A GRAVITY SURVEY OF THE IGNEOUS BODY AT LITTLE MOUNTAIN, VANCOUVER, B.C.†

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ABSTRACT

Little Mountain is an igneous body which forms the height of land within the City of Vancouver. The outcrops there are part of the series of igneous rocks known as the Prospect Point eruptives, which intrude the Lower Tertiary sediments in Vancouver and vicinity. Most of the sediments in the area are covered by a thick layer of Pleistocene glacial deposits and interglacial sand and clay. To better understand the origin of the igneous body which forms Little Mountain, a gravity survey has been carried out over the immediate area surrounding it. Standard reductions have been applied to the data to obtain a terrain-corrected residual Bouguer anomaly map. An iterative modelling procedure was carried out using computer programs based initially on two-dimensional and subsequently on three-dimensional algorithms. The final model obtained suggests the igneous body may be likened to a broad, asymmetrical cone, roughly 500 m in diameter, attached to the underside and near the edge of a polygonal slab at or near the surface and approximately 60 m thick. Consideration of this gross shape together with geological data suggests the igneous body probably results from an upwelling of magma to produce a lava flow of small volume.

INTRODUCTION

One of the principal physiographic features of Vancouver, British Columbia, is the topographic high at Little Mountain. The high, around which Queen Elizabeth Park has been developed, is due to an igneous body. This paper reports the results of a detailed gravity survey which has been carried out over the body.

Little Mountain is located in the Burrard Peninsula which forms part of the highland areas of the general Fraser Valley lowland, near the Fraser River delta. The peninsula is bounded on the south by the north arm of the Fraser River, on the north by Burrard Inlet and extends from Point Grey to Pitt River, east of Burnaby (Figure 1). It includes the cities of Vancouver, New Westminster and Burnaby.

GEOLOGICAL SETTING

Figure 1 shows a geological sketch map of this general region and a north-south geological cross section. The distribution of rock material is the result of three distinct phases in the geological evolution of the west coast. During early to mid-Cretaceous time, magma intruded volcanic islands and marine basins to form the coarsely crystalline rocks of the Coast Mountains; in late Cretaceous time, this Coast Crystalline Complex was uplifted above sea level. From then to Lower Tertiary time, the rocks were subjected to erosion, with the eroded material eventually cementing into conglomerate, sandstone and mudstone. Small seams of lignite were formed from thin layers of plant debris. Volcanic activity occurred sporadically throughout the Tertiary and continued at least until a few thousand years ago when there were eruptions on Mount Garibaldi

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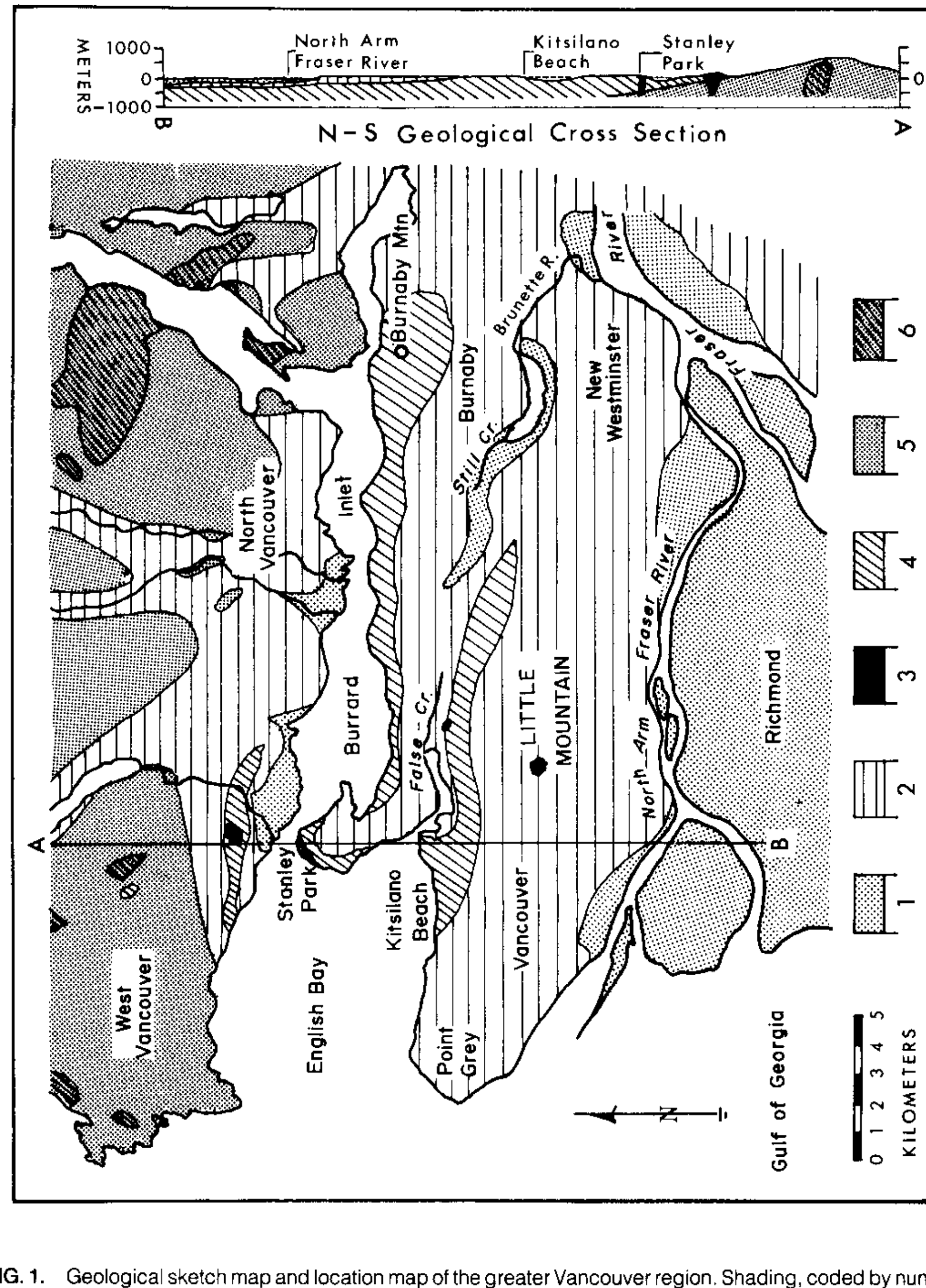

