THE INTERPRETATION OF A GRAVITY ANOMALY

IN THE CANADIAN ARCTIC

By

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ABSTRACT

The possible cause of a gravity anomaly found in the Thumb Mountain Formation of Cornwallis Island in the Arctic was investigated. Frost-fractured and porous pseudo breccia zones were found to have an effect on the gravity. Some limestone units and dolomite units had lithological differences which gave rise to anomalies. Correlation of lithology with the density was done by examining the core densities from two drill holes. It was also found that the anomaly was accentuated by a flanking fault to the east and a shale bed to the west. Depth calculations were applied to the anomaly to determine if there could exist a mineralized body beyond the depths drilled in the drill program. It was found that the drill program was quite adequate to find a causative body especially for the small anomalies on the north side of the main gravity anomaly.

In conclusion it was found that a gravity low may indicate a high porosity pseudo breccia zone. Broad anomalies over a formation may be the result of a density contrast throughout the formation with respect to surrounding formations.
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<tr>
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<td>Theorem 4, Line 8 + 00 S</td>
<td>61</td>
</tr>
<tr>
<td>O</td>
<td>Theorem 4, Line 16 + 00 S</td>
<td>62</td>
</tr>
<tr>
<td>P</td>
<td>Theorem 4, Line 24 + 00 S</td>
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Plate 1: Density logs, DDH #1, DDH #2 (in pocket)
ACKNOWLEDGMENTS

I would like to thank Canadian Superior Exploration for the release of the data contained in this thesis.

I thank the members of my committee Dr. R.H. Carpenter, Dr. R.C. Holmer, and Dr. G.V. Keller for their contributions to this thesis with special gratitude to my advisor, Dr. Holmer, for his advise and patience.
INTRODUCTION

This study is based on the gravity and geological data of Canadian Superior Exploration. The data were obtained by the company in the summer of 1973, on Cornwallis Island, near the North Magnetic Pole, as shown on Figure 1.

The gravity survey by Canadian Superior in 1973 found a gravity anomaly of .5 milligals. The location of this anomaly on Cornwallis Island is shown in Figure 2 and the anomaly itself in Figure 3.

The above gravity survey was part of an exploration program designed to locate Mississippi Valley type lead and zinc deposits. A major lead-zinc deposit is held by Cominco on Little Cornwallis Island. Cominco's Arvik mine is shown in Figure 2. This deposit does have a gravity anomaly.

At first the gravity anomaly discussed above seemed to indicate the presence of such a deposit. A drill program completed in the summer of 1974 gave negative results. The purpose of this thesis is to find out why this anomaly exists. For the purpose of this thesis the drill logs and the company geological report and maps were supplied. Density logs on two drill holes in the center of the anomaly were also given. All geological maps and cross-sections, gravity profiles, and density charts in this thesis are based on these data.

Canadian Superior Exploration is the mineral exploration arm of Canadian Superior Oil. This company does exploration in British Columbia, the Yukon, and in the Arctic on Cornwallis Island. In the Arctic, gravity is the only geophysical method used by Canadian Superior. In using electrical methods such as Induced Polarization penetration of current into nonconductive permafrost is difficult and spurious anomalies result from frost fractured zones. Electromagnetic methods were not used because the deposits in these regions consist mainly of nonconductive sphalerite. Magnetic methods would be unreliable because of intense magnetic fluctuations associated with the nearby magnetic pole.
FIG. 1 LOCATION MAP OF CORNWALLIS ISLAND
FIG. 2 LOCATION MAP OF THE ANOMALY
GEOLOGY

General geology

The major tectonic elements of the Arctic archipelago are shown in Figure 4. Cornwallis Island is in the Franklinian miogeosyncline which is comprised of the Parry Island, Cornwallis and Central Ellesmere Fold Belts. The Cornwallis Fold Belt is composed of north trending folds and faults, broad shallow synclines separating closely folded anticlines. The fold belt is the northern extension of the Boothia Arch.

Five intervals of conformable strata can be recognized on Cornwallis Island. There are angular unconformities in the Late Tertiary, Early Cretaceous, Late Devonian, Middle Devonian, Early Devonian and basal Devonian. The interval of conformable strata which exists in the subject area of this thesis is the basal Ordovician to Early Devonian sequence. This sequence is shown in Table A.

The Thumb Mountain strata over which the anomaly lies is Ordovician in age. In the Franklinian Geosyncline the majority of exposed strata is described as miogeosynclinal. In Ordovician time carbonates and fine grained clastics were deposited. In restricted basins evaporitic sediments were deposited during the Middle Ordovician. During the Silurian and Upper Ordovician periods extensive carbonate deposits were formed in shallow waters and shales in deeper waters under open marine conditions.

