Geophysical Investigation of the Taku-Llewellyn Divide: A NASA Earth Systems Field Research Project Juneau Icefield, Alaska 1997

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INTRODUCTION

During the 1997 summer field season of the Juneau Icefield Research Program, a grid consisting of 30 GPS stations was established on the high ice divide between the Taku and Llewellyn glacier systems. The purpose of the grid was to study in detail the ice divide to determine its suitability as a site for a future research borehole to study past climatic fluctuations. In conjunction with GPS strain measurements, two geophysical methods, seismic reflection and gravity, were employed to determne the thickness of the ice and to study the relationship between ice movement on the surface and sub-glacial morphology. This report describes the geophysical measurements and their interpretation.

Seismic reflection and gravity surveys have long been used for glaciological investigations on the Juneau Icefield as well as elsewhere. However, the ice divide provided particular challenges for both methods. Because of the three-dimensionality of the divide geometry, simple two-dimensional interpretation of the results was not possible. Considerable effort had therefore to be employed to obtain a meaningful model of the divide from the geophysical measurements.

In this report, the location of the grid will be described, followed by a description of the geophysical measurements taken. The procedure developed to interpret the three-dimensional seismic data will be presented as will be the three-dimensional gravity interpretation procedure. The seismic and gravity results will be presented. Finally a model of the ice divide consistent with both the seismic and gravity results will be given.

The geophysical results show that the high divide is a locality of surprisingly rugged sub-glacial topography, not at all what one might surmise from the featureless flat plain of the ice surface. Below the ice, the divide appears as a saddle-shaped morphology with an ice thickness of 925 m at the center of the saddle. A central bedrock trough bounded by 45 degree slopes shows a relatively flatter bottom widening toward the Llewellyn Glacier side. A tributary subglacial trough trends up the neve field between Mt Olgilvie and the Storm Range. The location of the sub-glacial topographic divide is coincident with the surface ice-strain divide at least to the resolution of the geophysical results.

THE TAKU-LLEWELLYN DIVIDE

The Juneau Icefield is one of the largest remaining centers of high ice on the North America Continent. This sub-Arctic glacier complex lies along the longitudinal axis of the Boundary Range, straddling the border between southeastern Alaska and northern British Columbia. The Juneau Icefield encompasses thousands of square kilometers of interconnected glacial tributaries and highland neve zones, representing the most heavily glaciated sector along the axis of the Coast Ranges. The highlands have the appearance of being ice-flooded with a much larger percentage of neve exposed than nunataks. The uppermost snowfields crest at 6,000-6,500 ft (1830-1980m). The highest peaks reach elevations over 8,000 ft (2,440 m).

The Taku-Llewellyn Divide, a flat ice plain at an elevation of 6150 ft (1875 m) separates two of the world's most famous glacial systems (Figure 1). The Taku system includes, among others, the Mendenhall, Herbert, Norris, Eagle Glaciers as well as its namesake, the Taku Glacier. The Taku Glacier is unique in that it is the only advancing glacier in the region; it is also said to be the deepest and thickest temperature glacier yet discovered. The Llewellyn system of British Columbia is renowned for its rapid decline during the past century. The Taku-Llewellyn Divide also has the geographic distinction of being the true headwaters both of the Yukon River (via Atlas Lake) and the Telsequah River (via the Telsequah Glacier).

The divide is of considerable glaciological interest because ice movement is theoretically very slow because of the subglacial topography. Being in the upper neve zone, little ablation occurs. Thus a long record of annual ice accumulation may be preserved in the ice stratigraphy at the divide. Ice cores from a future borehole on the divide might provide information on the climate at this unique location for the last hundreds to thousands of years.

THE GRID

Based on some initial results in the previous season, a rectangular grid of 30 stakes was placed on the suspected location of the ice divide (Figure 1). The stakes were emplaced about 300 m apart in five lines 300 m apart tranverse to the longitudinal axes of the Llewellyn Glacier to the north-northeast and the Matthes Glacier to the south-southwest (Figure 2). Geodetic measurements using GPS provided relative stake locations accurate to 0.005 m and elevations accurate to about 0.05 m. The strain measurements found are described in the 1997 Geodetic Activities JIRP Report.

SEISMIC REFLECTION SURVEY

The seismic reflection survey took advantage of the surveyed grid, placing geophones and shots along flag lines (Figure 2). An L-shaped geophone spread was employed to ensure three-dimensional coverage. Each arm of the L-spread included 12 geophones spaced 30m apart. An initial plan to place a shot at each stake on the grid was vetoed due to a lack of sufficient explosives. A total of nine shots, each employing 20 vials of Kinepack (1/3 sticks), were taken at locations in-line with one arm or the other of the L-spread. This large amount of explosives was necessary to get sufficient seismic energy through the firn pack, which is thought to be as thick as 20 m on the divide. The explosives were buried at a depth of about 1 m and each shot produced a crater, 2 m deep and 3m wide, in the snow.

A Bison 9000 Series 24-Channel Seismograph was used to record the signals from the 24 high-frequency (100 Hz) geophones. The nine seismic records obtained are reproduced in Appendix 1. Lacking a radio trigger in the field, we used the measured shot-receiver distances and an ice velocity of 3660 m/s to compute the time break on the records. The records are all of high quality and the reflecting events from the base of the ice were easily picked.

PROCESSING OF SEISMIC DATA

The three-dimensional seismic reflection problem was first solved by Roman (1932). The method was applied to the Salmon Glacier by Doell (1962). A re-statement of the calculations involved in a form readily programmed on a calculator or computer is given below. The case considered is that of the shot and receivers all being on the same horizontal plain. The general case of shot and receivers being at different elevations can also be solved uniquely but is much more tedious. If the differences in elevations are small, then it is far simpler to estimate a static correction as is done in conventional seismic surveys. At the study site considered in this report, the differences in elevations were negligible.

Consider a coordinate system (Figure 3) with the x-axis east, the y-axis north, and the z-axis down. Then let

$S(xs, ys)$	Shot
$R(xi, yi)$	Receiver $(i=1,2,3)$
$I(x', y', z')$	Image point
$P_i(x, y, z)$	Point of reflection for $R(xi, yi)$
b	Perpendicular distance to reflecting plane
v	Seismic velocity (3660 m/s)
t_i	Reflection time at $R(x_i, y_i)$

The fundamental equations to be solved are:

$$v^2 \, t_i^2 = (x_i - x')^2 + (y_i - y')^2 + z'^2 \qquad (1)$$

If three non-collinear receivers are employed, these equations have an unique subsurface solution for the coordinates of the image point. The primary assumption here is that all three reflections are from the same subsurface plane.

The order of solution is as follows. First solve the simultaneous equations below for x', y':

$$\begin{vmatrix} 2(x_2-x_1) & 2(y_2-y_1) \\ 2(x_3-x_2) & 2(y_3-y_2) \end{vmatrix} \begin{vmatrix} x' \\ y' \end{vmatrix} = \begin{vmatrix} v^2(t_1{}^2-t_2{}^2)+(x_2{}^2-x_1{}^2)+(y_2{}^2-y_1{}^2) \\ v^2(t_2{}^2-t_3{}^3)+(x_3{}^2-x_2{}^2)+(y_3{}^2-y_2{}^2) \end{vmatrix} \qquad (2)$$

Then calculate z' and b (taking the positive root in both cases) using:

$$z'^2 = v^2 t_1{}^2-(x-x_1)^2-(y-y_1)^2$$

$$4\,b^2 = (x'-x_s)^2+(y'-y_s)^2+(z')^2 \qquad (3)$$

Then solve the following equations three times (for $i=1,2,3$) to find the subsurface reflection point for each receiver:

$$\begin{vmatrix} x'-x_s & y'-y_s & z' \\ y'-y_i & x_i-x' & 0 \\ 0 & x_i-x' & z'-z_i \end{vmatrix} \begin{vmatrix} x \\ y \\ z \end{vmatrix} = \begin{vmatrix} 2b^2+(x'-x_s)x_s+(y'-y_s)y_s+(z'-z_s)z_s \\ (x'-x_i)y_i-(y'-y_i)x_i \\ (z'-z_i)y_i-(y'-y_i)z_i \end{vmatrix} \qquad (4)$$

SEISMIC RESULTS

The average subsurface reflection points for each shot are plotted as ice thickness in Figure 4. The ice thickness appears to decrease dramatically to the southwest, creating an illusion that the topographic divide was actually southwest of the grid. However, the seismic control is insufficient to make that judgment. The strong dip on the results from the southwestern stations suggested that these reflections were actually coming from the sideslope of the glacial valley, not from the thickest section of ice. Had more shots been taken, not all collinear with the geophone spread arms, then a more complete three-dimensional picture of the glacial base would have been obtained.

The ice divide, as judged from 1996 strain measurements lies just southwest of the center of the grid (between the second and third row of GPS stations). The seismic reflection results (Figure 4) provide little control on the actual subglacial divide location. Simple interpolation of the seismic depths would suggest an ice thickness of roughly 800m at the ice divide.

