GRAVITATIONAL PROFILES ON THE TAKU GLACIER SYSTEM

by

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ABSTRACT

GRAVITATIONAL STUDIES ON THE JUNEAU ICEFIELD

Gravitational anomaly studies were done on the Juneau Icefield in conjunction with the Juneau Icefield Research Program and the National Science foundation's Research Experience for Undergraduates program. Under the direction of Dr. Maynard M. Miller and Dr. Ken Sprenke, both University of Idaho, two gravity profiles were made to determine the depth to bedrock. Gravity measurements utilizing a W. Sodin gravimeter were made on the Mathes glacier. The measurements were taken at profile flags surveyed in by GPS methods. Thus a high degree of vertical and horizontal position accuracy was available. Rock nunatak USGS survey bench marks were used as control points. The looping-in method of station reoccupation was used to determine drift profiles. Data reduction was done under the direction of Dr. John S. Klasner, Western Illinois University. The data was corrected using the standard Free Air, Bouger, and Latitude corrections to obtain Bouger anomaly values. Regional Gravity was then determined and the differences between regional and Bouger gravity values were recorded. Two dimensional model profiles were constructed using the Grav 2D computer program for Macintosh computers. This method was compared to an earlier method of interpretation. The value density of ice used was .90gcm^{3}. Isolated depth determinations from seismic data were used to constrain the gravity interpretations. The model shows a typical U shaped valley with depths to bedrock ranging from 0 to 450 meters.

INTRODUCTION

Determining the depth of glaciers is key to understanding their flow rate and discharge. By using the glacial flow law and its derived equations, these two parameters can be determined. Measurement of the glacier's discharge is critical to determining the mass balance ~~balance~~ of the glacier, which is the most accurate indicator of a glacier's health. The only variable for using the flow law equations on temperate glaciers is the depth of the ice. Therefore, accurate depth determinations are essential.

The first gravitational surveys were done on the icefield during the summer of 1952 to extend the seismic profiles already completed on the Taku glacier. This method was deemed feasible for determining the depth of ice because of the high density contrast between glacier ice (.90 g/cm^3) and surrounding bedrock (2.75 g/cm^3). The gravity method was employed because the method allows for faster survey times, is relatively inexpensive, and is more easily transported than seismic equipment. (Miller, 1963 p.53)

Two major disadvantages of gravity surveying are the need for accurate elevation points for correction calculations and the difficulties of two dimensional modeling, which can become quite complex. By utilizing Global Positioning Systems and a Grav 2-D computer modeling program, this study attempts to simplify these problems.

PROCEDURE

Measurements were made using a W. Sodin gravimeter to determine a relative gravity profile as no absolute gravity stations are present on the icefield. The instrument has a limited range and has to be recalibrated when elevation changes of more than a couple hundred meters are made. The instrument was calibrated to 796.5 instrument readings at the red flag benchmark near C-18. (N-1 Camp 18). This station was also used to get a large time scale drift profile but was not incorporated into the interpretation of the survey itself.

The JIRP program sets up flag profiles normal to glacier flow to determine the surface velocity of the glacier. In the summer of 1993 Hienz Lang and Dr. Christian Hiepke used a Wild GPS system to survey in 13 flags on the Mathes glacier. These were put in a line from C-8 (Mt. Moore) to the other side of the glacier near the 8-18 junction (Blizzard Peak). The GPS data used in this survey is located in the Figures section under JIRP 1993 Survey-Projects. The survey is located on the Juneau 1:250,000 map put out by the U.S. Geological Survey (figure1). Using differential GPS allowed the flag position and elevations to be calculated to within centimeters. This flag profile provided very accurate and convenient stations for gravity measurements. The flag end points were on shallow dead ice on both sides of the profile which facilitated regional gravity calculation.

The survey was done on August 7, 1993 using the looping in method of station reoccupation to determine drift corrections. In this method each station is measured in the order 1, 2, 1, 3, 2, 4, 3 etc.. so that drift can be taken out by assuming all measurements are taken at the same time.(Miller, 1963 fig. 18A)

Gravity surveying on glaciers presents many problems. One is doing the survey quickly so that the drift calculations are minimized. Due to the fragility of the instrument, doing surveys on foot or skis is not recommended. A Thiokol oversnow vehicle was used which provided surveying speed and protection for the instrument in transit. Another problem is leveling the gravimeter on the suncupped and downwasting glacier surface. A 1' * 2' plywood board was used to provide a stable and level surface.(MIller, 1963 p.57) This worked marginally well. Readings had to be made very quickly before the instrument went out of level. Another problem in this survey was the afternoon temperature fluctuation. Normally this is not a problem as Sodin gravimeters have an electronic temperature compensator. But battery problems were encountered in this survey which required that the electronic compensator be turned off. Temperature effects were corrected within the drift profile.

