THE BOTTOM TOPOGRAPHY OF GULKANA GLACIER, ALASKA RANGE, ALASKA*

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Abstract. As an extension of an intensive study of Gulkana Glacier a 42 station gravimeter survey was made to gain some insight into its third dimension. This survey showed that the glacier's main tongue occupies a complex valley composed essentially of two parallel channels separated by a medial ridge which extends southward from rock bastions in the accumulation zone. At mid-glacier the ice thickness in the larger eastern channel is 225 m., in contrast to 130 m. in the western channel. The medial ridge degenerates down-glacier probably disappearing within 2 km. of the glacier terminus. The basic surface flow pattern of the glacier described by Moores can be adequately explained by this basal topography. Seasonal velocity variations are possibly caused by melt-water basal lubrication with one channel being favored over the other at different times of the year, in agreement with observations by Elliston on the Gorner-Gletscher, Switzerland, and with the glacier sliding theory of Weertman.

Résumé. *Topographie sous-glaciaire du Gulkana Glacier, Alaska Range, Alaska.* L'étude intensive du Gulkana Glacier a été étendue par la mesure de la gravité en 42 stations pour obtenir une idée de sa troisième dimension. Ce levé a montré que la langue principale du glacier occupait une vallée complexe composée essentiellement de deux chenaux parallèles séparés par une arête médiane qui s'entend vers le sud à partir de bastions rocheux de la zone d'accumulation. Vers le milieu du glacier, l'épaisseur de glace est de 225 m dans le chenal est le plus large comparativement aux 130 m du chenal ouest. L'arête médiane diminue vers le bas pour disparaître dans les deux derniers km du front. Les traces superficielles de l'écoulement du glacier décrites par Moores peuvent être bien expliquées par cette topographie sous-glaciaire. Des variations saisonnières de la vitesse sont probablement causées par lubrifaction basale de l'eau de fonte qui favorise l'un des chenaux au détriment de l'autre à différents moments de l'année, en accord avec les observations d'Elliston sur le Gorner-Gletscher, Suisse, et avec la théorie du glissement des glaciers de Weertman.

Zusammenfassung. *Die Gestalt des Untergrundes am Gulkana Glacier, Alaska Range, Alaska.* In Erweiterung einer ausführlichen Untersuchung des Gulkana Glacier wurden auf 42 Stationen Schweremessungen vorgenommen, um einige Daten über den Untergrund des Gletschers zu gewinnen. Die Messungen ergaben, dass der Hauptarm des Gletschers ein kompliziertes Tal einnimmt, das im wesentlichen aus 2 parallelen Rinnen — getrennt durch einen Mittelrücken, der sich südwärts von Felsbastionen in der Akkumulationszone erstreckt — besteht. In Gletschermitte beträgt die Eisdicke in der grösseren östlichen Rinne 225 m, im Gegensatz zu 130 m in der westlichen Rinne. Der Mittelrücken nimmt gletscherabwärts an Höhe ab und verschwindet 2 km vor der Gletscherzunge. Die Fliessbewegung auf der Oberfläche des Gletschers, wie sie von Moores dargestellt wird, kann im wesentlichen aus dieser Untergrundsgestalt erklärt werden. Jahreszeitliche Geschwindigkeitsschwankungen sind möglicherweise durch die Schmierwirkung von Schmelzwasser am Untergrund verursacht, wobei eine Rinne gegenüber der anderen zu verschiedenen Zeiten des Jahres bevorzugt wird. Dies steht in Übereinstimmung mit Beobachtungen von Elliston am Gorner-Gletscher, Schweiz, und mit der Gleittheorie von Weertman.

Gulkana Glacier has undergone intensive study since 1960 under a program of integrated investigation conducted by the Department of Geology, University of Alaska. From this effort four extensive papers have been written on the budget, foliation and flow of the glacier (Rutter, unpublished; Sellmann, unpublished; Mayo and Péwé, 1963; Moores, unpublished). As an extension to this program a gravity survey was made over a large part of the glacier during September 1961 in the hope that some insight might be gained into its third dimension.

