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# EFFECTS OF A DEBRIS SLIDE ON "SIOUX GLACIER", SOUTH-CENTRAL ALASKA

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ABSTRACT. The lower one-third of "Sioux Glacier" in south-central Alaska was buried beneath a debris slide during the 27 March 1964 earthquake. Investigations to determine the effect of this cover on the regimen of the glacier revealed that it has increased in thickness by as much as 28 m, primarily as a result of the insulating effect of this debris cover. In areas where debris has continuously veneered the surface, at least since 1938, the ice is also thicker. A longitudinal profile reveals that the area near the upper extent of the slide debris has become intensely crevassed and has been lowered as much as 8 m between 1965 and 1966, while the terminal area is up to 5 m higher and is characterized by thrusting. It is concluded that a kinematic wave passed through this glacier sometime between 1965 and 1966.

The upper zone of debris-veneered ice is moving at 175 m/year while the terminal area is flowing at only 21 m/year. The rate of down-glacier decrease in velocity is about 0.06 m/year per meter of horizontal distance except for an area approximately 1 km from the terminus. Here, the rate of decrease in velocity is 0.1 m/year per meter. The change in rate is presumed to be related to topographic control caused by the recent thinning of the ice here.

RÉSUMÉ. *Effets d'un glissement de débris morainique sur le "Sioux Glacier", centre sud de l'Alaska.* Le tiers inférieur du "Sioux Glacier" dans la partie centrale sud de l'Alaska fut enseveli sous un glissement de débris morainique au cours du tremblement de terre du 27 mars 1964. Des études visant à déterminer l'effect de cette couche sur l'évolution du glacier révélèrent que l'épaisseur du glacier avait augmenté de 28 m, résultat du pouvoir isolant de cette couche de débris. Là où les débris ont couvert la surface de manière continue depuis au moins 1938, il faut noter cependant que la glace est également plus épaisse. Une coupe longitudinale révèle que la surface qui se trouve aux alentours de la partie supérieure des débris de glissement, est devenue crevassée de manière intense et s'est abaissée de huit mètres entre 1965 et 1966, cependant que la partie extrême s'est élevée de plus de 5 m caractérisée par un soulèvement. On en conclut qu'une onde kinématique a traversé ce glacier à un certain moment entre 1965 et 1966.

La partie supérieure de la glace recouverte par le glissement se déplace à raison de 175 m par an, tandis que la partie extrême glisse à raison de 21 m par an seulement. La vitesse de descente diminue d'environ 0,06 m par an par mètre de distance horizontale, sauf pour une étendue qui se trouve à environ 1 km de l'extrémité. A ce point, la diminution de la vitesse est seulement de 0,1 m par an par mètre. On suppose que le changement de vitesse est du au contrôle topographique causé par un récent amenuisement de la glace en ce point.

ZUSAMMENFASSUNG. *Die Auswirkungen eines Erdrutsches auf den "Sioux Glacier" im Süden Zentralalaskas.* Bei dem Erdbeben von 27 März 1964 wurde das untere Drittel des "Sioux Glacier", der im Süden Zentralalaskas liegt, unter einem Erdrutsch begraben. Die Untersuchungen, zur Erfassung der Auswirkungen dieser Schuttdecke auf das Verhalten des Gletschers ergaben, dass das Eis bis zu 28 m dicker wurde, was in erster Linie auf die isolierende Wirkung der Schuttdecke zurückzuführen ist. Das Eis ist auch an den Stellen dicker geworden, wo ununterbrochen, wenigstens seit 1938, Schutt lagert. Ein Längsprofil zeigt, dass das Gebiet nahe dem oberen Teil des Erdrutsches sich stark zerklüftet und zwischen 1965 und 1966 bis zu 8 m gesenkt hat, während das Gebiet an den Ausläufern der Schuttdecke bis zu 5 m höher geworden ist und durch Stauwülste gekennzeichnet ist. Man kann annehmen, dass eine kinematische Welle irgendwann zwischen 1965 und 1966 durch den Gletscher lief.