The data was then reduced by using the drift correction and standard Bouger anomaly corrections to remove all differences in gravity except those caused by the ice-rock density contrast. The drift was calculated using station two as the control point because of the inaccessibility of station 1. All drifts were corrected assuming zero drift at station 2. To put each station in the same time, the rate of drift was determined for each station reoccupation time interval. The looping in method places the station to be corrected between the reoccupation interval so that the amount of drift for that station may be determined. For example- station 2 is read and then 1 and 3 are read. Then station 2 is read again. The drift is calculated for three by figuring the amount of drift at the time that station three was read. Then the amount of drift from the previous station is added to the station drift, as drift is accumulative. The final value is then subtracted or added to the reading to remove the drift effect. If done correctly, the drift should return to zero when station two is reoccupied for the final time.(Klasner, personal communication) In this calculation it returned to .4 instrument readings. Final drift values are given in instrument readings and graphed in figure 2 with the raw data in the SYSTAT editor file on the next sheet. The total drift was more than usual instrument tolerances (around .8 mGals). This was attributed to temperature changes as it correlates well with afternoon heating. Then the drift corrected instrument readings were multiplied by the gravimeter constant (.09442 mGals/division) to determine a drift corrected G value.

Next the G values were converted to a G observed value. Since an absolute value for G is not known, station two was arbitrarily set at 1000 mGals and the rest of the values were expressed as a difference relative to station two.

The latitude correction was then applied by first measuring the latitude of the northern most point (station 1) on the topo map (58 50' 30"). Because the survey area is relatively small, only one absolute latitude equation was needed. The latitude correction was then calculated by the standard international formula ($1.307\sin 2\phi = $ mGals/mile, where ϕ is latitude) and expressed as a value $7.19{*}10^{-4}m = \Delta G$/meter. The latitude correction value was determined for each station by using the number of meters south relative to station 1. (Dorbin, 1973)

The free air and Bouger corrections were calculated using a datum elevation of 1700m, well below the lowest surface point. This was chosen instead of sea level to keep the numbers smaller and more manageable (using a sea level datum would only produce a DC shift difference in numbers, which is of no consequence in relative gravity surveying). The standard free air equation (+.3086 mGals/meter) was used to remove the change in gravity due to the differences in station elevation. For later residual anomaly determination, all the material between the stations and datum level was considered be a infinite slab of rock with a mean density of 2.68 g/cm^3. This density was then used in the standard Bouger correction (-.04185d mGal/meter). This value was combined with the free air correction to derive a total Bouger correction equation: .19623h, where h is in meters. This value was then calculated for each station and added to the G observed value to obtain Bouger anomaly values. (Robinson et. al, 1988 pp. 260-262)

The final regional anomaly value was calculated by first determining the regional gravity and its gradient. This was done by the graphical smoothing method, in which regional gravity is estimated by inspecting the Bouger Anomaly data and subjectively interpreting the regional gradient. (Robinson et. al, 1988 p301-302) The two end stations are taken at points that are assumed to be at similar, very shallow ice depths. These points are off the main glacier level on the slopes of two nunataks. The ice is dead and is probably much less than 100 feet deep. This enables the points to be used to determine the equation for the regional gravity by assuming an equal depth at the end points. By this assumption, the difference in Bouger gravity at the endpoints is assumed to be due to the regional gravity gradient. An equation for this line was calculated by inputing the two endpoints into the linear regression function on an HP 20S calculator. The equation for a the straight line regional in this survey is gravity regional= $6.67*10^{-3}x+16.48$, where x is horizontal position in meters. This equation was used at each data point to calculate the value of gravity to be expected if there was no glacier. This value is then subtracted from the Bouger gravity to obtain the residual gravity anomaly, which is the change in gravity caused by the glacier (fig 2A). All calculated numbers are located in the CALCULATED VALUES spread sheet in the figures section.

This data was then fed into a two dimensional gravity modeling program to obtain a cross sectional profile of the depth of the glacier. Two dimensional modeling calculates the effect on a background gravitational field that a body of differing density would have. This is determined by finding a bodies volume by two dimensional integration and then multiplying by the density contrast. The computer program Grav2D, written for Macintosh computers, was used for this purpose. It allows data to be input into the program and then it compares this data to bodies drawn on the screen using a graphic interface. Grav 2D calculates the expected gravity anomaly by assuming that bodies drawn on the screen extend infinitely into and out of the screen and that the background density remains constant (2.67). It uses this principle to apply a gravitational field algorithm that calculates the gravity values that would be expected from the bodies drawn on the screen. By comparing the field residual data with the drawn body computer calculated data, bodies can be redrawn and adjusted to obtain a best-fit profile. This procedure was done to obtain the final profile.(fig 3 and fig 3 data sheet (note- the data stations are reversed on this data sheet and the profiles are drawn as if one was looking down glacier (south west). This is the only way the computer will accept the positional data)). The top graph is a comparison of calculated gravity (line) and measured gravity (open dot). This shows the level of agreement with the computers's calculated value for the body drawn and the reduced field data.