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Physical Setting and Flow Structure

Gulkana Glacier is situated on the south flank of the Alaska Range (lat. 63° 17′ N., long. 145° 25′ W.) bordering the Denali fault, which is a major tectonic element running the full length of the mountain system. It is one of the most accessible of the many valley glaciers in the rugged central Alaska Range, being only 2 km. off a short access road leading from the Richardson Highway. The structure of the glacier is complex as it originates from what appears to be three or four separate accumulation basins whose combined area is 12 km.^{2} (Fig. 1). The maximum elevation of the firn zone extends to about 2,000 m. From the

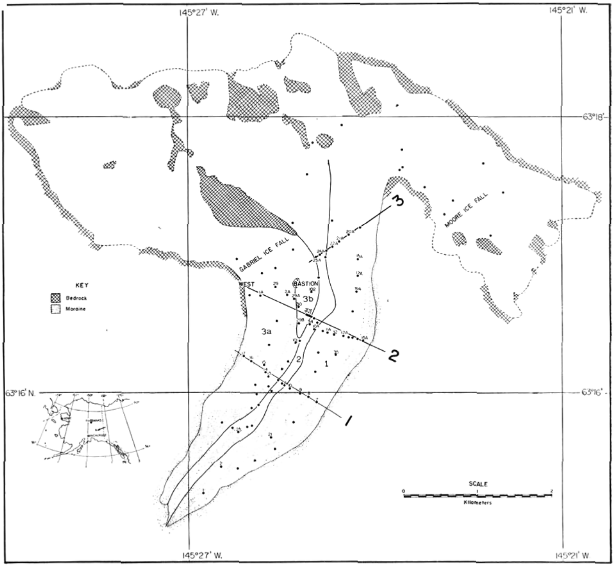

Fig. 1. Gulkana Glacier and accumulation basins. The glacier is laterally divided into four physical ice streams: 1, 2, 3a and 3b. Physical ice streams 1, 2 and 3b flow as a unit forming the eastern velocity ice stream. Physical ice stream 3a flows at a different rate as the western velocity ice stream (after Moores, unpublished). Black dots indicate ice movement survey markers. The numbered dots are also gravity stations. Transverse profiles 1, 2 and 3 refer to Figure 2

accumulation basins the ice coalesces to form a glacial tongue 7·2 km.^{2} in area, being approximately 4·5 km. long, 1·75 km. wide and terminating at an elevation of 1,130 m. The glacial tongue is divided laterally into four ice streams which Moores (unpublished) has numbered 1, 2, 3a and 3b (Fig. 1). The ice streams originate from separate accumulation areas and are delineated by medial moraines and longitudinal bands of rock debris. Ice stream 3 originates at the Gabriel Ice Fall. A second ice fall, the Moore Ice Fall, is located towards the head of the easternmost accumulation basin.

Moores (unpublished) described the unique surface velocity structure of Gulkana Glacier in considerable detail and has shown that the glacier flows faster in summer than in winter and that the relative motion between the ice streams changes with the seasons (Fig. 2). The mean yearly velocity distribution shows two parallel ice streams flowing at different velocities in the central part of the glacier and as a single unit farther down-glacier (Fig. 3). The eastern velocity stream is composed of physical ice streams 1, 2 and 3b, whereas the western velocity stream consists of physical ice stream 3a. An area of relatively low velocity which separates the two ice streams is coincident with a surface topographic low, despite a uniform rate of ablation across the glacier. Longitudinal velocity profiles drawn along the center lines of the ice streams show an irregular decrease in velocity towards the glacier terminus. Moores interpreted this irregular movement as being due to probable changes in bedrock slope.