GRAVITY SURVEY

Thirty gravity measurements were made on the survey grid. The instrument was placed on a wood platform near the base of each stake. The stakes were not surveyed the same day as the gravity survey was performed; thus the full accuracy (0.05 m) of the grid stations was not available due to ablation, which is several centimeters per day even on the high divide. However, the elevations were certainly accurate to 0.3 m, resulting in a relative gravity accuracy of 0.1 mGal. The Sodin gravimeter used was very stable during the survey, drifting at most 0.02 mGal between hourly base station readings. The entire survey (30 stations) took six hours to complete. The field notes, compiled by M.M. Miller, are reproduced in Appendix B.

GRAVITY REDUCTIONS

Conventional gravity corrections were applied to the measurements, including drift, free-air, and latitude reductions. A specific gravity of 0.91 for the glacial ice was used in a Bouguer reduction. No absolute gravity stations are available on the Juneau Icefield, so the readings are completely relative.

Terrain corrections are always a major concern for gravity surveys in mountainous terrain. However, the grid is on an amazingly flat ice plain. The nearest mountains (Mount Olgilvie, the Storm Range, and Mount Moore are several kilometers away (Figure 1). Terrain corrections were performed by manually digitizing the elevations of the ridge and nunatak elevations within 7 km of the grid, estimating the mean elevation in subareas 0.5 km on a side. The gravity effect of each prism in the digital elevation model was then estimated using the well known formula for a vertical rod (e.g. Telford et.al, 1974):

$$g = -0.00666 \; \sigma \; A \; [r^{-1/2} - (r+h)^{-1/2}] \qquad (5)$$

where g is the gravity effect in mGal

σ is the specific gravity of the mountains

A is the area of the prism in m^2

r is the horizontal distance to the prism (m)

h is the height of the prism above the station (m).

For each station, the gravity effects of all the prisms in the digital elevation model were summed to obtain a terrain correction. The specific gravity of the largely granitic and low-grade metasedimentary rocks in the surrounding terrain was estimated at 2.5. The terrain effect across the grid ranges smoothly from 0.09 to 0.04 mGal as the distance from Mount Olgilvie increases(Figure 5). This variation across the grid (0.05 mGal) is less than the estimated precision of the survey (0.1 mGal).

GRAVITY RESULTS

The Bouguer gravity map of the grid (Figure 6) shows a range of over 8 mGal, a surprising variation for an area less than 2 km^2 in area. The pattern of the gravity contours is suggestive of an valley cut into a topographic divide located south-southwest of the grid. However, considerable care must be taken before making such simplistic gravity interpretations, particularly since the seismic results indicated that 500-1000 m of ice separate the gravity measurements from the anomalous densities beneath the glacier creating the gravity anomalies and nothing is known of the lateral homogeneity of the subglacial bedrock. A strong correlation (r=0.98) exists between the Bouguer gravity measurements and the seismic derived subglacial elevations (Figure 7). This result strongly suggests that the gravity field is responding to changes in ice thickness, rather than changes in rocktype beneath the glacier. On the other hand, little correlation (r=0.38) is apparent between the gravity measurements (Figure 6) and the surface elevations (Figure 2), indicating that ice surface contours are a poor predictor of subglacial morphology, at least on a local scale.

COMBINED SEISMIC-GRAVITY MODELING

Three-dimensional modeling of gravity data is an ambiguous procedure that rarely produces a unique result. However, the divide provides an exceptional environment for gravity inversion in that considerable seismic control on the ice thickness exists and the bubbly glacial ice itself is virtually homogeneous in density, eliminating the possibility of shallow anomalous densities above the base of the glacier. If we assume that the gravity anomaly is due only to ice thickness variations and that the density of underlying bedrock is constant, than a well-constrained model of subglacial topography can be determined. We assumed a constant bedrock specific gravity of 2.5; constant values higher or lower than this will affect the degree of relief in the final model but not the overall morphologic shape.

The interpretational procedure used was to begin with an estimated guess of the subglacial topography, calculate the theoretical gravity for that model, compare the theoretical gravity values with the gravity observations, change the subglacial model accordingly being careful to honor the seismic control points, and recalculate the theoretical gravity. This procedure is repeated until the calculated and observed gravity agree to within the accuracy of the observations.

Because the gravity observations were 300 m apart, we used the same grid locations to control the subglacial topography model, not allowing the possibility of features narrower than this, a reasonable procedure for gravitational sources 500-1000 km deep. Conventional inverse-distance-squared interpolation was used to compute subglacial elevations at any location on the model from the thirty grid points. Subglacial elevations outside of the grid were estimated by interpolating from the outer rows of the grid to the distance edges of the glacier, assumed infinite longitudinal to the glaciers but bounded by the ridges and nunataks on the sides.

Forward gravity computations for each grid point were made by dividing the model into 97 cylindrical sectors of increasing radii out to 4.5 km, centered on the grid point. The subglacial topographic model was then used to find the find the mean subglacial elevation for that sector. The gravity effect of each sector was then calculated using the conventional formula for a cylindrical sector(e.g. Telford, 1974), and the results summed.

The initial subglacial topographic model was formed by applying the best-fit regression equation, shown in Figure 7, between the seismic results and the interpolated gravity field at the seismic control points. This equation was used to estimate the first guess of the subglacial topography at each of the 30 grid points. The theoretical and observed gravity values for this initial model differed on the average by 0.9 mGal. After 89 subsequent iterations of the subglacial topographic model, the mean difference between the theoretical and observed gravity values was reduced to 0.1 mGal, the accuracy of the gravity survey, while still maintaining less than a 16 m difference between the model subglacial elevations and the seismic control points, a value well within the accuracy of the seismic survey.

The subglacial topographic model of the divide (Figure 8) is consistent both with the seismic reflection control points and the gravity measurements. The convergent gravity contours on the south-southwest side of the grid can only be satisfied by an increased thickness of ice in the zone of convergence. Thus a subglacial divide geometry, not at all apparent in the seismic results or in a casual inspection of the Bouguer Gravity map, is apparent in the results.

The subglacial topographic divide appears as a saddle-shaped morphology with an elevation of 950 m at the center of the saddle. The ice thickness immediately above the saddle is 925 m. A perspective view (Figure 9) from the Matthes glacier across the divide into the Llewellyn Glacier illustrates distinctly different morphologies of the two glaciers as well as a broad irregular region in the divide separated by steep valley walls approaching 45 degrees.

Although the surface strain measurements on the grid suggest an influence of some ice moving to the southeast into the Telsequah system, the subglacial topography divide appears to have a steep wall in that direction. On the other hand a tributary subglacial valley appears to be going up the west into the ice field between Mt Olgilvie and the Storm Range, suggesting that ice flow from that direction might be important in understanding ice movement in the divide.

DISCUSSION

A combined interpretation of gravity and seismic reflection results performed on a grid of GPS stations on the high ice divide between the Taku and Llewellyn glacier systems has provided an impressive picture of the subglacial morphology of the divide. The result could not have been obtained purely by seismic means unless a large number of shots were employed. The result also could not have been obtained with gravity alone because the seismic results provided crucial control on the gravity interpretation.

The seismic results show that three-dimensional methods are critical in glacial environments, particularly high neve areas where surface topography may be unrelated to subglacial morphology. Had we only shot a single longitudinal seismic profile, the results would have been completely misleading, putting the subglacial divide well south-southwest of its actual position.

The gravity results show the importance of applying three-dimensional modeling to gravity results. The final subglacial model is considerably different from the form of the contours on the gravity map. Qualitative inspection alone of the gravity contours would have mislead an interpreter into placing the ice divide south-southwest of the correct location.

REFERENCES

Doell, R.R., 1962. Seismic depth study of the Salmon Glacier, British Columbia: Journal of Glaciology.

Roman, I., 1932. Least squares in practical geophysics. Transactions of the American Institute of Mining and Metallurgical Engineers, v. 97, p. 460-506.

Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1990. Applied Geophysics, Cambridge University Press, 770 pp.