Geology of the anomalous area

The geology of the area over which the anomaly in Figure 3 lies is shown in Figure 5. The symbols of the geological formations are shown in Tables B and C. On the Island there is a facies front where the Cape Phillips Formation grades into the Read and Allen Bay Formations which are in equivalent time periods. In the subject area of the thesis only the Cape Phillips is present. The Thumb Mountain is the mineralized formation and an orebody in this formation is the target of the survey.
FIG. 4 TECTONIC MAP OF THE ARCTIC
<table>
<thead>
<tr>
<th>PERIOD</th>
<th>FORMATION</th>
<th>LITHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEVONIAN</td>
<td>READ BAY</td>
<td>Limestone; minor shale, dolomite, sandstone, siltstone (marine)</td>
</tr>
<tr>
<td></td>
<td>8,500 ft.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ALLEN BAY</td>
<td>Dolomite, minor limestone, shale (marine)</td>
</tr>
<tr>
<td></td>
<td>5,500 ft.</td>
<td></td>
</tr>
<tr>
<td>SILURIAN</td>
<td>IRENE BAY</td>
<td>Shale, limestone (marine)</td>
</tr>
<tr>
<td></td>
<td>30-150 ft.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THUMB MOUNTAIN</td>
<td>Limestone, dolomite (marine)</td>
</tr>
<tr>
<td></td>
<td>1,700 ft.</td>
<td></td>
</tr>
<tr>
<td>ORDOVICIAN</td>
<td>BAY FIORI</td>
<td>Gypsum, anhydrite, limestone; minor shale, siltstone (marine)</td>
</tr>
<tr>
<td></td>
<td>1,000 ft.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ELEANOR RIVER</td>
<td>Limestone, minor dolomite (marine)</td>
</tr>
<tr>
<td></td>
<td>2,000 ft.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BAUMANN FIORD</td>
<td>Gypsum, anhydrite; minor limestone, lime-pebble conglomerate (marine)</td>
</tr>
<tr>
<td></td>
<td>2,400 ft.</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE A** LITHOLOGY
FIG 5 GEOLOGY OF THE ANOMALOUS AREA
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<thead>
<tr>
<th>FORMATION</th>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read Bay</td>
<td></td>
<td>varied limestones with minor shale, dolomite, siltstone and sandstone</td>
</tr>
<tr>
<td>Allen Bay</td>
<td>OSaps</td>
<td>dolomite with minor limestone; the formation grades up into Read Bay carbonates</td>
</tr>
<tr>
<td>Allen Bay</td>
<td>OSacm</td>
<td>the basal section of the Allen Bay Formation and is succeeded by up to 40 ft. of petrolierous, pyritous and calcareous limestones</td>
</tr>
<tr>
<td>Cliff Member</td>
<td></td>
<td>Note: On the Island there is a facies front where the Cape Phillips formation grades into the Read Bay and Allen Bay Formations which are in equivalent time periods.</td>
</tr>
<tr>
<td>Cape Phillips</td>
<td>ODcp</td>
<td>calcareous, petrolierous, pyritous shale; argillaceous petrolierous limestone, calcareous siltstone; cherty argillaceous limestone and chert.</td>
</tr>
<tr>
<td>Cape Phillips</td>
<td></td>
<td>a cherty carbonate horizon at the base of the Cape Phillips</td>
</tr>
<tr>
<td>Cape Phillips</td>
<td></td>
<td>Irene Bay Oci calcareous shale and siltstone, thin nodular argillaceous limestones</td>
</tr>
<tr>
<td>Cape Phillips</td>
<td></td>
<td>Thumb Mountain limestone and dolomite</td>
</tr>
<tr>
<td>Bay Fiord</td>
<td>Ocb</td>
<td>Has two stratigraphic units. The lower unit includes gypsum and anhydrite with minor limestone and is 500 ft. thick. The upper unit consists of argillaceous limestone, some gypsum, anhydrite, calcareous shale and siltstone gysiferous shale</td>
</tr>
<tr>
<td>Eleanor River</td>
<td></td>
<td>medium to thickly bedded limestone with subordinate dolomite</td>
</tr>
<tr>
<td>Baumann Fiord</td>
<td></td>
<td>thinly bedded gypsum and anhydrite, minor limestones and limestone conglomerates</td>
</tr>
</tbody>
</table>

**TABLE B** FORMATION DESCRIPTION AND SYMBOL
<table>
<thead>
<tr>
<th>MEMBER</th>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Mixed Fauna</td>
<td>U MF</td>
<td>Dense, thinly bedded lime mudstone, lime wackestones and minor lime packstones and their dolomitized equivalents. Dolomitization is present in varying degrees.</td>
</tr>
<tr>
<td>120 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foram Member</td>
<td>F M</td>
<td>Massive to thinly bedded lime mudstone and lime wackestone and dolomitized equivalents. Lithology is similar to overlying member.</td>
</tr>
<tr>
<td>50 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Mixed Fauna</td>
<td>L MF</td>
<td>Lithologically indistinguishable from the uppermost member.</td>
</tr>
<tr>
<td>40 to 50 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D.B. Chert</td>
<td>D-B</td>
<td>Lithologically similar to the uppermost member but is differentiated on the presence of abundant secondary black chert nodules.</td>
</tr>
<tr>
<td>20 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tetradium Member</td>
<td>T M</td>
<td>Lime mudstone and lime wackestone and dolomitized equivalents. Bedding is thin (in feet). The Formation is dominated by the coral Tetradium cf. cellulosium and occurs as disaggregated stick like fragments which may or may not be filled with secondary carbonate. If thoroughly dolomitized the Tetradium fragments are leached out to leave a dolomite with veiniform cavities centimeters long and up to 3 mm across.</td>
</tr>
<tr>
<td>70 to 90 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tidal Flat Member</td>
<td>T FM</td>
<td>Thinly interbedded (in feet) wackestones and lime mudstones. Tetradium is included in the fauna. A prominent chert horizon may occur near the base.</td>
</tr>
</tbody>
</table>

**TABLE C**

**SUBDIVISIONS OF THE THUMB MOUNTAIN**
GRAVITY AND DENSITY DATA

Gravity data

The gravity data in this thesis were collected by Canadian Superior Exploration in the summer of 1973. The instrument used was a Sintrex CG-2 Worden-type gravimeter with an accuracy of 0.025 mgals. Elevations for individual gravity stations were obtained by level and rod traverses. Station elevation accuracy was within half a foot. Instrument drift was determined by checks at an established base station.