Der weiter oben gelegene Teil des von Schutt überlagerten Eises bewegt sich mit einer Geschwindigkeit von 175 m im Jahr fort, während das Zungengebiet nur mit einer Geschwindigkeit von 21 m im Jahr abfliesst. Die Geschwindigkeitsabnahme von oben nach unten beträgt 0,06 m/a pro Meter Horizontaldistanz, ausser in einem Gebiet etwa 1 km vor dem Gletscherende. Hier beträgt die Geschwindigkeitsabnahme nur 0,1 m/a pro Meter. Dieser Unterschied ist wahrscheinlich auf die topographische Bremswirkung zurückzuführen, die hier durch die rezente Dickenabnahme des Eises verursacht wurde.

## INTRODUCTION

### *Location*

"Sioux Glacier" is located in south-central Alaska at lat. 60° 30′ N., long. 144° 18′ W. (Fig. 1). It is 96 km due east of Cordova and 34 km north-north-east from the site of the former town of Katalla. "Sioux Glacier" (Fig. 2) apparently was once a tributary of the much larger Martin River Glacier but it now lies about 1.1 km north of the terminal ice of that glacier. Melt water from "Sioux" and Martin River Glaciers flows eastward across the Copper River delta and into the Gulf of Alaska.

*Previous work*

Although many of the Alaskan coastal glaciers were studied as early as the 1700's, very little was known about the Martin River Glacier area until Martin (1908) reported on 4 years of study of the coal fields and oil indications of the Controller Bay region south of Martin River and "Sioux" Glaciers. Martin's (1908, p. 49–52) report included the first known photograph of Martin River Glacier and a brief description of its geomorphology. "Sioux Glacier", however, was not described and probably was not even seen by him.

Numerous nearby glaciers were apparently well known by this time; reports both by Russians, who attempted to ascend the Copper River valley in the late 1700's, and later by members of U.S. Army mapping expeditions in the late 1800's, included descriptions of several now famous glaciers (Martin, 1908, p. 10). But, because of the inaccessibility of Martin River and "Sioux" Glaciers, no study was made of this area until Martin's time and even his descriptions were incidental in his search for coal and oil.

One of the members of Martin's expeditions was Lawrence Martin who continued glacial research and later collaborated with Ralph Tarr in a comprehensive report on the glaciers of coastal Alaska. In their report, Tarr and Martin (1914, p. 394) noted that "the covering of ablation moraine on the terminus renders the glacier relatively inconspicuous from the Copper River railway, and it would not be noted here were it not for the extensive outwash gravel plain built up by its glacier streams".

The first glacial studies after Martin, and Tarr and Martin, were initiated during the summer of 1962 by the Department of Geology, University of North Dakota, working under grant G-22016 from the National Science Foundation and under the supervision of Dr Wilson M. Laird, Chairman, Department of Geology. In 1963 the author initiated and participated in a preliminary examination of "Sioux Glacier".

During the following summer, shortly after the Good Friday earthquake, the glacier was visited briefly by a team from the Department of Geology, University of North Dakota, under the auspices of grant GP-2998 from the National Science Foundation.

Numerous publications have resulted from the first 3 years of glacial research, including those by Reid and Clayton (1963), Tuthill (1963, 1966), Clayton (1964), Laird and Tuthill (1964), Reid and Callender (1965), Tuthill and Laird (1966), and Reid (1967). Other authors have reported the existence of the debris slide on "Sioux Glacier" subsequent to the Good Friday earthquake (Grantz and others, 1964; Post, 1965, 1967; Ragle and others, 1965).

The following report is a result of field investigations begun during the summer of 1965 and completed the following summer. Financial support was provided by grant G-4448, National Science Foundation.

*Purpose of investigation*

The Good Friday earthquake of 27 March 1964 triggered a debris avalanche which buried one-third of "Sioux Glacier". Although no pre-earthquake ice-movement data are available for this glacier, surface characteristics (including morphology and structure) were known from the 1963 visit. The purpose of the investigation was to evaluate the effects of the avalanche debris load and insulation, as well as the effects of the regional regimen on the morphology and movement of the glacier.

