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A GRAVITY SURVEY IN THE HAULAGE TUNNEL
OF THE HENDERSON MINE
NEAR BERTHOUD PASS, COLORADO

By
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An Engineering Report submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Engineering (Geophysical Engineer).

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Abstract

A gravity survey was conducted in the haulage tunnel of the Henderson Mine, followed by the reduction and interpretation of the data and analysis of errors. The gravity survey consisted of 64 stations in the tunnel and five stations on the surface, all of which were tied to a North American gravity grid bench mark. A correction for the earth tides and the complete Bouguer correction requiring a special terrain correction for the subsurface data were applied. Finally, the bulk density was calculated using Hammer's (1950) formula. The computed bulk densities show a slightly higher than average density implying that the country rock is a mixture of granite and metasediment.

The uncertainties in the complete Bouguer-corrected data are as large (± 1.30 mgals) as most of the anomalies. The large relief ($\approx 2,500$ feet to 3,300 feet or ≈ 0.75 km to 1.0 km) caused usually trivial errors in the terrain correction to account for most of the uncertainty in the data. Thus, a criterion utilizing the surface gravity survey and the deviation from the regional gradient was developed.

Four anomalies based on the criteria appear to be caused by granite or metasediment pods in the mixed granite-metasediment country rock, rather than uncertainties in the data. Models of the source of the anomalies range in size from

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between 500 ft. (152 m.) and 3,000 ft. (914 m.) from the tunnel.

The bulk density of the near surface (<4,000 ft. (1215 m.)) rock was calculated in three locations from the gravity gradient. The following results were obtained:

<u>Surface Station*</u>	<u>Density</u> <u>g/cm³</u>
HT-2	2.79
Vent Raise	2.65
Jones Pass	2.68

*For location see Plate 1.

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Introduction

During the last part of August and the first part of September, 1975, a gravity survey was conducted for Climax Molybdenum Corporation in the Henderson Haulage Tunnel. The survey was done in an attempt to define an anomaly near the tunnel found on Brinkworth's (1970) complete Bouguer gravity map of the area, and to determine the bulk density of the rock between the tunnel and the surface (a distance of approximately 2,000 ft. or about 0.6 km).

The haulage tunnel connects the Henderson orebody, located directly beneath Red Mountain ($39^{\circ}46'0''\text{N}$, $105^{\circ}52'50''\text{W}$) near Berthoud Pass, Colorado, with the mill site near Darling Creek ($39^{\circ}47'30''\text{N}$, $105^{\circ}00'00''$). Trending $N77.5^{\circ}\text{W}$ for ten miles, the tunnel passes under the Continental Divide at Jones Pass, continuing to its west portal near Darling Creek (Plate 1). It has a three percent grade toward the orebody over its entire length. The cover varies from less than 100 feet (30 metres) near the west portal to 2,500 feet (765 m.) under the first ridge (HT-2), to only 1,500 feet (460 m.) near the vent raise, to around 4,600 feet (1400 m.) under Jones Pass on the Continental Divide.

There are four phases of the survey which will be discussed: field work, correction of the data, the density determinations and interpretation of the data.

The survey consists of sixty-four stations in the

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haulage tunnel and five stations on the surface either directly above the tunnel or near the west portal. A North American gravity bench mark in Golden, Colorado was used to obtain the absolute gravity values for the stations. The complete Bouguer correction was applied to the data with a special terrain correction for the mass above the sub-surface stations. Next the density for the rock between the tunnel and the surface was calculated using Hammer's (1950) equations. Modifications of the equations were necessary to handle the large terrain corrections. Interpretation of the data defined four anomalies and established a set of criteria for distinguishing the anomalies from noise in the data.

The field work, reduction of data, and interpretation required a total of around 385 man-hours to complete. The field work took five days to complete. About 220 man-hours were required in reducing the data. Development of the equations and calculation of the density required about 24 man-hours; while the analysis of anomalies and interpretation took nearly 100 man-hours to complete.

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Acknowledgements

The survey was conducted for Climax Molybdenum Corporation, owner of the mine and my employer at the time. Climax provided samples for density determinations and geologic information about the tunnel.

I am grateful to Arnie Ward, Resident Geologist at the Henderson Mine and his staff for their assistance. I am particularly grateful to Mr. Jack McCoy, geologist, who assisted with the field work and in obtaining location and elevation data for the stations. Tim Zeisloft, student at Colorado School of Mines, also assisted with the field work.

Dr. T. L. Lefehr, president of EDCON, provided the Hayford-Bowie charts used in the terrain correction.

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Authors Note

The metric system of measurement as described in the Systeme Internationale d'Units (S.I.) has been accepted by the United States Government. In the next ten years S.I. will become the standard measuring system worldwide. Thus the S.I. units will be given in parentheses after the commonly used unit, throughout this thesis.

The S.I. gives the units and spelling as follows:

metre	m	length
(metre) ²	m ²	area
(metre) ³	m ³	volume
joule	J	energy
newton	N	force
kilogram	Kg	mass

The units used in the thesis will mainly be metre and gram.

Though the milligal is not a recognized unit in the S.I. system, due to its wide acceptance in the industry and the academic world it will be used in this thesis instead of micrometre/sec². The micrometre/sec² is approximately equal to the gravity unit or 0.1 mgal.

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Supportive Work

Geology of the tunnel and surface near the tunnel as mapped by the Climax Molybdenum Corporation geologists shows an area of Precambrian metasediments underlain by granites. The Idaho Springs metasediments are a Precambrian-age biotite-schist which is almost a gneiss in some areas. Below and within the metasediments are granites of the Silver Plume Granite suite. The granites appear to have been mobile during metamorphism intruding into the metasediments along bedding or foliation planes. Also during metamorphism tight folds developed in the metasediments and granites. Later in Tertiary time the area near Jones Pass and Red Mountain was intruded by porphyries causing hydrothermal alteration of the surrounding rocks. The area has also been intruded by a diabase, though at what relative time is unknown.

George Brinkworth (1970) conducted a gravity survey covering an area approximately 1° latitude by 1° longitude nearly centered about the haulage tunnel. He performed the complete Bouguer corrections on the data carrying the terrain corrections out to a radius of 60 miles (100 km). His data indicated a low defined by one station. He reoccupied and rechecked the station to verify the value (personal communication). I checked the contours by retrieving the data for stations within two miles of the tunnel and recontouring the data. My contours and Brinkworth's contours agreed very closely.