RESULTS

There are several potential sources of error in this profile. The main problem with gravity surveying is the problem of determining the background densities. In this survey it is impossible to know the density values of the rock below the glacier which could change the profile significantly. Another source of error is the side pull gravitational field produced by surrounding mountains. This in normally taken out by a terrain correction. This was not used in this survey because of the complication in its determination and the minimal effect it has on a broad glacier. This effect tends to cancel itself out at the middle stations and can only cause the profile to become deeper. Miller estimated a maximum effect at the outer stations of about .5 mGals, which would produce an error of around 10 meters. The final source of error is in the calculation of the regional gradient. The depths the endpoints are assumed to be shallow due to their high position on a slope and the total lack of crevassing (no crevassing at depths under 100 feet), but an absolute value of the depth to bare rock is not known. Also the regional smoothing is an interpretive estimation and therefore subject to error.

This procedure yielded the final profile (fig3 and 4) which produced a maximum depth of around 440 meters or 1440 feet. This is deeper than the maximum depth of 287.7 meters determined by Miller in the 1950s (Miller, 1963). To investigate this further, the residual gravity values from this survey were plugged into the interpretation equation that was used for the past profiles. This equation is derived from reversing the Bouger corrections from sea level to determine an expected value of gravity. This value is then referenced to a control station. By manipulating an equation derived from this method the final depth of the glacier can be calculated by the equation -x=residual gravity/.0774 (Miller, 1963).(fig 5) Although residual gravity is calculated in a different manner in this study than the past one, the profile produced is in very good agreement with the past studies. The maximum depth calculated from this summer's data was 288 meters, almost exactly what was found by Miller. The difference in the two profiles is due to the differences in interpretative methods. (Old and New Methods data table, figures section.

DISCUSSION

The potential of the GPS system in gravity surveying is great. It allows tremendous accuracy and relatively speedy survey times. The main barrier to doing extensive gravity surveying on the icefield has been the time needed to survey in the stations by theodolite. Now with GPS it will be possible to survey in more stations for better gravity resolution.

The Grav 2-D profile done by the computer raises questions due to the differences between it and the depths found in Miller's surveys. The computer model is more accurate in that by using integration, it takes into account the gravity field interactions produced by the anomalies. The proximity of the stations to one another means that the depth at one station will greatly effect the ones adjacent to it. The reversing Bouger corrections method only estimates this effect. The integration method does, however have problems at the outer stations which is shown by the differences in computed and calculated gravity in figure 3. This is probably due to the fact that the computer calculates the body as extending to infinity into and out of the profile. When the depths become shallow and nearer to irregularities like mountainsides, this approximation method breaks down. This only affects the second and twelfth stations significantly. The computer also has trouble fitting the endpoints which is related to the lack of terrain correction in this study.

The deeper model is supported by preliminary seismic interpretations made this summer on the same profile. The seismic results are even deeper than this model (Benedict, personal communication). With the seismic data and this gravity profile, evidence that the glaciers in the area may be deeper than previously thought is building. With the importance of knowing the depth for calculating the total discharge of the glacier, more careful study is needed to determine the depth with absolute certainty.

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JIRP 1993 Survey-Projects

Coordinate listing movement profiles around C-18

Point	Easting Y[m]	Northing X[m]	Height [m]	Time
N1 CAMP~~-18~~	484075.116	6524264.276	1697.694	-
FFGR 31 (C8)	492138.301	6521149.283	2050.849	-
FFGR 39	487444.833	6524362.484	1983.625	-

***

Upper Matthes Profile Epoch 0   1.8.1993

Point	Easting Y[m]	Northing X[m]	Height [m]	Time
MATTHES 01	487762.872	6524124.905	1898.394	17:22
MATTHES 02	488063.516	6523894.096	1839.289	16:46
MATTHES 03	488350.547	6523674.824	1823.558	16:16
MATTHES 04	488610.367	6523476.459	1815.980	15:38
MATTHES 05	488826.185	6523310.806	1811.724	15:33
MATTHES 06	489050.353	6523140.553	1807.348	15:08
MATTHES 07	489261.733	6522980.391	1804.125	15:00
MATTHES 08	489470.099	6522821.450	1799.966	14:38
MATTHES 09	489690.589	6522653.121	1794.097	14:32
MATTHES 10	489896.076	6522496.642	1790.057	14:05
MATTHES 11	490096.744	6522344.028	1787.190	14:03
MATTHES 12	490353.532	6522147.744	1792.764	13:30
MATTHES 13	490580.025	6521975.168	1815.083	13:32

Upper Matthes Profile Epoch 1   5.8.1993

Point	Easting Y[m]	Northing X[m]	Height [m]	Time
MATTHES 01	487762.955	6524124.839	1898.180	15:38 [illegible]
MATTHES 02	488063.589	6523893.959	1839.091	15:04
MATTHES 03	488350.584	6523674.615	1823.380	14:35
MATTHES 04	488610.328	6523476.106	1815.781	16:18
MATTHES 05	488826.090	6523310.354	1811.532	16:45
MATTHES 06	489050.195	6523140.001	1807.160	17:12
MATTHES 07	489261.518	6522979.825	1803.890	17:31
MATTHES 08	489469.885	6522820.832	1799.762	17:06
MATTHES 09	489690.344	6522652.521	1793.883	16:40
MATTHES 10	489895.785	6522496.188	1789.803	16:15
MATTHES 11	490096.464	6522343.486	1787.020	15:50
MATTHES 12	490353.144	6522147.390	1792.580	15:22
MATTHES 13	490579.578	6521974.897	1814.811	14:58

