shows a depth of 1,100 feet. This estimate is, of course, less valuable than the previous one (1,400 feet) since the assumption of infinite extent is even further from the truth. However, the schist itself appears to cause a positive closure on the contour map of about 3.5 milligals with respect to the gneiss around it; with a density contrast of 0.2 this indicates a depth of 1,400 feet, the same as the depth of the serpentine. It is thus reasonable to assume that the schist and the serpentine both extend to a relatively shallow depth. The serpentine is apparently surrounded, and presumably underlain, by something denser than itself, and the schist by something less dense; this is apparently the gneiss.

If the same kind of computation is made for the west end of the serpentine mass, using an anomaly of about 1.2 milligals, the depth is found to be 500 feet.

Assumption of Finite Dimensions.—The next step is to see if it is possible to refine the assumptions from two-dimensional to three-dimensional, considering the known geology and the general aspect of the data. Assuming the eastern end of the serpentine and schist to be upright cylinders should give a better result, since on the surface they are almost as broad as they are long.

Using the formula for the attraction of an upright cylinder (see Appendix, equation (i)), we compute the depth from the gravity anomaly of 3.5 milligals. This gives a result $z_2 = 2{,}000$ feet, instead of 1,400 feet as previously estimated. There is no reason for assuming that this depth is in error one way more than another because of the geometric assumptions (except as the schist anomaly may reduce the apparent serpentine anomaly), so the only sources of gross error in it are the gravity difference and the density difference. It may therefore be assumed that the depth of 2,000 feet represents the actual depth of the bulk of the serpentine mass, unless some unknown geological feature is involved.

A similar assumption for the Packsaddle schist gives a probable depth of 1,650 feet. The schist depth changed less than that of the serpentine because of the greater radius ($a = 1.5$ km) used in the computation.

A factor which might influence the sizes of the schist and serpentine anomalies is their interference with each other, which might tend to make both anomalies seem smaller than they really are. To estimate the magnitude of this effect, we compute the downward attraction of each of the assumed cylinders at the center of the upper surface of the other, assuming also that their sides are in contact, according to the formulas for the attraction of a cylinder, as listed by Romberg and Barnes.[13] The result is that the attraction of the assumed serpentine cylinder at the center of the assumed schist cylinder is less than 0.1 milligal, and the attraction of the schist cylinder at the center of the serpentine is less than 0.2 milligal. These effects are not large enough to modify the computations appreciably.

Dip of Serpentine.—As evidence of the dip of the serpentine, we have two qualitative facts from profile *AA'*. First, the serpentine anomaly is approximately centered between the boundaries of its outcrop. Second, the value of gravity at each boundary is about halfway between the maximum on one side of the boundary and the minimum on the other. Both these facts indicate that the contacts between the serpentine and the rocks on either side of it are nearly vertical.

The slope of such a contact can be computed for the case of a contact between two masses that are horizontally infinite by measuring the gravity value at the contact with respect to the maximum on one side and the minimum on the other (see Appendix, equations (3)–(7)). Thus if the gravity value at the contact is halfway between the maximum and the minimum gravity value, the contact is vertical. Though in the present case there is not sufficient detail to encourage computing the slope accurately, the measurements taken from the graph yield a dip northward of 83°, ± 5°, for both contacts. This contradicts the geological data.

Possibility of Peridotite under Serpentine.—The geophysical evidence for peridotite under the serpentine mass can be evaluated only under the assumptions that there are no large unknown masses present except peridotite, and that the observed masses of gneiss, granite, and schist are simple in shape. Without

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[13] Romberg and Barnes, *op. cit.*, p. 91.

this assumption it is, of course, impossible to speculate on the meaning of any gravitational anomaly, since any force field may be caused by an infinite number of different geological configurations. With the assumption, however, we may set limitations on the existence of peridotite. If the masses of gneiss, schist, and granite are present as computed in the preceding section, the peridotite can only be a thin feeder or a uniform level sheet, as these forms would not affect the gravitational field. However, such forms are not geologically probable. It is more likely that the peridotite, if it is present, is in some form whose dimensions are comparable to those of the serpentine itself. If this is the case, of course, our previous idea of the gneiss, schist, and serpentine must be modified so as to leave the gravitational field the same as before. It is also likely, in view of the symmetry of the serpentine anomaly, that the peridotite is directly underneath the serpentine and not off to one side. In addition, the bulk of the peridotite has to be under the east end of the serpentine mass, as there is very little disturbance to hide peridotite under the serpentine on the west end.