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Field Work

There were sixty-four subsurface stations and five surface stations in the gravity survey. In the tunnel, the stations were at about 1,000 ft. (305 m.) intervals with about 500 ft. (152 m.) intervals near the center of the tunnel (see Plate 2). Three of the surface stations (HT-2, Vent Raise, and Jones Pass) were located on surface tunnel-line bench marks, while the subsurface stations were located on tunnel or laser monuments (like U.S.G.S. bench marks) or laser mounts or targets (similar to U.S.G.S. survey points) for which Climax Molybdenum Corporation provided the latitude, longitude, and elevation data. Gyro 1 was the base station for the latitude, longitude, elevation, and gravity surveys at the Henderson Mine.

The survey was conducted with a LaCoste-Romberg gravimeter model G-395 provided by AMAX Exploration, Inc. The gravimeter can be read to 0.01 mgal while the thousandths place must be estimated. LaCoste-Romberg gives the accuracy of the instrument as ± 0.005 mgal.

Gyro 1, the east portal surface base station, was tied to the North American gravity bench mark, which is located on the curb in front of the Illinois Street entrance to Berthoud Hall, Colorado School of Mines, Golden, Colorado. A reading was taken at the bench mark in Golden, then at Gyro 1 at Henderson, and then again at Golden tying Gyro 1 to the North

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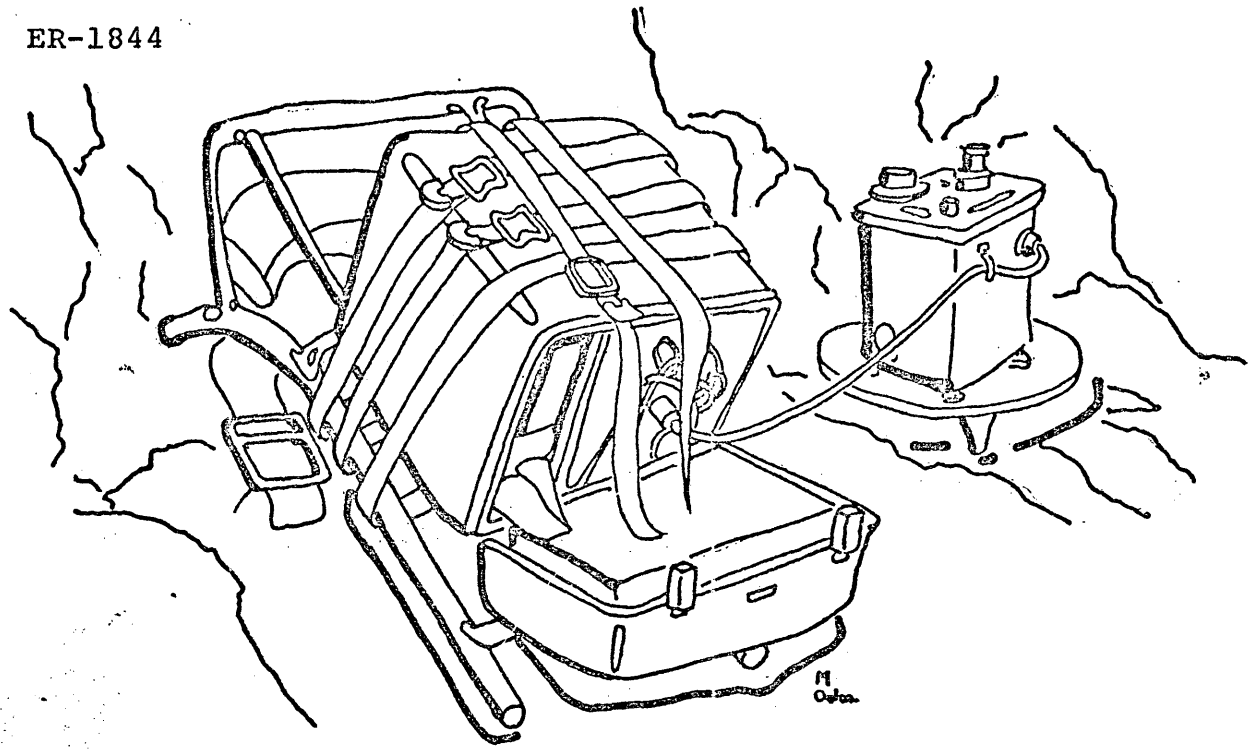
American Gravity Network. Corrections were applied to the above loop using a linear interpolation of the tidal drift, since the LaCoste-Romberg recording gravimeter in the Department of Geophysics of the Colorado School of Mines showed a linear drift during the time the loop was being made.

The three surface stations and the west portal base were tied to Gyro 1. The loop went from Gyro 1 to the west portal base, then HT-2, Vent Raise, Gyro 1, Jones Pass, and Gyro 1. Linear drift corrections as above were applied. Five hours and a helicopter supplied by Climax Molybdenum Corporation were required to complete the tie.

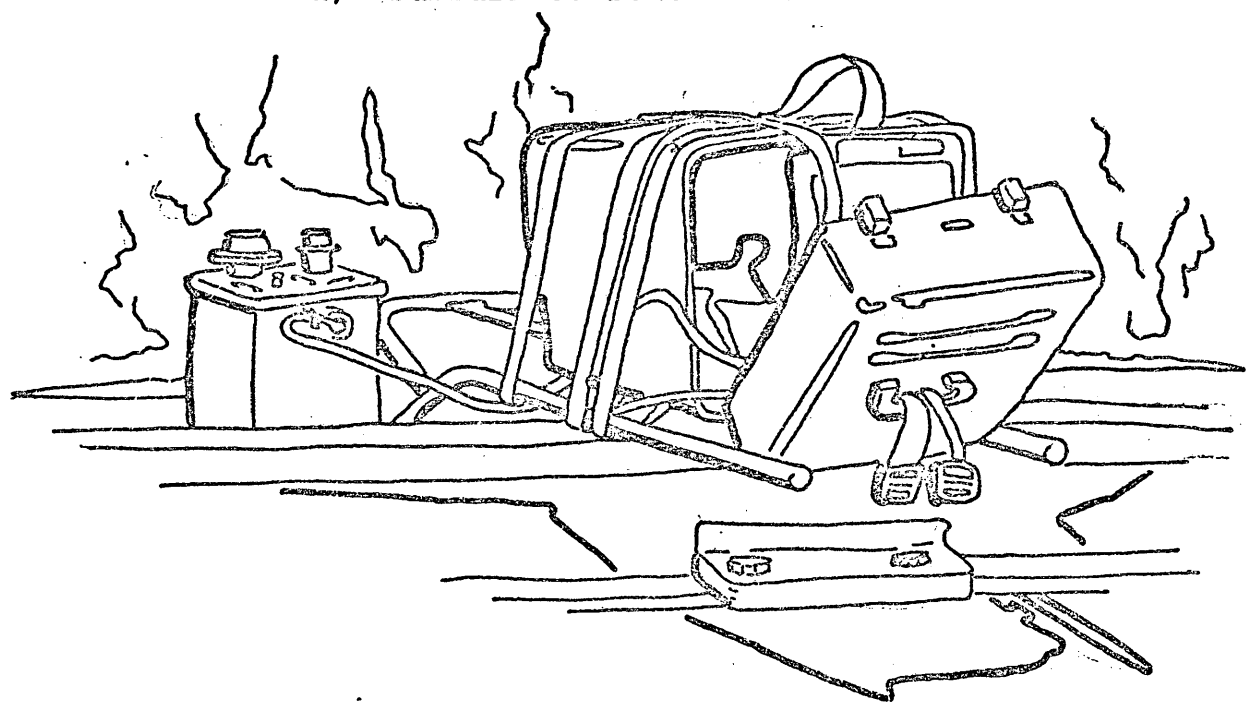
The subsurface stations were tied either to the west portal base or Gyro 1, depending on the portal used for access to the tunnel. The surface base station was occupied at the start and end of each day. Within the tunnel, base stations were reoccupied every two to three hours.

