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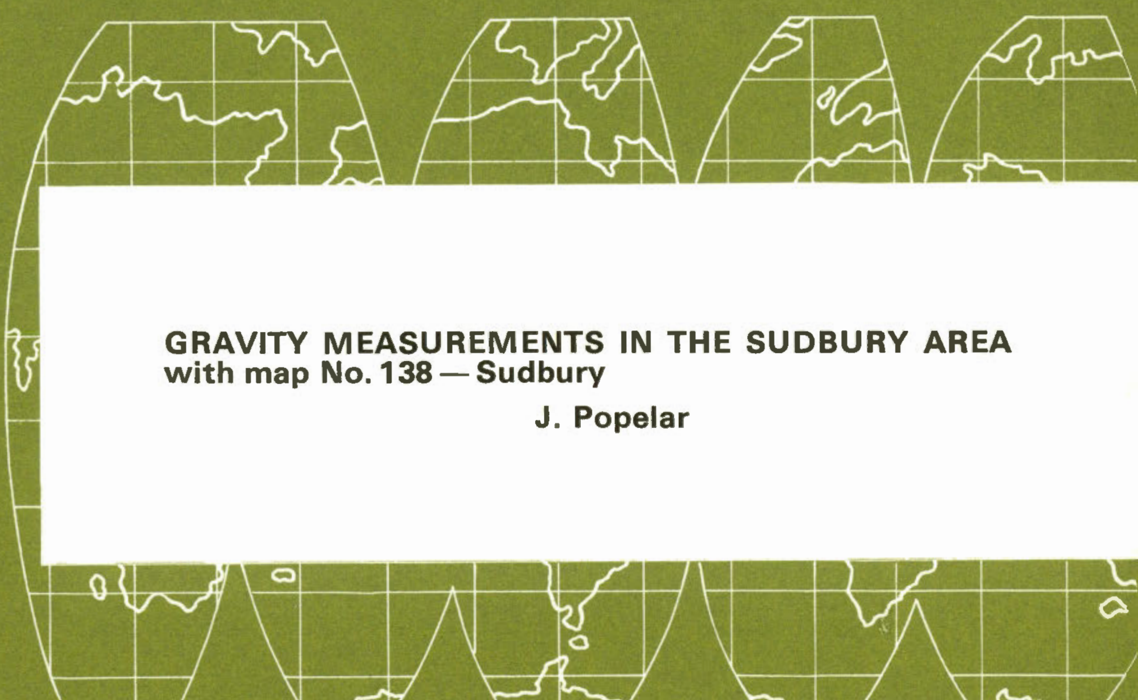

GRAVITY MEASUREMENTS IN THE SUDBURY AREA
with map No. 138 — Sudbury

J. Popelar

DEPARTMENT OF ENERGY, MINES AND RESOURCES
OTTAWA, CANADA 1971

GRAVITY MAP SERIES

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GRAVITY MEASUREMENTS IN THE SUDBURY AREA

J. Popelar

ABSTRACT - A total of 2,302 gravity stations established in the Sudbury area (N. T. S. map sheet 41 I) in the period 1945-1969, was used to compile the Bouguer gravity anomaly map (scale 1:250,000) with 2 mgal contour interval. Most of the area is characterized by a relatively positive regional gravity anomaly which in its western part includes the Sudbury structure; it may reflect the distribution of gabbro-anorthositic rocks within the crust. Regional gravity lows appear to be related to large bodies of granite, such as the Cartier granite and the Killarney granite, or to granite-gneisses of the Grenville Province. Many local gravity anomalies correlate well with the geology but the Sudbury structure itself cannot be related to a simple gravity anomaly.

RÉSUMÉ - Les 2,302 stations gravimétriques établies dans la région de Sudbury (coupure de carte 41 I du Système national de référence cartographique) entre 1945 et 1969 ont servi à compiler la Carte gravimétrique des anomalies de Bouguer (échelle au 1:250,000, équidistance des courbes, 2 mgals). La majeure partie de la région est caractérisée par une anomalie gravimétrique régionale relativement positive qui comprend dans sa partie ouest la structure de Sudbury; c'est peut-être le résultat de la répartition du gabbro et des roches anorthositiques dans la croûte. Les anomalies négatives régionales semblent se rattacher aux importants massifs de granite, comme les granites de Cartier et de Killarney, ou les granites-gneiss de la province de Grenville. Plusieurs anomalies gravimétriques locales correspondent bien à la géologie, mais la structure de Sudbury ne peut être rattachée à une simple anomalie gravimétrique.