No terrain corrections were applied to the gravity data as the maximum relief over the survey area was 180 feet. The relief over the portion of the survey used in this thesis is 60 feet. The free air correction applied was 0.094 mgals/ft. The Bouguer correction was 0.013σ mgals/ft where σ is the density of the local rock type. This density was assumed near 2.75 g/cc based on the average rock density of surface samples. These surface samples are discussed later in the thesis. A latitude correction was made based on the standard formula for geocentric latitude. Gravity stations were 100 feet apart on the cross-lines.

The above information was obtained from the geological report of Canadian Superior Exploration for 1973.

The profiles of the Bouguer gravity to be used in the interpretation section of this thesis are illustrated in Figures 6 and 7 with the mapped geology. These profiles comprise the anomaly of Figure 3.

Density data

Core densities were collected by Excalibur International Consultants in the summer of 1974 on two drill holes in the peak of the anomaly. The position of these holes are shown in Figure 3. Plate 1 illustrates the variation of density down
these holes. Core densities were determined for every four feet of core using the following relation:

\[ D = \frac{W_a}{W_a - W_w} \]

where: \( W_a \) = sample weight in air
\( W_w \) = sample weight in water

Using a field balance the densities were determined with an accuracy of ±0.03 g/cc.

Surface samples were determined by C.A. Ager, Consulting Geophysicist, in 1973. These densities are listed in Table D, in the section on 'Densities'
FIG. 6 BOUGUER GRAVITY AND GEOLOGY, NORTH PART
**DENSITIES**

**Surface densities**

The results of the surface sampling of the anomalous area are shown in Table D. The average density is 2.75 g/cc. The average for dolomite rocks, from these surface samples, is 2.77 g/cc and is 2.69 g/cc for limestones.

The dolomite of evaporite sedimentary deposits might have a grain density of 2.80 to 3.00 g/cc (Nettleton, 1971). Porosity in the dolomite would reduce the bulk rock density. In general the density of limestone is less than that of dolomite.

Taking the density contrast between limestone and dolomite to be .1 g/cc and using the formula for an infinite slab \((.013σt)\) where \(σ\) is the density contrast and \(t\) is the thickness of a limestone or dolomite sequence it may be found that the thickness required to produce a .1 mgal anomaly is 75 feet. This means that the overburden which ranges from 10 to 25 feet may be neglected as a cause for anomalies in the Thumb Mountain Formation.

**Densities from core samples**

Core measurements of density were taken for two vertical drill holes on line 8 + 00 S at the peak of the anomaly. These holes are shown in the anomaly in Figure 3. The density results are plotted in Figures 8 and 9 and Plate 1 (in pocket).

The average density in each drill hole is 2.75 g/cc which is the same as the average of our surface samples. It was noted that there did seem to be areas of high and low density when the density values taken every four feet were averaged for twenty, forty, and eighty foot intervals then plotted as in figures 8 and 9. The drill logs of these high and low areas
were examined to see if there was any association with lithology. It was noted that the lower density values seemed to be in the deeper parts of drill hole #1 and associated with vuggy dolomite and porous pseudo breccia. In drill hole #2 the rocks were tighter and pseudo breccia was not as common, but the density at the lower end of the hole was lowered by limestone units. Chert nodules in the formation also had the effect of reducing the bulk density. The effects of chert nodules, limestone and vuggy pseudo breccia are shown in Plate 1.

In drill hole #1, the average density from 150 feet to 400 feet was 2.77 g/cc. In drill hole #2 the average density down to 250 feet is 2.79 g/cc. A model using these densities is constructed in the next section.

Previous density studies

A previous density study of the rocks in the Arctic Archipelago was conducted by Sobczak, Weber and Root, 1970. Densities were compiled from sampling surface rocks and rock material from drill holes for a total of 1,900 density measurements. Indirectly, densities were determined from seismic velocities and sonic logs.

For their density measurements of surface rock samples, 142 samples of limestone had a mean density of 2.70 g/cc with a standard deviation of ± .08 g/cc. Dolostone had a mean density of 2.73 g/cc with a standard deviation of ± .08 g/cc for 37 samples. For 26 samples of shale the mean was 2.44 g/cc with a deviation of ± .33 g/cc. From chip densities and sonic logs, Ordovician limestones on Cornwallis Island had mean densities ranging from 2.70 to 2.73 g/cc.
For the final conclusion of the study, dolostone of Silurian and Ordovician age was determined to have a density range of 2.73 to 2.86 g/cc with a mean density of 2.82 g/cc. Limestone of the same age ranges from 2.70 to 2.71 g/cc with a mean of 2.70 g/cc. It's noted that the mean for dolostone is not reflected in their study of surface samples.

