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Application of Gravimeter Observations to the Determination of the Mean Density of the Earth and of Rock Densities in Mines

BY

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APPLICATION OF GRAVIMETER OBSERVATIONS TO THE DETERMINATION OF THE MEAN DENSITY OF THE EARTH AND OF ROCK DENSITIES IN MINES

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INTRODUCTION

Subterranean observations of gravity are of value for two reasons:

(1) As first shown by Airy[1] from pendulum measurements at the top and bottom of Harton Colliery, they may be used to determine the mean density of the earth from the following equation which he derived:

$$\frac{\rho}{\bar{\rho}} = \frac{r}{3\Delta r} \cdot \frac{g_a}{g_b} - \left[\frac{r}{3\Delta r} - \frac{2}{3}\right] \cdots\cdots\cdots (1)$$

where Δr is the thickness of the spherical shell corresponding to the depth of the mine and ρ the corresponding density. The radius of the earth is represented by r, while g_a and g_b are gravity at the top and bottom of the mine respectively, and $\bar{\rho}$ is the mean density of the earth.

(2) Such observations may also be employed to determine the densities of rock layers beneath the surface, and it has been one of the objects of this paper to demonstrate, this application in connection with the results at Lake Shore and Noranda.

In Airy's experiment a pendulum and a pendulum clock were set up at the top of the mine, and a similar set was installed at the bottom of the mine. Six swings of four hours were made with the pendulums per day and compared with the respective clocks by the method of coincidences. The observations lasted from October 2 to October 21, 1854. The pendulums were interchanged between bottom and top of the mine three times on October 9, 16 and 19, following the initial set-up on October 2. Eighty-two swings were made between October 2 and October 21. Eight observers were employed, representing, in addition to the Royal Observatory, Oxford, Cambridge, and Durham observatories. Every assistance was given by Mr. William Anderson, principal owner of the mine. Mr. G. W. Arkley, local viewer and superintendent of the mine works, assisted with some of the required measurements and "furnished a complete account of the strata passed through in sinking the Harton shaft with specimens of a great number of rocks. These were submitted to Professor W. H. Miller, who, with great labour, determined their specific gravities". Airy gives a table which lists the thicknesses of the

[1] Account of Pendulum Experiments undertaken in the Harton Colliery, for the purpose of determining the mean density of the earth, by G. B. Airy, Esq., Astronomer Royal, Phil. Trans. Roy. Soc. London, Vol. 146, 1856, pp. 297-352, with an addendum by Professor Stokes, pp. 353-355.

142 strata composing the mine section with the corresponding specific gravities and summarizes them into 1,211 feet of rocky and shaly beds of specific gravity 2·56, 30 feet of coaly beds of specific gravity 1·43, 15 feet completely worked out and, from these, found the mean specific gravity to be 2·50. Employing this in his formula for the mean density of the earth, he obtained for that quantity the value $6 \cdot 566 \pm 0 \cdot 182$. In order to correct for irregularities of the terrain in the vicinity of the mine, a map showing elevations for a distance of three miles was prepared. The effect of the ellipticity and rotation of the earth forms the subject matter for the addendum by Stokes who showed that, for the latitude of the Colliery, the corrections for these would only alter Airy's value by one unit in the third place of decimals, or from 6·566 to 6·565. Everything in connection with this interesting experiment, including the preparation of an equally valuable paper, was carried out with such meticulous attention to detail that it is at first sight rather amazing that the result should differ so much from the generally accepted value, now, of 5·52[1].

Possibly the explanation lies in the difficulty of determining the precise gravitational effect of rock formations from measurement of the corresponding densities. In a recent article Sigmund Hammer[2] remarks: "It is clear that sample measurements have so large a scatter that prohibitively many measurements would be required to form a representative average density log over sufficiently large intervals. It is also evident that the attempts to recover initial conditions by soaking and vacuum saturating (under atmospheric pressure) the samples were completely futile. We are convinced that sample measurements on shales of this type are on the one hand prohibitively laborious and, on the other hand, practically valueless for the purpose of constructing a density log of the actual rocks as they exist underground."

Locations and Depths of Shafts at Lake Shore and Noranda and Tabulation of the Gravimeter Results

Relative locations of shafts 4, 5, and 6 at Lake Shore are shown in Figure 1, and those of shafts 3, 4, 5, and 6 at Noranda in Figure 2; Figure 3 shows the relative depths of the shafts of both mines. The essential data are tabulated principally in columns 1 to 4 of Tables 1 to 7. The corresponding deduced gravity gradients and densities are given in the following two columns. The gradients are all negative although they are not so indicated in the tables. They correspond to an increase of gravity with depth.

It will be noticed in the tabulations that the gravity gradients in the uppermost section at the surface are always the largest. This may be due to the fact that any irregularities in the terrain above or below the uppermost gravimeter stations have the effect of decreasing gravity at the uppermost station. As the area is partially drift covered, and therefore overlain by masses of lower density, this may also contribute to the result.

[1] Smithsonian Physical Tables, p. 75, Eighth Revised Edition, 1933.

[2] Density Determinations by Underground Gravity Measurements, Geophysics XV, No. 4, pp. 637-652, October, 1950.

