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Gravimetric Ice Thickness Determination, South Cascade Glacier, Washington

It is often important to know the thickness of a glacier in order to relate theory and observations of glacier behavior. The vertical dimension of a glacier is the most difficult to measure directly, requiring a large number of expensive bore holes. Of the indirect methods, gravimetric seems most practical because of the large density contrast between ice and rock, known upper surface, and simple field procedure. Of course, the interpretation of gravity data gives non-unique results. Nevertheless, if combined with other bits of information, limits can be applied so that the final results of the analysis should be fairly dependable. Gravimetric studies on other glaciers have shown that good results can be obtained (*e.g.,* Corbato, 1965).

A gravimetric analysis was carried out on the South Cascade Glacier. This is a small valley glacier (approximately 1 km wide and 3 km long) in the North Cascades of Washington, on which the Water Resources Division of the U.S.G.S. has been carrying out many aspects of glacier study for over 10 years. Earlier estimations of bedrock topography had been made by considering surface velocities, crevasse patterns, and surface topography (Meier, oral communication). The thickness had been determined by a hot point bore at two points (Tangborn, oral communication) and cross-sectional areas had been calculated from surface velocities and ice discharge (Meier and Tangborn, 1965).

Data Collection and Reduction

Field work was completed in two weeks of moderate weather in early July of 1968. Twenty-two transverse profiles were spaced approximately 150 m apart. A station spacing of approximately 100 m along each profile resulted in the establishment of about 200 stations. Stations were lined up by eye and marked with a survey flag. Each station was surveyed from two triangulation points with a Wild T2 theodolite. The triangulation network had been previously established. Station elevations were calculated by triangulation from the two points, and in most cases the elevations agreed to within 20 cm. The positions were plotted on a 1:6000 map. In all cases the gravity reading at a station was taken within 24 hours of the position survey to minimize errors due to the vertical and horizontal surface movements.

A Worden model #358 gravimeter was used. A bedrock base station was established, and all readings were tied to it in loops not exceeding three hours. Instrument drift was corrected by using this base as a standard and assuming a linear time relationship.

The standard Bouguer, free air, and latitude corrections were added to the station gravity readings. Eleven rock samples from localities around the glacier were collected for density determination. Since densities ranged from 2.58-2.74 g/cm^3 without indicating any systematical density variation due to rock type, rock density was considered to be a constant 2.67 g/cm^3.

The most difficult correction to make in a rugged mountain region is the terrain correction. The terrain was divided into vertical prisms (Danes, 1960) of horizontal cross-section varying from 100 x 100 m over the glacier and its immediate vicinity, to 500 x 500 m to a distance of 5 km from the glacier, and 1000 x 1000 m beyond that distance. Terrain corrections were terminated at a distance where their effects produced a variation of 0.1 mgal or less over the entire glacier. The computation was programmed and performed on a Quiktran computer terminal. The terrain correction introduces a small error since it does not differentiate between the density of ice and rock. Since most of the terrain correction comes from the surrounding peaks and valleys, this error is tolerable.

The terrain-reduced Bouguer values (Fig. 1) were then corrected for a regional trend. Positive anomalies on the most northern profile indicated that this was necessary. Data from an earlier survey in the area were used (Danes, oral communication). The southern two-thirds of the glacier required no regional correction. Toward the northern end a progressive correction, grading to –3 mgal at the northernmost profile was necessary.

Interpretation

After all the corrections have been applied, gravity values would have been the same had the density of all the material been the same. The anomalies that are observed are due to the difference in density between rock and ice, which was taken to be 1.77 g/cm^3. A first estimation of ice thickness can be made using an approximation considering the ice to be a uniform sheet of infinite extent. If this were the case, a one mgal anomaly would indicate 13.5 m of ice. An infinite sheet is a poor model of a valley glacier because this approximation tends to exaggerate ice thickness toward the edges and to lessen the apparent thickness in the center.

Since the length of the glacier is considerably greater than the width, a more accurate model is the assumption of infinite length for any given transverse section. The gravity at points on the surface of a section (that results from an estimated bottom topography) can be determined by the numerical integration of imagined infinite rods of ice perpendicular to the cross-section by means of a dot chart.