FIG. 1. Geological sketch map and location map of the greater Vancouver region. Shading, coded by number, shows the distribution of rock types and unconsolidated sediments: (1) recent gravel, sand, clay, peat; (2) glacial till, stoney clay, interglacial sands and clays; (3) basalt-andesite (dikes, plugs, flows); (4) upper Cretaceous-lower Tertiary mudstone, sandstone, conglomerate; (5) granite, granodiorite, quartz diorite, diorite; (6) volcanic and sedimentary rocks (roof-pendants). (5) and (6) are part of the Coast Crystalline Complex. To the left of the map, a north-south geological cross section (line from A to B on the map) is shown on an approximately 1:1 scale. (Map and cross section after Eisbacher, 1973).

(about 80 km north). The third phase is the effects over the last million years of volcanic activity, ice sheets, and water; these formed the glacial till, gravel, sand, clay and peat.

As shown by Figure 1, the Burrard Peninsula is formed primarily of glacial drift with some Tertiary bedrock and recent deltaic material. The bedrock forms the northern part of two easterly trending ridges which are separated by the west-draining False Creek and the east-draining Still Creek, Burnaby Lake and Brunette River system. The northern ridge extends from Stanley Park, where bedrock outcrops are well exposed, to Burnaby Mountain, the height of land on the peninsula. The southern ridge extends from Point Grey to the Fraser River, with good exposure of Tertiary bedrock along Kitsilano beach. Little Mountain is the height of land along this southern ridge.

The outcrop at Little Mountain is part of the series of igneous rocks known as the Prospect Point eruptives (Johnston, 1923) which intrude the Lower Tertiary sediments in Vancouver and vicinity. These sediments are divided into the Burrard, Kitsilano and Boundary Bay formations.

The Burrard formation unconformably overlies the Coast Crystalline Complex. No contacts are known in the map area. It consists of a basal conglomerate and an overlying series of sandstones and shales with a vertical thickness of at least 600 m. A disconformity separates the Burrard and the overlying Kitsilano formation. The slight erosion surface is reflected in the composition of the Kitsilano formation, which varies from a basal conglomerate to sandstones and shales, with a total vertical thickness of at least 300 m.

A number of intrusive contacts with the Prospect point eruptives are known to occur in the Burrard and Kitsilano formations. These igneous rocks consist of a series of basic dykes, sills or flows and volcanic tuffs. The largest dyke occurs at Prospect Point in Stanley Park. A number of smaller dykes and volcanic tuffs intruded by dykes occur at other locations in the Vancouver area (Wooton, 1959). The igneous body at Little Mountain is considered to be a sill or flow by Johnston (1923), while Armstrong (1954) has suggested it is a laccolithic body. According to Wooton (1959), the igneous activity took place over considerable time, possibly extending from the Mid-Eocene into the Miocene with major activity being post-Eocene but pre-Pleistocene. Well-glaciated outcrop at Little Mountain substantiates this view.

The Kitsilano formation is overlain by the Boundary Bay formation, which is presumed to be of the same age as the Prospect Point eruptives. Evidence is provided by the volcanic ash which occurs with the relatively unconsolidated sandstones and shales.

The Upper Tertiary sediments are separated from Quaternary deposits by a major unconformity. They consist primarily of Pleistocene glacial deposits and recent deltaic and alluvial deposits with some interglacial sediments. The lack of significant outcrop and non-exposure of contacts with sedimentary deposits at Little Mountain is due to this layer of overburden. Only on the northern side, where two quarries have been excavated, are exposures good (Figure 2).