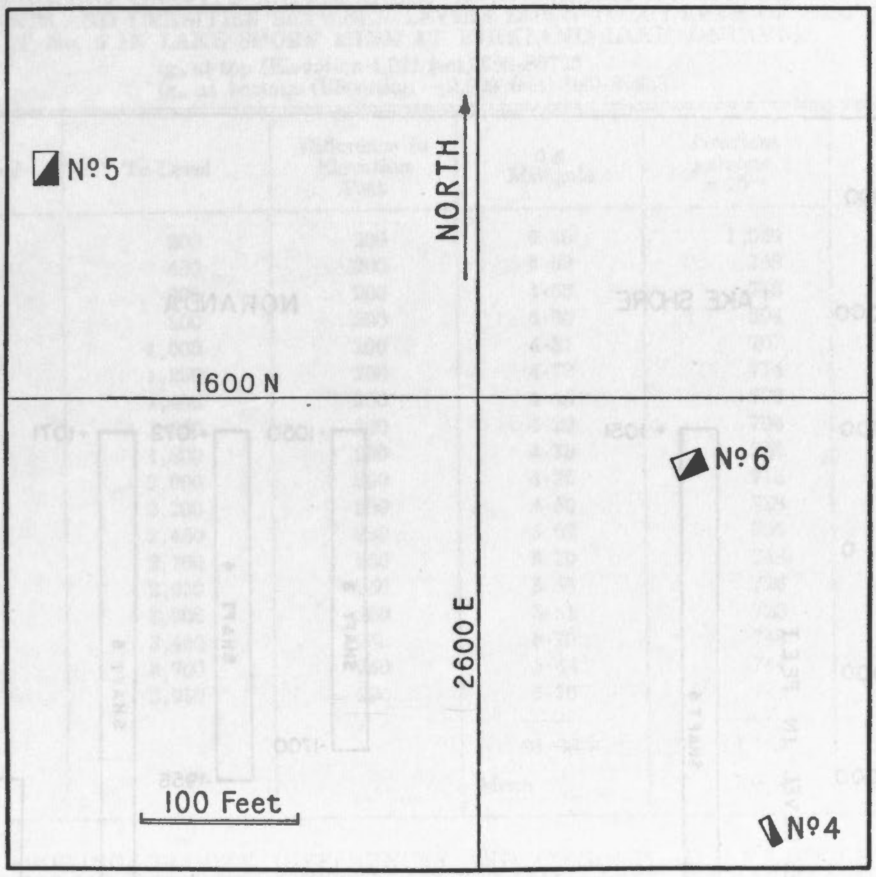

FIGURE 1—Showing location of shafts at Lake Shore.

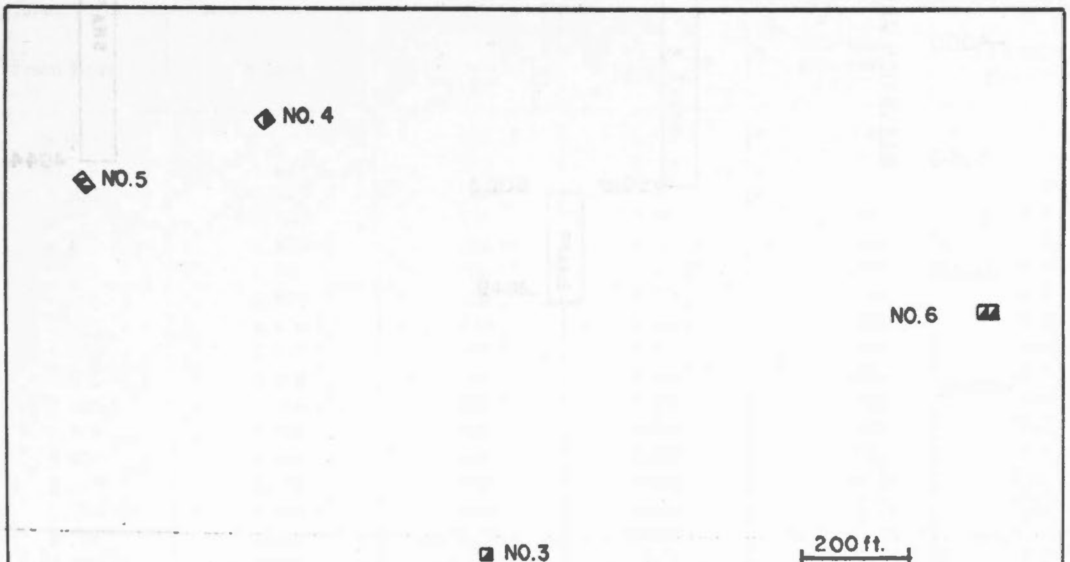

FIGURE 2—Showing location of shafts at Noranda.