The surface velocity structure of Gulkana Glacier during the winter differs little from the annual mean except that both velocity streams move only about 94 per cent of their yearly average. Although the summer velocity pattern also preserves the same general configuration of the yearly mean, the deviations are considerably more complex than those noted during the winter months. The most striking change in the summer flow structure is the marked increase in down-glacier velocity. However, unlike the winter uniform decrease in flow rate, the relative increase in velocity is greater in the eastern ice stream than that in the western stream. The former increases by about 170 per cent over the annual mean, whereas the latter increases by only 140 per cent. Furthermore, the increase in velocity is greater at transverse profile 2 than it is farther down-glacier at profile 1 (Fig. 2). At transverse profile 1 the east and west velocity ice streams flow at different relative velocities during the summer, whereas in winter they flow essentially as a single unit. During July the east velocity ice stream flowed appreciably faster than it did in August. In contrast, the west velocity ice stream flowed slower in July than in August.

The motion in the terminal part of the glacier is complicated by thrusting, collapse (Rutter, unpublished) and relatively large surveying errors (Moores, unpublished), and will not be considered in this discussion.

GRAVIMETER SURVEY

The gravity survey consisted of 42 stations on the glacier or just off its margin (Fig. 1; Table I). These stations were located at movement survey stakes and were identified according to the University of Alaska numbering system. The movement study network has been very carefully surveyed and is reported as being accurate to an estimated ±0·4 ft. (12 cm.) vertically and ±0·2 ft. (6 cm.) horizontally at mid-glacier (Moores, unpublished). The gravity survey was conducted with a thermostated LaCoste and Romberg geodetic gravimeter (No. G-26) and observations are believed to be accurate to ±0·2 mgal. Because Gulkana Glacier is situated in a deep mountain valley, the terrain effect is significant and corrections had to be applied to all the observations. These corrections were determined by the zone chart (out to a radius of 15 km. around a station) and tables computed by Hammer (1939). The magnitude of the corrections varied from 3 mgal. for a central station to 8 mgal. for a station at the margin of the glacier.

In 1955 a similar gravity survey was made of the less complex Jarvis Glacier (Ostenso and