The rock which outcrops at Little Mountain is a medium to fine grained, vesicular, augite-olivine basalt. The vesicules are generally few and small, although larger ones with a filling of natrolite have been noted (Wooton, 1959). Composition is about 50% plagioclase, with abundant small grains of augite. Secondary minerals include epidote, magnetite and purite. Although no contacts have been exposed, they are reflected by sandstone xenoliths and inclusions of sand with igneous material in the matrix (Wooton, 1959).

A prominent feature of the larger quarry is its well-developed columnar structure. The columns are nearly vertical, up to several feet in diameter and several tens of feet high. The convergent arrangement of the columns is possibly due to a rapid cooling or radiation of heat from a focal point (Johnston, 1923). The rock exposed in the smaller quarry is predominantly massive. Although nearly vertical, the columns do show a minor inclination to the south. Johnston (1923) has attributed this to a tilting of the body with enclosing sediments to form a gentle monoclinal structure in the Vancouver area.

A small outcrop also occurs on Cambie Street about 500 m south of the nearest quarry. Survey evidence presented in this report indicates it is not a dyke offshoot of the main body as considered by Wooton (1959), but is more likely formed by the southwest edge of the main body.

Survey Measurements and Their Reduction

The gravity survey was carried out with Worden gravimeters. Most of the observations were

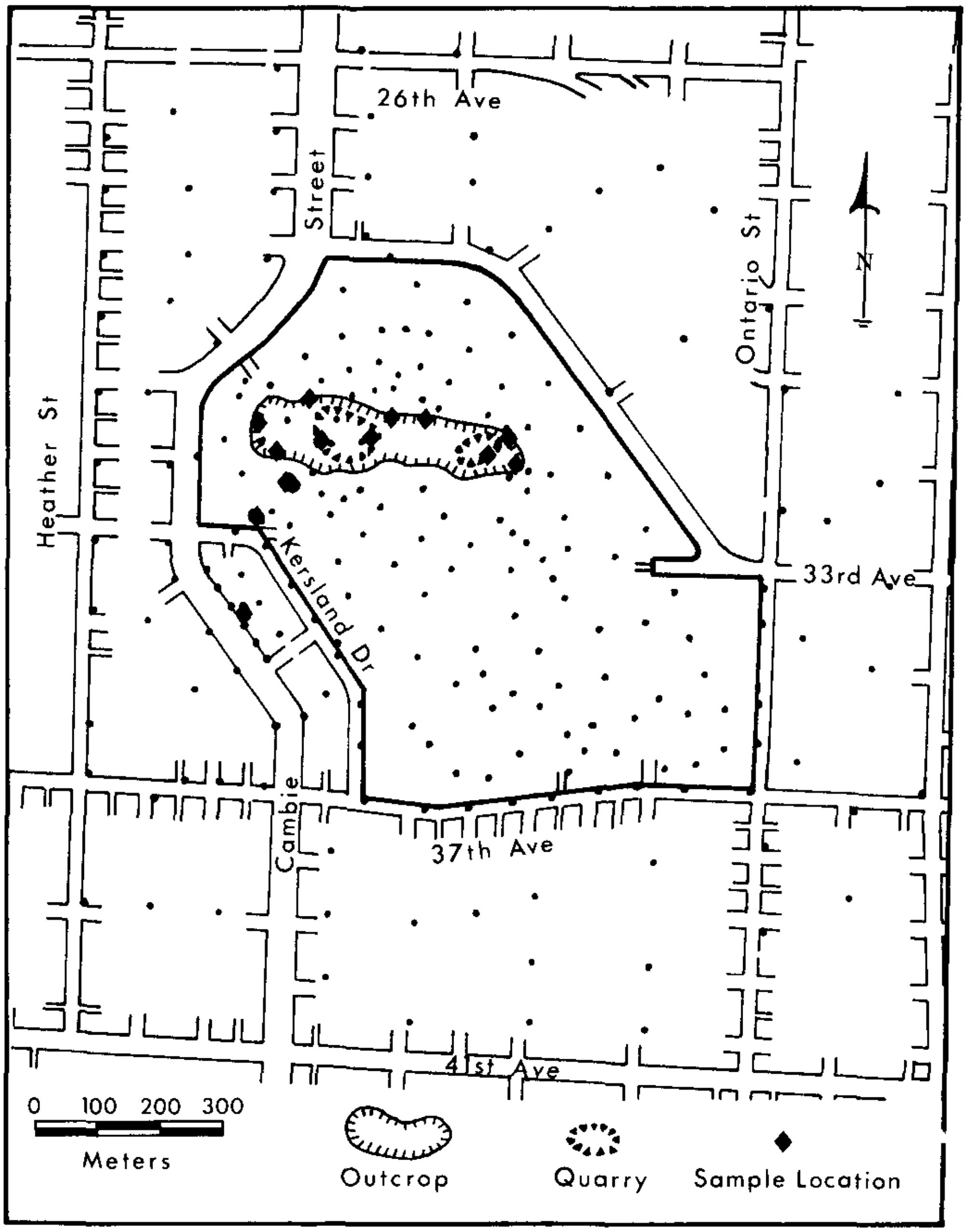

Fig. 2. Location map of the area within Vancouver in which the gravity survey was carried out. Queen Elizabeth park is outlined by the heavy line. Solid dots show the locations at which gravity readings were taken. Extent of the known outcrops at Little Mountain, position of the two quarries, and sample locations for the igneous body are indicated. Samples of the other rock materials were taken at locations where exposures were good.

recorded on a Prospector Model with dial constant of 0.0908 mgals per scale division although some preliminary measurements utilized an Educational Model with a dial constant of 0.4201 mgals per scale division.