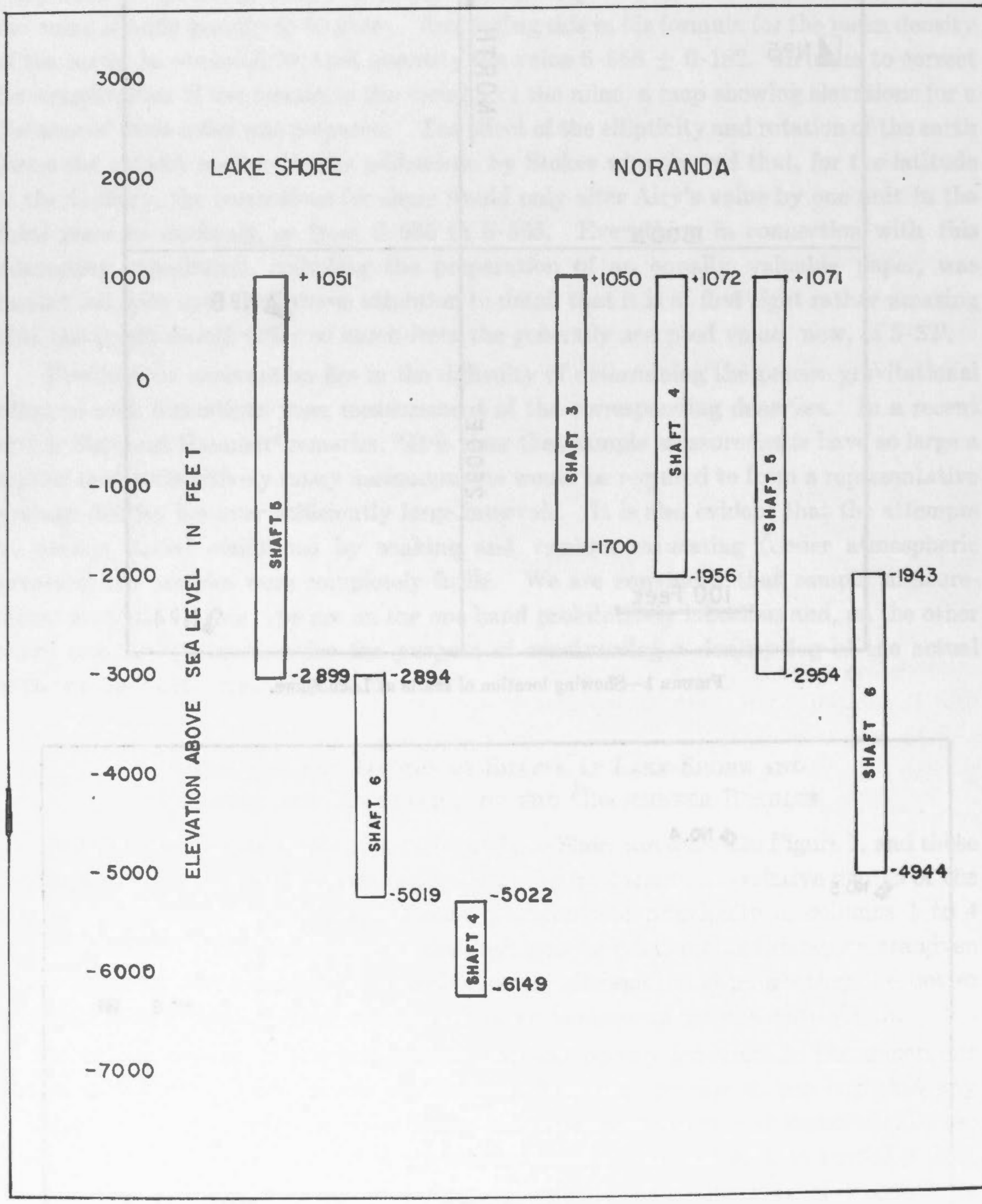

FIGURE 3—Showing elevations of shafts at Lake Shore and Noranda.

TABLE 1.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS DOWN TO A DEPTH OF 3,950 FEET IN SHAFT No. 5 IN LAKE SHORE MINE AT KIRKLAND LAKE, ONTARIO.

(g_o at top (Elevation 1,051 feet) 980·80725
(g_o at bottom (Elevation −2,899 feet) 980·89833

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	200	200	6·40	1,050	2·427
200	400	200	4·62	758	2·775
400	600	200	4·53	743	2·793
600	800	200	4·90	804	2·720
800	1,000	200	4·31	707	2·836
1,000	1,200	200	4·72	774	2·756
1,200	1,400	200	4·45	730	2·809
1,400	1,600	200	4·29	704	2·840
1,600	1,800	200	4·79	786	2·742
1,800	2,000	200	4·36	715	2·827
2,000	2,200	200	4·50	738	2·799
2,200	2,450	250	5.63	739	2·798
2,450	2,700	250	5·70	748	2·787
2,700	2,950	250	5·53	726	2·813
2,950	3,200	250	5·51	723	2·817
3,200	3,450	250	5·70	748	2·787
3,450	3,700	250	5·44	714	2·828
3,700	3,950	250	5·70	748	2·787
			91·08	13,655	49·941
			Mean	758·6	2·775

TABLE 2.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS 3,950 and 6,075 FEET IN SHAFT No. 6 IN LAKE SHORE MINE AT KIRKLAND LAKE, ONTARIO.

(g_o at top (Elevation −2,894 feet) 980·89779
(g_o at bottom (Elevation −5,019 feet) 980·94539

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
3,950	4,075	125	2.65	696	2·849
4,075	4,200	125	2·79	732	2·806
4,200	4,325	125	2·81	738	2·799
4,325	4,450	125	2·91	764	2·768
4,450	4,575	125	2·61	685	2·862
4,575	4,700	125	2·83	743	2·793
4,700	4,825	125	2·72	714	2·828
4,825	4,950	125	2·93	769	2·762
4,950	5,075	125	2·77	727	2·812
5,075	5,200	125	2·63	690	2·856
5,200	5,325	125	2·84	745	2·791
5,325	5,450	125	2·94	772	2·758
5,450	5,575	125	2·94	772	2·758
5,575	5,700	125	2·60	682	2·866
5,700	5,825	125	2·84	745	2·791
5,825	5,950	125	2·84	745	2·791
5,950	6,075	125	2·95	774	2·756
			47·60	12,493	47·646
			Mean	734·9	2·803

TABLE 3.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS 6,075 and 7,200 FEET IN LAKE SHORE MINE AT KIRKLAND LAKE, ONTARIO.

(g_o at top (Elevation −5,022 feet) 980·94502
(g_o at bottom (Elevation −6,149 feet) 980·97016

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
6,075	6,325	250	5·51	732	2·817
6,325	6,575	250	5·81	762	2·770
6,575	6,825	250	5·42	711	2·831
6,825	7,200	375	8·40	735	2·803
			25·14	2,940	11·221
			Mean	735	2·805

TABLE 4.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING DEDUCED GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS DOWN TO A DEPTH OF 2,750 FEET IN SHAFT No. 3 IN THE HORNE MINE OF NORANDA MINES LIMITED AT NORANDA, QUEBEC.

(g_o at top (Elevation 1,050·4 feet) 980·82080 gals
(g_o at bottom (Elevation −1,700·2 feet) 980·88442 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	123·1	123·1	4·17	1,111	2·354
123·1	222·8	99·7	2·35	773	2·757
222·8	324·4	101·6	2·32	749	2·786
324·4	424·8	100·4	2·44	797	2·729
424·8	524·0	99·2	2·56	847	2·669
524·0	625·7	101·7	1·99	642	2·914
625·7	745·1	119·4	2·86	786	2·742
745·1	873·7	128·6	3·17	809	2·714
873·7	998·9	125·2	3·02	791	2·736
998·9	1,123·8	124·9	2·96	778	2·751
1,123·8	1,244·4	120·6	3·07	835	2·683
1,244·4	1,373·9	129·5	2·98	755	2·779
1,373·9	1,495·3	121·4	3·37	911	2·593
1,495·3	1,623·5	128·2	3·38	865	2·647
1,623·5	1,748·4	124·9	2·27	596	2·969
1,748·4	1,873·8	125·4	2·37	620	2·940
1,873·8	1,998·6	124·8	2·65	697	2·848
1,998·6	2,124·4	125·6	2·65	692	2·854
2,124·2	2,249·1	124·9	2·96	778	2·751
2,249·1	2,374·0	124·9	2·69	707	2·836
2,374·0	2,499·0	125·0	1·93	507	3·075
2,499·0	2,750·5	251·5	5·46	712	2·830
			63·62	16,758	60·957
			Mean	761·7	2·771