***

Hhenvergleich mit Daten von 1952   2.8.1993 (3.8.1993 = *)

Point	Easting Y[m]	Northing X[m]	Height [m]	Time
1952_P01	485783.430	6523141.660	1756.583	14:10
1952_P02	486082.231	6523048.205	1760.843	14:18
1952_P03	486401.326	6522948.043	1765.568	14:58
1952_P04	486678.816	6522860.967	1772.232	15:46 *
1952_P05	486977.650	6522767.351	1780.846	15:29
1952_P06	487297.557	6522667.017	1790.074	15:29
1952_P07	487595.842	6522573.717	1790.429	16:00
1952_P08	487916.177	6522473.487	1784.292	16:02
1952_P09	488213.466	6522380.233	1778.711	16:30
1952_P10	488512.470	6522285.500	1776.024	16:41 *

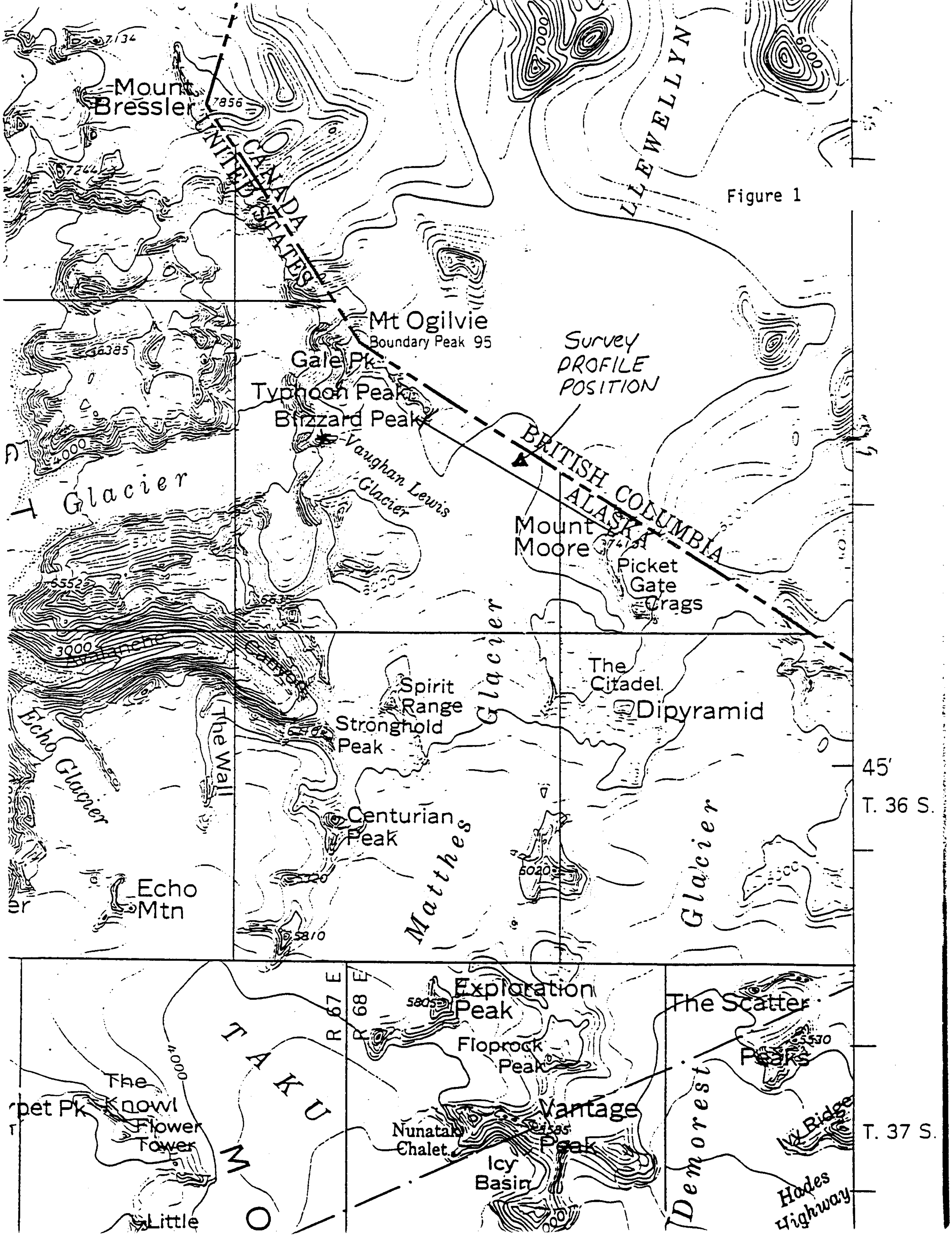


Figure 1

Mount Bressler
7856
7134
7244
CANADA
UNITED STATES
LLEWELLYN
Mt Ogilvie
Boundary Peak 95
Gale Pk
Typhoon Peak
Blizzard Peak
Survey PROFILE POSITION
BRITISH COLUMBIA
ALASKA
Vaughan Lewis Glacier
6385
4000
Glacier
Mount Moore
7461
Picket Gate Crags
5552
6000
3000
Avalanche Canyon
The Wall
Echo Glacier
The Citadel
Dipyramid
Spirit Range
Stronghold Peak
Centurian Peak
Matthes Glacier
Glacier
6020
Echo Mtn
5810
45′
T. 36 S.
R 67 E
R 68 E
Exploration Peak
5805
The Scatter Peaks
5530
Floprock Peak
TAKU
The Knowl
Flower Tower
Nunatak Chalet
Vantage Peak
Icy Basin
Demorest
Ivy Ridge
Hades Highway
T. 37 S.
Little
O
M
pet Pk
er