INTRODUCTION

For more than 80 years the Sudbury area has been subjected to intense geological investigations. Because of its economic importance this interest of geologists has never lessened and a large amount of geological information has been collected. Nevertheless, the basic problems of Sudbury geology have not been solved and many of the main geological features of the area remain a matter of different geological interpretations. Unfortunately, the role of geophysics in the Sudbury area has been greatly underestimated, and there are few geophysical data compared with the extensive geological studies.

The first gravity measurements in the Sudbury area were carried out in 1945 when nine gravity stations were established by the Dominion Observatory (now the Earth Physics Branch of the Department of Energy, Mines and Resources). In 1948 the first attempt to map the gravity field of the area was made and in the following years, 1949-1952, additional observations were made in connection with other gravity surveys of the Dominion Observatory. On the basis of these measurements the Bouguer gravity anomaly map that accompanied the Dominion Observatory publication by Miller and Innes (1955) was compiled. Although the number of stations, 494 altogether, and their irregular distribution were hardly adequate for detailed geological interpretations, the major features of the gravity field of the area were established and a good correlation between the gravity anomalies and densities of the surface rock formations was clearly indicated. The quantitative computations for Collins' model of the Sudbury structure (Miller and Innes, 1955) undoubtedly established the effect such a structure should have on the gravity field. Its magnitude and extent ensured that it would be detected by a detailed gravity survey. The groundwork for further gravity studies was laid.

In the decade from 1955 to 1965 many more gravity stations were established, most of them by the mining companies in the region. The work by the Dominion Observatory was limited to providing the gravity control station network and to some regional gravity surveys outside the Sudbury structure in connection with the systematic gravity survey of Canada. Results of this regional work were published in 1968 in the form of a Bouguer anomaly map at a scale of 1:500,000 (Dominion Observatory Gravity Map Series No. 84). This map although very useful for studies of major crustal units is of little help for detailed geological interpretation in the Sudbury area.

Through the courtesy of Falconbridge Nickel Mines the Dominion Observatory obtained the principal facts for an additional 911 gravity measurements made by this company in 1961 mainly within the limits of the Sudbury Irruptive. This increased the number of gravity observations in the Sudbury area considerably and the need for a new compilation detailed enough to show the gravity information available was evident. In 1968 a project was initiated aimed at re-evaluating all the gravity data in the Sudbury area and preparing a new gravity anomaly map. Additional field work was done by the author in 1969 to fill in some major gaps in the regional gravity survey within the limits of the N.T.S. sheet 41 I - Sudbury. Eight detailed gravity profiles were also measured to support the geological interpretation. These measurements were planned so that they would be an effective check on the accuracy of the older observations and would provide a common base for a new evaluation of all the gravity data.

This report describes the characteristics of the gravity data, the methods of their reduction and the compilation of the gravity anomaly map. Only a brief description of the major features of the gravity field is given. A more comprehensive geological interpretation of the gravity anomalies will be given in separate publications.

GRAVITY MEASUREMENTS

Altogether 2,302 gravity stations observed in the Sudbury area (N.T.S. map sheet 41 I) in the period 1945-1969 were available for the compilation of the new Bouguer gravity anomaly map at a scale of 1:250,000. Table I summarizes the contributions of the different gravity surveys. The following description of the data depends on the available records which particularly for some of the older measurements are not always complete. The field procedures of each survey were determined by their specific objectives and prevailing conditions such as the type of instruments used and the means of transportation. Many different methods of transportation have been used in the area (car, train, aircraft, helicopter, boat, snowmobile, etc.).

Gravity Control and Accuracy

The older measurements taken during the period 1945-1952 were uniformly processed by Miller and Innes (1955) and tied to an adopted value of 980,686.00 mgal at the Sudbury Technical High School. There is no exact record of which instruments were used in the Sudbury area during those surveys but it is probable that most of the gravity measurements were made with Atlas and North American gravimeters. The error of the observed gravity values was estimated to be ±0.1 mgal (Miller and Innes, 1955).