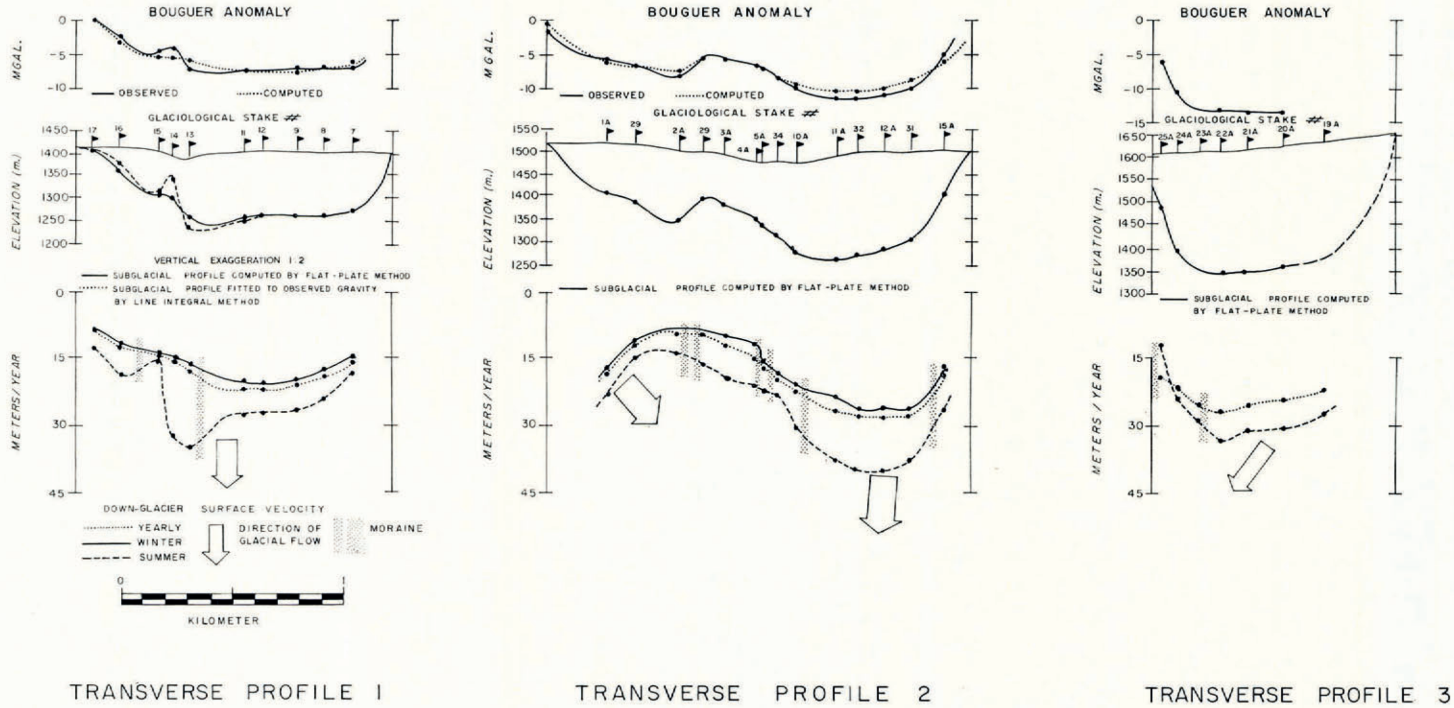

Fig. 2. Top row of curves shows the observed Bouguer gravity anomalies (solid lines) and Bouguer gravity computed from simple flat-plate theory (dotted line) at transverse profiles 1, 2 and 3. The middle row of curves shows gravity stations, surface elevation, bottom topography computed from flat-plate calculations (solid line) and bottom topography computed by Hubbert's line-integral method (dashed line). Lower row of curves show the winter, summer and yearly average down-glacier surface velocity (after Moores, unpublished)