The estimation of the first profile was made much more accurate by using data from a bore hole near the center of the glacier (Fig. 1). The bore reached the bottom at 207 m (Tangborn, oral communication). The location of the bore hole coincided with the greatest gravity anomaly, and therefore this was assumed to be the thickest point on the profile. Bottom topography was successively reestimated considering comparison of the graphically calculated and observed gravity values of the previous estimation. The reestimation was considered satisfactory when the calculated gravity at all points differed from observed gravity by 0.2 mgal or less. Modifications of the first profile completed (A-A′) were used to help estimate adjacent sections. This process was continued until a close agreement of observed and calculated anomalies was obtained for every profile. This technique is tedious, and based largely on trial and error. Surface topography and adjacent terrain are helpful in the first estimations.

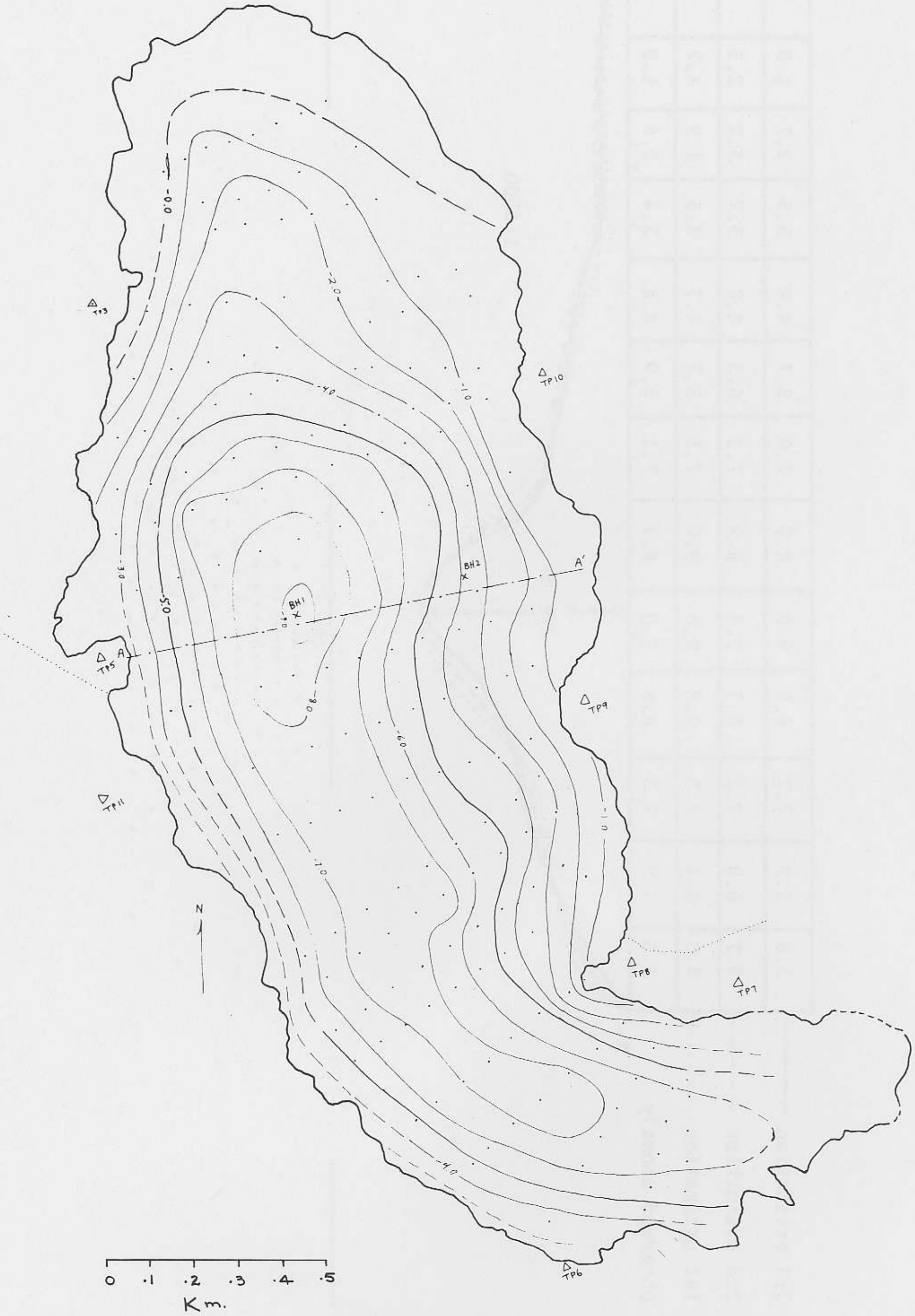
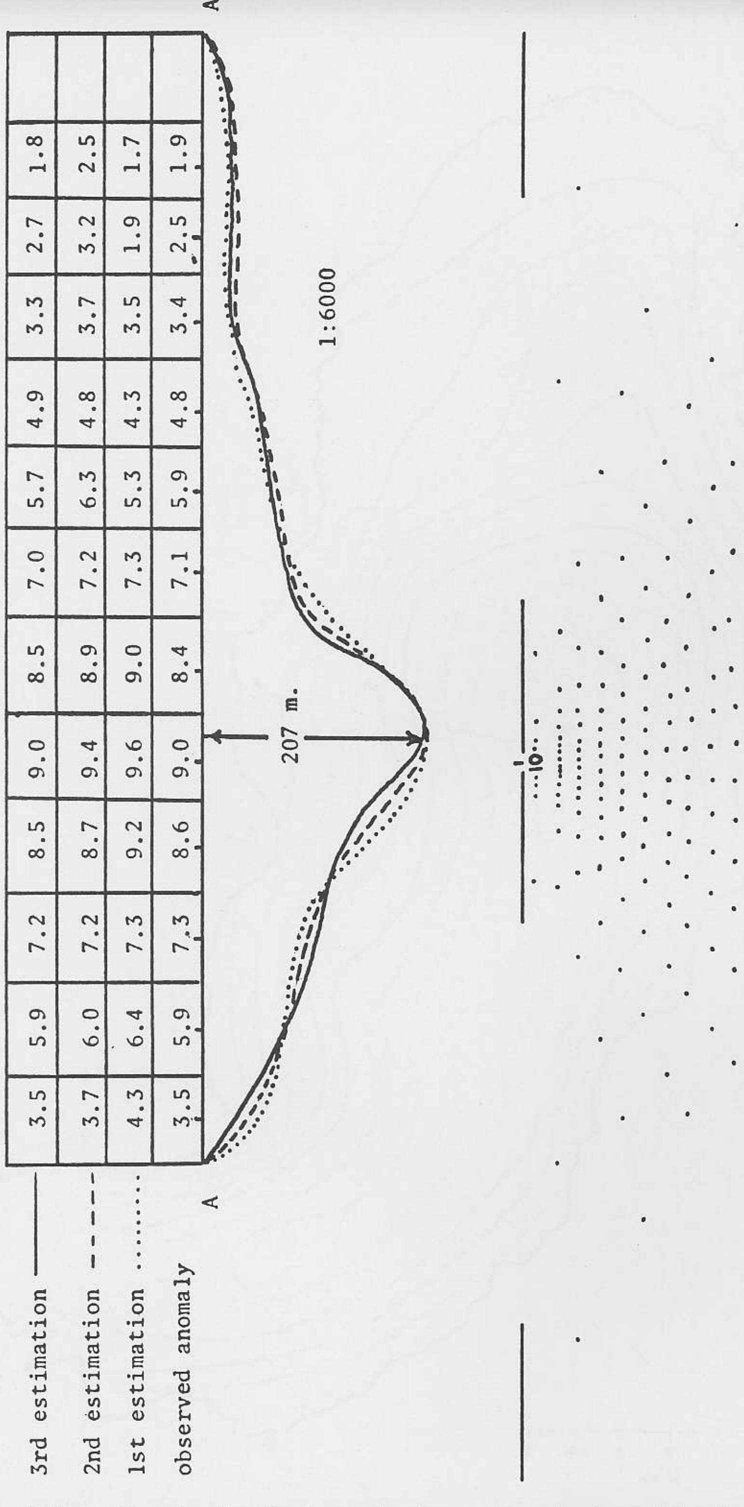


Figure 1. South Cascade glacier, Washington. Gravity anomaly map, Robert M. Krimmel, July, 1968. Dotted line—contact; x bore hole; · gravity station; △ triangulation point; C.I. = 1.0 milligal.