This previous study seems to agree with Canadian Superior's density data. It was in consideration of the densities determined by Canadian Superior Exploration and this previous study that the author's density model for limestone and dolomite in the subsection 'Effect of the flanking shale and fault' of the section 'Interpretation' was chosen.
Sept. 28, 1973

<table>
<thead>
<tr>
<th>STATION NUMBER</th>
<th>SAMPLE DENSITY (g/cc)</th>
<th>AVERAGE DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>20N 4E (Dol.)</td>
<td>2.84 2.84</td>
<td>2.840</td>
</tr>
<tr>
<td>2S 15E</td>
<td>2.73 2.73 2.74</td>
<td>2.733</td>
</tr>
<tr>
<td>8S 23W (Dol.)</td>
<td>2.75 2.77</td>
<td>2.760</td>
</tr>
<tr>
<td>8S 18W (Lms.)</td>
<td>2.64 2.63</td>
<td>2.635</td>
</tr>
<tr>
<td>8S 15W (Dol., Lms.)</td>
<td>2.71 2.73</td>
<td>2.720</td>
</tr>
<tr>
<td>8S 11W (PsBx)</td>
<td>2.72 2.72</td>
<td>2.720</td>
</tr>
<tr>
<td>8S 4W (Dol.)</td>
<td>2.78 2.76</td>
<td>2.770</td>
</tr>
<tr>
<td>8S 1W (Dol.)</td>
<td>2.73 2.74</td>
<td>2.735</td>
</tr>
<tr>
<td>8S 1E (Dol.)</td>
<td>2.76 2.75</td>
<td>2.755</td>
</tr>
<tr>
<td>8S 8E (Lms.)</td>
<td>2.70 2.74</td>
<td>2.720</td>
</tr>
<tr>
<td>8S 17E (Lms.)</td>
<td>2.73 2.70</td>
<td>2.715</td>
</tr>
<tr>
<td>8S 20E (PsBx)</td>
<td>2.76 2.78</td>
<td>2.770</td>
</tr>
</tbody>
</table>

Average density:
Average density of limestones: 2.69
Average density of dolomite: 2.77

TABLE D   ROCK DENSITY MEASUREMENTS
FIG. 8  DENSITY VS. DEPTH, DDH^1

HIGH DENSITY

LOW DENSITY

FM  |  LFM  |  DB  |  TM  |  TFM

DDH^1

DENSITY (g/cc)

2.8

2.7

2.6

200  |  400  |  600  |  800
INTERPRETATION

All gravity anomalies come from horizontal variations in density (Nettleton, 1971). An example is shown in Figure 10. Here, uplift of the layers produce a density contrast as the formation contacts are lifted from the horizontal. On the flanks of the illustrated gravity anomaly the density variations are still vertical and no anomaly is seen.

Rock density is controlled by grain density, porosity, and the fluid in the pore-spaces. The dependence of bulk rock density on porosity is illustrated in Figure 11. Using a grain density of 2.75 g/cc taken from the average rock density in the Thumb Mountain formation and the density of ice (permafrost) in place of water as is common in southern latitudes a density vs. porosity graph was constructed and is shown in Figure 12.

Effect of porosity

The effect of porosity on gravity is shown in Figure 13. The anomaly at 8 + 00 W is caused by a horizontal variation in density from east to west as we pass from a high porosity pseudo breccia zone to a higher density dolomite zone flanked by a suspected frost-fractured limestone zone. A frost-fractured limestone zone was found on line 12 + 00 N in Figure 14 by a drill intersection. At the base of the drill holes a pseudo breccia zone was found and could be the cause of the gravity decrease to the east. The tighter dolomite between these lower density zones would account for the gravity high shown.

Now, having stated the cause of these anomalies illustrated by Figures 13 and 14, next should be considered the porosities and densities involved as well as formation thicknesses which
would create these anomalies. Surface sampling of the area
gave an average density of 2.75 g/cc for the Thumb Mountain
Formation. It was on this basis that the porosity chart in
Figure 12 was constructed.

In the drill hole shown in Figure 15 the circulation
was poor indicating a high permeability. At the end of the drill
hole circulation was lost entirely. For these type of zones
a trial porosity of 10 % was selected. This porosity results in
density of 2.57 from Figure 12. If dolomite is considered to
have a density of 2.80 g/cc, then the density contrast is
.23 g/cc. The maximum gravity and thickness of the slab or
depth of the porous material may be estimated from the formula
for a horizontal infinite slab provided that the depth of
overburden can be neglected and the gravity high (or low) is
broad enough to make this a reasonable approximation. For the
area under consideration the overburden depth is 15 to 20 feet.

For the infinite slab: \[0.013 \sigma t = G_{\text{max}}\]
where: \(\sigma = .23\) g/cc
\(t = \text{thickness of the slab}\)
\(G_{\text{max}} = .3\) mgals (magnitude of the gravity decrease
in Figure 15)

With these above figures a thickness of 100 feet was
calculated. If the contrast with dolomite of the frost-
fractured limestone zones were .12 g/cc due to a lower porosity
of 3.75 % then the thickness would be 200 feet. For a semi-
infinite slab which would take the overburden thickness into
account the same figures are calculated since the depth of
overburden is small compared with the thickness of the slab.
Effect of the flanking shale and fault

From the core measurements of density for the drill holes on line 8 + 00 S a density model was constructed. In drill hole #1, the average density of dolomite was 2.77 g/cc from 150 feet to 400 feet and in hole #2 the average density down to 250 feet was 2.79 g/cc. From a drill hole at 8 + 30 S, 16 + 00 W it is known that the Upper Member Formation is limestone and this was taken to have a density of 2.70 g/cc. So a dolomite core of 2.80 g/cc was placed in a host of 2.70 g/cc. The amplitude of the observed gravity profile was .5 mgals.