A base station was established and gravity measurements were made on loops from this location, with repetition every two hours to enable calculation of drift corrections. Station sites were distributed in favorable and convenient locations to enable a uniform density of coverage (Figure 2). Inside the park area, the stations are approximately 63 m apart and were located by chain and compass measurements, then spotted on a Vancouver Parks Board map of Queen Elizabeth Park. Elevations of stations obtained from this map are accurate to 0.3 m while locations are accurate to within 3 m. Outside the park, station spacings average about 125 m. The stations were located on a map of the City of Vancouver which provides elevations accurate to 0.8 m and locations accurate to within 30 m. Figure 2 shows the specific area within which the survey was made.

Rock samples representing the igneous body (Figure 2), the underlying Burrard and Kitsilano formations (from exposures in the Vancouver area) and samples of the unconsolidated till and sand surrounding the body were collected for density determinations. Density values were obtained for the basalt and sandstone samples with a Jolly balance and for the till and sand by water displacement. These results were averaged to obtain an overall representative density value for each of the four major rock types. This minimizes the variations due to weathering of the samples and the finely vesicular nature of the basalt. The results are summarized in Table 1.

The maximum and minimum density contrasts of the unconsolidated material and the basalt were averaged to obtain a figure of 0.7 gm/cc, the density contrast used in modelling. This implicitly assumes that the unconsolidated material has a depth extent of greater than 100 m. Evidence supporting this may be found in the geological studies of the Vancouver area discussed previously.

To enable a direct comparison between the survey data and the Bouguer anomaly map of southwestern B.C. (Walcott, 1967), the survey base point was tied to National Gravity Network base station no. 9279-60, located at the University of British Columbia. After application of corrections for instrument drift, the complete Bouger anomaly was calculated on the basis of the Geodetic Reference System (1967) and a Bouguer density of 2.67 gm/cc. The program described by Ager (1972) was used to make the calculations and included terrain corrections for distances to 600 m around each station.

The Bouger anomaly map showed a regional trend which was removed by visual smoothing. A map of this trend was drawn by extrapolation of the contour curves, from areas where the effects of the anomalous body were minimal, through the region where its effects were obvious. This map of the regional field was subtracted manually from the Bouguer anomaly map to yield the residual Bouguer gravity anomaly map shown in Figure 3.

The major source of error in the survey is that involved with elevations. For all stations inside the park boundaries, elevations are known to a precision of 0.3 m, assuming the maps are near perfect. This yields a combined free air and

TABLE 1.
Representative density values for materials in thr region of Little Mountain.

Material	**No. of samples**	**Density (gm/cc)**	**Density contrast with basalt (gm/cc)**
Basalt (Prospect Point Eruptives at Little Mountain)	25	2.75	
Sandstone (Burrard and Kitsilano formations)	15	2.55	0.20
Unconsolidated till	10	1.92	0.83
Unconsolidated sand	5	2.17	0.58

Average density contrast of unconsolidated material and basalt is 0.71 gm/cc.

Bouguer correction accuracy of ±0.06 mgals. Outside the park boundaries, elevations are known to within 0.8 m so that the combined free air and Bouguer corrections are accurate to within ±0.15 mgals. The reading accuracy of the Prospector gravimeter is within ±0.01 mgals and that of the Educational model within ±0.04 mgals.

The most difficult error to evaluate is that due to the terrain corrections. A major portion of it may be contributed by the uncertainty in the density estimates. However, because Little Mountain is located in an area of very low local relief, excepting the immediate park area where relief is less than 31 m, the correction factor is generally less than 0.2 mgals. In the fourth correction zone (300 m) the correction factor is less than 0.03 mgals. From this it is concluded that the terrain correction factor is reasonably accurate and probably contributes less than ±0.05 mgals in error to the survey. Based on the foregoing discussion the residual Bouguer anomaly map is considered to be accurate to within ±0.25 mgals.

INTERPRETATION

Interpretation of the data utilized computer based iterative model studies. An initial model determined from anomaly half-widths, geological reasoning and an assumed density contrast was established. This model was refined using the two-dimensional computational procedures of Talwani, Worzel and Landisman (1959). Final results were obtained by three-dimensional modelling procedures utilizing the computational technique described by Talwani and Ewing (1960).