TABLE I

Surveys Contributing Data to this Report

Year	Area of Survey	Party Chief	Number of Stations within Map Area
1945	Ontario	A.H. Miller	9
1948	Sudbury Basin		389
1949	Ontario		16
1951	Ontario	M.J.S. Innes	74
1952	Sudbury		8
1957	Manitoulin Island		122
1961	Sudbury Basin Falconbridge Nickel Mines	D. Fraser	911
1963	Northern Ontario		12
1965	Northern Ontario	R.K. McConnell	109
1969	Sudbury	J. Popelar	652

The 1957 survey was based upon the value of 980,674.20 mgal for gravity at the Espanola station. The gravity measurements were carried out with Worden and North American gravimeters. No specific estimate of the accuracy of the measurements is available.

The 1961 survey by Falconbridge Nickel Mines was done with two Worden gravimeters. The local control station network was established by the Dominion Observatory and was adjusted with respect to a base value of 980,679.51 mgal for gravity at Sudbury Airport. There is no specific information about the accuracy of these gravity measurements.

The 1963 and 1965 regional surveys were tied to gravity control stations established by the Dominion Observatory (Winter, 1967). The gravity measurements were made with Worden gravimeters and errors of the observed gravity values were estimated to be in the range 0.15 to 0.25 mgal (Gibb and McConnell, 1970).

In 1969, as part of the additional gravity survey of the Sudbury area, new measurements in the Gravity Control Station Network were made with two LaCoste and Romberg gravimeters. Five new control stations were established and ties between National Gravity Net stations were included. Local adjustment of the control network was based upon the value of 980,679.49 mgal for gravity at the Sudbury Airport. The mean square error of the adjusted gravity values relative to the Sudbury Airport is ± 0.05 mgal. Data for all gravity control stations and their descriptions according to N.T.S. map sheets can be obtained from the Gravity Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa.

All the observed gravity values were transformed to this new base. This was accomplished by a shift of -0.35 mgal in the observed gravity values for the data listed by Miller and Innes (1955) and a shift of -0.42 mgal for the data from the Manitoulin Island survey in 1957. All the rest of the gravity measurements (1961-1969) were reprocessed and tied directly to the newly adjusted control network, traverse by traverse.

The additional gravity measurements in 1969 consisted of 365 regional stations and 287 stations situated along eight detailed gravity profiles. All regional and most of the detailed measurements were made with Worden gravimeter No. 807. The remaining 62 stations on the ice of Lake Wanapitei were measured with LaCoste and Romberg gravimeter No. 172 which has a special damping mechanism. The accuracy of the gravity measurements was determined from 92 repeated readings at 38 stations; the mean error of the observed gravity was ± 0.07 mgal.

Although an attempt was made to re-occupy 84 of the older gravity stations, a direct comparison of the observed gravity values could not be made as no detailed descriptions of the older sites were available. Of the resulting uncertainties in position, those with regard to elevation caused the main problem. Therefore only a comparison of the Bouguer anomaly values has been made, as given below.

Elevations

Elevations for most of the gravity stations were derived from altimeter readings taken concurrently with the gravimeter measurements. Appropriate corrections for temperature and humidity variations and pressure patterns were usually applied. The main difficulty in obtaining accurate elevations for the gravity stations comes from an insufficient network of reliable vertical control points. In the Sudbury area it is particularly regrettable that a large number of bench marks have been thoughtlessly damaged during road building and other construction works. This interferes with field measurements which are usually planned in advance and requires the observer to tie vertical traverses to less reliable datum points. Except for bench marks, the quality of other vertical control points is questionable. Their accuracy is not better than ± 10 feet which is the limiting factor for elevation measurements during regional surveys. Unfortunately some data from earlier altimeter surveys can be in error by as much as 50 feet.

Miller and Innes (1955) estimated that the mean elevation error in their survey was ± 8 feet. Gibb and McConnell (1970) adopted an elevation error in the range 10 to 30 feet. No other information about the accuracy of the older elevation measurements is available.