Taking an infinite slab of .1 g/cc contrast a depth of 307 feet was calculated from the formula \(0.013 \sigma t\), where \(\sigma\) is the density contrast and \(t\) is the thickness. At the peak gravity value the depth of the higher density dolomite extends only to 250 feet. Using this depth for the infinite slab calculation we come up with only a value of .33 mgals. This indicates that the anomaly on line 8 + 00 S is not entirely due to the higher density core which is drawn in Figure 17 based on the density measurements and core data.

In order to model the density slab more exactly the equation for the ribbon model was used. This equation, from Grant and West, 1965, is:

\[
g(x) = 2Gp \left[ \frac{1}{2} \sin d \left( \ln \frac{A-Y}{A+Y} - \ln \frac{B-Y}{B+Y} \right) \right]
\]

\[
+ \cos d \left( \tan \frac{Y(1 + h \sin d - x \cos d)}{A(x \sin d + h \cos d)} - \tan \frac{Y(h \sin d - x \cos d)}{B(x \sin d + h \cos d)} \right)
\]

\[
A = \sqrt{(x - l \cos d)^2 + (h + l \sin d)^2 + y^2}
\]

\[
B = \sqrt{x^2 + h^2 + y^2}
\]
\( Y = \) half the strike length of the ribbon
\( d = \) the angle of the dip
\( s = \) thickness of the ribbon
\( l = \) the subsurface extent of the ribbon
\( h = \) the depth from the surface to the ribbon
\( G = \) the gravitational constant
\( p = \) the density contrast

The ribbon model is illustrated in Figure 18.

A strike length of 1,000 feet for this model seemed to be in keeping with the geology and the length of the anomaly as shown in Figure 3. The density model shown in Figure 19 was composed of a series of vertical ribbons 50 feet in width. The depth of overburden was taken to be 15 feet. Figure 17 shows the theoretical effect of the dolomite core model in a limestone host. The maximum amplitude was .207 mgals.

In Figure 7 it was noted that the gravity seemed to decrease as the profile entered the Irene Bay Shale Formation. This was particularly evident on line 12 + 00 S. The curve moved on an upward trend as the profiles passed into the pyritous Cape Phillips shales and limestones. From this it seems as though we enter a formation of low density shales as we pass from the Thumb Mountain Formation.

The density model was placed in the area where the shales occur in line 8 + 00 S and assigned a value of 2.50 g/cc. The combined effect of the shales and dolomite in a host of limestone is shown in Figure 17. If this model is accepted so far then it would appear as though something is pulling down the gravity profile to the east beyond 0 + 00.

In Figures 3 and 5 it can be noted that the fault which separates the Thumb Mountain from the Bay Fiord Formation is the site of a high increase in gravity with a steep gradient.
This gradient at the fault is similar to a fault anomaly. The Bay Fiord Formation to the east of the fault contains a lower unit of gypsum and anhydrite. To the southeast, .75 miles off the map shown in Figure 3, there is a gravity low of -4.0 mgals. This low may be due to a thickening of the gypsum anhydrite in the Bay Fiord. This would accentuate the anomaly at the fault.
FIG. 10 DENSITY LAYERS, CONTRAST, AND ANOMALY
(NETTLETON, 1971)

\[ D = D_r (1 - \phi) \]
\[ D = D_r (1 - \phi) + \phi \]

\( D = \text{BULK DENSITY} \)
\( D_r = \text{GRAIN DENSITY} \)
\( \phi = \text{POROSITY} \)

FIG. 11 POROSITY VS. DENSITY
(NETTLETON, 1971)
density relation: \[ D = D_r (1 - \phi) + 0.914 \phi \]

\[ D_r = 2.75 \] (grain density)

Density of ice (permafrost) = 0.914

**FIG. 12** DENSITY VS. POROSITY
frost fractured to 214 ft in far west drill hole

* drill hole

GRAVITY PROFILE

FIG. 14 LINE 12°00'N
Gravity Profile

* drill hole

Gravity low
(PsBx & lms)

0
dol.?

-400 ft.

800 ft.

16+00 W

8+00 W

0+00

FIG. 15 LINE 16+00 N
FIG. 16  LINE 8+00 S
FIG. 17  LINE 8+00S DENSITY MODEL
FIG. 18  THE RIBBON MODEL
(from Grant & West, 1965)

FIG. 19  DENSITY MODEL
DEPTH DETERMINATIONS

The depth rules given by Bott and Smith, 1958, were applied to the following lines.

<table>
<thead>
<tr>
<th>LINE</th>
<th>STATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>00 N</td>
</tr>
<tr>
<td>4</td>
<td>00 N</td>
</tr>
<tr>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>8</td>
<td>00 S</td>
</tr>
<tr>
<td>16</td>
<td>00 S</td>
</tr>
<tr>
<td>24</td>
<td>00 S</td>
</tr>
<tr>
<td>1</td>
<td>00 W</td>
</tr>
<tr>
<td>11</td>
<td>00 W</td>
</tr>
<tr>
<td>0</td>
<td>00</td>
</tr>
<tr>
<td>14</td>
<td>00 W</td>
</tr>
<tr>
<td>12</td>
<td>00 W</td>
</tr>
<tr>
<td>2</td>
<td>00 E</td>
</tr>
<tr>
<td>20</td>
<td>00 E</td>
</tr>
<tr>
<td>2</td>
<td>00 E</td>
</tr>
<tr>
<td>18</td>
<td>00 W</td>
</tr>
<tr>
<td>18</td>
<td>00 W</td>
</tr>
</tbody>
</table>

The authors mentioned above give a statement and proof of six depth theorems. Calculations were completed using all of these theorems. However, only the results of two of the theorems are presented because the inclusion of all the results in this section would not be any more instructive than the results which are included. The rest of the results from the application of the other depth theorems have been inserted into the appendix. The theorems used in this section are stated below and a test case using a horizontal cylinder to illustrate the theorems may be found in the appendix.