To facilitate calculation of the gravitational attraction of a two-dimensional body of arbitrary shape, the body cross section is approximated by an appropriate polygon. The periphery of this polygon is defined by specifying the co-ordinates of adjacent points at vertices of the body. Calculation of the vertical component of gravitational attraction at any external point may be made by

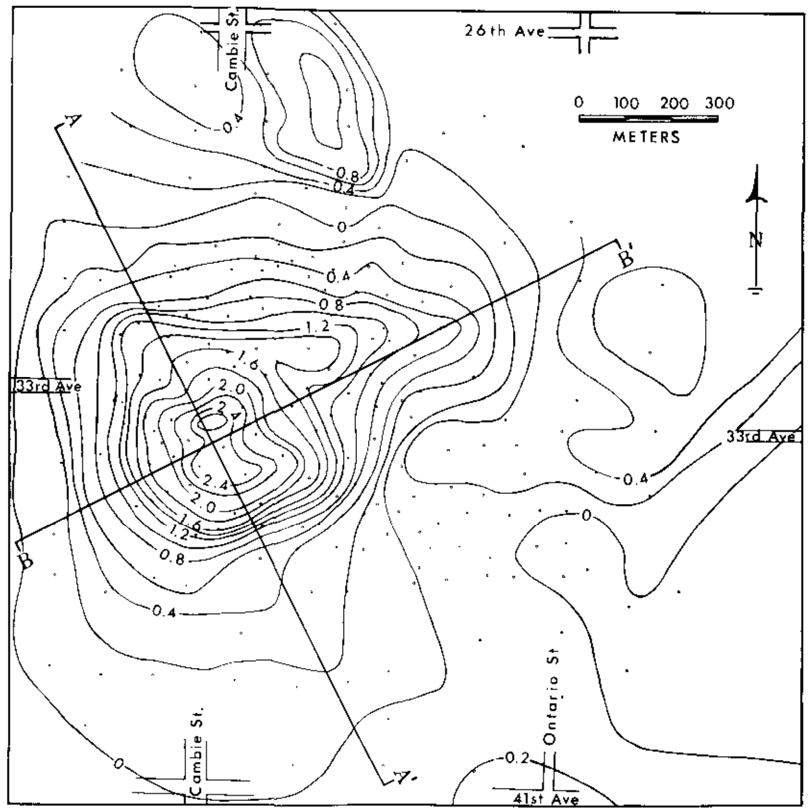

Fig. 3. Residual Bouguer gravity anomaly map of the Little Mountain region. Small circles are gravity stations. Contour intervals is 0.2 mgal. AA' and BB' are lines of cross sections as shown in Figures 5 and 6.

using the following expression (Talwani, Worzel and Landisman, 1959):

$$\Delta g = 2G\rho \sum_{i=1}^{n} R_i$$

G = universal constant of gravitation

ρ = volume density of the body

n = number of sides of polygonal cross section

R_i = an expression involving the co-ordinates of each of the polygon vertices relative to the gravity station

To make numerical calculations on a computer, the position of points at which the magnitude of the gravitational attraction is desired, the coordinates of the vertices of the body, and the density contrast need to be specified.

For calculations of the gravitational attraction of a three-dimensional model, the body volume is divided into thin horizontal polygonal laminae, each having a specific depth extent. The gravitational anomaly caused by each individual lamina may be computed for any external point. By a system of linear interpolation between layers defined by the laminae, combined with numerical integration, the gravity anomaly caused by a three-dimensional body can be calculated according to the following expression (Talwani and Ewing, 1960):

$$\Delta g = \int_{z_{bottom}}^{z_{top}} V\,dz; \text{ where } V = G\rho \sum_{i=1}^{n} Q_i$$

z = vertical co-ordinate axis

V = vertical component of the gravitational attraction per unit thickness of a thin horizontal polygonal lamina

G = universal constant of gravitation

ρ = volume density of the lamina

n = number of sides of the polygonal lamina

Q_i = an expression containing the co-ordinates of the vertices of the polygonal lamina

The coordinates of the laminae which define the body, the elevation of the top surface of each lamina, the density contrast and the coordinates of the points at which the anomaly is to be determined form the input data necessary for computer calculations.

Consideration of geological data suggested the initial model could consist of a tube-like structure forming a feeder system, overlain by a more massive structure formed by the upwelling of magma. Analysis of the anomaly half-widths indicated the width of the feeder pipe to be of the order of 100 m. The density contrast was taken to be 0.7 gm/cc based on the sample density measurements.

A series of two-dimensional models were generated and the associated anomalies were compared with profiles taken from the residual Bouguer map. The results implied that the lower order portions of the anomaly may be attributed to a thin, shallow slab approximately 500 m in width. The higher order portion or peak most likely results from a feeder pipe offset to one side of the slab.

Using the two-dimensional models as the basis for defining an initial three-dimensional model, additional calculations using the three-dimensional algorithm were carried out. The thickness of the layers specified for the models ranged from 5 to 40 m, depending upon their depth. For the numerical integration there was a linear interpolation to infinitesimally thin laminae within the specified layers.