In 1969 the mean square error of the altimeter elevations of the gravity stations computed from 382 repeated altimeter measurements at 174 stations was ± 9.4 feet. Each measurement represents independent readings on two Wallace and Tiernan altimeters. Elevations of the stations along the detailed gravity profiles were levelled or tied to a levelled railroad profile and their mean square error is better than ± 1 foot.

The mean elevation for all the gravity stations in the Sudbury area is about 940 feet with a standard deviation of ±180 feet. The relief of the area is moderate with only a few exceptions and slopes gently to the northwest.

Horizontal Control

The gravity stations were originally positioned according to topographic maps which were available to the observers at the time of various surveys. From those maps geodetic co-ordinates of the gravity stations were determined. Accuracy of the scaling differed from survey to survey depending on the quality and scale of the maps used. Because this caused some confusion in more densely covered parts of the Sudbury area, it was decided to replot all the gravity stations from the older maps on to the latest N.T.S. maps at a scale of 1:50,000. This has been done using points readily identifiable on both old and new topographic maps. All the gravity stations were then rescaled. The estimated error in the station positions is ±100 m for the regional survey and ±25 m for the detailed profiles.

Bouguer Anomaly Values

The gravity observations were reduced to Bouguer anomalies using a computer oriented system (Tanner and Buck, 1964). The standard density of 2.67 g/cm^3 was used for the Bouguer reduction. Terrain corrections which are not considered to exceed 2 mgal for most of the stations were not applied. For the stations measured on the ice of Lake Wanapitei and on its shore exact corrections for the body of water were introduced; a contoured bathymetric map of the lake was obtained for this purpose from the Ontario Department of Lands and Forests.

All the errors mentioned above contribute to the error of the final Bouguer anomaly values. By far the largest contribution comes from the uncertainty in elevation measurements. The final mean square error of the Bouguer anomalies without terrain corrections is ±0.61 mgal. This value agrees very well with a figure obtained by comparing the Bouguer anomalies at the "re-occupied" older stations. From 84 such stations only four were rejected because of large unexplainable differences of 2.3 to 8.8 mgal. The remaining 80 stations show satisfactory agreement in Bouguer anomaly values, the mean difference being ±0.65 mgal.

Clear relationships were noted in the Sudbury area between the reduction density σ, the variation of the Bouguer anomalies and their correlation with station elevations (Figure 1). The correlation coefficient $\mathbf{r}$ between the Bouguer anomalies and the station elevations shows a very regular decrease with increasing reduction density. The positive correlation for the free-air anomalies ($\sigma = 0.0$ g/cm^3) drops to zero for $\sigma \sim 1.46$ g/cm^3 and changes to a negative correlation for the Bouguer anomalies using higher reduction densities. The variance of the Bouguer anomalies is shown in Figure 1 in terms of a standard deviation from the mean, δ. The minimum variance corresponds to Bouguer anomalies with a reduction density of about 1.5 g/cm^3. Although the differences in both variables, $\mathbf{r}$ and δ, are very small their dependence on the reduction density is unquestionable. The fictive optimum reduction density of about 1.5 g/cm^3 clearly disagrees with the actual densities of the surface rock formations in the area. This could mean that the topographic masses are partially compensated within the earth's crust or at its lower boundary.

Isostatic corrections were evaluated in the Sudbury area according to the Vening Meinesz model for isostatic compensation. All the isostatic corrections for the N.T.S. sheet 41 I - Sudbury show very regular gradients in the north-northwest direction. This amounts to as much as 20 mgal for local compensation with a normal crust 20 km thick or as little as 8 mgal for the maximum computed regional compensation (R = 232.4 km) with a normal crustal thickness of 40 km.