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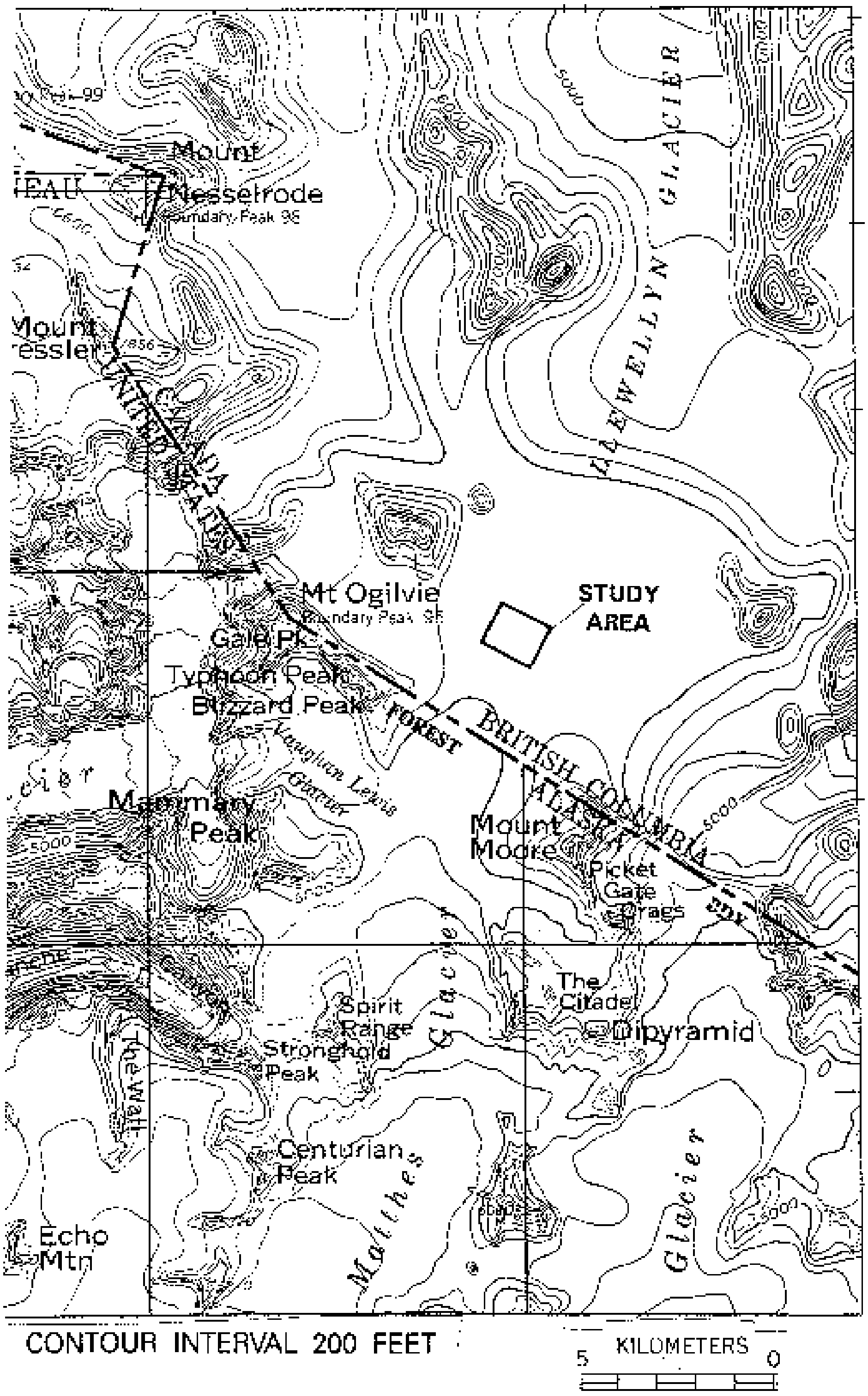


Figure 1. The Taku-Llewellyn Divide. The small rectangle shows the location of the GPS survey grid, established in the 1997 field season, the study area for the geophysical surveys described in this report.

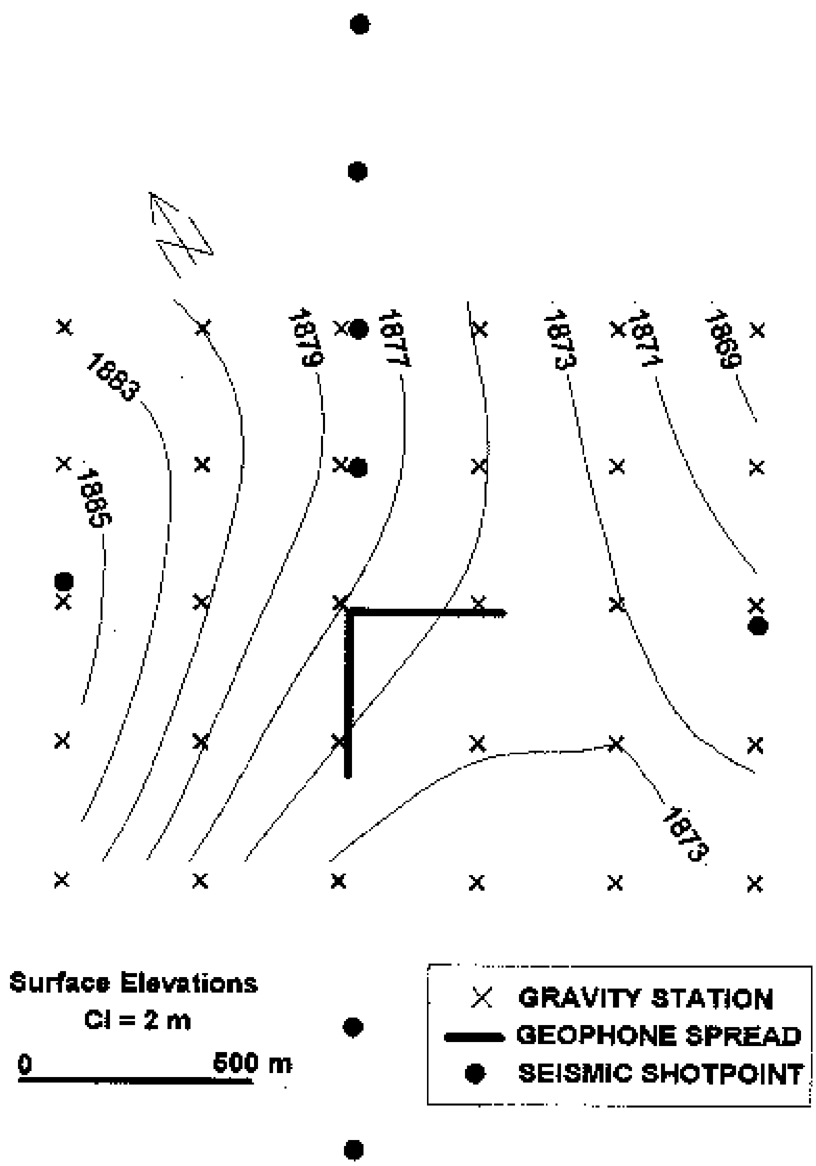


Figure 2. The GPS survey grid on the divide, showing the location of geophysical survey layouts.