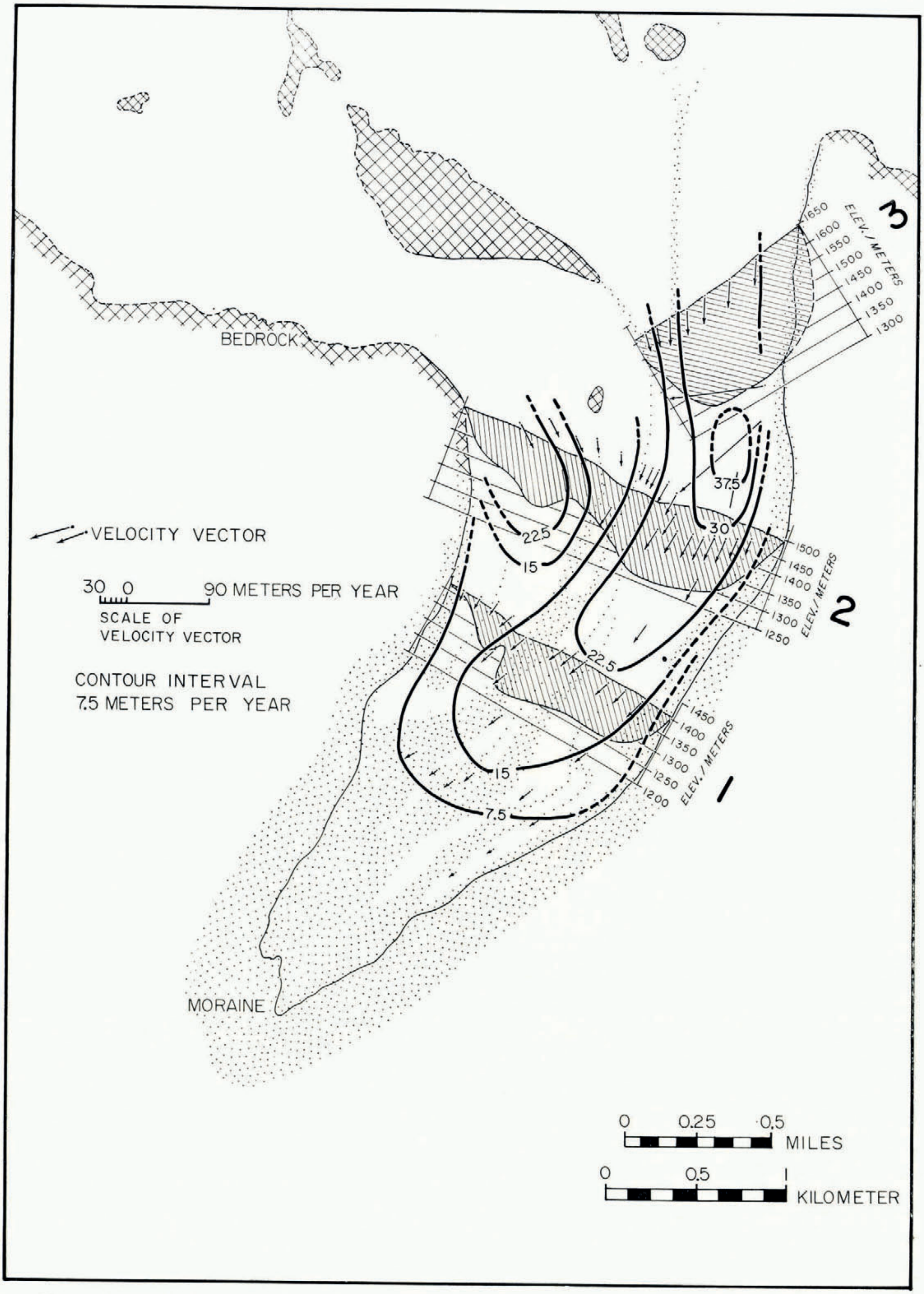

Fig. 3. Gulkana Glacier yearly average surface velocity and cross-sectional profiles calculated from gravity observations

TABLE I. GRAVITY STATIONS ON GULKANA GLACIER, ALASKA

Station[1]	*Latitude* N.	*Longitude* W.	*Elevation* m.	*Observed gravity*[2] gal. (±0·5 mgal.)	*Terrain correction*[3] mgal. (±0·5 mgal.)	*Bouguer anomaly relative to Bastion* mgal. (±0·5 mgal.)	*Equivalent ice thickness* m. (±20 m.)
Bastion[4]	63° 16·8′	145° 25·2′	1,539	981·7866	3·4	0·0	0
0[4]	17·2′	25·3′	1,664	7620	4·8	+0·9	18
West[4]	16·8′	26·1′	1,494	7910	8·0	−1·5	30
6	15·8′	25·3′	1,362	8148	3·8	−5·1	102
7	15·9′	24·9′	1,403	8059	3·2	−6·6	132
8	63° 16·0′	145° 25·1′	1,404	981·8049	3·6	−7·0	140
9	16·0′	25·2′	1,403	8051	3·7	−7·1	142
10	16·0′	25·4′	1,408	8038	3·9	−7·2	144
11	16·1′	25·4′	1,405	8038	4·4	−7·4	148
13	16·1′	25·7′	1,395	8667	4·2	−6·8	136
14	63° 16·2′	145° 25·8′	1,393	981·8077	5·9	−4·4	88
15	16·2′	25·8′	1,403	8069	4·4	−4·8	96
16	16·2′	26·0′	1,414	8063	5·1	−2·7	54
17	16·3′	26·1′	1,417	8069	6·2	−0·2	4
21	15·7′	26·1′	1,321	8092	4·8	−3·8	76
25	63° 15·7′	145° 26·2′	1,280	981·8324	4·7	−2·6	52
29	16·8′	25·6′	1,513	7866	4·8	−6·6	132
31	16·4′	24·4′	1,497	7834	4·4	−9·8	196
32	16·4′	24·7′	1,493	7837	3·6	−11·3	226
34	16·5′	25·1′	1,473	7914	3·2	−9·2	164
35	63° 16·3′	145° 24·6′	1,472	981·7887	3·8	−10·2	204
101	16·4′	25·3′	1,451	7951	3·7	−8·1	162
102	16·7′	25·0′	1,513	7876	3·6	−4·1	82
1A	16·7′	25·8′	1,523	7835	4·1	−5·6	112
2A	16·7′	25·4′	1,499	7866	3·2	−7·9	158
3A	63° 16·6′	145° 25·2′	1,486	981·7919	3·1	−5·6	112
4A	16·6′	25·1′	1,473	7934	3·1	−6·4	128
5A	16·6′	25·1′	1,471	7931	3·1	−7·0	140
10A	16·5′	25·0′	1,470	7900	3·5	−9·7	194
11A	16·4′	24·8′	1,486	7850	3·8	−11·2	224
12A	63° 16·4′	145° 24·5′	1,495	981·7829	4·5	−10·8	216
15A	16·4′	24·2′	1,496	7864	6·7	−5·0	100
16A	16·7′	24·3′	1,553	7739	4·8	−13·3	266
17A	16·9′	24·3′	1,572	7709	4·0	−12·8	256
18A	17·0′	24·3′	1,603	7657	4·0	−12·0	240
20A	63° 17·2′	145° 24·4′	1,624	981·7604	3·3	−13·4	268
21A	17·1′	24·6′	1,617	7616	3·0	−13·5	270
22A	17·1′	24·7′	1,611	7632	3·0	−13·1	262
24A	17·0′	24·9′	1,608	7661	3·3	−10·6	212
25A	17·0′	25·3′	1,607	7675	3·3	−6·0	120
29A	63° 16·7′	145° 25·3′	1,493	981·7907	3·2	−5·3	106
29B	16·5′	25·2′	1,469	7927	3·4	−7·3	146