TABLE 5.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING GRAVITY GRADIENTS AND DENSITIES BETWEEN LEVELS DOWN TO A DEPTH OF 3,028 FEET IN SHAFT No. 4 IN THE HORNE MINE AT NORANDA, QUEBEC

(g_o at top (Elevation 1,072·3 feet) 980·81853 gals
(g_o at bottom (Elevation −1,955·6 feet) 980·89066 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	137·6	137·6	4.88	1,164	2·291
137·6	342·0	204·4	5·18	831	2·688
342·0	543·1	201·1	5·04	822	2·699
543·1	768·3	225·2	5·42	790	2·737
768·3	1,021·9	253·6	5·77	746	2·790
1,021·9	1,147·0	125·1	2·86	750	2·785
1,147·0	1,271·2	124·2	3·05	806	2·718
1,271·2	1,397·0	125·8	2·79	728	2·811
1,397·0	1,522·0	125·0	2·81	738	2·799
1,522·0	1,650·6	128·6	2·93	747	2·788
1,650·6	1,772·0	121·4	2·89	781	2·748
1,772·0	1,901·4	129·4	2·86	725	2·815
1,901·4	2,023·8	122·4	2·88	772	2·758
2,023·8	2,151·9	128·1	2·82	722	2·818
2,151·9	2,277·1	125·2	3·33	873	2·638
2,277·1	2,402·2	125·1	2·43	637	2·920
2,402·2	2,527·8	125·6	2·82	737	2·800
2,527·8	2,651·6	123·8	2·77	734	2·804
2,651·6	2,777·7	126·1	2·88	749	2·786
2,777·7	2,901·6	123·9	2.70	715	2·827
2,901·6	3,027·9	126·3	3·02	784	2·744
			72·13	16,351	57·764
			Mean	778·6	2·751

TABLE 6.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING GRAVITY GRADIENTS AND DENSITIES DOWN TO A DEPTH OF 4,025 FEET IN SHAFT No. 5 IN THE HORNE MINE AT NORANDA, QUEBEC.

(g_o at top (Elevation 1,070·8 feet) 980·81865 gals
(g_o at bottom (Elevation −2,954·0 feet) 980·91313 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
0	133·9	133·9	4·38	1,073	2·399
133·9	338·1	204·2	5·42	871	2·640
338·1	762·8	424·7	10·58	817	2·705
762·8	1,016·9	254·1	5·46	705	2·838
1,016·9	1,269·4	252·5	6·26	813	2·710
1,269·4	1,518·7	249·3	5·63	741	2·795
1,518·7	1,769·0	250·3	6·12	802	2·723
1,769·0	2,019·5	250·5	5·39	706	2·837
2,019·5	2,272·9	253·4	6·01	778	2·751
2,272·9	2,525·2	252·3	5·58	726	2·813
2,525·2	2,773·6	248·4	5·79	765	2·767
2,773·6	3,023·9	250·3	5·42	710	2·833
3,023·9	3,273·9	250·0	5·93	778	2·751
3,273·9	3,523·3	249·4	5·60	737	2·800
3,523·3	3,774·2	250·9	5·56	727	2·812
3,774.2	4,024·7	250·5	5·35	701	2·843
			94·48	12,450	44·017
			Mean	778·1	2·751

TABLE 7.—SHOWING GRAVITY DIFFERENCES AND CORRESPONDING GRAVITY GRADIENTS AND DENSITIES FROM THE TOP OF THE SHAFT No. 6 DOWN TO A DEPTH OF 3,001 FEET IN THE SHAFT CORRESPONDING TO A DEPTH OF 7,026 FEET BELOW THE TOP OF SHAFT No. 5 IN HORNE MINE AT NORANDA, QUEBEC.

(g_o at top (Elevation −1,943·2 feet) 980·89078 gals
(g_o at bottom (Elevation −4,943·9 feet) 980·95848 gals

From Level	To Level	Difference in Elevation Feet	Δ g Milligals	Gradient gals/cm. x 10^{-9}	Density gms./cc.
3,014·9	3,513·5	499·5	10·83	711	2·832
3,513·5	3,762·8	249·3	5·70	750	2·785
3,762·8	4,013·7	250·9	5·49	718	2·823
4,013·7	4,264·5	250·8	5·39	705	2·838
4,264·5	4,514·5	250·0	6·10	801	2·724
4,514·5	4,764·5	250·0	5·60	735	2·803
4,764·5	5,014·7	250·2	5·84	766	2·766
5,014·7	5,264·7	250·0	5·63	739	2·798
5,264·7	5,514·7	250·0	5·82	764	2·768
5,514·7	6,014·7	500·0	11·30	741	2·795
			67·70	7,430	27·932
			Mean	743	2·793

Application of Airy's Method to Lake Shore and Noranda

The accuracy of Airy's method to determine the mean density of the earth depends primarily[1] upon the accuracy of the gravity measurements and of the value to be used for the mean density of the rocks lying between the upper and lower gravity stations. If $\bar{\rho}$ is to be determined with an error not exceeding $\frac{1}{500}$th part of the whole, g_a, g_b must be known to one part in a million or to 1 milligal, while the error in ρ must not exceed 0·005 gms. per cc.

The errors in the gravity measurement for Lake Shore and Noranda are considered to be less than $\frac{1}{10}$ milligal and therefore would not affect the results within the desired limits of accuracy. On the other hand no direct determinations of density by weighing were made by the authors either at Lake Shore or Noranda. The most plausible density available seemed to be that obtained by Garland for thirteen listed groups of Precambrian rocks[2] and equals 2·794 gms. per cc. When this value of ρ is substituted in Airy's formula, and if the values of gravity obtained by Innes at the top of shaft 5 and the bottom of shaft 4 at Lake Shore (a depth of 7,200 feet corresponding to Δr) are used for g_a and g_b, there is obtained

$$\frac{\rho}{\bar{\rho}} = 0\cdot506 \text{ or } \bar{\rho} = 5\cdot52 \text{ gms. per cc.}$$

[1] The results are insensitive to large error in the value adopted for r, the radius of the earth, while Δr the depth of the mine is ascertained by direct measurement.