Each computer-calculated anomaly that resulted from a specific model was contoured and compared with the residual Bouguer anomaly map. Systematic perturbations were made to each subsequent model, resulting in the consideration of more than twenty different models. While it is realized that the procedure is non-unique and depends to some extent on the choice of a starting model, it is felt that a reasonable and simple model consistent with the observations was achieved by this approach.

A plan view of the "best fit" three-dimensional model obtained in this manner is shown in Figure 4. It suggests that the igneous body may be likened to a broad, asymetrical cone attached to the underside and near the edge of a thin polygonal slab. The density contrast of this model is 0.7 gm/cc.

The gravity anomaly computed from this model is shown in Figure 5. This map agrees reasonably with the overall character of the residual Bouguer anomaly map (Figure 3). The anomaly peak, which is centered over the cone, is flanked on the southwest side by a steep gradient, and on the northeast side by a gentle gradient that results from an offset of the cone from the centre of the slab. Slight differences arise from low-order flank anomalies and perturbations due to other irregularities which cannot be considered easily in a model.

To obtain a better understanding of the comparison between the actual and calculated anomalies, two cross sections were constructed (Figures 6 and 7). The sections emphasize the offset nature of the anomaly peak and correspondingly that of the thin polygonal slab and cone. The agreement between the residual Bouguer anomaly and the calculated anomaly is in most cases within the error bounds of the survey. A better fit probably could be obtained by further refinements of the models, such as including features on the body's upper surface and varying density within the body. It should be noted, however, that the procedure involved in direct modelling is essentially an infinite process. It has been arbitrarily terminated at a point where further perturbations of the model to obtain a better match with the residual anomaly are not significant enough to affect the interpretation.

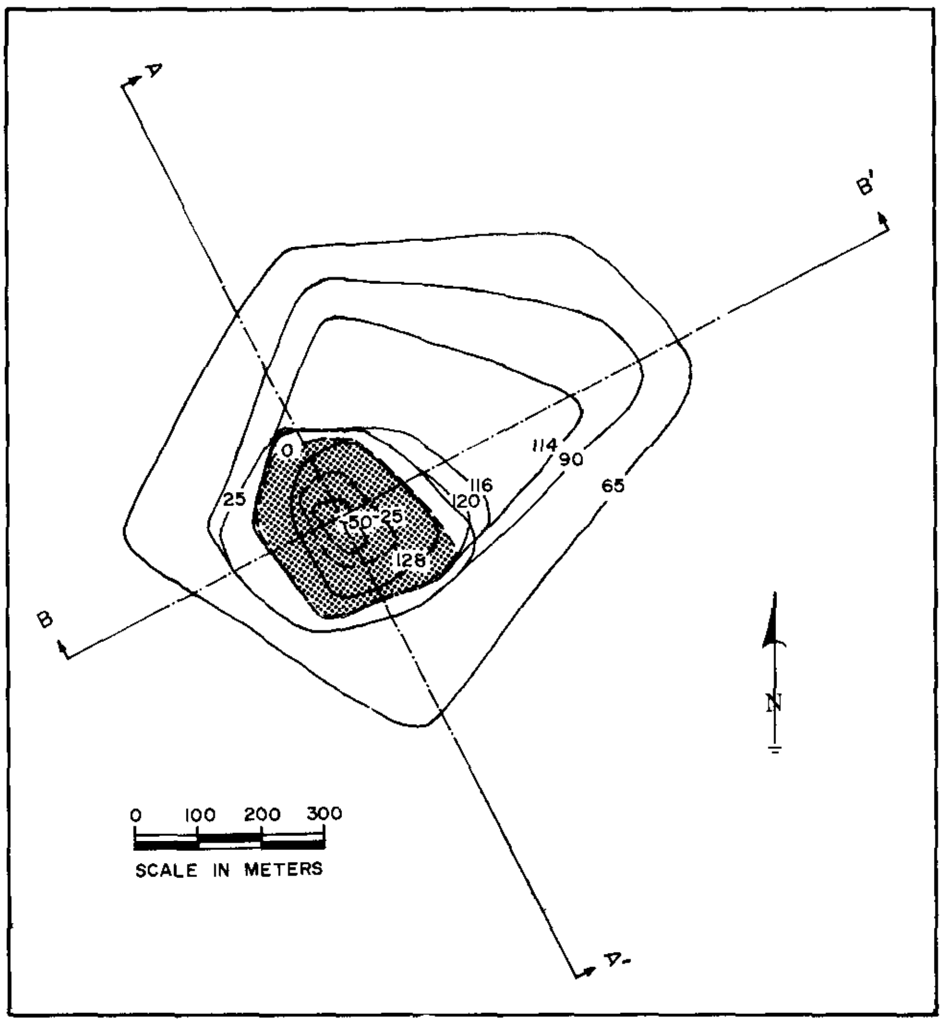

Fig. 4. Plan view of the "best fit" three-dimensional model. Contours are in metres with mean sea level equal to O m. Area within zero contour is stippled. Note that due to shape of body, the -25 m and -50 m contours and the +128 m contour are superposed on the stippling. Density contrast = 0.7 gm/cc. AA' and BB' as in Figure 3.