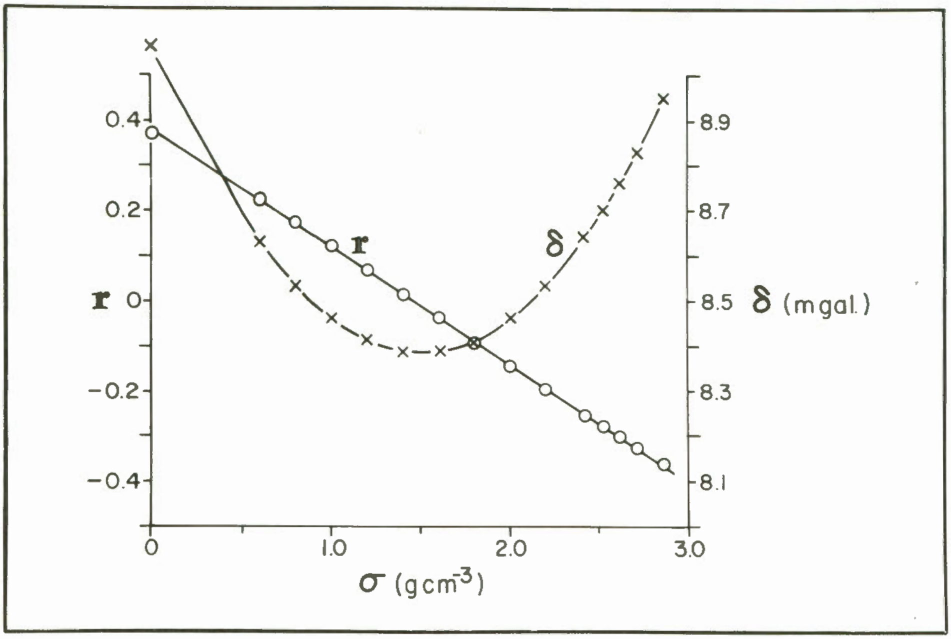

Figure 1. Dependance of the correlation coefficient between station elevations and Bouguer anomalies, **r**, and the standard deviation of the Bouguer anomalies from their mean, δ, on the Bouguer reduction density, σ, in the Sudbury area.

A preliminary analysis of the isostatic anomalies has been made in the Sudbury area. Variances of the different isostatic anomalies, expressed as the standard deviation from the mean, lie within a very small interval from 8.65 to 8.80 mgal. Correlation coefficients between the isostatic anomalies and the station elevations are in the range +0.37 to -0.31. The minimum variance points to a normal crust about 40 km thick and to local compensation rather than regional distribution of the compensating masses. From the minimum correlation between the isostatic anomalies and the elevations a value of 30 km or less for the normal thickness of the crust would be preferred. However, because of the very small differences in both variables these results are not conclusive. The area lacks strong topographic features and is apparently too small to provide sufficient evidence about the type of compensation. It is concluded that introduction of the isostatic corrections does not affect interpretation of the gravity anomalies on the Sudbury sheet. On the other hand it seems evident that isostatic corrections have to be taken into account for large regional gravity interpretations, even in areas such as the Canadian Shield.

THE BOUGUER ANOMALY MAP

The Bouguer gravity anomaly map was prepared at a scale of 1:250,000 with a 2 mgal contour interval to accompany this report. Two major geological features of the area, the Sudbury structure outlined by the irruptive and the Grenville Front are also diagrammatically shown on the map. To facilitate more detailed analysis of the gravity anomaly field in the most important parts of the area, Bouguer anomaly maps were prepared at a scale of 1:50,000 with 1 mgal contour interval for the Sudbury Basin and for the Agnew Lake area. These maps may be obtained from the Gravity Division, Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa.

To emphasize major features of the gravity anomaly field in the Sudbury area, a map representing an upward continuation of the original field at an elevation of 8 km is shown in Figure 2. A relatively positive regional gravity anomaly extends over most of the area under investigation. This anomaly seems to form a single unit lying well within the limits of the Sudbury sheet (41 I) with a significant extension only to the northeast. Its maximum (A) in Figure 2 lies north of Hagar, just south of the Grenville Front. The part north of the Grenville Front characterized by slightly lower anomaly values extends to the area west of Emerald Lake (B) and farther northeast. West of the Grenville Front the positive regional anomaly forms a ridge extending to Sudbury (C) and farther west to the area south of Agnew Lake (D). This dominant feature of the gravity field in the area which completely includes the Sudbury structure may reflect the distribution of mafic magmatic rocks, probably of gabbro-anorthositic composition, within the crust.