[2] Publications of the Dominion Observatory, XVI, No. 1, p. 48.

Similar application of the results obtained for shafts 4 and 5 of Noranda mine (a depth of 6,016 feet) gives

$$\frac{\rho}{\bar{\rho}} = 0\cdot 502 \text{ or } \bar{\rho} = 5\cdot 57 \text{ gms. per cc.}$$

These results are within one per cent of the accepted[1] value of the mean density of the earth, and are as good as one would expect considering the uncertainty of the value used for ρ.

The Vertical Gradient and the Mean Density of the Earth

The formula[2] for the vertical gradient of gravity in a sphere is given by

$$\frac{dg}{ar} = 4\,\pi\,G\left[\rho - \frac{2}{3}\bar{\rho}\right] \qquad \text{.......... (2)}$$

where $\frac{dg}{ar}$ is the gradient, G is the gravitational constant, ρ is the density at radius r, and $\bar{\rho}$ is the mean density of the earth regarded as spherical and without rotation. Before applying the observations (obtained on the earth which is rotating) it is of interest to make an estimate of the effect of the ellipticity and rotation of the actual earth which approaches the form of that of a spheroid. The matter has previously been investigated by Stokes in connection with Airy's observations.

Stokes developed the following equation[3] for the vertical gradient of gravity neglecting squares and higher powers of ϵ and m:

$$-\frac{1}{g}\frac{dg}{dr} = \frac{2}{r}\left(1 - 2\,\epsilon\cos^2\theta + \epsilon + m\right) \qquad \text{.......... (3)}$$

where θ is the co-latitude, ϵ is the ellipticity and m is the ratio of the centrifugal force to gravity at the equator, equal respectively to $\frac{1}{297}$ and $\frac{1}{288\cdot 36}$ for the international spheroid.

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[1] The generally accepted value of $\bar{\rho}$ is $5\cdot 52$ (Smithsonian Physical Tables, p. 75, Eighth Revised Edition, 1933), while the international formula for gravity implies a mean density for the spheroid of $5\cdot 5124$ gm./cm.³ (Gravity Anomalies and the Figure of the Earth, Professional Paper No. 30, Survey of India, 1940, p. 34, by B. L. Gulatee).

[2] Note on the Variation of Gravity with Depth, by A. E. Benfield, Zeitscrift fur Geophysik, Vol. XIII, p. 157, 1937. Gravity in the Interior of the Earth, by R. Meldrum Stewart, Contributions from the Dominion Observatory, Vol. I, No. 4, 1950.

For a spherical earth of radius r and mean density $\bar{\rho}$, gravity on it is given by

$$g_b = \frac{4}{3}\pi\,G\,r\,\bar{\rho} \qquad \text{.......... (i)}$$

If surrounded by a spherical shell of radius r+Δr and of density ρ, neglecting second order terms, gravity at the surface will be

$$g_b = \frac{4}{3}\pi\,G\,r\,\bar{\rho}\left[1 - 2\frac{\Delta r}{r} + 3\frac{\Delta r}{r}\frac{\rho}{\bar{\rho}}\right] \qquad \text{.......... (ii)}$$

Airy's formula (1) and the formula for the vertical gradient (2) are obtained by division and subtraction respectively of these two equations.

It is also of interest to note that the formula frequently employed for reduction of subsurface observations of gravity is equivalent to equation (2); namely

$$-\Delta g = \text{Free Air Correction} - 2 \text{ x Bouguer Correction for an infinite slab}$$

$$= \left(2 \text{ x } \frac{4}{3}\pi\,G\bar{\rho} - 4\,\pi\,G\,\rho\right)\Delta r$$

$$\text{or} \quad \frac{\Delta g}{\Delta r} = 4\,\pi\,G\left(\rho - \frac{2}{3}\bar{\rho}\right)$$

[3] This equation reduces to equation (2) on the assumption of ϵ and m = 0, as is the case for a sphere without rotation, and assuming also that ρ = 0, as it is effectively on the surface of the earth.

TABLE 8.

(1)	(2) Depth	(3) Δ g (Observed) (gals)	(4) Centrifugal Effect (gals)	(5) Δ g (Corrected) (gals)	(6) $\frac{dg}{dr}$ (gals per cm. x 10^9)	(7) $\bar{\rho}$ (gm./cm.^{3})	(8) G x 10^9	(9) ρ (gm./cm.^{3})
1. Lake Shore Mine Shafts No. 4, 5	Surface to 7,200 ft.	0·16291	0·00052	0·16239	739·97	5·516	66·46	2·797
2. Noranda Mine Shafts No. 4, 6	Surface to 6,016·2 ft.	0·13995	0·00043	0·13952	760·87	5·553	68·34	2·772
3. Lake Shore Mine Shaft No. 5	200 ft. to 3,950 ft.	0·08468	0·00027	0·08441	738·50	5·513	66·33	2·799
4. Noranda Mine Shaft No. 5	133·9 ft. to 4,027·7 ft.	0·09010	0·00028	0·08982	757·740	5·547	68·03	2·776

This equation shows that in relation to unity the combined effects of ellipticity and rotation are at the equator $\epsilon + m$, at latitude 45° m, and at the pole $-\epsilon + m$. The effect on the gradient at latitude 45° is thus entirely that due to centrifugal force. At Kirkland Lake and approximately also at Noranda $\cos^2\theta = 0{\cdot}5549$, so that $-2\epsilon\cos^2\theta + \epsilon + m = -0{\cdot}111\,\epsilon + m$, and the combined effect of ellipticity and rotation is largely due to centrifugal force at that latitude also. This combined effect corresponds to somewhat more than one part in 300 of the total gradient.