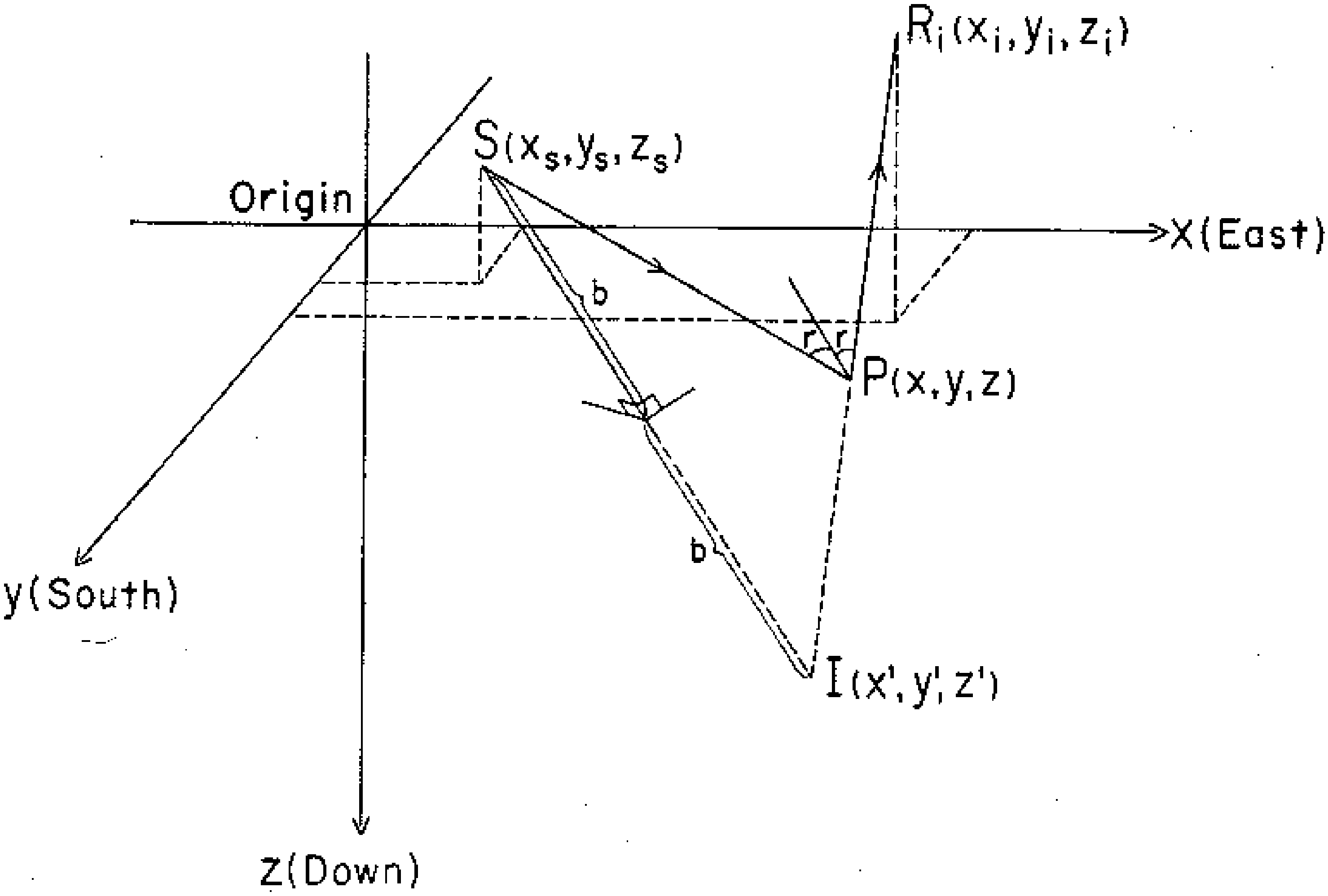


Figure 3. The coordinate system for the three-dimensional seismic reflection. In this report, we consider only the case of the shot and receivers all being on the same horizontal plane (Modified from Doell, 1962).

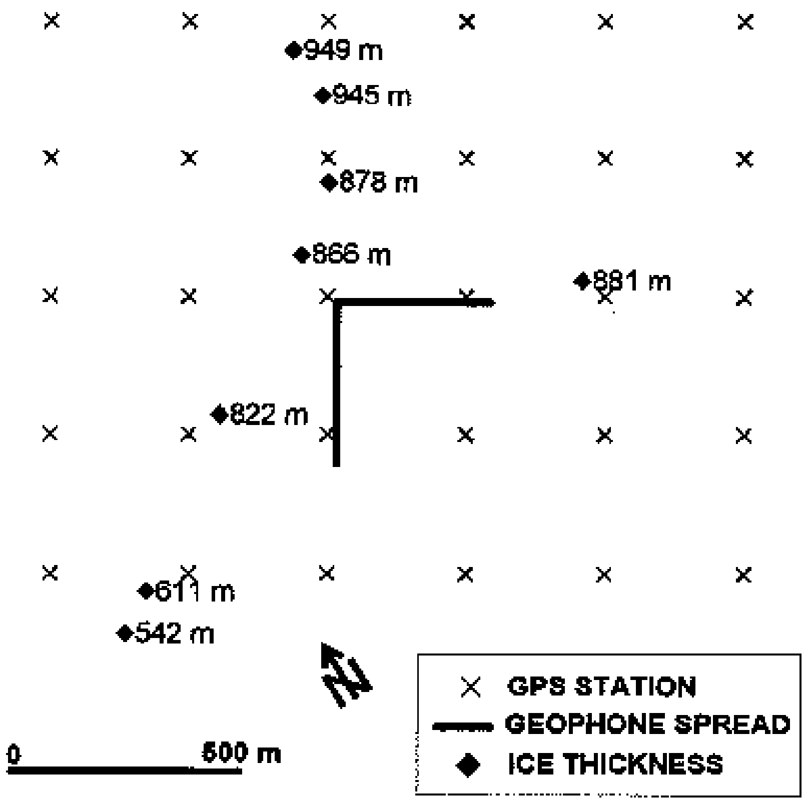


Figure 4. Ice thickness beneath the divide as determined from the seismic reflection survey.

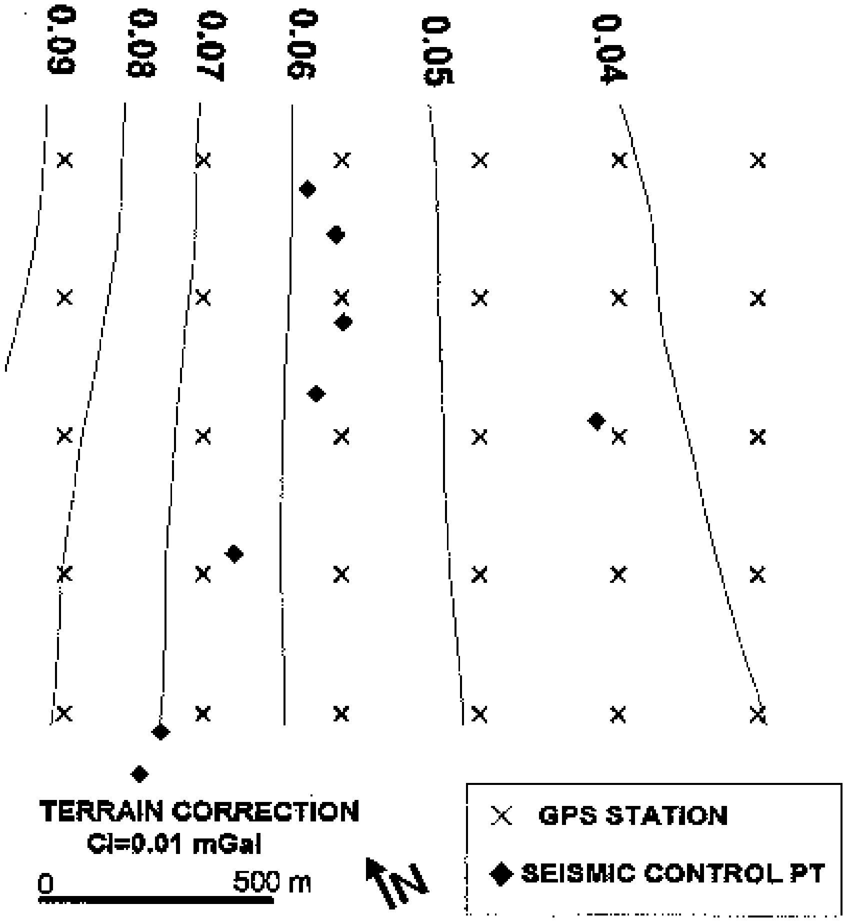


Figure 5. Variation in the the terrain correction on the grid.

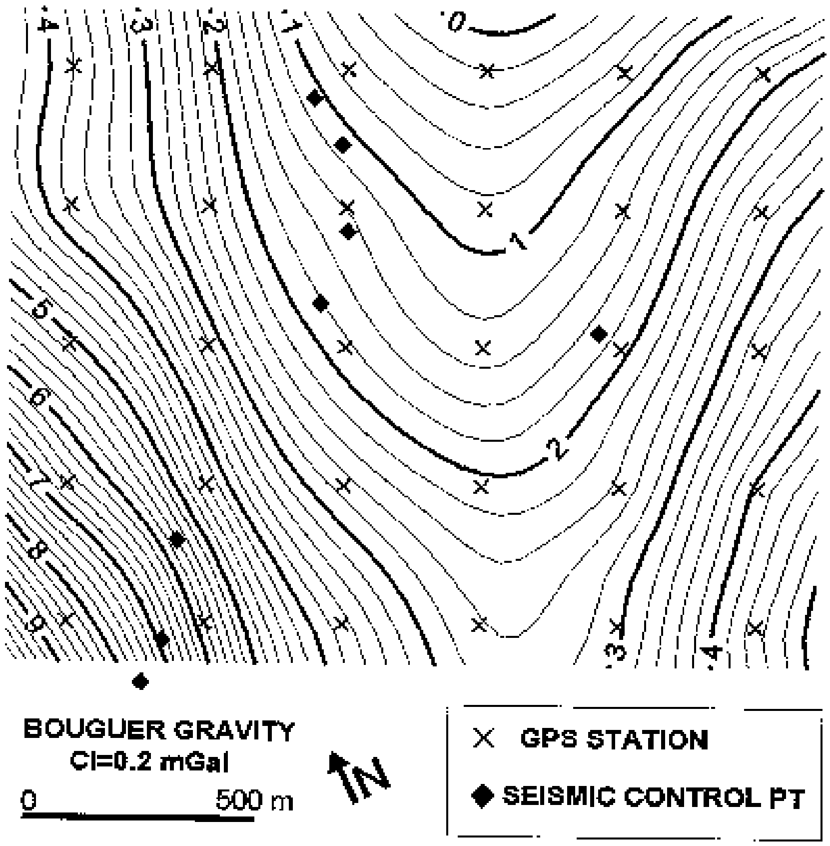


Figure 6. Bouguer gravity map of the grid.