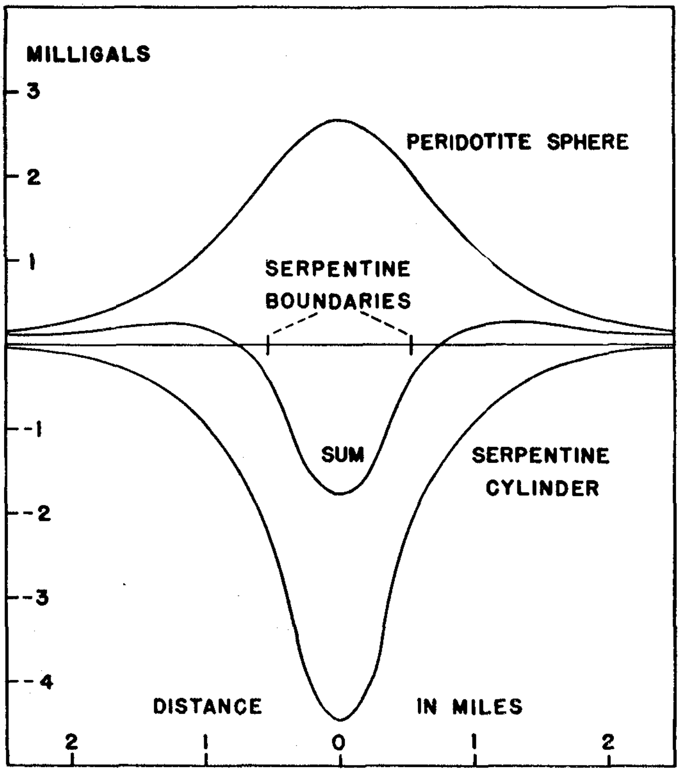

FIG. 4. Computed profiles showing possibility of peridotite under serpentine.

The gravitational field, then, imposes the following conditions on the peridotite-serpentine combination, according to profile AA' of Figure 3: (1) The peridotite is directly under the serpentine. (2) The gravity effect of the combination must resemble the gravity effect assumed for the serpentine itself before the peridotite was considered. That is, the combined effect must be about 2 milligals less at the center of the serpentine than it is at the outer edges of the gneiss and schist anomalies. This condition can be expressed analytically, of course, and will have a variety of permissible solutions, somewhat limited by the condition that the gradients of the combined profile must resemble the observed gradient. (If the serpentine were very deep, its negative anomaly would be much larger and not so sharply cut off.) The combination of a serpentine cylinder 3,300 feet deep, with a peridotite mass underneath it with a radius of 2,900 feet, fulfills the conditions, giving (see Fig. 4) a resultant gravity profile which resembles the observed anomaly over the serpentine.

Mass of Serpentine.—A minimum estimate for the mass of serpentine present can be arrived at by measuring the area and multiplying by the estimated depth. This depth, of course, varies, and may probably be taken to be 2,000 feet in the eastern part of the mass and 500 feet in the western. Dividing the area roughly into two parts, and multiplying each by its estimated depth, yields a mass of 10^{10} metric tons. If peridotite is present under the serpentine, the serpentine will be deeper at the east end, so the estimate of mass will be a minimum.

The mass may also be estimated by the integrating of the anomalous figure,[14] but the method was not used because it would have necessitated subtracting the regional gradient from the gravity map and did not promise results that would be much more accurate than the straight geometric method.

APPENDIX

Heiland[15] gives, for the attraction of an upright cylinder at a point on its axis,

$$\Delta g = 2\pi ks(z_2 - z_1 + \sqrt{a^2 + z_1^2} - \sqrt{a^2 + z_2^2}), \qquad (1)$$

where a = radius of the cylinder,
z_1 = depth to top of cylinder,
z_2 = depth to bottom of cylinder,
k = gravitational constant,
s = density contrast.

If we set $z_1 = 0$ and solve for z_2, we get

$$z_2 = B(2a - B)/2(a - B) \quad \text{where} \quad B = \Delta g/2\pi ks. \qquad (2)$$

Then if a is assumed to be 0.86 km (2,820 feet), z_2 comes out to be 2,000 feet.

To measure the dip of an interface between two masses with horizontal

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[14] Sigmund Hammer, "Estimating Ore Masses in Gravity Prospecting," *Geophysics,* X (Jan., 1945), 50.

[15] Heiland, *Geophysical Exploration* (New York: Prentice-Hall, 1940), p. 147.

boundaries and infinite horizontal dimensions, we begin with Heiland's equation[16] for the attraction at various locations above such an interface.

$$\Delta g = 2ks\{D\phi_2 - d\phi_1 - (x \sin i + d \cos i)[\sin i \ln (r_2/r_1) + \cos i(\phi_2 - \phi_1)]\}, \quad (3)$$

where i = dip of interface,
D = depth to bottom of interface,
d = depth to top of interface,
r_1 = distance to top of interface,
r_2 = distance to bottom of interface,
φ_1 = angle between r_1 and horizontal,
φ_2 = angle between r_2 and horizontal,
x = horizontal distance to top of interface.

If $d = 0$, then $\varphi_1 = 0$, and we have

$$\Delta g = 2ks\{D\varphi_2 - (x \sin i)[\sin i \ln (r_2/r_1) + \cos i]\}. \quad (4)$$

Now if $x = 0$, and since $\lim_{x \to 0} x \ln (r_2/r_1) = 0$,

$$\Delta g_x = 2ksD\pi. \quad (5)$$

If x is infinite, then for the asymptotic value of Δg, we can write the Bouguer equation

$$\Delta g_{\max} = 2ksD\pi. \quad (6)$$

The ratio of these yields φ

$$\varphi = \Delta g_x / \Delta g_{\max}. \quad (7)$$

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[16] Heiland, *op. cit.*, p. 153.