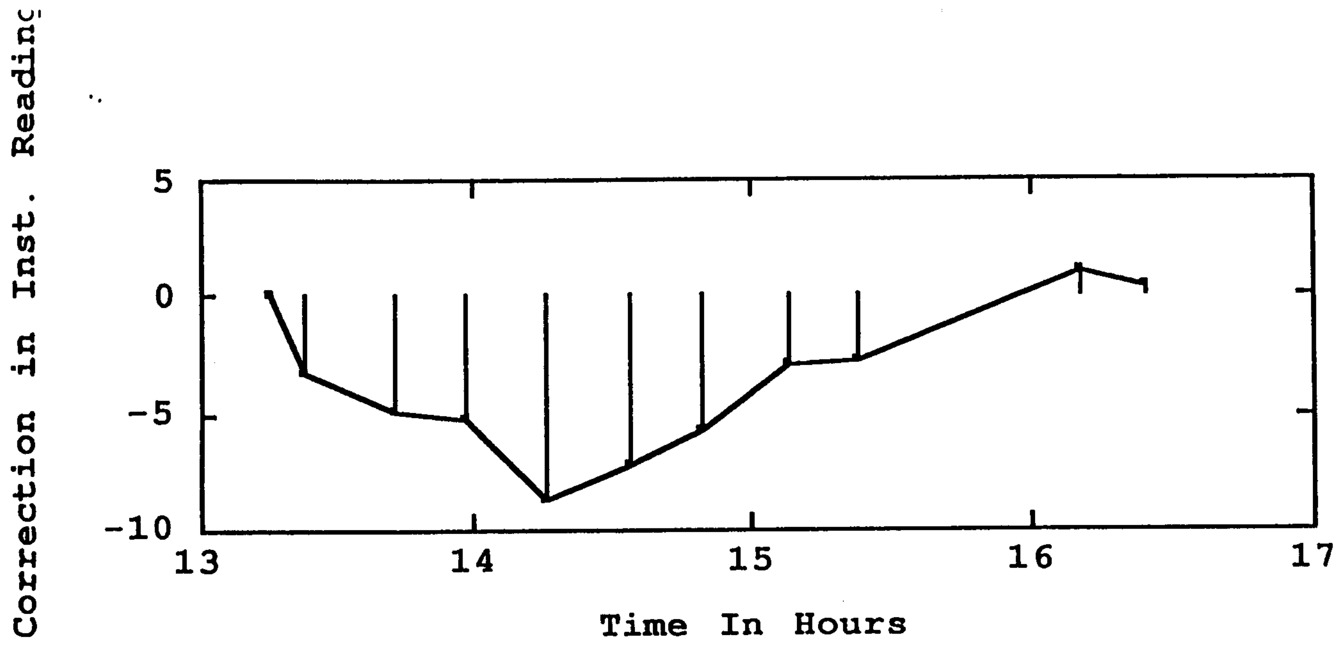
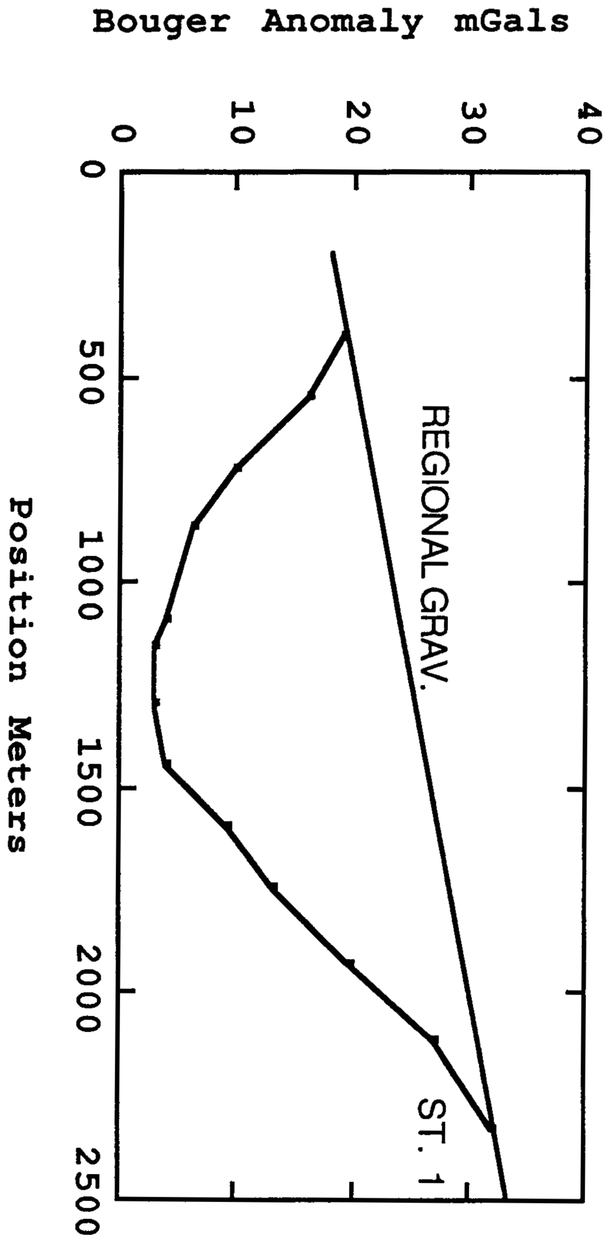