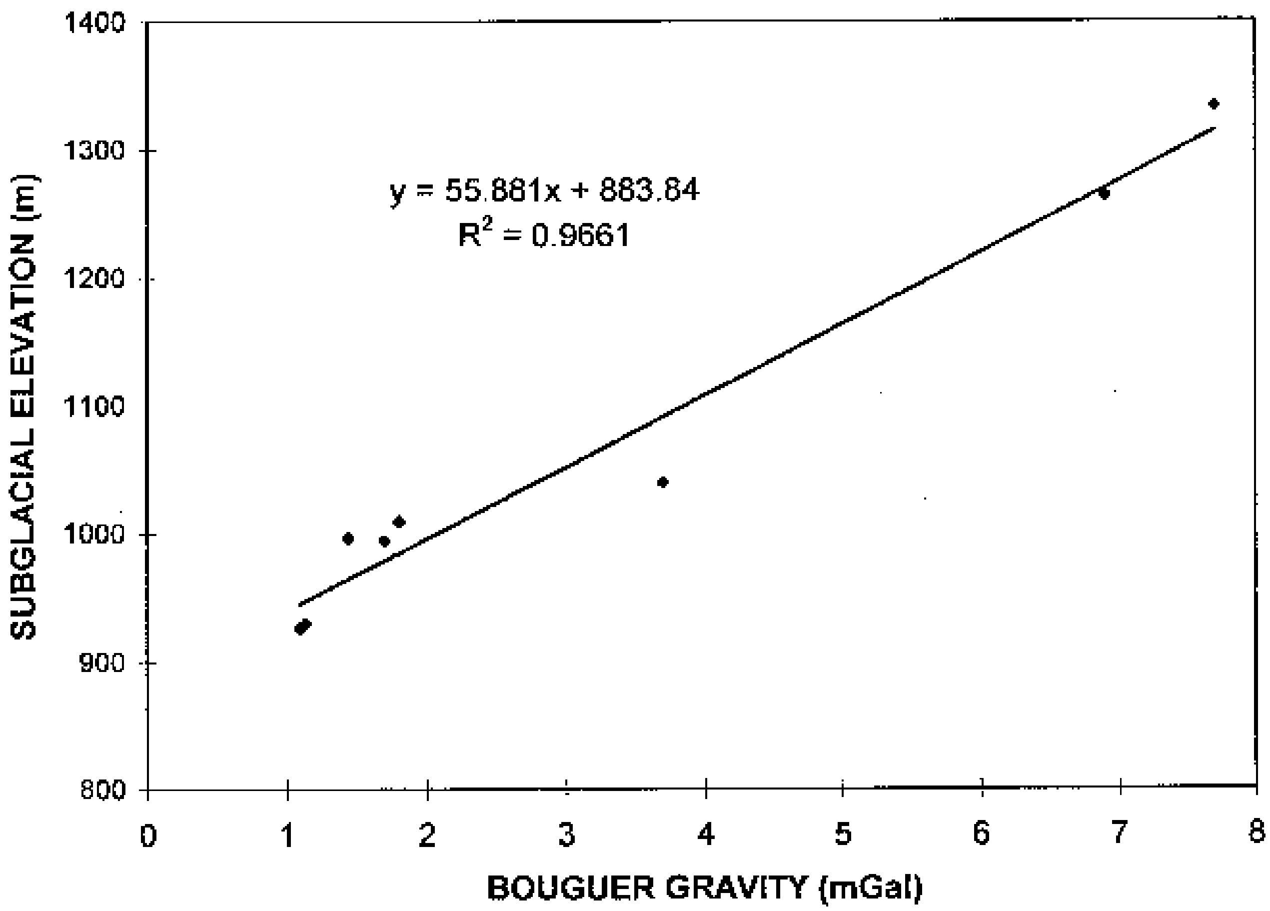


Figure 7. Scatter plot of subglacial elevations and Bouguer gravity at the seismic control points. The coorelation coefficient (R^2) and regression equation are also shown.

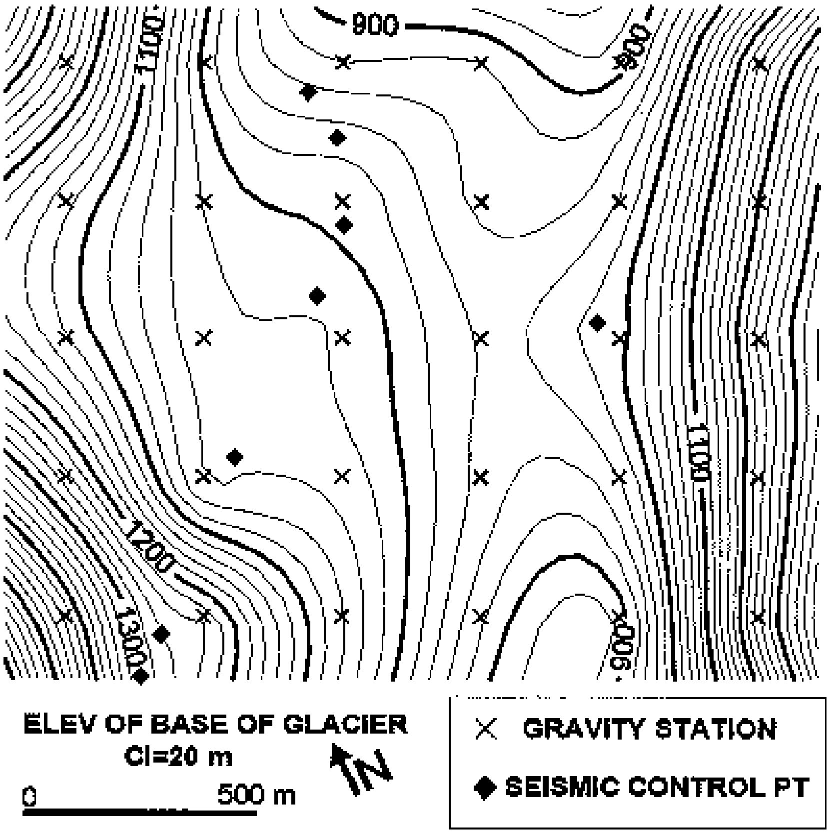


Figure 8. The subglacial morphology of the Taku-Llewellyn divide as determined by combined inversion of the seismic and gravity data.