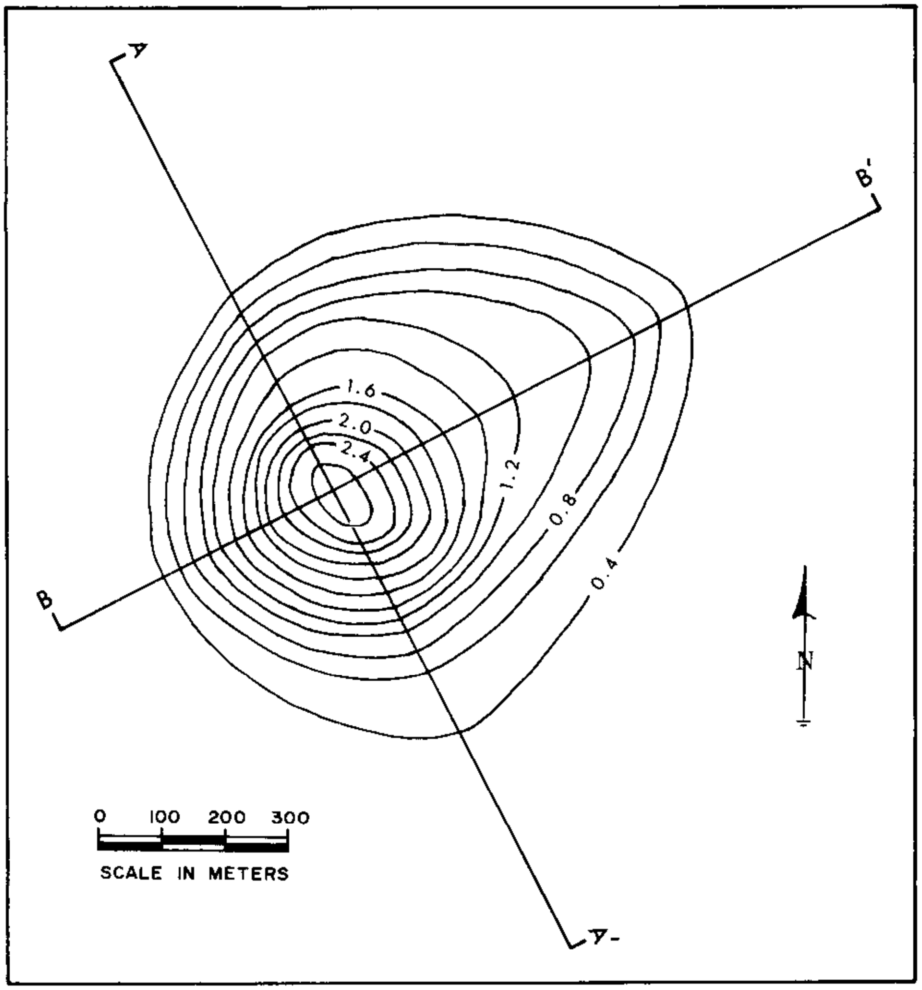

Fig. 5. Gravity anomaly computed for the model shown in Figure 4. Contour interval is 0.2 mgal. AA' and BB' as in Figure 3.

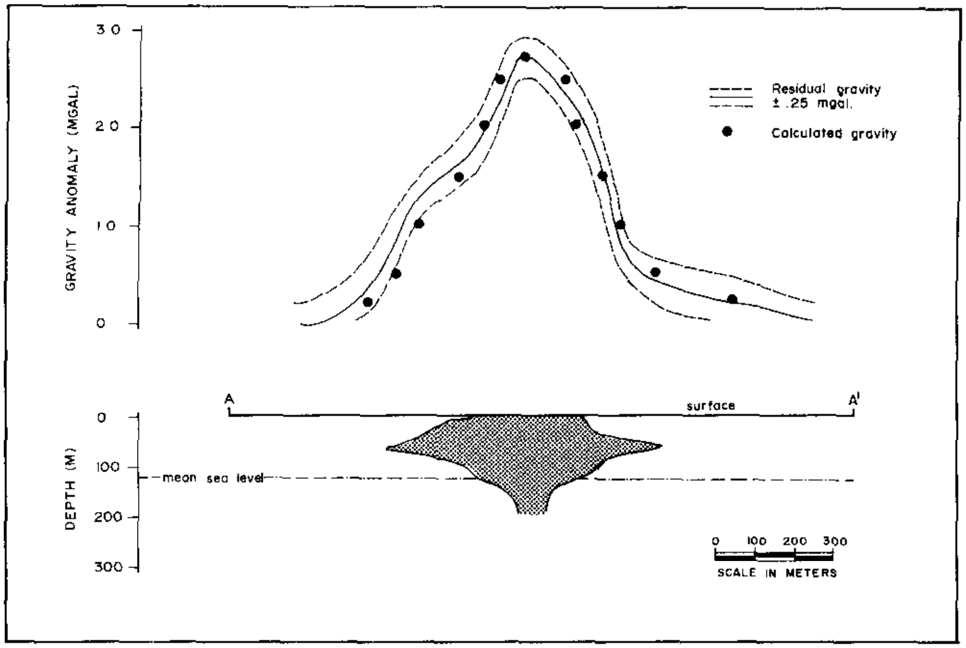

Fig. 6. Lower: Section AA' across the model of Figure 4.
Upper : Comparison of calculated gravity anomaly with the residual Bouguer anomaly.