To minimize the effect of the existence of the tunnel, the subsurface stations were located on the south side of the tunnel. Stations were sited on a 6 in. (0.15 m.) cement curb in most cases; however, where the curb was absent they were located on the gravel muck floor (Figure 1). Terrain correction charts by Hayford-Bowie (1936) were used to calculate the terrain correction. Tables accompanying the charts were designed for elevation changes of 30 ft. (9 m.) or less in zone A to 3,000 ft. (914 m.) or less in zone J.

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a) Subsurface Station on Muck



b) Subsurface Station on Curb

Figure 1: a) Location of gravimeter in areas where there was only a gravel floor.
 b) Location of gravimeter in areas where there was a cement curb.

The changes in elevation from subsurface stations to the surface were much larger in this case, varying from 1,000 ft. (305 m.) to 4,500 ft. (1,372 m.). Thus the terrain correction was calculated from Hammer's (1939) original equation:

$$T = \frac{2\pi G \sigma}{n} (R_1 - R_2 - \sqrt{R_1^2 + h^2} + \sqrt{R_2^2 + h^2}) \quad (1)$$

where R_1 is the inner radius of the zone R_2 is the outer radius, h is the difference between the mean elevation of the zone and the elevation of the station, σ is the density, n is the number of compartments in the zone, and G is the gravitational constant. The corrections were calculated out to zone K. While calculating the terrain correction it was observed that small programmable calculators have made the use of the terrain correction tables obsolete. The tables were originally calculated for only one terrain chart and only one degree of accuracy in the terrain correction. However, using a programmable calculator and the equation, one can have an accuracy consistent with accuracy of the survey, use any terrain chart, and obtain the answers as quickly as looking the values up in a table.

One correction unique to a survey in a tunnel is a correction for the rock removed in digging the tunnel. All the subsurface stations were next to the south wall; causing

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the correction for the tunnel to be a constant, except near the west portal. For stations 2,000 ft. (610 m.) or farther from the surface portal (west portal), the attraction of the mass now missing due to the tunnel, as modeled by an infinite cylinder, was 0.68 mgal. Near the west portal, the correction is smaller since there is no correction of the surface.

Therefore, a constant correction of 0.68 was applied to the data except for the three stations near the west portal. Corrections of 0.63 mgal, 0.54 mgal, and 0.34 mgals were applied to these stations starting with the east most.

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Errors in Complete Bouguer Correction Data

Four sources of error cause uncertainties in the complete Bouguer-corrected data. First, the method for correcting for the drift of the meter and earth tides is not a perfect model, thus introducing error. Second, the uncertainty in the location of the station causes errors in the calculation of the free-air and latitude corrections. Third, uncertainty in the location of contours on the topographic maps causes errors in the terrain correction. Lastly, assumptions about the direction and amount of slope in the terrain correction algorithm are erroneous in this area; thus, creating errors in the corrected data.

First, error in the data results from the assumption that the drift of the instrument and earth tides are linear. The tidal correction was calculated on each hour interpolating linearly for the readings taken between the hours. The largest error, (less than ± 0.01 mgal) was produced near the maxima or minima on the tidal curve. Thus the largest error due to the assumed tidal drift is ± 0.01 mgal. LaCoste-Romberg contends that the instrument drift is only slightly non-linear, less than ± 0.005 mgal when observed over three days. Thus the error due to non-linearity of the drift is insignificant. The error caused by the assumption of linearity of the tide and instrument drift is ± 0.01 mgal.

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Uncertainties in the latitude and elevation of a station cause errors in the latitude, free-air, and Bouguer-slab corrections. Climax Molybdenum Corporation provided locations to an accuracy of ± 1 ft. (0.30 m.) in plan which corresponds to an error in the latitude correction of ± 0.001 mgal. The elevation of each station was provided by Climax Molybdenum Corporation to an accuracy of ± 0.01 ft. (0.03 m.), which corresponds to an uncertainty in the Bouguer-slab and free-air corrections of ± 0.0006 mgal. Because the calculations and instrument readings are to the nearest 0.01 mgal, the errors due to uncertainties in station locations are insignificant.

Uncertainty in the location of contours on topographic maps causes errors in the terrain correction. Contour maps, covering a 1000 ft. (305 m.) wide strip directly above the tunnel, with a five ft. (1.5 m.) contour interval were provided by Climax Molybdenum Corporation. These maps were used for terrain corrections in zones B (inner radius 6 ft. (2 m.)) through zone C (outer radius 755 ft. (230 m.)). The uncertainty in the contours (± 2.5 ft. (0.8 m.)) corresponds to the following maximum errors:

Zone	Error (mgal)
B	± 0.000
C	± 0.008

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(errors being the correction caused by a 2.5 ft. (0.8 m.) elevation change on the surface as seen 2,000 ft. (610 m.) above the tunnel). For zones D through J, the 7½ minute United States Geological Survey (U.S.G.S.) topographic maps with a 40 ft. (12.2 m.) contour interval were used. The U.S.G.S. gives the error as ±20 ft. (6.1 m.) which gives rise to the following maximum errors:

Zone	Error (mgal)
D	±0.010
E	±0.009
F	±0.004
G	±0.002
H	±0.001
I	±0.0019
J	±0.0019

Thus the total error caused by the inaccuracies in the topographic maps is ±0.04 mgal.