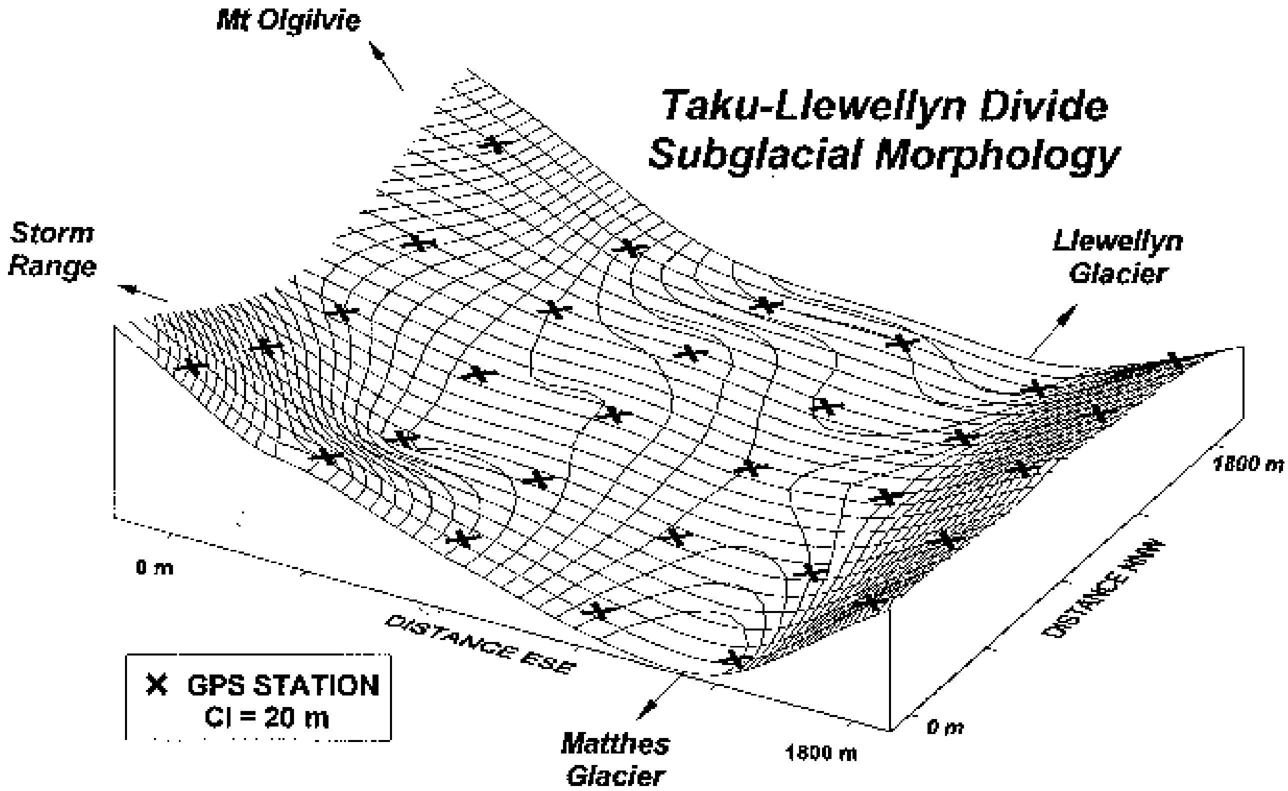
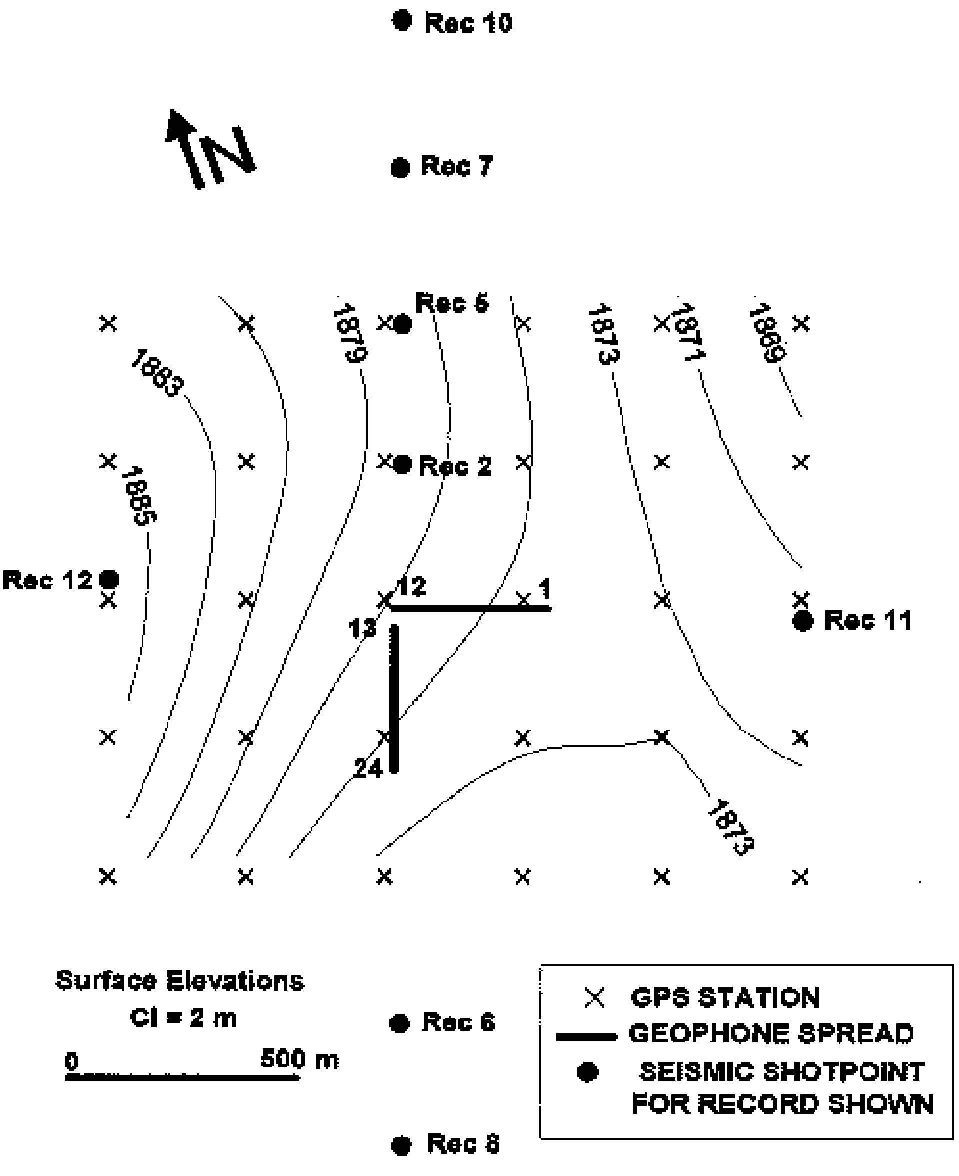
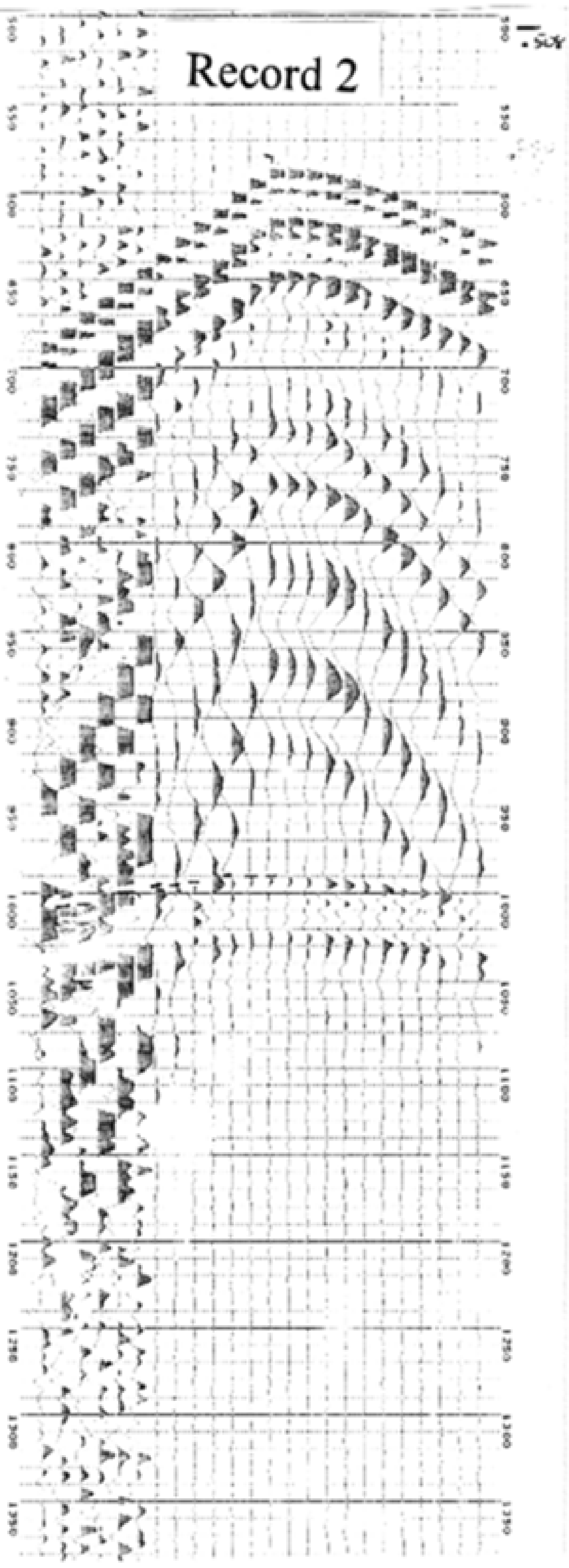


Figure 9. View from the south of the subglacial topography of the Taku-Llewellyn divide.