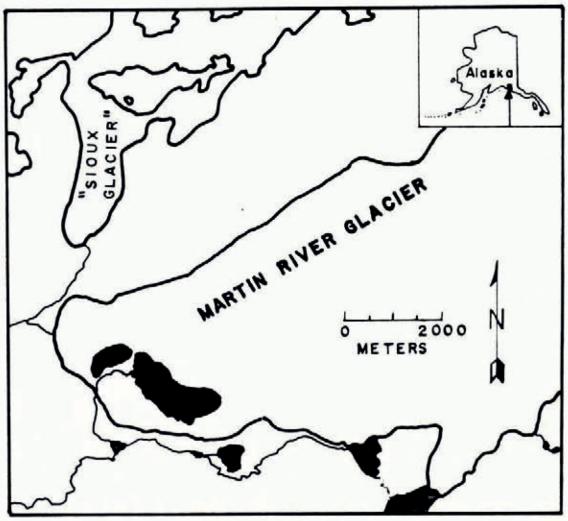


*Fig. 1. Map of the Martin River–"Sioux Glacier" area.*

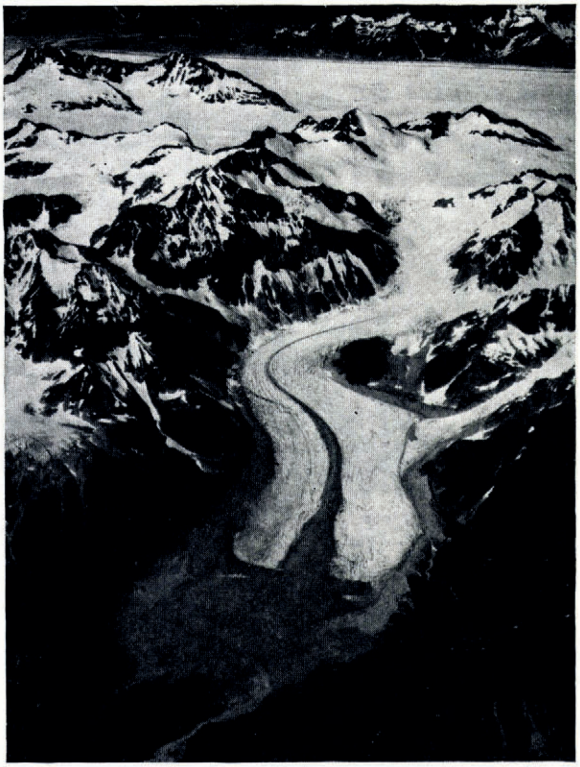

*Fig. 2. "Sioux Glacier" as seen from 4 200 m elevation in August 1938. Note the medial moraine and the apparent thrusting at the terminus. (Photograph by Bradford Washburn, Boston Museum of Science, No. 974, 3 August 1938.)*

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## Physical Characteristics

*Size*

"Sioux Glacier" is a valley glacier a little more than 10 km in length. It originates in a snow field at an elevation of about 1 400 m and the terminus is at an elevation of about 156 m (U.S.G.S., Cordova, B-1 and C-1 Quadrangles). The accumulation area is approximately 12 km² and the ablation area is about 5 km² (Post, 1967, p. D13). There is only one main tributary and this joins the trunk glacier from the north approximately half-way between the head and the terminus. A smaller tributary, "Hochstetter Glacier", meets the trunk glacier less than 3 km from the terminus. Although it no longer contributes material to the glacier, it is considered as a distinct part of the glacier system (Fig. 3).


*Fig. 3. "Sioux Glacier" as it appeared in August 1960. Note the attenuation of terminal debris and the general thinning since 1938. (Photograph by Austin Post, U.S. Geological Survey, F6-61, 12 August 1960.)*

*Former ice levels*

Former higher levels of "Sioux Glacier" are indicated by lateral moraines along both sides of the valley. The most striking is the pair of very steep-sided moraines immediately adjacent to the glacier margin. Their crests are as much as 35 m above the present glacier.

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Examination of the air photograph taken in 1938 (Fig. 2) reveals that the active ice then was only slightly thicker than now. It is presumed that the ice was at the level of these moraines at the turn of the century (Reid, in preparation).

At a significantly earlier time, a tongue of the glacier flowed through a saddle immediately up-glacier from "Hochstetter Glacier", leaving a nunatak exposed where a bedrock spur and knob remains today (Fig. 3). There is no evidence that the glacier was ever appreciably thicker than when it was at this level; the crest of the former nunatak appears not to have been glaciated.

*Surface morphology*

Crevasses are present on the surface of "Sioux Glacier" even within 0.5 km of the terminus. The most intensely crevassed area of the lower part of the glacier, however, is at the head of the avalanche debris cover, 3.5 km from the terminus. Here, an ice fall has broken the surface into numerous seracs and the glacier is impassable beyond this point. There are numerous additional crevasse fields up-glacier from here but most of them are hidden beneath the snow and firn cover. The firn zone is approximately half-way up-glacier from the terminus.