The last error is due to assumptions in the terrain correction algorithm. Hammer (1939) assumed a fairly flat terrain within a compartment in the chart in deriving the attraction of the mass between an irregular surface (the ground) and a flat plane (the datum). However, in the area surrounding the survey the slopes are up to 20°, trending in several directions. In an attempt to quantify the errors

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due to the steep ($>10^\circ$) slopes, an experiment was performed. The terrain correction for the mean elevation a compartment was compared to the sum of the terrain corrections of 16 divisions of that compartment. In the worst case, (a slope of 15° in each zone) the errors are:

Zone	Error
B	± 0.51
C	± 0.14
D	± 0.15
E	± 0.08
F	± 0.07
G	± 0.06
H	± 0.08
I	± 0.09
J	± 0.06

The error was calculated for a slope about 2,000 ft. (610 m.) above a station. The total error due to the steepest slopes in the area is ± 1.24 mgal (worst possible case).

In summary, the total error is:

Drift Error	± 0.01 mgal
Free-Air and Bouguer Correction Error	± 0.01
Terrain Correction	
1. Contour Errors	± 0.04

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2. Algorithm Errors	±1.24
Total Error	±1.28

The total being the sum of errors in the data, ignoring the drift, free-air and Bouguer corrections which are insignificant. This error is for the worst possible terrain and so most of the data will have a much smaller error.

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Interpretation of Anomalies

The data from the tunnel define a linear regional gradient of about -0.000353 mgal/foot as found by a least-squares fit of the complete Bouguer-corrected data. The deviations of interest will be defined by more than one station. Variations from the trend are all less than 2 mgals. Since the uncertainties in the data are ±1.28 mgals, there is a question as to whether the anomalies are caused by the geology, or errors in the data.

The plot of the deviation from the least-squares fit verses the times that the deviation occurs (Figure 2) shows most of the data fits under a normal distribution curve except between 1.5 and 2.3 mgals except for a one station anomaly at 4 mgal which shall be ignored. Thus any anomalies not due to errors would be between 1.5 and 2.3 mgal. To further insure that the anomalies are caused by the surrounding rock rather than errors in the survey, only anomalies which correspond to anomalies in Brinkworth's (1970) gravity survey will be used. Thus the criteria for an anomaly will be that it must be a deviation of 1.5 to 2.3 mgal from the regional gradient and correspond to an anomaly in the survey gravity survey.

The linearity of the data suggests a possible error in the assumed density of the Bouguer correction. The density used was 2.67 g/cm³. The density measured in the samples from the tunnel was around 2.65 g/cm³. Since the calculated density,

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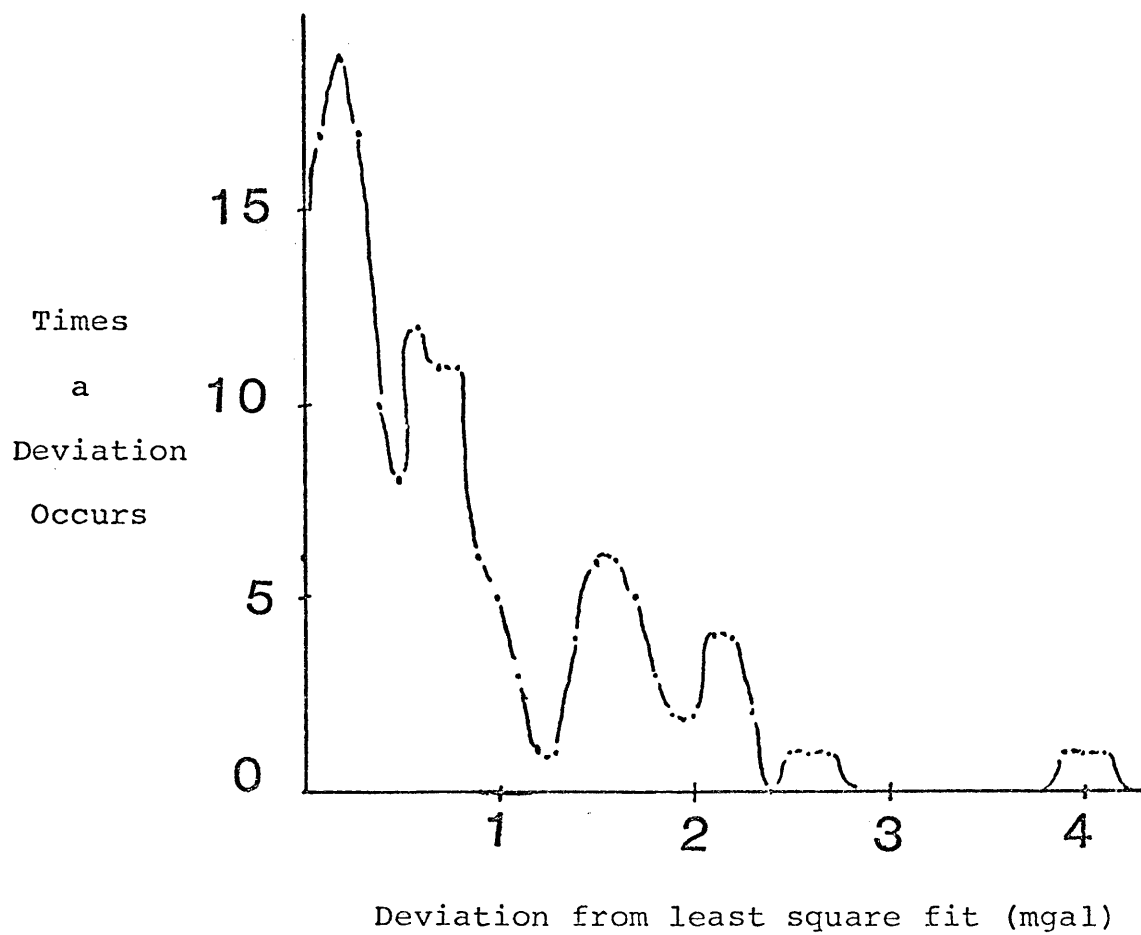


Figure 2: Plot of deviation from the regional trend versus times the deviation occurs; averaged using a 0.3 mgal window.

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which did not use the Bouguer-corrected data, was about 2.67 2.67 g/cm³, the trend is probably not caused by the linear trend of the change in elevation at the stations.

The first deviation is a high which occurs near LM-3 (Plate 1). In the surface survey, Brinkworth (1970) showed a bulge in the -285 mgal contour to the east of the west portal. The country rock around LM-3 is mostly biotite schist and metasediments. This is more dense than the granite which makes up a majority of the country rock (see Appendix B). The width (about 1.5 miles (2.5 km) across) and breadth of the anomaly imply that the source is fairly small and deep. Because the anomaly is positive both on the surface and in the tunnel, the source must be more dense than the country rock and deeper than the tunnel. The source may be modeled by a spherical body (300 ft. (91 m.) in diameter) of biotite in the granite-metasediment country rock giving a density contrast of 0.12 g/cm³. Its center would be approximately 2,000 ft. (610 m.) to the north and about 500 ft. (152 m.) deeper than the tunnel. The actual shape and density of the anomaly are not unique although the amount of excess mass is unique.