Drift Correction in Inst. Reading
5
0
-5
-10
13
14
15
16
17
Time In Hours

FIGURE 2

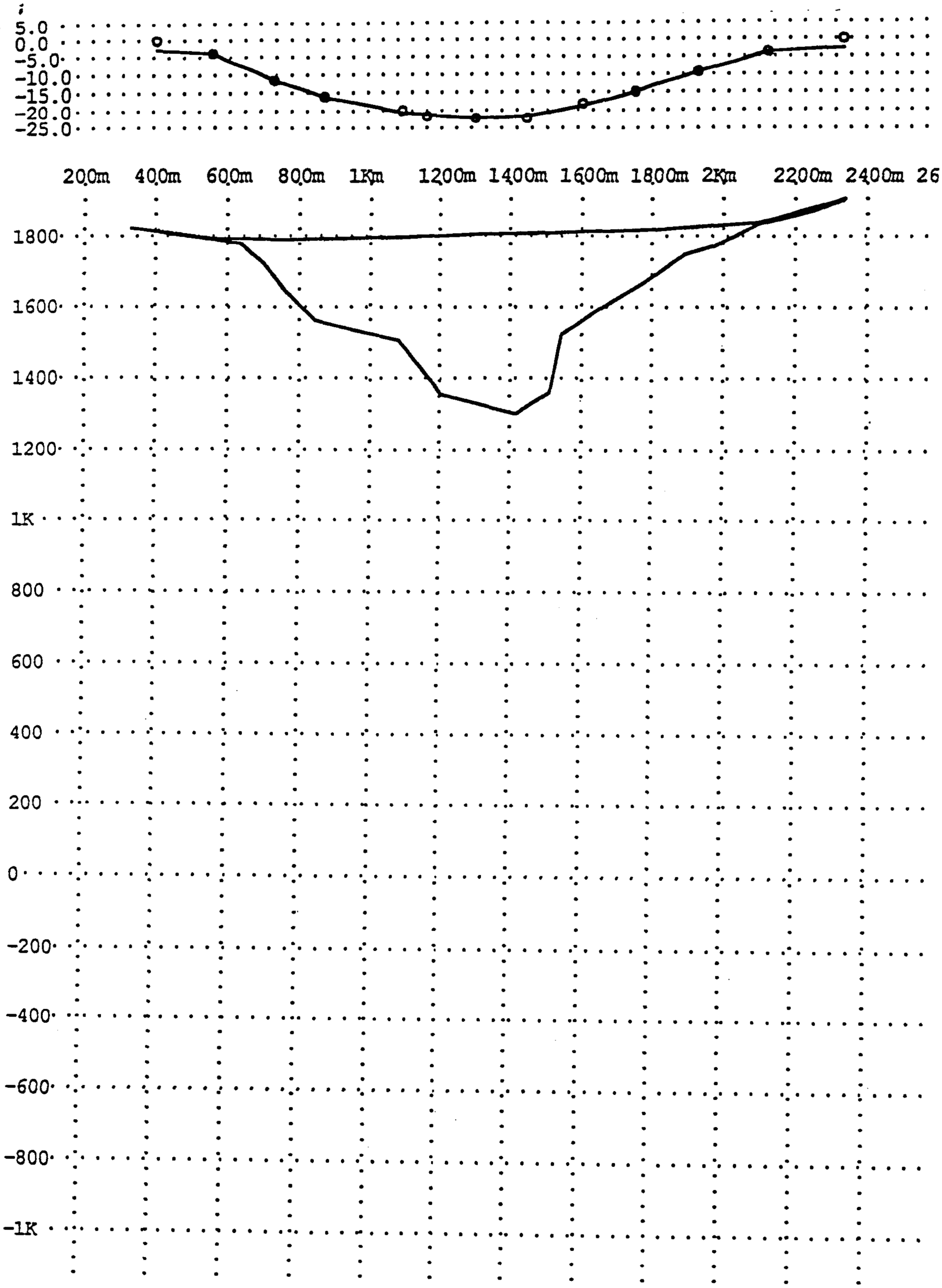
```
Date:  08-MAR-94
Time:  09:20:20
File: SYSTAT Data Editor
      has     2 variables and      12 cases.

OBS

  1       0.000         11.500
  2       0.000         13.250
  3     -33.000         13.370
  4     -49.000         13.700
  5     -53.000         13.970
  6     -88.000         14.250
  7     -72.000         14.550
  8     -58.000         14.820
  9     -29.000         15.130
 10     -27.000         15.380
 11      10.000         16.170
 12       4.000         16.410

   12 cases printed out of       12 cases in the file.
```