*Fig. 4. Thrust ridges near the terminus of "Sioux Glacier". Terminus is to the left. (Photograph by John Reid, 19 July 1965.)*

Another feature of the glacier surface is the thrust planes; some of them are so active that the up-glacier side of a thrust plane stands as much as 0.5 m above the other side even at the height of the ablation season (Fig. 4). Although most of these planes dip up-glacier, there is an area 1 km from the terminus where the planes are dipping toward the center line and slightly down-glacier. These planes apparently originated as marginal crevasses orientated approximately 45° up-glacier, but they rotated into a shear position as the glacier moved towards the terminus. The shear direction became further distorted by flow of the ice into a slight topographic low created by the rapid ablation of the drift-free ice at this location.

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Farther down-glacier the ice is relatively stagnant and is covered by a medial moraine which until 1964 was the main surface feature on the glacier (Fig. 3). This moraine was an ice-cored ridge extending over half the glacier length. Near the terminus the moraine crest was about 20 m above the exposed ice on either side. It was apparent that the morainal sediment had insulated the underlying glacier ice, thereby inhibiting ablation even though the sediment was only a surface veneer. On most parts of the moraine the veneer was only one particle thick and the typical particle was pebble size or smaller. The medial moraine and the rest of the lower 4 km of the glacier were traversed during the summer of 1963, less than 1 year before the avalanche occurred. Ciné film and slides taken during that traverse have been especially useful in comparing present and past topography.

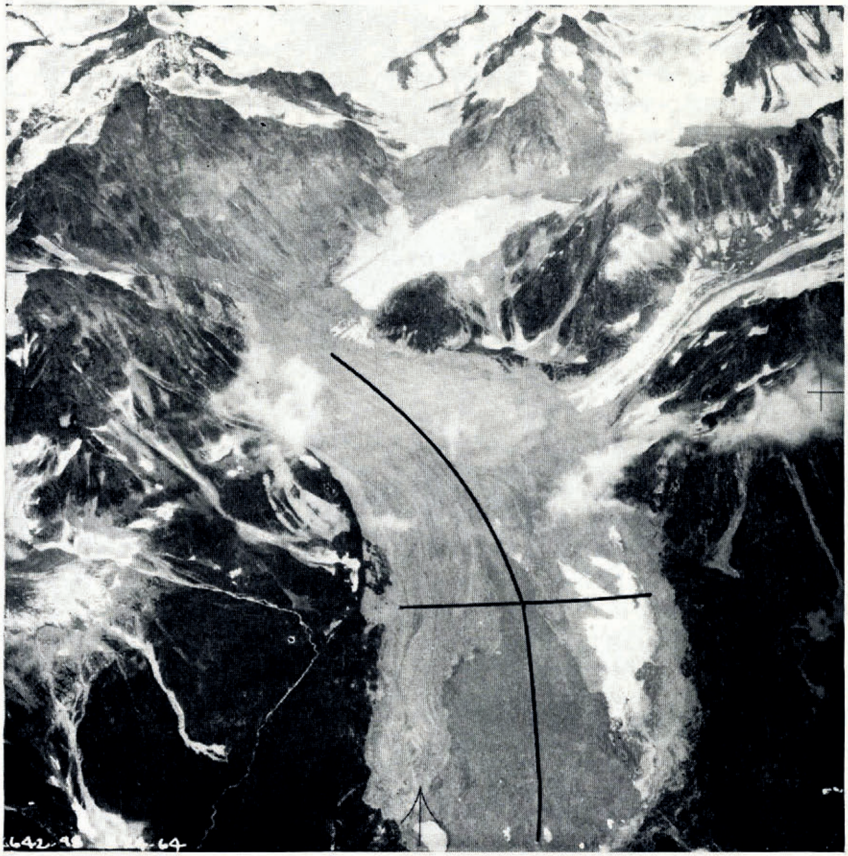

*Fig. 5. "Sioux Glacier" on 24 August 1964, showing extent and characteristics of the debris-slide cover and location of transverse and longitudinal profiles. Source of slide is the exposed slope on far left side. (Photograph by Austin Post, U.S. Geological Survey.)*

## Characteristics of the Debris Slide

### *Area affected*

The outstanding surface feature of the glacier today is the slide debris (Fig. 5).