The Centrifugal force at latitude φ resolved in the direction of the vertical is $r\,w^2\cos^2\varphi$ and at a depth h is $(r-h)\,w^2\cos^2\varphi$, where r is the radius of the earth and w the angular velocity. Between the surface and a point in the interior the difference is $h\,w^2\cos^2\varphi$. For the latitude of Kirkland Lake and Noranda, 48°09·0 and 48°14·9 respectively, the values of $h\,w^2\cos^2\varphi$ are $0{\cdot}721 \times 10^{-4}$ and $0{\cdot}719 \times 10^{-4}$ in units of cm. per sec.^{2} for h equal to 1,000 feet.

The total centrifugal effect in the observed gravity difference between upper and lower stations is tabulated in column (4) of Table 8. It amounts to $5{\cdot}2 \times 10^{-4}$ and $4{\cdot}3 \times 10^{-4}$ cm. per sec.^{2} for Lake Shore mine and Noranda mine respectively. Column 5 gives the gravity difference and column 6, the gradient of gravity corrected for rotation. The gradients have been employed using formula (2) to derive a value for each of the quantities ρ, G, and ρ, in turn, on the assumption of the accepted values of the other two. The results are given in columns 7, 8 and 9 of Table 8.

The values obtained for ρ, the mean density of the earth, do not differ significantly from those obtained using Airy's method which does not involve assumption of the value[1] of the gravitational constant.

As objection may be reasonably raised to determination of gradients from observations of gravity which do not lie on the same vertical, lines 3 and 4 of Table 8 were prepared from observations taken in shaft 5 at Lake Shore and the same numbered shaft at Noranda. The results differ slightly but not significantly from those previously obtained for the respective mines (lines 1 and 2, Table 8).

In order to eliminate the apparently anomalous gradient usually observed at the top levels, the gradients for these shafts have been computed from the second level to the bases of the shafts.

Column 9, Table 8, shows that the assumed mean value for the density of the rocks (2·794) fits Lake Shore mine as well as might reasonably be expected, but that this value is somewhat too large for Noranda. However, even for Noranda the difference between the previously assumed value and that computed from the observations is only 0·02 from Garland's mean value for Precambrian rocks of the district, namely 2·794.

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[1] Heyl gives $66{\cdot}64 \times 10^9$ for G in his paper "A Redetermination of the Newtonian Constant of Gravitation", Proc. Nat. Acad. of Sciences, pp. 601-605, Vol. 13, 1927. The value $66{\cdot}7 \times 10^{-9}$ has usually been employed by the writers as it has frequently been adopted by others and is convenient in computation, being nearly equivalent to

$$\frac{200}{3} \times 10^{-9}$$

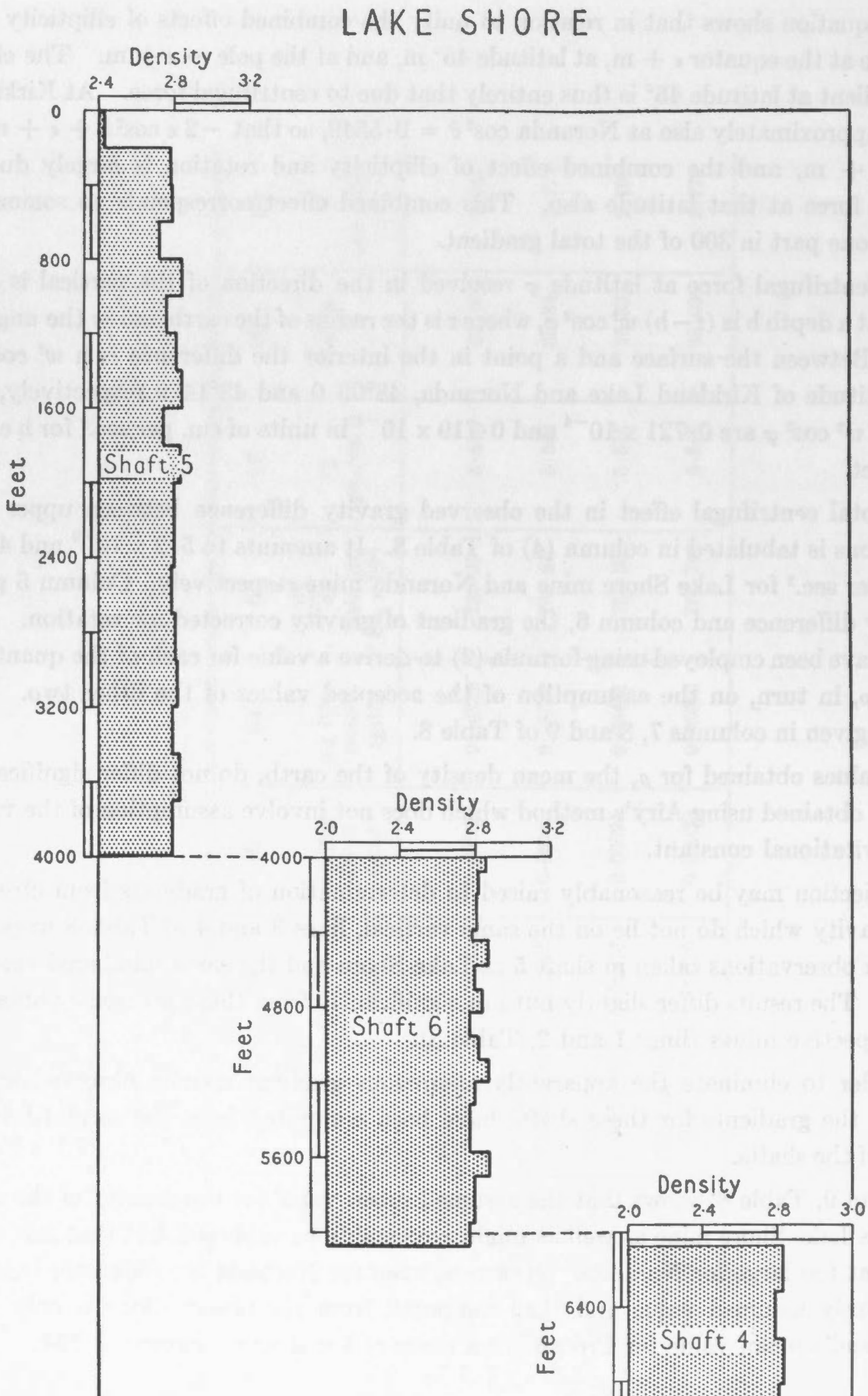

FIGURE 4—Showing density profiles for shafts 5, 6, and 4 at Lake Shore.