The regional positive gravity anomaly is surrounded by gravity lows which all extend beyond the boundaries of the map sheet. They have not been completely outlined but they appear to be related to large bodies of acidic magmatic or metamorphic rocks in the area. Thus, the relatively negative gravity anomalies correspond to major granitic intrusions, the Killarney granite (E) and the Cartier granite (F). A gravity low in the Venetian Lake area (G) may indicate an extension of the Cartier granite or a similar intrusion. Only marginal parts of much larger bodies of granite or granite gneiss of the Grenville Province extend into the Sudbury area north of Field (H) and around the west end of Lake Nipissing (I).

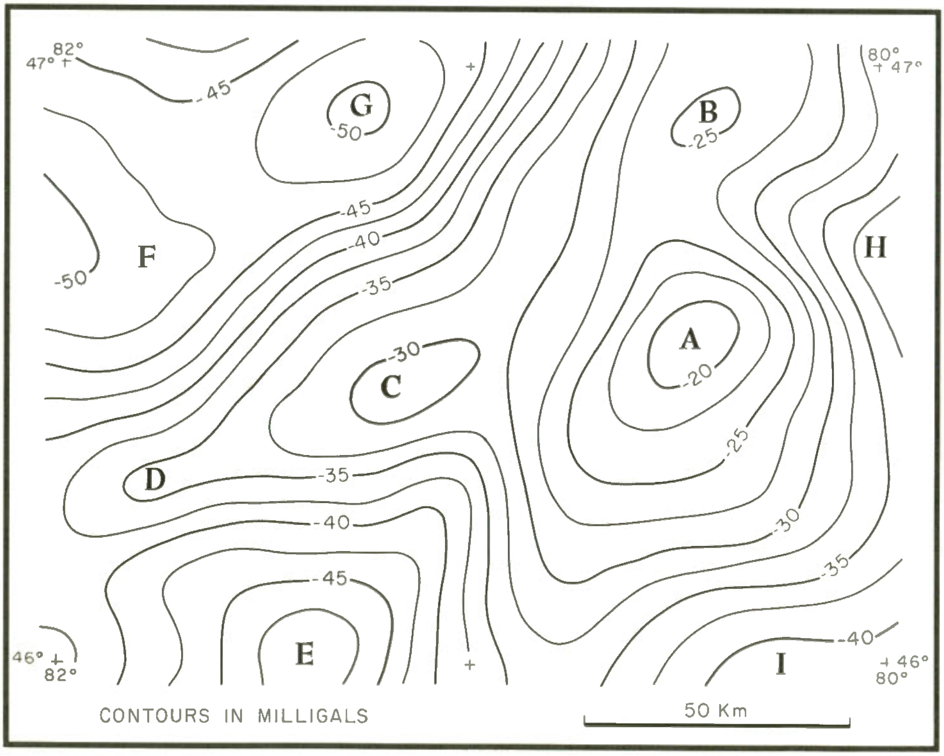

Figure 2. Gravity map representing an upward continuation of the Bouguer anomaly field in the Sudbury area at an elevation of 8 km.

Superimposed on this regional field the Bouguer gravity anomaly map (GMS 138) shows local anomalies which relate more closely to density distribution in the upper part of the crust and on the surface. Some local gravity anomalies can be easily correlated with certain geological features. Thus, a local gravity high on the west shore of Agnew Lake corresponds to an intrusive body of anorthosite as mapped by Card (personal communication). An east-west positive gravity ridge in the Benny-Stralak area follows very well a belt of Archean greenstones. Local gravity depressions correlate with bodies of the Killarney granite outcropping along the Grenville Front from Killarney village northeast to Chief Lake. A very intense local negative gravity anomaly at Lake Wanapitei is, with other evidence (M. R. Dence, personal communication), a strong argument in favour of an impact origin for this structure. A strong gravity gradient striking northeast through Wanapitei village from Raft Lake to Crerar is very likely an expression of the change from Huronian sediments to heavier Grenville rocks along this part of the Grenville Front.

The Sudbury structure lying within the region of relatively positive Bouguer anomalies cannot itself be related to a single or simple gravity anomaly as is the case with many other geological features in the area. However, close inspection of the gravity anomaly map indicates a correlation between some details of the gravity field and certain geological features of the Sudbury structure and the Huronian sedimentary basin. A detailed analysis with a quantitative interpretation of the gravity field in the Sudbury area will be given elsewhere.

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