The earthquake of 27 March 1964, that devastated Anchorage and other towns such as Whittier, also affected the "Sioux Glacier" area (Grantz and others, 1964; Post, 1965, 1967; Tuthill and Laird, 1966). The glacier is located approximately 200 km south-east of the epicenter of the initial shock; Anchorage is 125 km west of the epicenter. The earthquake triggered massive debris slides onto "Sioux Glacier". The largest of these slides originated from a point 1 525 m above the surface of the west margin of the glacier. The highly fractured bedrock broke loose and slid and rolled down a 40° slope to the glacier surface. From there it traveled 3.5 km over the 5° slope of the surface. The total horizontal distance of movement was approximately 4.2 km, and the area of glacier surface buried by this slide was 3.1 $km^2$ or about one-third of the glacier; the debris covered approximately 90% of the total ablation area.

The source area remained very unstable and during the summer of 1965, 1½ years after the earthquake, debris continued to roll and slide down the avalanche chute 24 h each day with a roar that could frequently be heard at the base camp about 9 km away. Debris was still moving down the chute during the 1968 summer season but much less frequently.

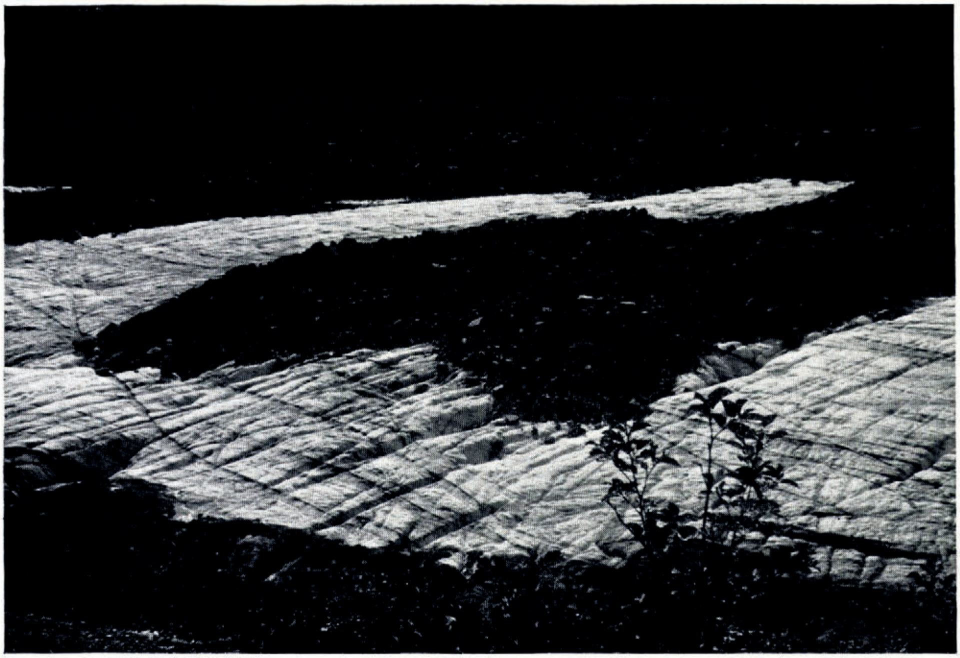

*Fig. 6. Tongue of the debris slide on "Sioux Glacier". The boulder at extreme end of the tongue is almost 6 m in diameter. Thrust planes and crevasses can be seen in exposed ice. (Photograph by John Reid, 19 July 1965.)*

*Particle size*

Some of the blocks left by the slide are as much as 15 m in diameter, but the average size is probably less than 0.5 m (Fig. 6). A few large blocks obviously were fragments of much larger blocks at least 30 m in diameter which broke on contact with the glacier. These blocks are estimated to have weighed more than 1 500 tons (1 530 Mg). The largest intact block on the surface now probably weighs about 850 tons (865 Mg).