INTERPRETED REGIONAL GRAVITY

Drift Corrected	G Observed	Lattitude Cor.	Bouger Cor.	B. Anomaly	Residual Anom.
St.1 35.22	993.2	0	38.85	32.05	0
St.2 42.02	1000	-0.27	27.27	27	-3.66
St.3 38.2	996.18	-0.37	24.14	19.95	-9.4
St.4 33.17	991.15	-0.57	22.76	13.34	-14.8
St.5 29.83	987.81	-0.69	21.98	9.1	-18.1
St.6 26.77	984.75	-0.81	20	3.94	-22.2
St.7 25.38	983.36	-0.92	20.41	2.85	-22.3
St.8 26.18	984.16	-1.03	19.62	2.75	-21.5
St.9 28.5	986.48	-1.17	18.45	3.76	-20
St.10 31.75	989.73	-1.27	17.66	6.12	-16.1
St.11 36.34	994.32	-1.38	17.07	10.01	-11.4
St.12 41.35	999.33	-1.53	18.25	16.05	-4.13
St.13 40.31	998.29	-1.71	22.57	19.15	0
	CORRECTED VALUES all readings in mGals				

Figure 3

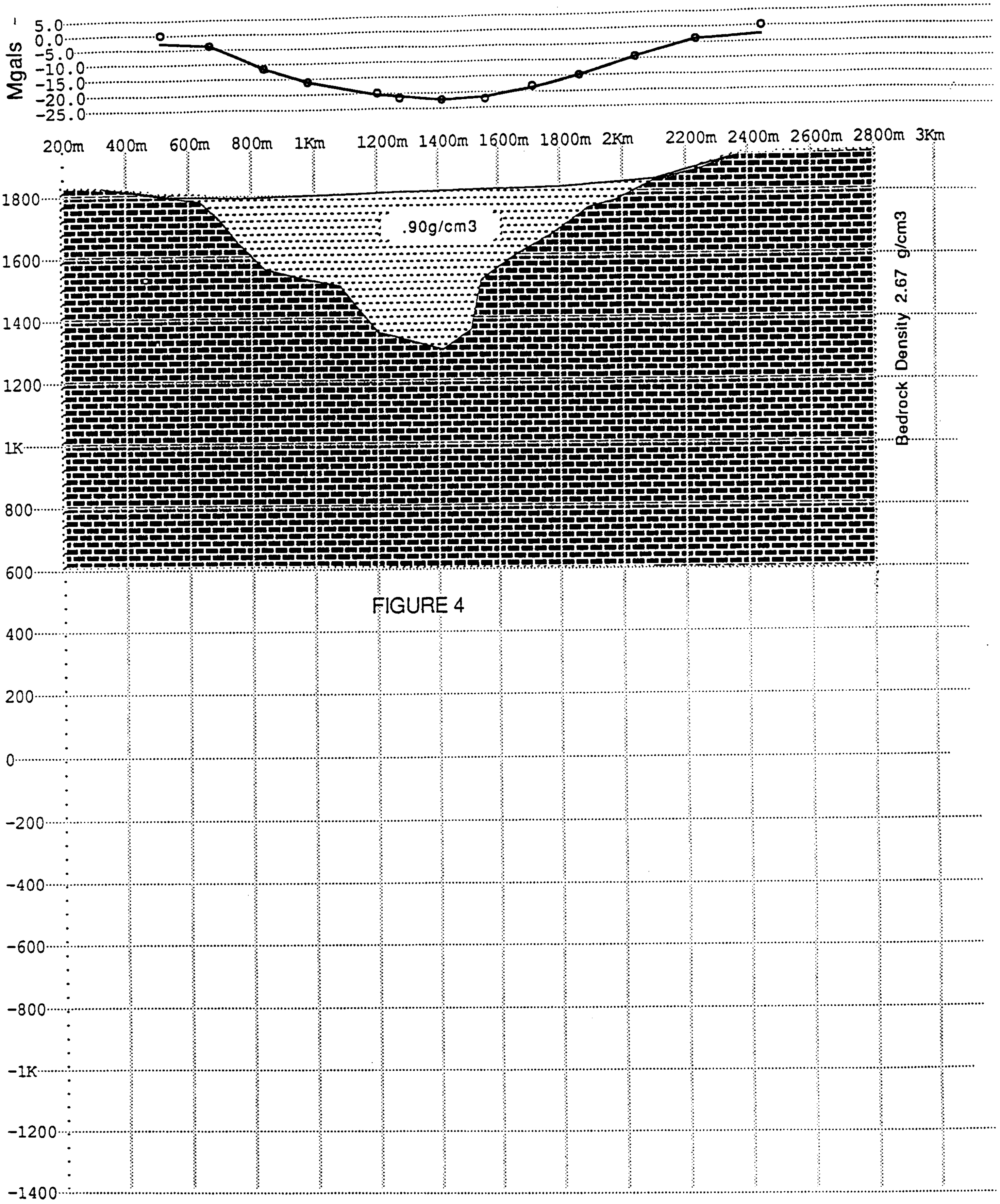


5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
200m
400m
600m
800m
1Km
1200m
1400m
1600m
1800m
2Km
2200m
2400m
26
1800
1600
1400
1200
1K
800
600
400
200
0
-200
-400
-600
-800
-1K