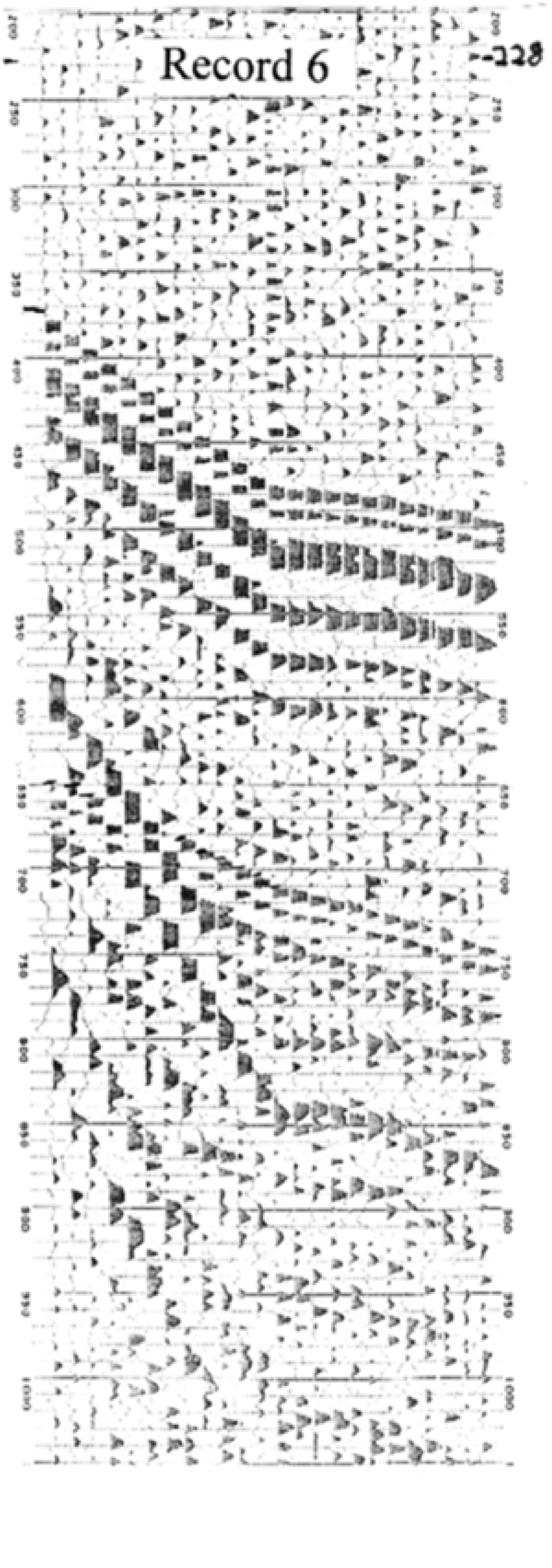
APPENDIX A
SEISMIC REFLECTION RECORDS

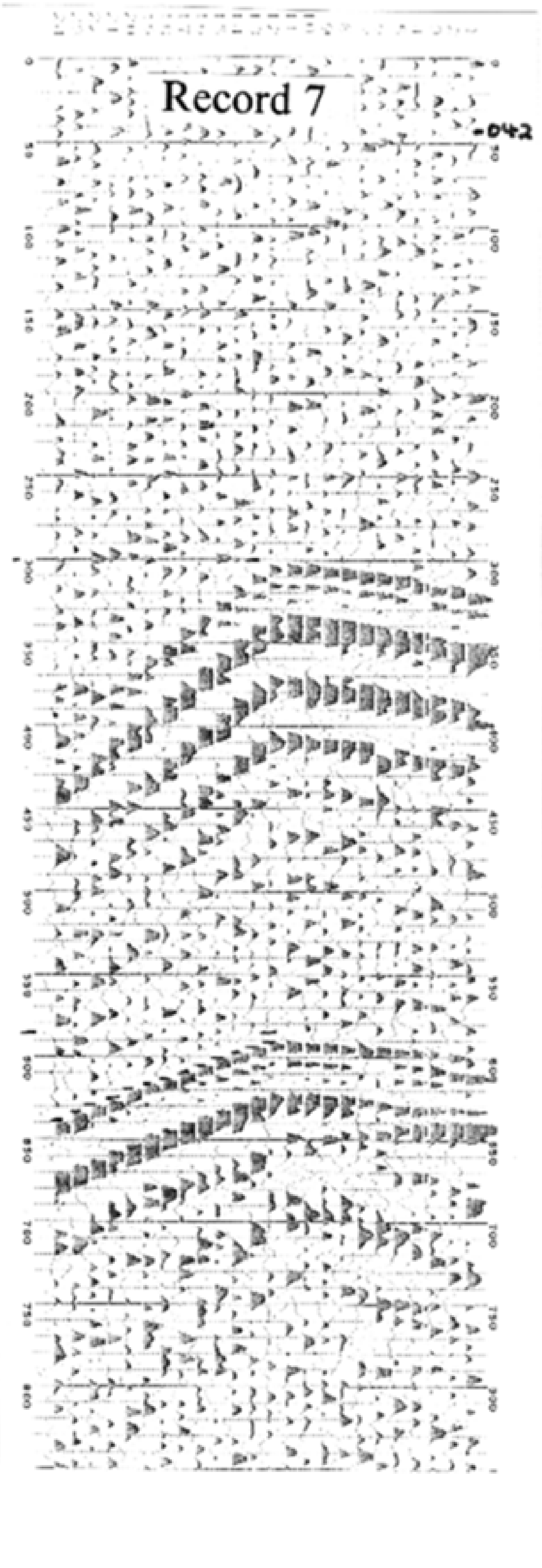
The following pages show the eight seismic records collected on the grid in 1997. The diagram on the next page explains the shotpoint locations and the layout of the geophones. The same geophone spread was used for all the shots. The geophone spacing was 30 m. Twenty four high frequency phones (100 Hz) were used. On all records, geophone 1 is on the right; geophone 24 on the left. The seismograph was a Bison 9000. The records are stored in the JIRP digital archives as PRIX0002 etc. Twenty containers of Kinepack (1/3 sticks) were used for each shot. The shots were buried about 1 m deep. The sample rate on all records was 1 msec. The time scale is 10 msec per division. The time break for each record is indicated. Note that the timing lines do not start at zero time.


Rec 10
N
Rec 7
Rec 5
1879
1873
1871
1869
1883
Rec 2
1885
Rec 12
12
1
Rec 11
13
24
1873
Surface Elevations
CI = 2 m
0
500 m
Rec 6
Rec 8
GPS STATION
GEOPHONE SPREAD
SEISMIC SHOTPOINT
FOR RECORD SHOWN


Record 2


Record 5


Record 6
-228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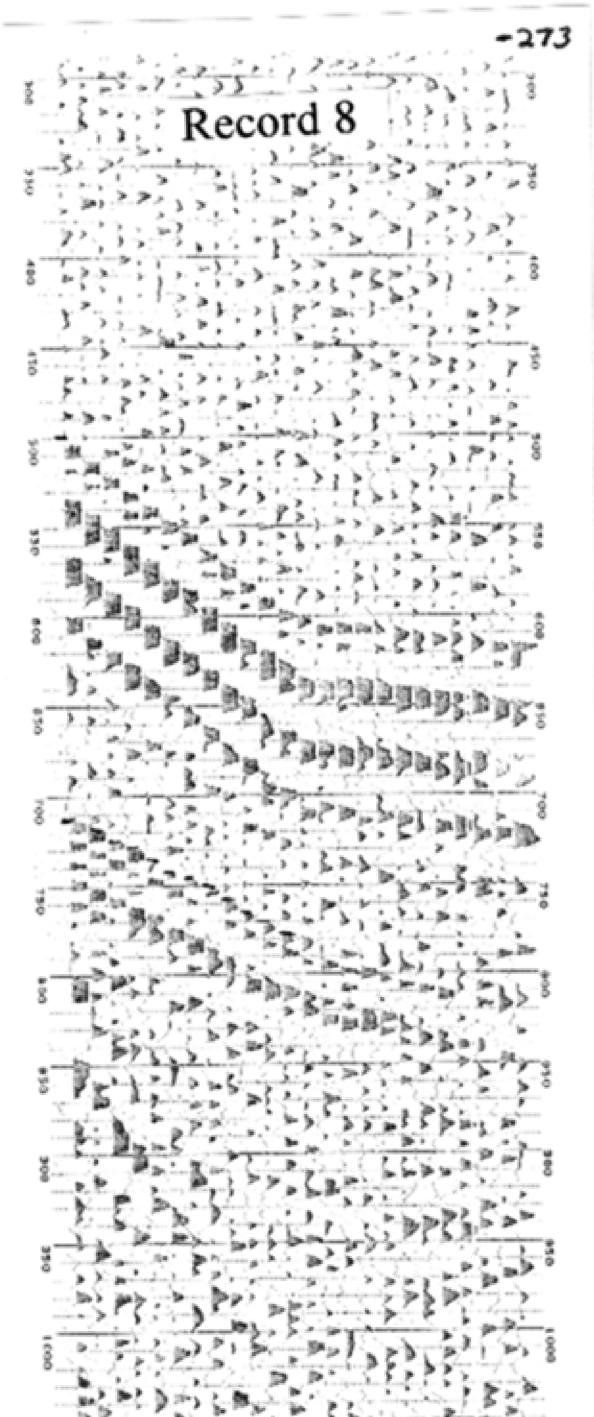
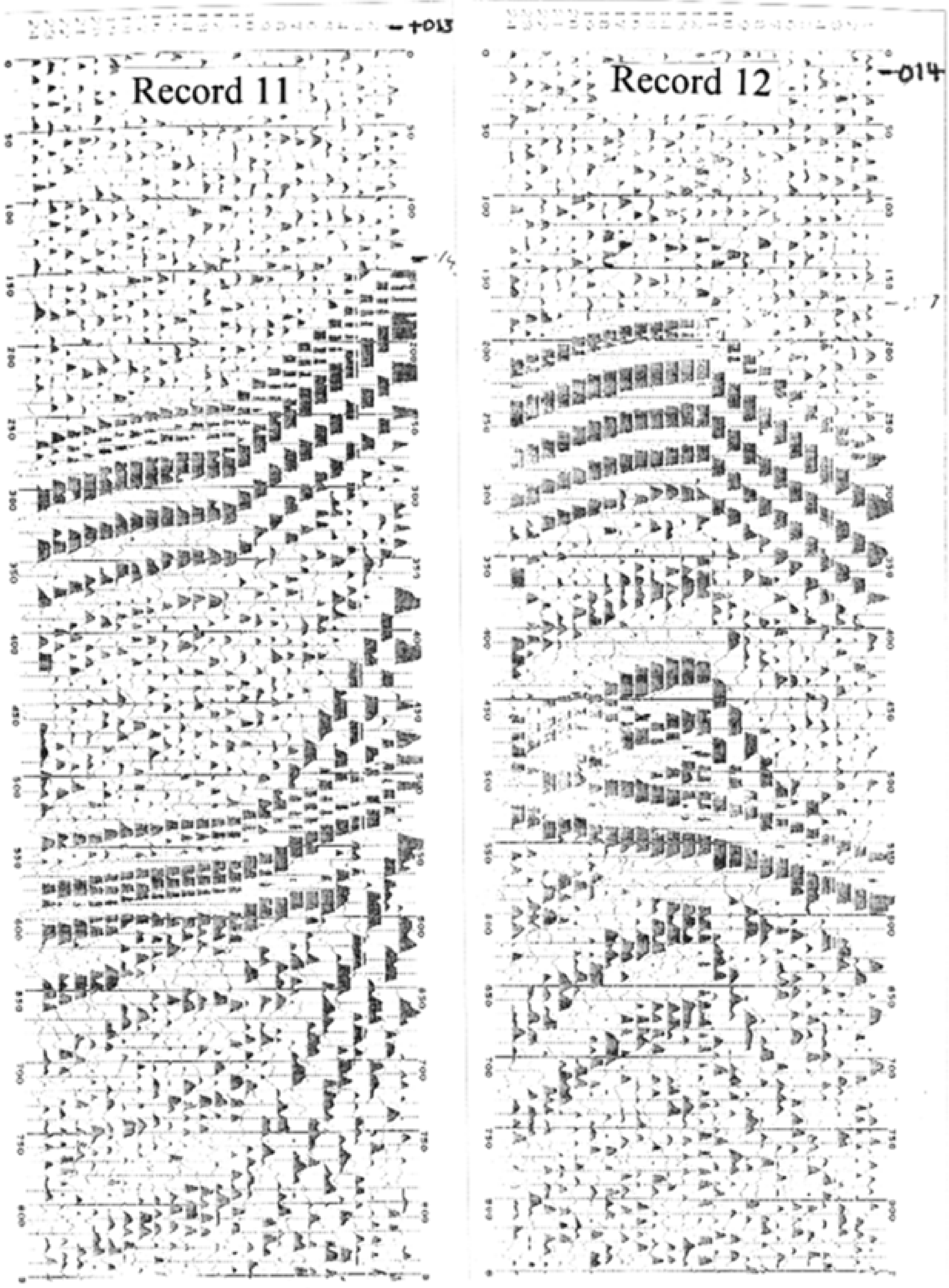
-042