[1] Station numbers correspond to University of Alaska glaciological stake numbering system.
[2] Based on station 340e (Thiel and others, 1959) value of 981·8800 gal.
[3] Computed by the Hammer (1939) method.
[4] Gravity stations located off the margin of the glacier.

Holmes, 1962) which lies just to the north of Gulkana Glacier on the other side of the mountain divide. The same method was used on both glaciers in calculating ice thickness from gravity observations, with the exception that the empirical relationship of 1 mgal. anomaly equals 20 m. change in ice thickness for regions of marked bottom relief (Bentley, 1964) was used rather than the relationship of 1 mgal. = 13·5 m. of ice as determined from simple flat-plate theory. Figure 2 graphically illustrates that Bentley's empirical relationship is sound. Here the points of calculated ice thickness are connected by smooth lines to form two transverse profiles of the glacier. The gravity effect of these cross-sections is then calculated using Hubbert's (1948) line-integral method assuming mean densities of 0·90 g./cm.^{3} for ice and 2·67 g./cm.^{3} for bedrock, which in this area consists of coarse-grained acidic igneous and complex metasedimentary rocks (Capps, 1940, p. 201; Moffit, 1954).

Discussion

In Figure 2 the computed gravity profiles are seen to be in excellent agreement with the observed Bouguer gravity profiles. Except for transverse profile 1, no attempt is made to obtain a better fit to the data, as the inherent lack of precision in this method of determining ice thickness would make such a refinement meaningless. In the case of profile 1, where the sharp subglacier ridge has a profound topographic effect on the gravity observations, an alternative bottom profile is given which represents a line-integral fit to the observed data. The down-glacier surface velocity profiles shown in this figure are modified after Moores (unpublished).

It is estimated that the accuracy of the glacier depth determinations is ±20 m. relative to each other, but the datum of the network may be in error by ±50 m. relative to sea-level. The computed ice thicknesses are plotted in Figure 4 using Rutter's (unpublished) foliation chart as a base map. In Figure 3 glacier thickness profiles are shown along transverse lines 1, 2 and 3 using Moores's (unpublished) yearly surface velocity chart as a base map.