3rd estimation ———	3.5	5.9	7.2	8.5	9.0	8.5	7.0	5.7	4.9	3.3	2.7	1.8	
2nd estimation - - - -	3.7	6.0	7.2	8.7	9.4	8.9	7.2	6.3	4.8	3.7	3.2	2.5	
1st estimation	4.3	6.4	7.3	9.2	9.6	9.0	7.3	5.3	4.3	3.5	1.9	1.7	
observed anomaly	3.5	5.9	7.3	8.6	9.0	8.4	7.1	5.9	4.8	3.4	2.5	1.9	

Figure 2. Upper. Example of estimation and subsequent reestimations of basal configuration of profile A-A′. 207 m depth is from bore hole data. Lower. Dot chart used in the calculation of graphically determined gravity. Each dot represents a .086 mgal anomaly.

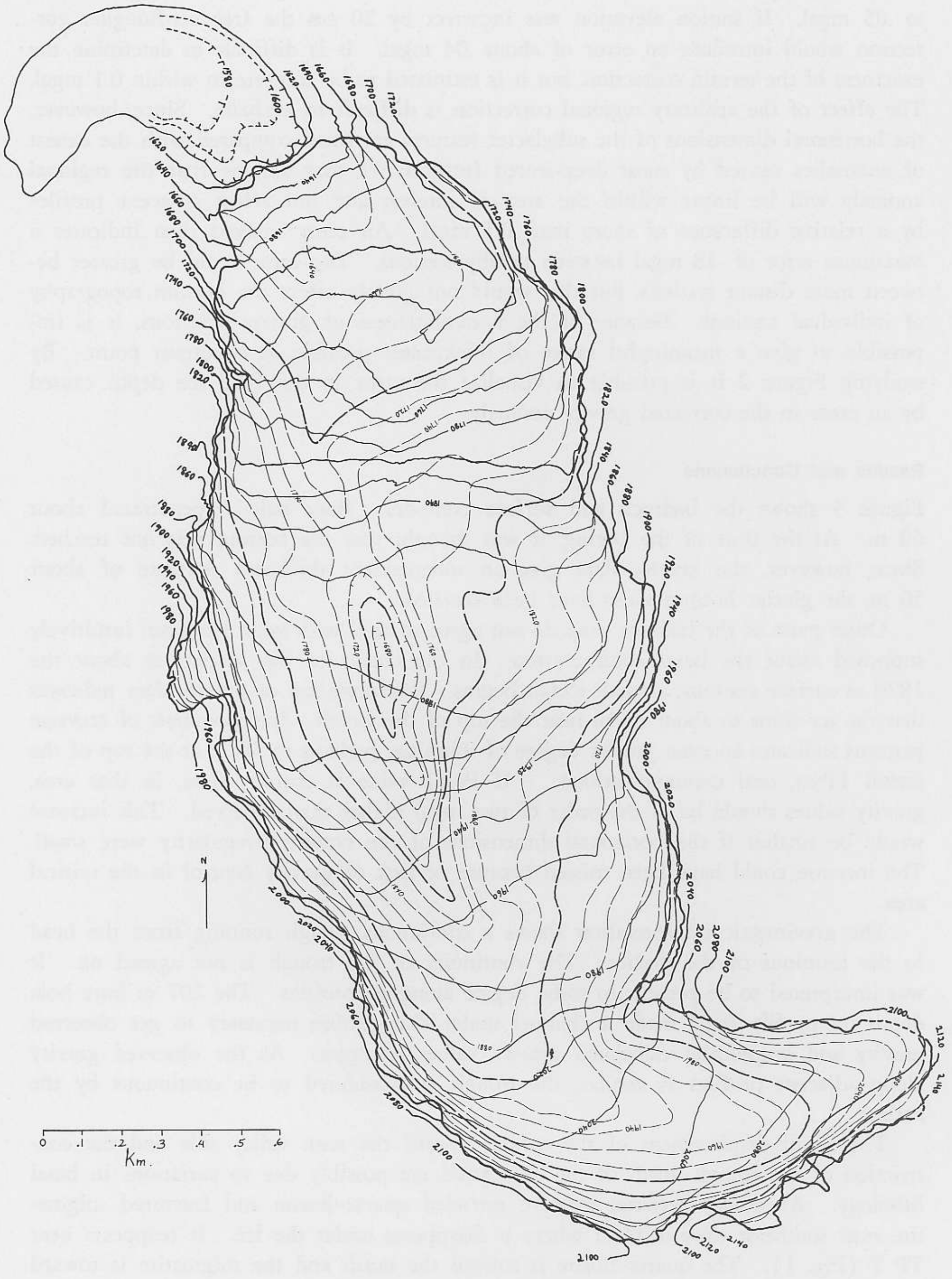


Figure 3. South Cascade glacier, Washington. Bedrock topography map (as interpreted from gravity survey), Robert M. Krimmel, July, 1968. Solid lines—surface contours; dashed lines—ice-buried bedrock contours. C.I. = 20 meters.