THEOREM 2
Theorem 2 is for three dimensional bodies.

If \( x, d \) are any numbers for which

\[
\mu = \frac{2A(x)}{A(x+d) + A(x-d)} > 1
\]

then

\[ h \leq |d| (\mu - 1)^{\nu \mu} \]

THEOREM 5
Theorem 5 is for two dimensional bodies of infinite strike length.

\( \mu \) is the same as in Theorem 2.

\[ h \leq |d| (\mu - 1)^{\nu \mu} \]
where: \( h \) = the depth to the top of a causative body.
\( A(x) \) = the gravity reading at the point \( x \).
\( d \) = any positive or negative distance

The proofs of these theorems are detailed so this thesis will omit a rigid proof and instead offer a heuristic proof for the two dimensional case of Theorem 5.

PROOF

see Figure 20

\( Q(\xi, \lambda) \) is any point in an arbitrary body.
\( d\lambda \) is a two-dimensional mass element of mass/unit length
\( \xi, \lambda \) are the \( x, y \) coordinates of the mass element \( d\lambda \)
\( h \) is the distance from the surface to the top of the body

The origin of the \( x \)-axis in figure may be placed anywhere. Since this is so, there is no loss of generality if for \( A(x), A(x+d) \) and \( A(x-d) \), we place \( x = 0 \).

\[
A(0) = \int G \frac{(-\lambda)}{\xi^2 + \xi^2} \, d\xi \, d\lambda \\
A(-d) + A(d) = \int \left[ \frac{(\xi^2 + \lambda^2)}{(d-\xi)^2 + \lambda^2} + \frac{(\xi^2 + \lambda^2)}{(d+\xi)^2 + \lambda^2} \right] \frac{-\lambda}{(\xi^2 + \lambda^2)} \, d\xi \, d\lambda
\]

consider \( Q = \frac{(\xi^2 + \lambda^2)}{(d-\xi)^2 + \lambda^2} + \frac{(\xi^2 + \lambda^2)}{(d+\xi)^2 + \lambda^2} \)

where \( \xi, \lambda \) are the coordinates of \( d\lambda \) and \( \lambda \geq h \).

If \( \lambda \) is held fixed \( Q \) is a minimum when \( \xi = 0 \), also if \( \lambda = h \) where \( h \) is the depth to the top of the body has taken on its minimum possible value and therefore \( Q \) is further minimized. Thus when \( \xi = 0 \), and \( \lambda = h \),

\[
Q = \frac{2}{\frac{d^2}{h^2} + 1}
\]
and it is at its minimum, therefore for all other possible values of $\xi$ and $I$, \( Q \geq \frac{2}{\frac{d^2}{h^2} + 1} \).

Now \( A(-d) + A(d) \) may be written as:

\[
A(-d)+A(d) \geq \frac{2}{\frac{d^2}{h^2} + 1} \int \frac{-L}{\xi^2 + L^2} \, dm
\]

\[
\geq \frac{2}{\frac{d^2}{h^2} + 1} A(0)
\]

\[
= \frac{2A(0)}{A(-d)+A(d)} = \frac{2A(x)}{A(x-d)+A(x+d)}
\]

and

\[
\frac{d}{h} + 1 \geq \mathcal{K}
\]

\[
h \leq |d| (\mathcal{K} - 1)^{\frac{1}{2}}
\]

What the above inequality means is that the quantity to the right of the above inequality will give a number somewhat greater than the actual depth $h$ to the top of the body. The true depth may be obtained only if the body degenerates into a single particle in the plane $z = -h$ and $A(x)$ is taken directly over the particle (eg) $\xi = 0$. The usefulness of this rule lies in the fact that it gives limiting depths beyond which it would not be possible to model a causative body. It is interesting to note that no knowledge of density contrasts are needed except for the fact that the contrast must be entirely positive, or negative and uniform.
Generally in using these rules it is the distance \( x \), where we calculate the smallest values of \( h \) which is of interest since this is where the near surface part of the body most likely occurs. The purpose in presenting the depth results as shown in Figures 21 & 22 was to determine if there was a causative body beyond the range of the depth of the drill program. Calculations were completed for all possible values of \( x \) and \( d \). It must be remembered that these are limiting depth rules and the values calculated are somewhat larger than what would be the true depths to the top of the body. So, if we have calculated only a few depths greater than 800 feet and the majority of calculations lie around 200 feet then it may be said that the top of a causative body could not lie beyond 800 feet, but could be at 200 feet and most likely lies at a depth less than 200 feet.

The graphs in Figures 21 & 22 were constructed in the following manner. Calculations for each line were completed for all possible values of \( x \), and \( d \). The number of values in each 100 foot interval were tallied. To get the relative frequency the sum in each 100 foot interval was divided by the total number of calculations. The relative frequency scale appears on the left hand side of each graph in Figures 21 and 22. The right hand scale is the absolute frequency which is the number of values summed for each 100 foot interval.