Figures 2, 3 and 4 show a marked correlation between subglacial topography and ice surface motion. Essentially, Gulkana Glacier can be regarded as occupying a complex valley composed of two parallel channels separated by a medial ridge. The eastern channel is the larger and deeper of the two. The medial ridge crops out to the north forming a series of rock bastions. Down-glacier the ridge narrows and stands out in sharper relief. The surface yearly velocity vectors, and particularly the foliation pattern, correspond well with the subglacial topography. The median ridge appears to terminate not far below transverse profile 1 and beyond this point the valley probably has a simple U-shape. It is here that the east and west velocity streams join to flow as a single unit as would be expected. The velocity vectors over the western trough in transverse profile 2 show a tendency of the ice to override the medial ridge. This could be caused by the influence of the Gabriel Ice Fall immediately to the north and/or the bend in the glacier at this point. In profile 1 the ridge is offset slightly to the east relative to the summer velocity profile. This apparent displacement is probably due to wide spacing between gravity observations and the inherent lack of resolution in the gravity method of subglacial profiling in a region of marked basal relief. Profile 3, which presents a simple U-shaped cross-section, exhibits the conventional simple distribution of surface velocity with increasing speed toward the center of the valley. The location of medial moraines is apparently influenced mainly by the source of the physical ice streams and exposed rock bastions, with subglacial topography playing only a minor role in distorting some of the lineations.

That there should be such a marked correlation between a glacier's basal topography and surface motion is not surprising in the light of what is known from the recently developed theory of glacier flow (e.g. Nye, 1952, 1959; Glen, 1955; Weertman, 1957) and from limited observational evidence.

Moores (unpublished) noted that the region of relatively low velocity which separates the eastern and western velocity streams is coincident with a surface topographic low despite a uniform rate of ablation across the glacier. This trough is best developed directly behind the rock bastion and becomes progressively narrower down-glacier. Its cause is probably a "shadow" effect of the bastion.