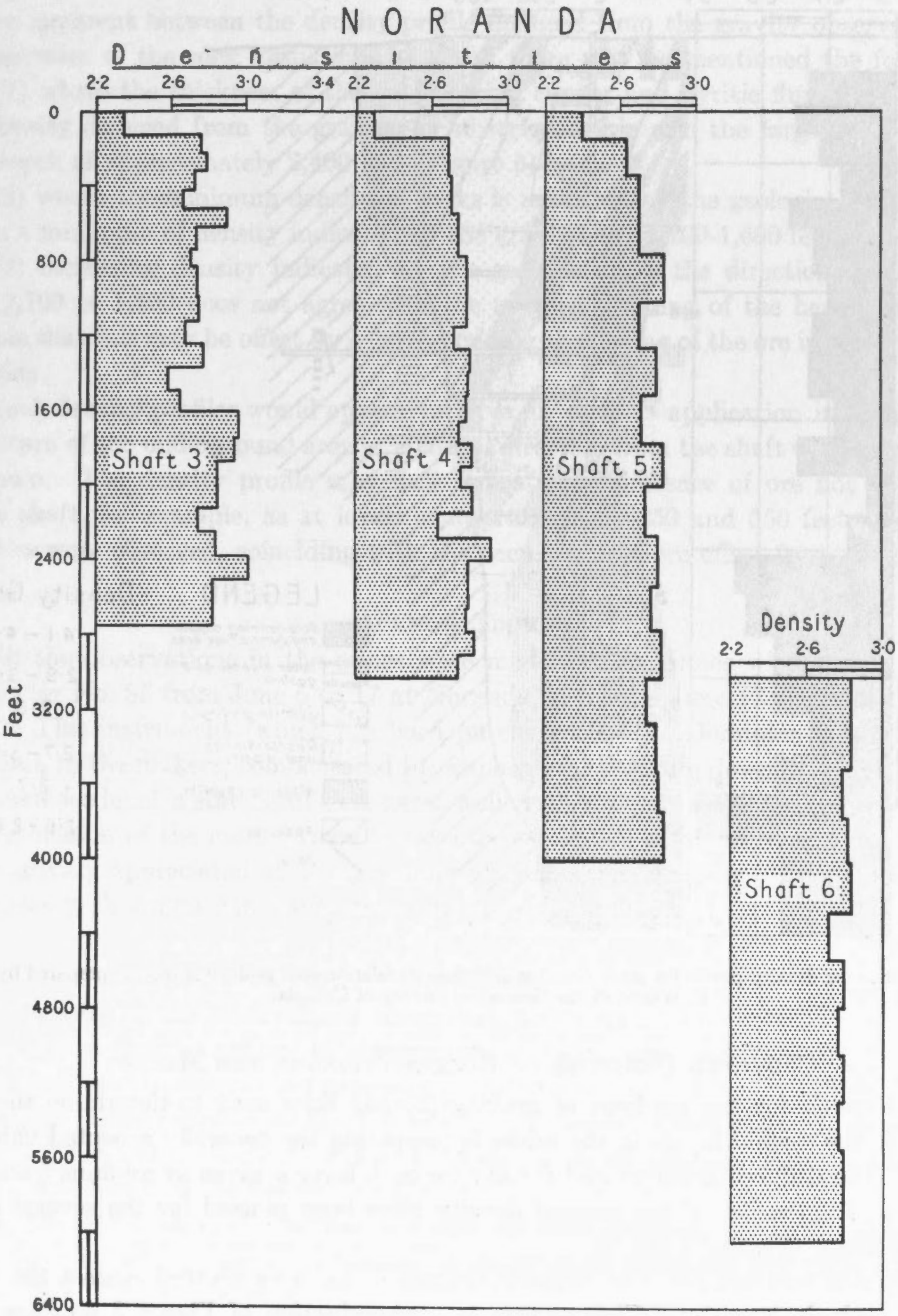

FIGURE 5—Showing density profiles for shafts 3, 4, 5, and 6 at Noranda.