In Figure 21 the line 8+ 00 N depth tabulations show that a causative body could not occur below 600 feet and the top of a body would most likely be at 300 feet or less. For line 4 + 00 N a body could not occur below 500 feet. A body wouldn't occur below 800 feet in line 0 + 00.

Lines 8 + 00 S, 16 + 00 S, 24 + 00 S, are lines with broad anomalies and the depth results are shown in Figures 22. As might be expected for broad anomalies the depths calculated
give deeper values than the lines examined in Figure 21.
The values for depth seem to be weighted to 1,000 feet or less. Theorem 2, for two dimensional bodies with an infinite strike length give deeper values than Theorem 5 which is for three dimensional bodies. While Figure 22 may show depths which lie beyond the range of the drill program it must be considered that either the density contrast at 1,000 or 2,000 feet, or the mass required in order to model the anomaly would have to be rather enormous. So, it may be concluded that if a mineralized body existed then the depths of drilling in the drill program were quite adequate to find it. The depths of drilling ranged from 500 feet to 700 feet.

The two theorems illustrated in this section were selected arbitrarily. The results of the other theorems, which may be found in the appendix, are summarized for line 8 + 00 S which was the subject of the subsection 'Effect of the flanking shale and fault'.

For Corollaries 2.1 and 5.1 depth calculations on line 8 + 00 S range from 200 feet to 600 feet. It is the shallowest depth estimates, near 200 feet, which are considered to be of interest. For Corollary 4.1 the depths calculated range from 600 feet to 4000 feet over the broad center part of the gravity anomaly on line 8 + 00 S. In this case it is the shallowest limiting depths which are considered. For Theorem 3 and 6, 107 feet and 81 feet were calculated respectively as limiting depths.
FIG. 20 DEPTH RULE
FREQ. VS. DEPTH

THEOREM 5

<table>
<thead>
<tr>
<th>REL. FREQ.</th>
<th>ABS. FREQ.</th>
<th>REL. FREQ.</th>
<th>ABS. FREQ.</th>
<th>REL. FREQ.</th>
<th>ABS. FREQ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>6</td>
<td>0.4</td>
<td>6</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>LINE 8+00 N</td>
<td>3</td>
<td>LINE 4+00 N</td>
<td>6</td>
<td>LINE 0+00</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

THEOREM 2

<table>
<thead>
<tr>
<th>REL. FREQ.</th>
<th>ABS. FREQ.</th>
<th>REL. FREQ.</th>
<th>ABS. FREQ.</th>
<th>REL. FREQ.</th>
<th>ABS. FREQ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>6</td>
<td>0.4</td>
<td>6</td>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>LINE 8+00 N</td>
<td>3</td>
<td>LINE 4+00 N</td>
<td>6</td>
<td>LINE 0+00</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
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<tr>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

MAX. DEPTH (IN FEET)

FIG. 21 THEOREMS 5 & 2, NORTH LINES
FREQ. VS. DEPTH

THEOREM 5
REL. FREQ.

ABS. FREQ.

REL. FREQ.

ABS. FREQ.

REL. FREQ.

ABS. FREQ.

LINE 8100 S

4

8

1

1

LINE 16100 S

9

9

6

1

LINE 24100 S

8

8

3

4

THEOREM 2

REL. FREQ.

ABS. FREQ.

REL. FREQ.

ABS. FREQ.

REL. FREQ.

ABS. FREQ.

LINE 8100 S

4

1

LINE 16100 S

9

6

1

LINE 24100 S

8

3

MAX. DEPTH (IN FEET)

FIG. 22 THEOREMS 5 & 2, SOUTH LINES
SUMMARY AND CONCLUSIONS

In the author's opinion lateral variations in formation densities are the cause of the anomaly. Slight changes in contrast of .1 g/cc over large sequences of rock are enough to cause anomalies with a broad flat top. Flanking shales in the Irene Bay Formation accentuate these anomalies. Anomalies of short wavelength may be caused by frost fracture and pseudo breccia zones flanking a denser core.

Density analysis of surface rocks gave a deceptive average of 2.75 g/cc which did not take into account in situ porosity of pseudo breccia and frost fracture zones. Porosity can have a profound effect on density.

The cause of anomalies in the Thumb Mountain of other areas may be speculated on from the surface geology. Pseudo breccia associated with a gravity low may indicate a subsurface pseudo breccia zone of high porosity. A prominent gravity high or low over a formation or member and which begins and ends at formational boundaries may indicate a density contrast throughout the formation or member. Contrasts could be caused in a formation if it is flanked by shales, limestone, or porous dolomite and limestone.

Generally, it is the broad anomalies which originate from slight variations in density of massive amounts of rock. These anomalies tend to lie over formations or members. Shorter anomalies of a few hundred feet may be caused by changes in in situ porosity due to frost fracturing or the occurrence of a pseudo breccia zone.
REFERENCES


APPENDIX
LIMITING DEPTH CALCULATIONS

The following theorems and graphs are the depth theorems and results of the depth calculations which were not included in the section on 'Depth Determinations'. These theorems and their proofs may be found in the article by Bott and Smith, 1958.