The next anomaly is a high occurring between LM-35 and TM-14 which corresponds to a gravity ridge on the surface survey by Brinkworth (1970) (see Plate 1). This anomaly must be due to a higher density material at a depth below the

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tunnel, since both surveys show a high. The size of the anomaly in the tunnel and its expression in the surface survey indicate that the bulk of the source is north and slightly west of the variation in the tunnel. The shape of the anomaly suggests that the source can be modeled by two nearly spherical bodies with their centers along a northwest-southeast trend. The anomaly can also be modeled in several ways including a cylinder or a prism. However, since the attraction of two spheres is easy to calculate and the models are very similar in overall shape, the model of two spheres was used. A density difference of 0.13 g/cm^3 between the granite-metasediment country rock and the metasediments suggests the anomaly be modeled by two spheres of metasediments 100 ft. (30 m.) in diameter, about 500 ft. (152 m.) deeper than the tunnel. The center of one sphere would be 500 ft. (152 m.) to the northwest, while the other would be 800 ft. (244 m.) to the northwest. This anomaly, then, corresponds to a higher density body, probably metasediments, extending from between LM-35 and TM-14 to the northwest and existing at a greater depth than the tunnel.

The last deviation is a very small high near TM-16 in the subsurface data, while the surface survey indicates a low. The surface survey low is defined by only one station, thus, its exact geometry is unknown. Since one survey shows

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a high and the other a low, the source must be between the tunnel and the surface. The center of the source is probably 3,000 ft. (914 m.) north of the tunnel and about 50 ft. (15 m.) shallower than the tunnel from its expression in the surface survey. A granite sphere, model, 200 ft. (61 m.) in diameter with a density of 0.013 g/cm^3 lower than the country rock (metasediment-granite mix), would account for both the surface and subsurface anomalies.

The remaining deviation occurs just east of Jones Pass. Several surface stations in the area do not reflect the anomaly seen in the tunnel, thus it fails the criteria for an anomaly with a possible geologic source. If it was not an error in the data one explanation could be a stratified anomaly with lower density material above the elevation tunnel and higher density material below the tunnel. Using this model both density contrasts (above and below the tunnel) create highs in the subsurface data, thus adding while canceling each other in the surface data. There is not enough information to define two separate anomalies since neither the size of either anomaly nor the areal extent is known. Thus the deviation could be caused by an error in reading the instrument, an error in the complete Bouguer correction or a pair of sources in the rock.

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Density Determinations

Hammer (1950) found that the bulk density of a rock can be determined from the gravity gradient. The derivation of the equation for density was not published by Hammer (1950). A brief derivation starts with the complete Bouguer-gravity equation:

$$g = g_0 - L + (0.09406)H - 2\pi G\sigma H + T \quad (2)$$

where g_0 is the observed gravity in mgals, L is the latitude correction in mgals, H is the elevation above sea level of the station in feet, T is the terrain correction for the lack of mass below and excess mass above the Bouguer datum in mgals. In the subsurface case, the equation becomes:

$$g = g_0 - L + (0.09406)h - 2\pi G\sigma h + t \quad (3)$$

where h is the subsurface elevation above sea level in feet, t is the subsurface terrain correction, and L and g_0 are as above. Subtracting equation 3 from equation 2, one obtains the following:

$$\Delta g = \Delta g_0 + L - L + (0.09406)(H-h) - 2\pi G\sigma(H-h) + (T-t) \quad (4)$$

where Δ is the symbol for the difference of two like variables. Because the latitude correction is independent of elevation, the L 's cancel leaving:

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$$\Delta g = \Delta g_0 + (0.09406 - 2\pi G\sigma)\Delta H + \Delta T \quad (5)$$

Since Δg equals zero when the density is correct, and solving for σ , equation (5) becomes:

$$\sigma = \frac{0.09406}{2\pi G} + \frac{(\Delta g_0 + \Delta T)}{2\pi G\Delta H}$$

In most cases T is so small that the inclusion of a density in the terrain correction is negligible. At Henderson, however, the terrain has nearly 3,300 ft. (about 1 kilometre) of relief. The terrain correction (T) then, must be expressed as $\tau \cdot \sigma$, where τ is the sum of all zones using equation 1 with σ factored out. Using this definition of T and τ , equation 5 becomes:

$$\begin{aligned} \sigma &= \frac{0.09406}{2\pi G} + \frac{(\Delta g_0 + \sigma\Delta\tau)}{2\pi G\Delta H} \\ \sigma - \frac{\sigma\Delta\tau}{2\pi G\Delta H} &= \frac{0.09406}{2\pi G} + \frac{(\Delta g_0)}{2\pi G\Delta H} \\ &= \frac{(0.09406)}{2\pi G} + \frac{(\Delta g_0)}{2\pi G\Delta H} / 1 - \frac{\Delta\tau}{2\pi G\Delta H} \\ &= (\Delta H(0.09406) + (\Delta g_0)) / 2\pi G\Delta H - \Delta\tau \\ \sigma &= \frac{\Delta H(0.09406) + (\Delta g_0)}{(2\pi G\Delta H - \Delta\tau)} \quad (6) \end{aligned}$$

$$\text{where } \Delta\tau = \frac{2\pi G}{n} \left(-\sqrt{R_1^2 + k^2} + \sqrt{R_2^2 + k^2} + \sqrt{R_1^2 + (k + \Delta H)^2} - \sqrt{R_2^2 + (k + \Delta H)^2} \right)$$

where k is the elevation change between the station and the compartment being calculated. Using equation 6, one obtains the following:

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<u>Surface Station</u>	<u>Subsurface Station</u>	<u>Δg_{\circ} mgal</u>	<u>ΔH feet</u>	<u>Density g/cm³</u>
HT-2	LM-21	86.34	2525	2.79
Vent Raise	TM-14	21.73	1560	2.65
Jones Pass	LM-67	162.84	4658	2.68

These densities agree closely with the densities measured in the rocks (see Appendix B).

The vent raise, (a shaft 20 ft. (6.1 m.) in diameter) extends from the tunnel to the surface slightly affecting the density calculation at the vent raise station. Since the surface station will be too low due to the vent raise and the subsurface station will be too high; the error in the gradient will be twice the attraction of a vertical cylinder. Thus, if the vent raise were not there the gradient would be smaller by 0.96 mgal (-0.48 mgals at the surface station and -0.48 mgals at the substation) giving a correction of -0.96 mgals to the measured gravity value. If this is added to Δg of equation 6, the calculated density at the vent raise B.M. station is 2.66 g/cm³.