Data For Fig 3

mathes final 2
Calculated and Measured Gravity at the Stations

Horz	Elev	Meas	Calc	Diff
400	1815	0.000	-2.59	2.59
554	1793	-4.13	-4.11	-0.021
730	1787	-11.4	-11.5	0.083
868	1790	-16.1	-16.1	-0.000
1088	1794	-20.0	-20.6	0.61
1160	1800	-21.5	-21.4	-0.119
1302	1804	-22.3	-22.1	-0.182
1447	1807	-22.2	-21.4	-0.81
1600	1812	-18.1	-18.8	0.73
1749	1816	-14.8	-14.9	0.104
1928	1823	-9.4	-9.5	0.112
2124	1839	-3.66	-3.63	-0.028
2332	1898	0.000	-2.55	2.55



Mgals
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
200m
400m
600m
800m
1Km
1200m
1400m
1600m
1800m
2Km
2200m
2400m
2600m
2800m
3Km
1800
1600
1400
1200
1K
800
600
400
200
0
-200
-400
-600
-800
-1K
-1200
-1400
.90g/cm3
Bedrock Density 2.67 g/cm3

FIGURE 4

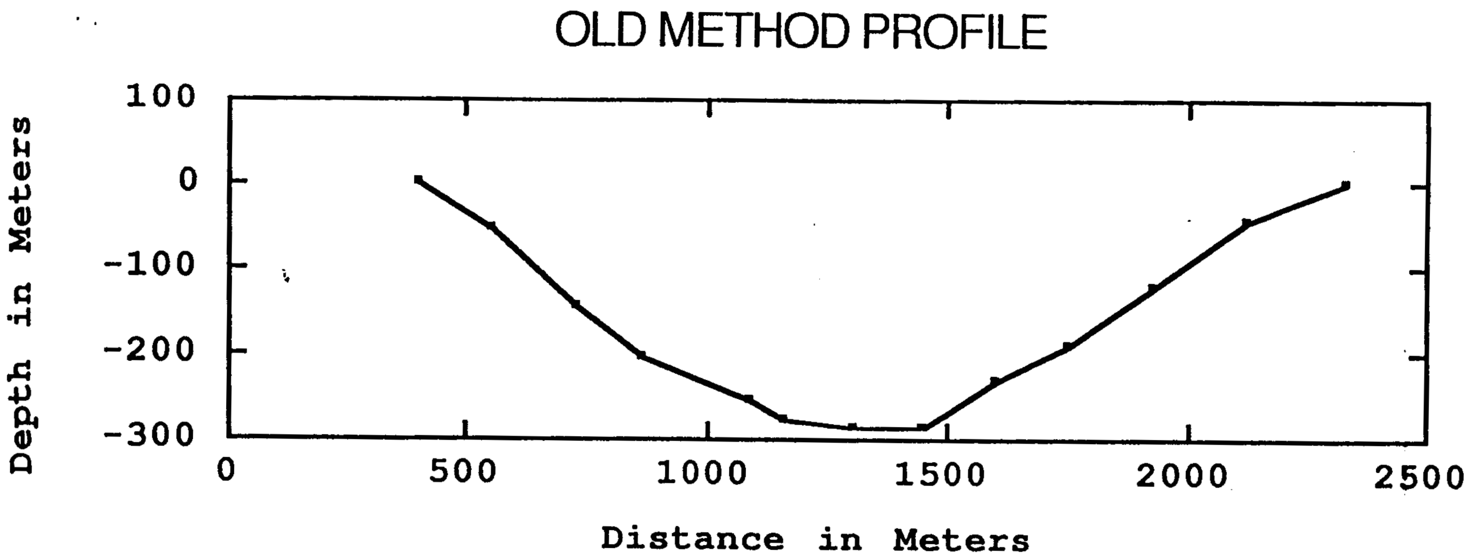

OLD METHOD PROFILE
Depth in Meters
100
0
-100
-200
-300
0
500
1000
1500
2000
2500
Distance in Meters

FIGURE 5

COMPARISON TABLE OLD AND NEW METHODS

Old Method		New Method	
Position Meters	Depth Meters	Position Meters	Depth Meters
400	0	250	0
554	-53.35	638	-22
730	-147.29	842	-244
868	-208.01	1088	-277
1088	-258.4	1200	-440
1160	-277.78	1410	-488
1302	-288.11	1511	-430
1447	-286.82	1532	-277
1600	-233.85	1899	-70
1749	-191.21	1976	-66
1928	-121.45	2300	0
2124	-47.28		
2332	0		