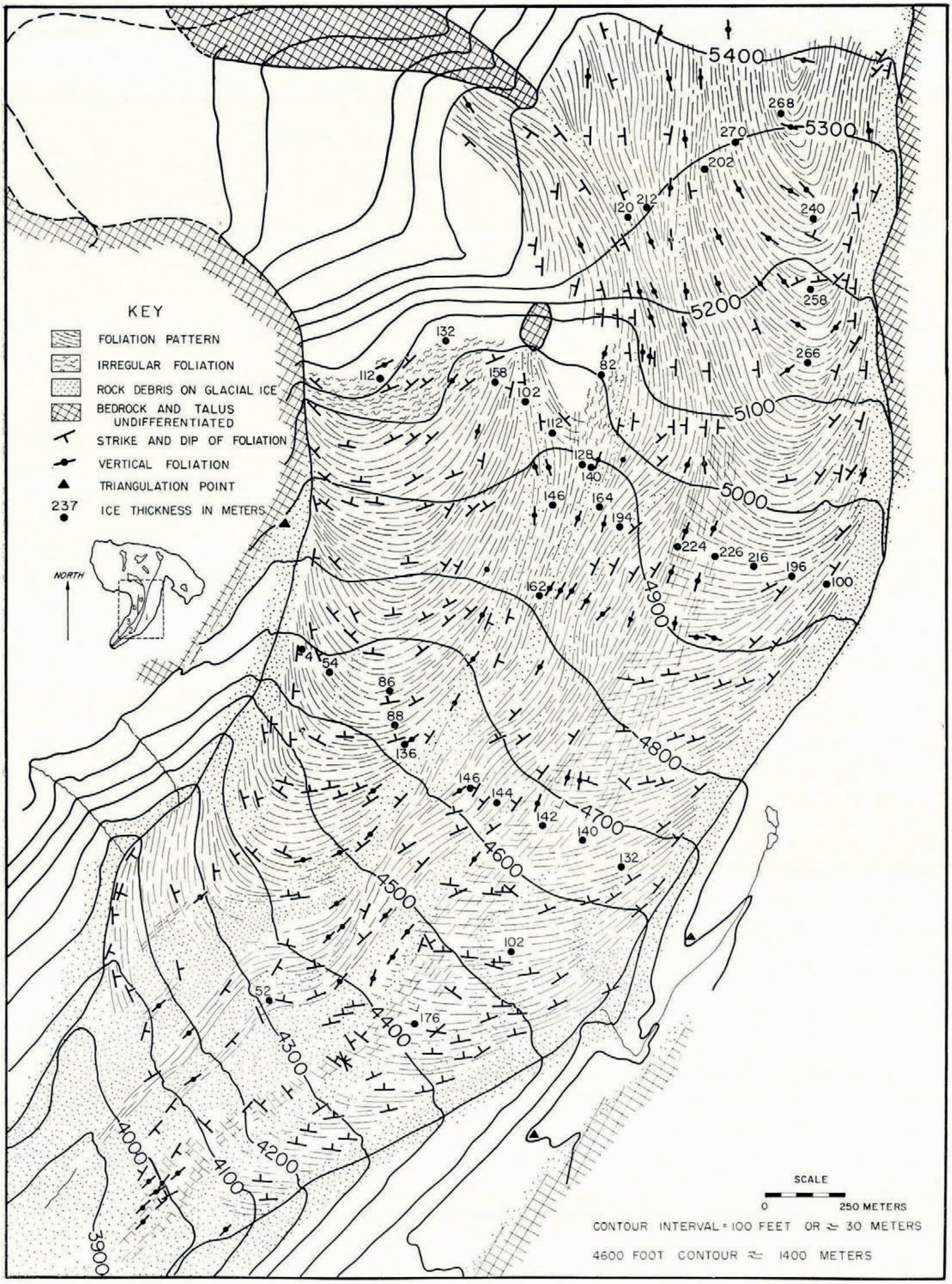

Fig. 4. Gulkana Glacier surface foliation pattern and topography (after Rutter, unpublished), and ice thickness values calculated from gravity observations

The reason that the eastern and western velocity streams reach their maximum velocities at different times (July and August, respectively) was explained by Moores (unpublished) as possibly being caused by one or a combination of the following factors: (1) The influence of the Gabriel Ice Fall, (2) the slope of the bedrock surface immediately above the ice falls, and (3) the eastward-flowing ice stream 3 applies a confining stress on the southward-flowing velocity streams 1 and 2. Elliston ([Union Géodésique et Géophysique Internationale], 1963, p. 65–66), in an attempt to explain similar seasonal velocity changes on the Gorner-Gletscher (a temperate valley glacier in southern Switzerland), measured the surface velocity of the glacier and discharge of the terminal melt-water stream. He found correlation between change in velocity and volume of stream discharge. It seemed that the availability of melt water at the ice–rock interface influenced the rate of glacier flow. Elliston's work, coupled with Weertman's (1962, 1964) water layer hypothesis, may explain why the east and west velocity streams' flow rates are accelerated during July and August. The east and west channels of the glacier valley could receive varying amounts of melt water throughout the summer months with consequent variability in basal lubrication. Subglacier lubrication variations could also explain the short-interval "jerky" movement observed during the summer. This mechanism is substantiated by the great volume of melt water that can be seen discharging into the glacier throughout the ablation season. In his most recent treatment of the problem of glacier sliding, Weertman (1964) shows that a water layer an order of magnitude thinner than the size of controlling obstacles (roughness) on the glacier bed can appreciably increase the sliding velocity.

CONCLUSION

The gravimeter survey of Gulkana Glacier shows that it occupies a complex valley composed essentially of two parallel channels separated by a medial ridge which extends southward from a rock bastion. The ridge degenerates southward, probably terminating just below transverse line 1 at which point the valley has a simple profile and the two velocity ice streams flow as a unit. The basic surface flow pattern of the glacier can be adequately explained by this basal topography. Seasonal velocity variations are believed to be caused by melt-water basal lubrication with one channel being favored over the other at different times of the year.

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