The density calculation is for an infinite slab, although at long distances from the stations the effect of the rock is very small. The ratio of the attraction of a cylinder to the attraction of an infinite slab gives the percentage of the density calculation affected by the rock within the

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cylinder. The equation for this percentage is:

$$((1-X) + \sqrt{1+X^2}) \times 100$$

Where X is the ratio of the radius of the cylinder to the height of the cylinder, which is also the height of the slab. At Jones Pass 90% of the rock affecting the density calculation is within a radius of 23,057 ft. (7,028 m.); for HT-2, 90% of the rock is within a radius of 20,100 ft. (6,126 m.); and at the vent raise, 90% of the rock is within 15,500 ft. (4,724 m.).

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Errors in Density Calculation

Density calculation errors arise primarily from the errors in correcting the data. It was shown previously that the error in the corrected data was ± 1.30 mgal, which causes an error in the density calculation at the vent raise of ± 0.03 g/cm³. The same error at HT-2 causes an error of ± 0.02 g/cm³ while at Jones Pass it causes an error of ± 0.01 g/cm³. The errors in the calculated density vary because the constant measurement errors are normalized over different distances to get the gradient.

In density calculations some error is introduced by the density assumed in the terrain correction when using Hammer's (1950) equation. The equation derived in this paper does not use the density in the terrain correction. In most cases, the terrain corrections are very small ($\pm 10\%$) when compared to the change in gravity and the equations given by Hammer (1950) work well. In areas where the terrain correction is significant such as at Henderson the equation derived in this paper must be used to avoid introducing large (± 0.1 g/cm³ and larger) errors. Since no densities are assumed in the equation used, then no errors are introduced by assuming the wrong density.

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Conclusions

A subsurface gravity survey requires the same Bouguer and free-air correction as a surface survey with an additional correction for the attraction of the mass above the station. This correction can be done in a one-step operation.

In areas of large relief (i.e., greater than 1,000 ft. (300 m.)) several otherwise negligible errors in the terrain corrections become significant:

1. Errors in the contours of the topographic maps near Henderson introduce an error of ± 0.03 mgal.
2. Using the mean elevation of the zone for all directions of slope introduces an error of about ± 1.2 mgals, for slopes varying up to 15° .
3. The total error in the corrected data from terrain corrections and other sources is ± 1.30 mgal since all errors are independent of each other.

Using the surface survey to distinguish anomalies from errors, three small anomalies were observed in the survey:

1. The anomaly near LM-3 could be caused by a spherical pod of biotite schist 300 ft. (91 m.) in diameter, 2,000 ft. (610 m.) below the tunnel, and about 500 ft. (152 m.)

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north of the tunnel.

2. The next anomaly, a ridge in the surface survey, could be modeled by two spheroidal pods of metasediment each about 100 ft. (30 m.) in diameter, and about 500 ft. (152 m.) below the tunnel.
3. An anomaly in the surface survey near the vent raise is a very small deviation in the subsurface survey. One model is a spherical pod of granite about 3,000 ft. (914 m.) north of the tunnel, 50 ft. (15 m.) deeper than the tunnel, and about 200 ft. (61 m.) in diameter.
4. An anomaly in the subsurface data, just east of Jones Pass, does not have a surface expression. It can be modeled by two anomalies one a lower density material above the tunnel, the other a higher density material below the tunnel, or it could be an error in the data. Not enough information is known about the anomaly to estimate the source.

Densities of the rock between the tunnel and the surface

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were determined where subsurface and surface readings were taken:

1. Due to high relief a formula to compute the density without assuming density in the terrain correction was derived:

$$\sigma = \frac{(\Delta H(0.09406))}{(4\pi G\Delta H - \Delta t)} + \frac{(\Delta g_0)}{(4\pi G\Delta H - \Delta t)}$$

2. The calculated density was:

<u>Station</u>	<u>Location</u>	<u>Density</u>
HT-2	12,057	2.79
Vent Raise	23,940	2.65
Jones Pass (HT-4)	38,476	2.68

3. The total error in the density, $\pm 0.05 \text{ g/cm}^3$ was due to errors in the Bouguer corrected data.

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APPENDIX A.

Principal Facts
of a Subsurface Gravity Survey
in the Henderson Haulage Tunnel

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In the table absolute gravity is the absolute gravity obtained from the tie with the North American base station. Bouguer gravity is the absolute gravity with the free-air, Bouguer, and drift corrections applied. The complete Bouguer gravity is the Bouguer gravity with the terrain correction applied.

Appendix A. Principal Facts of Gravity Survey

Station	Location*	Elevation (Feet)	Absolute Gravity (mgal)	Bouguer Anomaly (mgal)	Complete Bouguer Anomaly (mgal)
2	12	8,945	979,331.75	-294.93	-273.96
TM-3	816	8,926.7	979,322.40	-305.38	-288.35
LM-2	2,059	8,889.9	979,312.74	-317.25	-286.88
LM-3	3,011	8,861.3	979,307.25	-324.45	-289.10
LM-6	4,222	8,825.0	979,302.15	-331.73	-291.56
LM-8	5,168	8,796.5	979,298.47	-337.11	-292.94
TM-6	6,201	8,765.6	979,294.98	-342.46	-292.58
LM-11	7,037	8,740.6	979,292.52	-346.42	-292.52
LM-13	8,188	8,706.0	979,290.10	-350.92	-292.42
LM-16	9,367	8,670.7	979,288.81	-354.33	-292.51
LM-18	10,185	8,646.1	979,287.91	-356.70	-292.02
LM-19	11,115	8,618.2	979,287.08	-359.21	-294.05
LM-21	12,057	8,590.0	979,286.21	-361.77	-292.62
LM-23	13,057	8,560.0	979,285.68	-363.90	-293.05
LM-26	14,273	8,523.5	979,285.77	-366.20	-293.67
LM-27	15,116	8,498.2	979,286.18	-367.31	-296.01
LM-29	15,998	8,471.7	979,286.48	-368.60	-295.77
LM-31	17,305	8,432.5	979,287.81	-369.62	-295.98
TM-11	18,109	8,408.4	979,289.24	-369.64	-296.10
LM-35	19,345	8,371.3	979,291.37	-369.73	-294.88
LM-36	20,270	8,343.6	979,293.14	-369.62	-295.17
LM-38	21,084	8,319.2	979,294.10	-370.13	-294.79
LM-40	21,865	8,295.7	979,294.31	-371.33	-297.15
LM-41	22,738	8,269.5	979,293.92	-373.29	-298.07
TM-14	23,940	8,233.5	979,293.15	-376.22	-297.92
LM-45	25,006	8,201.5	979,292.85	-378.44	-298.53
TM-15	25,843	8,176.4	979,292.50	-380.30	-299.35
LM-48	26,803	8,147.6	979,291.96	-382.56	-298.31
LM-49	27,252	8,134.1	979,291.58	-383.75	-299.79
TM-16	27,811	8,117.4	979,291.11	-385.23	