Theorems 1 and 4

Theorem 1 is for the three dimensional case and is stated as follows: 
\[ \lambda = \frac{A(x)}{A(x')} \geq 1 \]
\[ h \leq \frac{|x_x - x_{x'}|^\lambda}{\lambda^{\lambda/3} - 1} \]

Theorem 4 is for the two dimensional case and is stated as:
\[ h \leq \frac{|x_x - x_{x'}|^\lambda}{\lambda^{\lambda/3} - 1} \]

where: 
A(x) = the gravity value at position x 
x = distance from an arbitrary origin 
h = limiting depth value to the top of the body

Corollaries 1.1 and 4.1

Corollary 1.1 is for the three dimensional case and is stated as follows:
\[ h \leq \frac{3A(x)}{2 \left| \frac{dA(x)}{dx} \right|} \]

Corollary 4.1 is for the two dimensional case and is stated as follows:
\[ h \leq \frac{A(x)}{\left| \frac{dA(x)}{dx} \right|} \]

The graph for the results of Corollary 1.1 is not shown since the results are 3/2 times the results of Corollary 4.1.
Corollaries 2.1 and 5.1

Corollary 2.1 is for the three dimensional case and is stated as follows: For all values of \( x \) at which \( \frac{d^2A(x)}{dx^2} \) is negative we have
\[
h \leq -\frac{3A(x)}{\frac{d^2A(x)}{dx^2}}
\]

Corollary 5.1 is for the two dimensional case and is as follows:
\[
h \leq -\frac{2A(x)}{\frac{d^2A(x)}{dx^2}}
\]

Theorems 3 and 6

Theorem 3 for the three dimensional case is
\[
h \leq \frac{48\sqrt{5}}{128} \frac{A_{\text{max}}}{\max \left| \frac{dA}{dx} \right|}
\]
and Theorem 6 for the two dimensional case is
\[
h \leq \frac{3\sqrt{3}}{8} \frac{A_{\text{max}}}{\max \left| \frac{dA}{dx} \right|}
\]

where \( A_{\text{max}} \) is the maximum gravity value and \( \frac{dA}{dx} \) is the maximum first derivative value.

The results for Theorem 3 and 6 are stated below.

<table>
<thead>
<tr>
<th>LINE</th>
<th>LIMITING DEPTHS (in feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THEOREM 3</td>
</tr>
<tr>
<td>8 + 00 N</td>
<td>107</td>
</tr>
<tr>
<td>4 + 00 N</td>
<td>286</td>
</tr>
<tr>
<td>0 + 00</td>
<td>167</td>
</tr>
<tr>
<td>8 + 00 S</td>
<td>186</td>
</tr>
<tr>
<td>16 + 00 S</td>
<td>172</td>
</tr>
<tr>
<td>24 + 00 S</td>
<td>151</td>
</tr>
</tbody>
</table>
Theorems 2 and 5 have already been discussed in the section on 'Depth Determinations'.

**TEST CASE FOR THE HORIZONTAL CYLINDER**

To test and give an example of the limiting depth theorems the gravity curve for a horizontal cylinder was calculated.

From Nettleton, 1942, the formula for a horizontal cylinder is: \[ g = K \left[ \frac{1}{1 + \frac{x^2}{z^2}} \right] \]

where: 
- \( x \) = horizontal distance
- \( z \) = depth to the center of the cylinder (\( z = 200 \) ft. for the test case)
- \( K = 12.77 \frac{R}{z} \) = density contrast
- \( R \) = the radius of the cylinder
- \( g \) = the gravity value in milligals

and all linear dimensions are expressed in kilofoots. A restriction on the formula is that the diameter of the cylinder is less than or not much greater than the depth.

Since the cylinder is a two dimensional structure only Theorems 4 and 6 and Corollaries 4.1 and 5.1 were used. The shape of the gravity curve was determined from \( 1/\left[1 + \frac{x^2}{z^2}\right] \) and the values calculated were as follows: .06, .08, .1, .15, .20, .31, .50, .71, 1.0, .71, .52, .31, .20, .15, .1, .08, .06.

The Theorems and Corollaries are based on the ratio's of the gravity intensities and so the values of \( K \) cancel. This ratio approach is the reason why the Theorems do not require a knowledge of the density contrasts.

The results of the test case for the Theorems 4 and 5 are shown in Figure A. Theorem 6 gave a limiting depth of 224 feet and Corollary 5.1 a depth of 156 feet at the gravity curve maximum.
FIG. A LIMITING DEPTHS FOR THE TEST CASE
FREQ. VS. DEPTH

MAX. DEPTH (IN FEET)

FIG. H THEOREM 1, LINE 800 S
FIG. 1  THEOREM 1, LINE 16400 S
FREQ. VS. DEPTH

MAX. DEPTH (IN FEET)

FIG.K THEOREM 4, LINE 800 N
REL. FREQ.

.20

.16

.12

FREQ. VS. DEPTH

MAX. DEPTH (IN FEET)

ABS. FREQ.

-14

-12

-10

-8

-6

-4

-2

0

2

4

6

8

10

12

14

FIG. L  THEOREM 4, LINE 4+00' N
FREQ. VS. DEPTH

REL. FREQ
-0.10
-0.08
-0.06
-0.04

MAX. DEPTH (IN FEET)

ABS. FREQ.
24
20
16
12
8
4

FIG. N THEOREM 4, LINE 8+00 S
FREQ. VS. DEPTH

MAX. DEPTH (IN FEET)

FIG. 0 THEOREM 4, LINE 16+00 S