With the gravimeter used it is possible to make relative gravity readings accurate to .05 mgal. If station elevation was incorrect by 20 cm the free air-Bouguer correction would introduce an error of about .04 mgal. It is difficult to determine the exactness of the terrain correction, but it is estimated to be accurate to within 0.1 mgal. The effect of the arbitrary regional correction is difficult to evaluate. Since, however, the horizontal dimensions of the subglacier features are small compared with the extent of anomalies caused by most deep-seated features, we may assume that the regional anomaly will be linear within the area of interest and not affect adjacent profiles by a relative difference of more than 0.1 mgal. An error analysis then indicates a maximum error of .18 mgal between nearby stations. The error could be greater between more distant stations, but this would not greatly affect the bottom topography of individual sections. Because of the nonuniqueness of gravity solutions, it is impossible to give a meaningful range of thicknesses possible at a certain point. By studying Figure 2 it is possible to visualize the error in the final ice depth caused by an error in the corrected gravity anomaly.

Results and Conclusions

Figure 3 shows the bedrock and surface contours. Bore hole 2 penetrated about 60 m. At the time of the boring, it was thought that the bottom was not reached. Since, however, the gravity data give an independent thickness estimate of about 50 m, the glacier bottom must have been reached.

Other parts of the bedrock map do not agree so well with what has been intuitively supposed about the basal configuration. In the center of the glacier, at about the 1820 m surface contour, a small icefall begins. Interpretation of gravity data indicates that the ice thins to about 60 m near the top of the icefall. Interpretation of crevasse patterns indicates an even greater degree of thinning, perhaps to 30 m at the top of the icefall (Post, oral communication). If Post's value is correct, then, in that area, gravity values should be of the order of two mgal higher than observed. This increase would be smaller if the horizontal dimensions of the bottom irregularity were small. The increase could have been missed because of lack of gravity control in the critical area.

The gravimetric interpretation shows a continuous trough running from the head to the terminus of the glacier. The continuity of the trough is not agreed on. It was interpreted to be present to some degree along all profiles. The 207 m bore hole depth on profile A-A′ made a channel under that profile necessary to get observed gravity and graphically calculated gravity values to agree. As the observed gravity along adjacent profiles is similar, the trough is considered to be continuous by the author.

The slight displacement of the trough toward the west valley side and the constriction of the trough north of the depression are possibly due to variations in basal lithology. A contact between massive intruded quartz-diorite and fractured migmatite runs southeast toward TP 5 where it disappears under the ice. It reappears near TP 7 (Fig. 1). The quartz-diorite is toward the north and the migmatite is toward the south. Comparing surface erosion of the different rocks, it would seem that the migmatite would be eroded much more easily by the glacier. Perhaps, under the ice, the migmatite extends toward the north just to the trough constriction, and is included where the trough is most pronounced.

North of the constriction the trough continues on the west side. Although it did not show in the gravity data, the trough must shift toward the east side because approximately ¾ of the subglacier drainage exits from the northeast side of the terminus (Tangborn, oral communication). Soundings in the southern end of the lake indicate a ridge exists. This ridge may be an extension of the bedrock ridge that begins to appear near the terminus.

A gravity survey can give a reasonable approximation of bedrock configuration of a glacier. Insufficient knowledge of regional anomalies can cause substantial error in calculated ice thickness. In this study, bedrock stations were sparse, and only very general regional corrections could be applied. A larger number of bedrock readings in the vicinity of the glacier would have been useful. Also, bore holes are helpful in calibration, assist in making first estimations, and increase the accuracy greatly. In this paper an attempt was made to consider only gravity data (with the exception of one bore hole) and to ignore what is intuitively imagined by looking at crevasse patterns. A bedrock map (Meier, unpublished) based on crevasse patterns and surface velocities agrees fairly well with the gravimetric determination. Combined with other estimations, gravity data can be very useful for determining the bedrock topography.

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