Station	Location*	Elevation (Feet)	Absolute Gravity (mgal)	Bouguer Anomaly (mgal)	Complete Bouguer Anomaly (mgal)
LM-50	28,246	8,104.3	979,290.81	-286.31	-300.36
LM-51	28,777	8,088.4	979,290.19	-387.89	-300.18
LM-52	29,249	8,073.6	979,289.31	-389.65	-299.41
LM-53	29,766	8,058.7	979,288.21	-391.65	-301.91
TM-17	30,249	8,044.2	979,288.05	-392.68	-299.72
LM-54	30,745	8,029.3	979,285.48	-396.14	-300.72
LM-55	31,168	8,016.6	979,285.00	-397.38	-301.04
LM-56	31,703	8,000.6	979,281.99	-401.35	-301.04
LM-57	32,191	7,985.9	979,280.33	-403.89	-301.64
TM-18	32,724	7,969.9	979,278.82	-406.36	-300.98
LM-58	33,215	7,955.2	979,277.49	-408.57	-302.20
LM-60	34,109	7,928.4	979,275.29	-412.38	-302.84
LM-61	35,125	7,897.9	979,273.43	-416.08	-303.12
LM-62	35,687	7,881.1	979,272.32	-418.20	-303.12
LM-63	36,529	7,855.8	979,271.16	-420.87	-304.20
LM-64	37,050	7,838.6	979,270.75	-422.31	-302.51
LM-65	37,573	7,824.6	979,270.12	-423.78	-304.68
LM-66	38,065	7,808.6	979,269.70	-425.16	-303.03
LM-67	38,476	7,796.2	979,269.29	-426.32	-301.99
SL-173	39,248	7,773.2	979,268.97	-428.01	-304.08
NL-165	39,930	7,752.5	979,270.03	-428.20	-304.10
SL-151	40,726	7,729.4	979,270.52	-429.20	-305.16
NL-137	41,430	7,709.5	979,271.51	-429.30	-305.15
SL-129	42,031	7,689.9	979,272.43	-429.56	-306.19
NL-123	42,867	7,664.8	979,274.00	-429.49	-305.11
SL-111	43,784	7,638.0	979,276.57	-428.53	-305.38
NT-107	44,446	7,627.0	979,277.22	-428.54	-306.28
ST-103	45,194	7,593.8	979,279.04	-428.71	-305.96
NL-94	46,336	7,558.7	979,281.87	-427.99	-305.65

Station	Location*	Elevation (feet)	Absolute Gravity (mgal)	Bouguer Anomaly (mgal)	Complete Bouguer Anomaly (mgal)
ST-87	47,140	7,535.2	979,283.75	-427.52	-306.58
NT-77	47,716	7,519.6	979,284.83	-427.37	-306.96
J-68	48,220	7,507.0	979,285.22	-427.14	-307.18
Gyro-1		10,454.24	979,227.95	-308.20	
G-1		8,949.5	979,334.54	-291.87	
HT-2		11,134	979,199.87	-295.47	-286.00
Vent Raise		9,799.53	979,271.42	-303.96	-290.30
Jones Pass (HT-3)		12,455	979,106.45	-309.63	-301.63

*Location in feet east of West Portal

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APPENDIX B.

Density of Selected Samples
from the Henderson Haulage Tunnel

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Appendix B:

The following table gives the densities measured on samples from the Henderson Haulage Tunnel rock library. Samples were chosen at random from boxes covering specific intervals in the tunnel. The samples were weighed dry, then submerged in water and weighed. The density was then calculated from the formula:

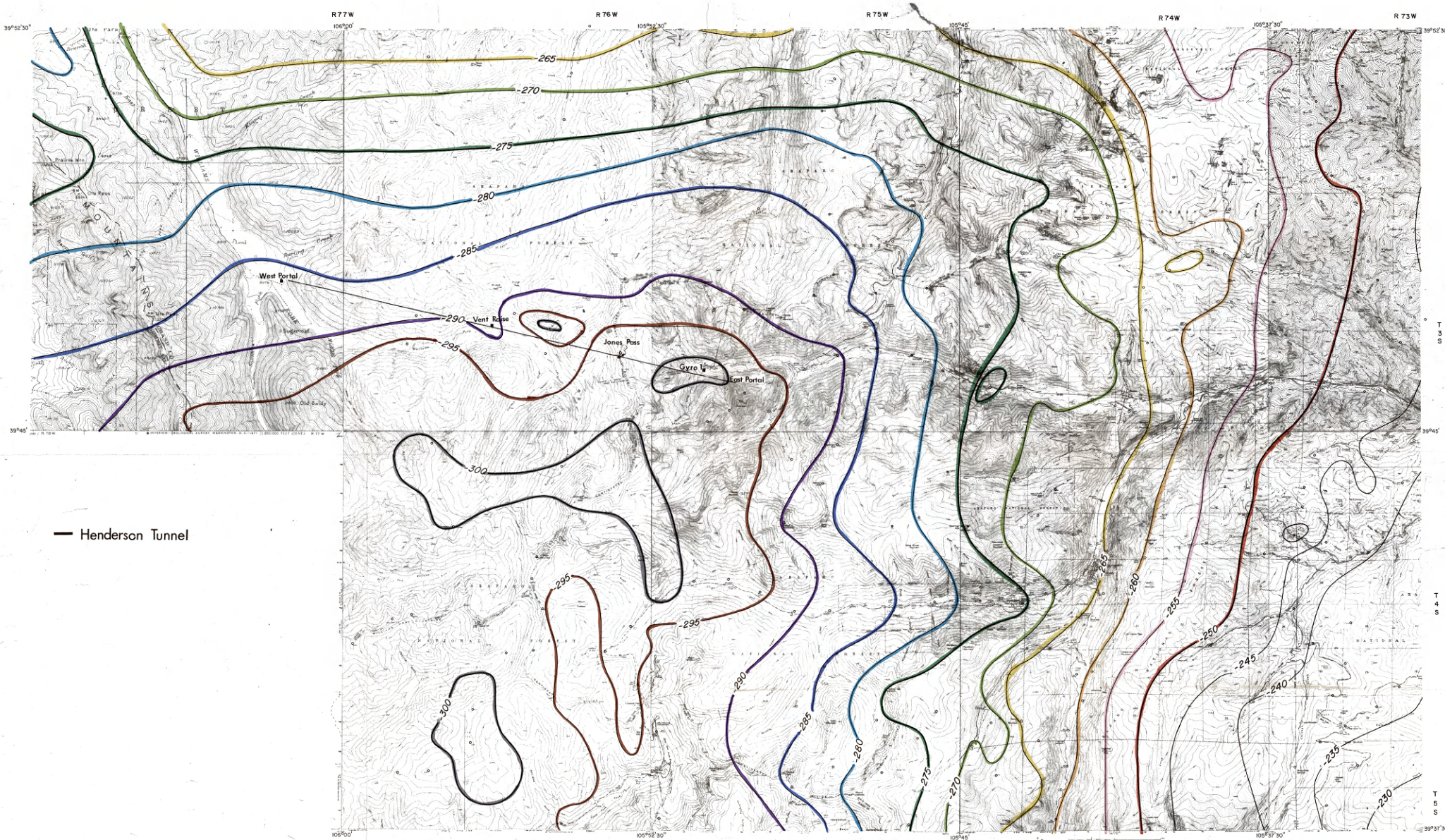
$$d = \frac{W_A}{W_A - W_W}$$

The uncertainty in the density measurement is $\pm 0.01 \text{ g/cm}^3$ arising from the sensitivity of the scales used, the porosity and permeability of the rock, and changes in the rock between insitu conditions and lab conditions. The scales were accurate to $\pm 0.001 \text{ g}$, as specified by the manufacturer, and calibrated by AMAX. The accuracy of the measurement is $\pm 0.001 \text{ g/cm}^3$ for samples that are at least 1 cm^3 in volume. Since all the samples had volumes greater than 1 cm^3 , the error is insignificant. The error due to trapped air in the samples is small since most of the samples are fairly impervious. To reduce the error from water or air clinging to the rock, the sample was first weighed in air then weighed in water. Using this procedure AMAX technicians found that the measurements on various granites and metasediments were repeatable to $\pm 0.01 \text{ g/cm}^3$. Thus the error in the data is $\pm 0.01 \text{ g/cm}^3$.

Appendix B. Density of Selected Samples from Haulage Tunnel

Location*	Densities (g/cm ³)	Rock Type
7,786	2.60	Granite
15,880	2.61	Pegmatitic granite
16,142	2.70	Metasediment-biotite schist
19,176	2.93	Mainly biotite schist
20,899	2.86	Metasediment biotite schist
23,304	2.61	Altered pegmatite-quartz & chlorite
23,521	2.92	Mostly biotite-schist
24,924	2.88	Biotite schist-metasediment
25,405	2.62	Quartz with some biotite
25,481	2.66	Granite with biotite veining
26,257	2.67	Highly altered Tertiary rhyolite
26,336	2.76	Chorite schist
27,176	2.78	Biotite schist-some quartz
27,482	2.65	Granite-some chloritization
27,906	2.80	Biotite schist-poor foliation
28,018	2.62	Pegmatite
29,829	2.73	Altered biotite schist
29,961	2.66	Pegmatite
31,262	2.62	Highly altered Tertiary porphyry
31,308	2.65	Quartz & biotite schists in veins
32,593	2.70	Granite
32,819	2.68	Pegmatite with some biotite schist veins
33,230	2.64	Granite
33,934	2.68	Granite
33,987	2.64	Binary granite
34,019	2.69	Biotite schist
34,673	2.64	Pegmatite
35,381	2.64	Pegmatite
35,737	2.66	Tertiary porphyry

*in feet east of the west portal

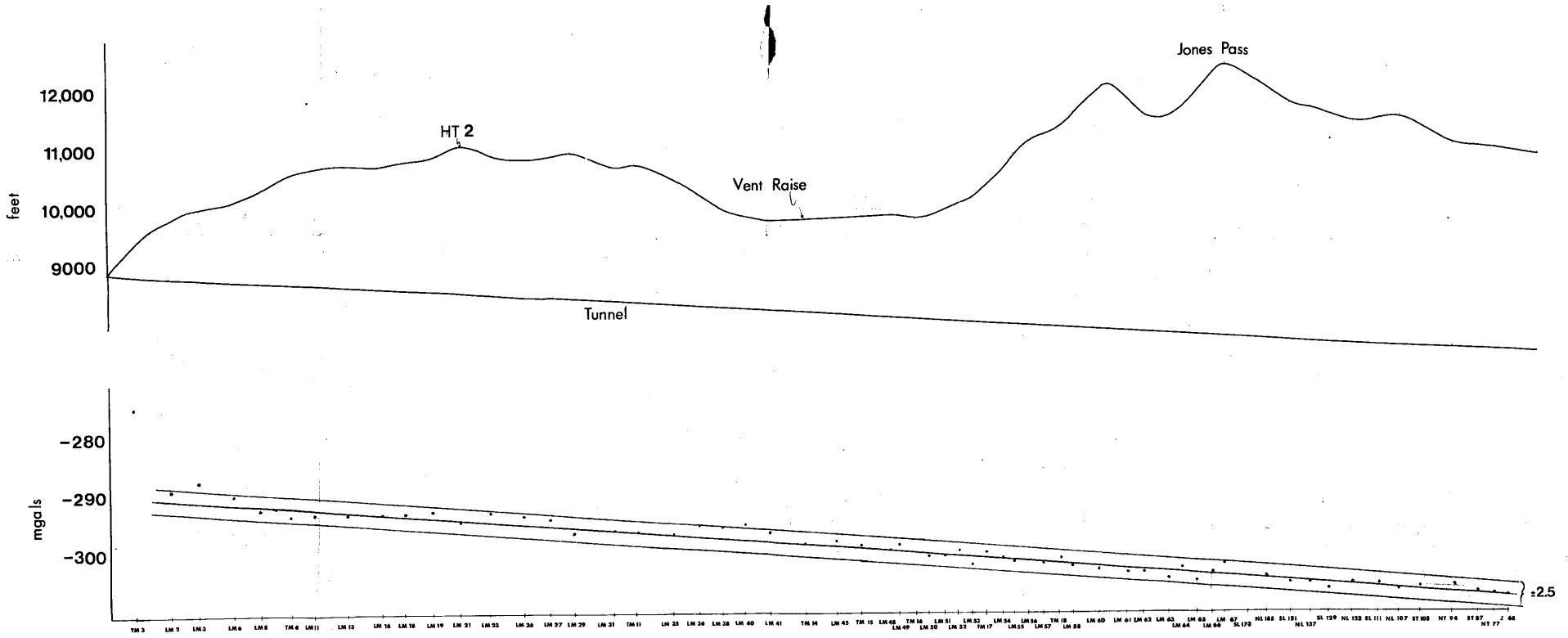


— Henderson Tunnel

SCALE: 1:42,000
C.I. = 5 milligals

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PLATE I
COMPLETE BOUGUER GRAVITY
Source: Brinkworth, USGS Open File, 1970.





0 2000
Feet

Gravity Profile & Cross section
 Henderson Haulage Tunnel
 Plate 2
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