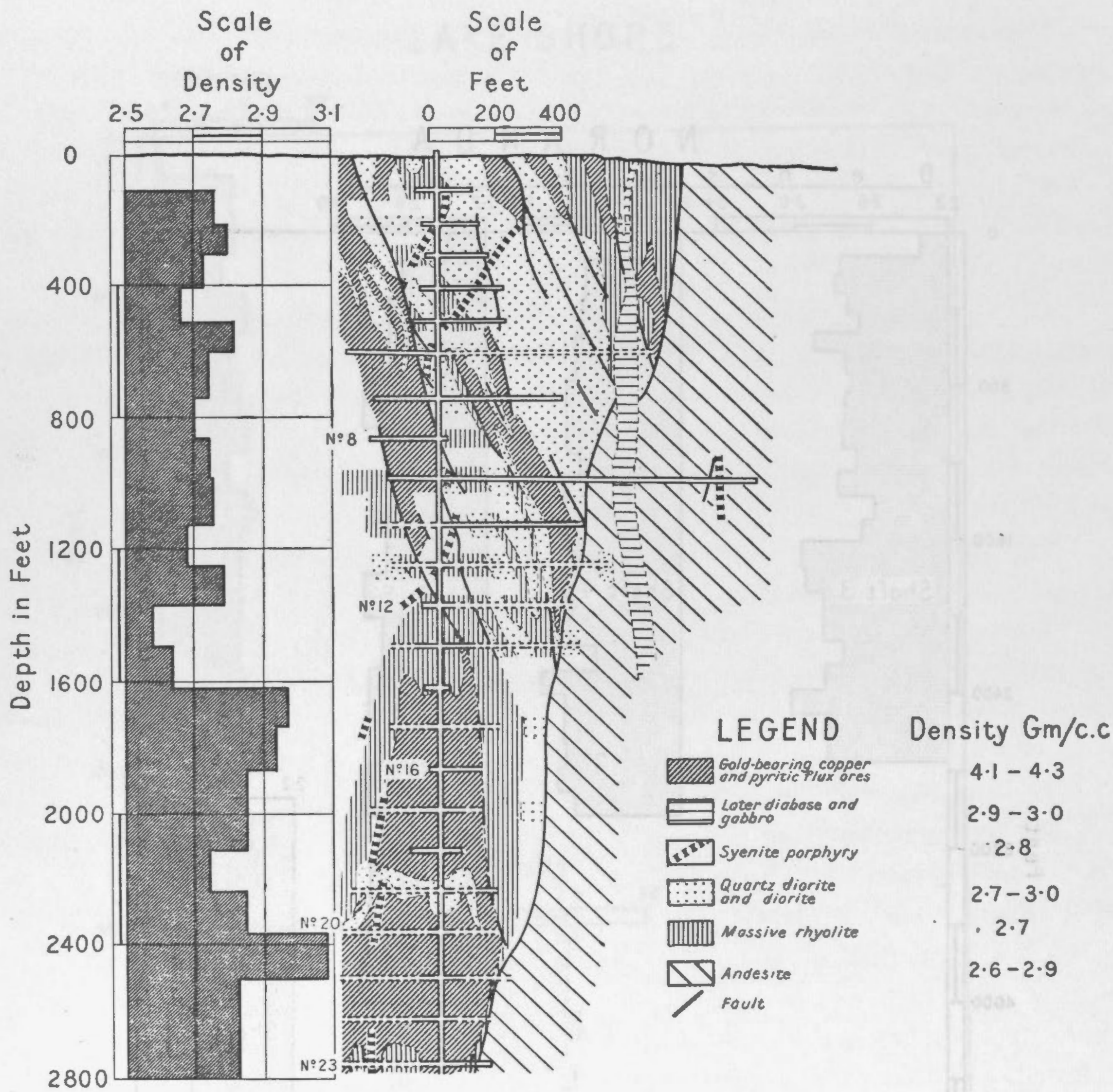

FIGURE 6—Showing density profile for shaft No. 3 at Noranda in relation to a geological section prepared by Dr. M E. Wilson of the Geological Survey of Canada.

COMPUTED DENSITIES OF ROCK SECTIONS IN THE MINES

The formula for the gradient of gravity (2) has been used to determine the rock densities of the several layers in the mines by assuming the generally accepted values of G and ρ. The deduced gradient and density for each layer is given in columns 5 and 6 of Tables 1 to 7. Profiles of the derived density have been plotted for the several shafts in the two mines (Figures 4 and 5).

The profile for shaft No. 3 at Noranda (Figure 6) has been plotted against the corresponding geological section. This section is a reproduction of Figure 3 on Page 62 of Geological Survey Memoir 229 by M. E. Wilson, 1941. Densities of the rocks listed in the legend have been added by the authors of this paper and were taken chiefly from values given by Heiland[1].

[1] Geophysical Exploration, C. A. Heiland, 1940.

A considerable amount of ore has been removed from the mine and it is possible that the distribution of the stopes could be such as to invalidate any comparison between the deduced densities and the geological section. Certain obvious relations are nevertheless apparent between the density profile deduced from the gravity observations and the densities of the rock formations of which there may be mentioned the following:

(1) where the thickness of the gold-bearing copper and pyritic flux ores is greatest, the density deduced from the gravimeter observations is also the largest. This occurs at a depth of approximately 2,400 feet (Figure 6);

(2) where the minimum density of rocks is indicated by the geological section, there is also a minimum of density indicated by the gravimeter (1,200-1,600 feet) in the profile;

(3) increasing density indicated by the gravimeter in the direction upwards from level 2,100 to 1,600 does not agree with the upward thinning of the heavy ore*. It is possible that this may be offset by a corresponding thickening of the ore in a perpendicular direction.

Such density profiles would appear to have an obvious application in a shaft where the nature of the underground area in a lateral direction from the shaft was comparatively unknown. The density profile may well indicate the presence of ore not encountered in the shaft, for example, as at levels of approximately 250 and 550 feet where larger densities were observed, coinciding with the occurrence of ore offset from the shaft.

Acknowledgment

All the observations in the mines were made by Mr. Innes with North American gravimeter No. 85 from June 5 to 17 at Noranda, and from June 17 to 22, 1948 at Lake Shore. This instrument (which has been purchased by the Dominion Observatory) is, according to the makers, compensated for atmospheric pressure down to a depth of 6,000 feet below sea level, a statement that seems well verified by the results of the observations.

Permission of the mine owners to take the observations rendered this work possible and is greatly appreciated as is the willing assistance rendered by all mine officials and employees with whom Mr. Innes came in contact.

Conclusion

1. Results of the observations show that Airy's method of determining the mean density of the earth as applied to observations at Lake Shore and Noranda yields values that are reasonably close to the generally accepted value of $5 \cdot 52$.

2. The density profile deduced from the gravimeter observations at Noranda, for which a geological section was available, shows a direct relation between the density and the occurrence of the ore.

3. The results also indicate that, in a mine not fully explored, gravimeter observations would be of value in giving an indication of the levels at which ore was most likely to be found.

* Since the above was written, samples of backfill employed in the mining operations have been supplied by the mining company. Measurement of several samples when saturated (as the backfill would no doubt be in the mine) gave a density of $2 \cdot 47$ gms. per cc. The backfill is therefore lighter than any of the rocks shown in Figure 6. Knowledge of this density would not appear to alter the validity of any statements made above. It may indicate, for example, that between the 14th and 19th levels proportionally increasing amount of backfill had been employed, that comparatively less backfill had been put in between the 20th and 21st level than between the 21st and 23rd.