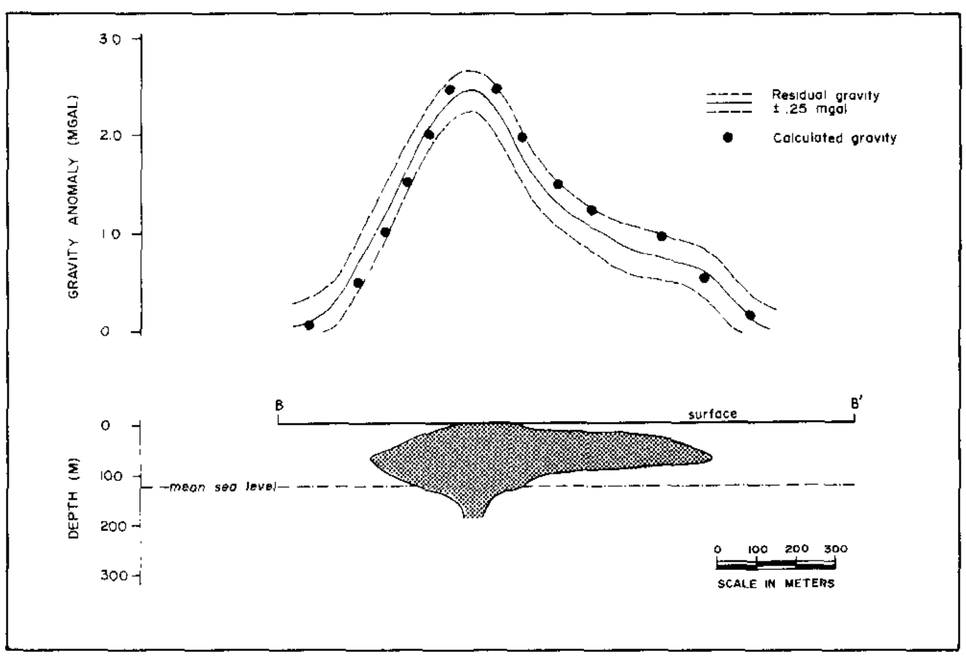

Fig. 7. Lower: Section BB' across the model of Figure 4, Upper:
Comparison of calculated gravity anomaly with the residual Bouguer anomaly.

CONCLUSION

The final model interpreted from gravity data taken around the igneous body at Little Mountain suggests the body may be likened to a broad, asymmetrical cone attached to the underside and near the edge of a thin polygonal slab. The cone axis underlies the southwestern edge of Queen Elizabeth Park. The slab, of average thickness 60 m, located at or near the surface, covers the majority of the northwestern half of the park and extends across Cambie St. on its southwestern edge. The lenticular shape of the upper surface suggests either a flow or a sill with the cone part forming a feeder system.

Because several periods of extensive erosion and glaciation and the absence of visible contacts have reduced the amount of geological information available, there is little evidence to show whether the body is a sill or a flow. Johnston (1923) states that "the smooth, rounded upper surface of the rock — which, however, may be due to glaciation — its finely vesicular character, and the convergent columnar structure possibly suggest that it is a sill rather than a flow." Since two periods of extensive erosion (including glaciation) have taken place in the time since the rock was formed, it is reasonable to assume the smooth upper surface of the outcrop is a result of these processes. The vesicular nature of igneous rocks is due to expanding, escaping gases and volatiles. Although a finely vesicular nature may suggest an intrusive origin, a flow may be finely vesicular if there does not exist appreciable amounts of water or other sources of gases in or near the flow. Columnar jointing is commonly found in flows, although more usually in vertical positions. A convergent structure may be attributed to a rapid cooling or radiation of heat from a focal point, but this does not necessarily imply a sill or a similar subsurface origin. It is reasonable to assume that rapid cooling takes place in a flow, and, due to varying thicknesses of lava, there may be uneven cooling or radiation of heat from a focus.

The shape of the final three-dimensional model suggests the igneous body at Little Mountain has been formed by the upwelling of a small volume of basic magma, most likely through a weak point in the crustal surface. The main flow appears to have been to the northeast, with a minor amount to the northwest and southeast. The lack of significant change in the local structure of the host rock also suggests an extrusive origin. Furthermore, traces of volcanic ash found in the Boundary Bay Formation, which is considered to be of the same geological age, also suggest a flow rather than a sill.

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