-273
Record 8


-(-047)
Record 10


Record 11
Record 12
+013
-014

APPENDIX B
GRAVITY DATA

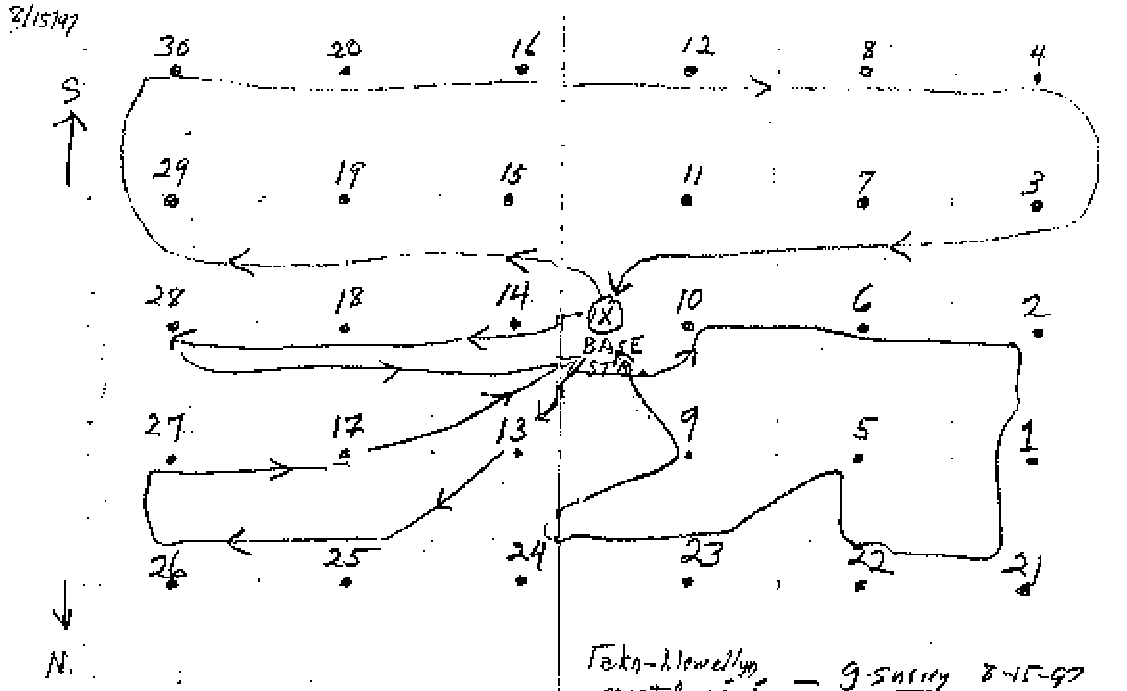
The following pages contain the data used to make the gravity interpretation contained in this report. The tabulation below shows the GPS survey data for the grid. The following page is a copy of the field notes.

The columns on the survey data show the stake ID number, the easting in meters, the northing in meters, the elevation in meters, the time, and the date. The stake numbers are also referenced in the field notes.

Divide Grid (Matthes/Llewellyn Glacier) Epoch 0

GRID 01	490493.921	6527357.998	1885.721	04.08.97	15:21
GRID 02	490359.933	6527089.935	1886.268	04.08.97	15:28
GRID 03	490227.049	6526821.963	1885.304	04.08.97	15:32
GRID 04	490091.980	6526552.018	1882.054	04.08.97	15:38
GRID 05	490762.197	6527223.032	1882.224	04.08.97	15:14
GRID 06	490629.094	6526955.470	1881.407	04.08.97	15:09
GRID 07	490495.007	6526687.307	1879.205	04.08.97	14:49
GRID 08	490360.468	6526418.406	1875.834	04.08.97	14:57
GRID 09	491031.565	6527088.902	1878.494	04.08.97	16:16
GRID 10	490898.193	6526821.510	1877.264	04.08.97	16:07
GRID 11	490763.203	6526553.263	1875.009	04.08.97	16:00
GRID 12	490628.068	6526284.358	1872.339	04.08.97	15:51
GRID 13	491299.551	6526956.015	1875.265	04.08.97	16:22
GRID 14	491164.879	6526686.845	1874.654	05.08.97	14:35
GRID 15	491031.057	6526418.465	1873.248	05.08.97	14:27
GRID 16	490897.134	6526149.497	1871.176	05.08.97	14:13
GRID 17	491567.976	6526821.939	1872.488	04.08.97	17:59
GRID 18	491434.248	6526552.486	1872.985	04.08.97	17:52
GRID 19	491299.039	6526285.199	1872.963	04.08.97	17:45
GRID 20	491164.886	6526015.697	1872.109	04.08.97	17:35
GRID 21	490629.119	6527625.650	1882.827	08.08.97	13:20
GRID 22	490896.417	6527492.440	1880.973	08.08.97	13:31
GRID 23	491165.013	6527358.088	1878.197	08.08.97	13:37
GRID 24	491432.939	6527223.977	1874.852	08.08.97	13:44
GRID 25	491702.288	6527089.990	1871.617	08.08.97	13:52
GRID 26	491970.566	6526956.073	1867.975	08.08.97	13:59
GRID 27	491836.738	6526687.888	1869.759	08.08.97	14:05
GRID 28	491702.112	6526417.988	1871.305	08.08.97	14:11
GRID 29	491567.379	6526149.934	1872.897	08.08.97	14:16
GRID 30	491433.609	6525883.058	1873.198	08.08.97	15:22

8/15/97



Fatn-Llewellyn crustal mine — G-survey 8-15-97
by H. Spinks
M. Miller
F. Macdonald

⟷ loop back routes

STAKE	Mgal	TIME	STAKE	Mgal	TIME
Base Sta	53.00	1235	#15	53.29	1612
#14	52.25	1253	19	53.66	1620
#18	53.35	13.02	29	55.25	1627
28	55.36	13.08	30	55.35	1633
Base	52.10	13.25	20	54.22	1642
10	51.95	13.30	16	54.32	1650
6	51.91	13.38	12*	55.06	1658
2	52.11	13.45	~~Base~~ 12	34.80 (31.84)	±1730
1	51.20	14.02	11	33.09	1747
21	52.48	14.13	7	33.39	1803
22	51.37	14.20	3	33.47	1811
5	51.03	14.27	4	36.36	1816
23	50.86	14.35	8	35.80	1825
24	51.48	14.46	12 again	34.78 (similar to Base)	1840
9	51.22	14.53			
Base	52.09	15.02			
13	51.76	15.11			
25	53.02	15.20			
26	53.35	15.30			
27	53.42	15.38			
17	53.14	15.47			
BASE	52.05	16.00			

* Student dame caused reset !! after this reading