*Thickness and volume*

Although parts of the surface of the slide debris are now over 20 m higher than the pre-earthquake surface, this is not a direct reflection of the thickness of the debris; the average thickness is apparently much less than the diameter of the largest block. No specific attempt was made to determine the average thickness of the cover, but numerous random observations indicate that it is probably about 2 m. The total volume of rock debris deposited by this slide is approximately 6 000 000 $m^3$. Tuthill (1966, p. 86) estimated the total volume of the snow and rock debris was 8 300 000 $m^3$, but recalculation of data presented by Tuthill and Laird (1966, p. B17) suggests the volume was 9 300 000 $m^3$, of which 2 300 000 $m^3$ was rock debris (personal communication from S. J. Tuthill).

Shreve (1966) concluded that the considerably larger slide on Sherman Glacier, 45 km farther west, was characterized by movement over a cushion of trapped compressed air. Definite evidence could not be found to prove that the "Sioux Glacier" slide also moved this way. But, the presence of longitudinal grooves on the slide surface, narrow flow-like lobes along its terminus and highly fractured but little-separated blocks suggest that at least part of the flow of the "Sioux Glacier" slide resulted from air lubrication (Shreve, 1966, p. 1640–42).

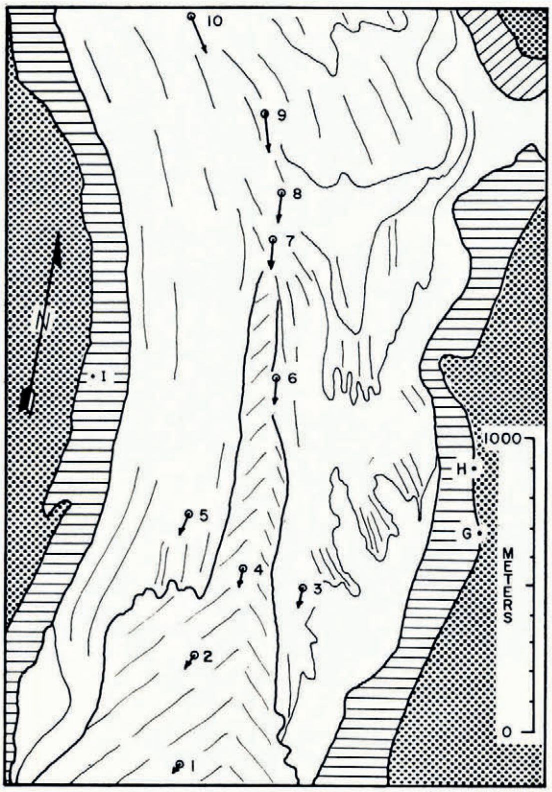


*Fig. 7. Map of the lower one-third of "Sioux Glacier", showing movement of stations 1–10. (Scale for movement arrows and map are the same Base line G–H is on far right lateral moraine. Point I is on moraine on west side of the glacier. Stations 1, 2, 4 and 6 are on the old medial moraine shown on Figure 3. Base map represents 1965 conditions.)*

## Field Procedures

### *Base line*

In order to evaluate the effects of the slide debris on the regimen of "Sioux Glacier", a grid of ice-movement stations was established on the glacier. A base line for this grid was situated along the sharp crest of the most recent lateral moraine on the east side of the glacier (the sharp vegetation-free segment to right of center; Fig. 3). Chaining of this 194 m-long

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base line was extremely difficult because of the presence of numerous large unstable blocks between the base points. The base points were tied to surrounding features to ascertain stability of the points over the years. A third base point was established on the opposite side of the glacier on the slope of the lateral moraine of the same age (point I in Figure 7). Every station of the glacier was surveyed from at least two of these base points using a Kern DK-1 theodolite.

### *Ice stations*

Two sets of ice-movement stations, consisting of 13 individual sites, were positioned on the glacier surface, one set longitudinal and the other transverse to the axis of the glacier (Fig. 7).

The stations used in this study consisted of cairns built either directly on the glacier surface, or, more commonly, constructed on the most obvious blocks. Aluminum poles, 1.5 m long, were set into the cairns and the poles marked with flags and streamers. The blocks were painted with a station number which was visible from the base line.

Of the 13 original stations, ten remained after a year's time. One station was not used in the final movement calculations because it could not be seen from two of the base points after the first season; it had moved out of the line of sight. The other two stations were lost as a result of rapid ablation which upset the cairns and thereby destroyed the sight points.

The risk of using superglacial blocks as ice-movement stations was well known, but every one of the selected blocks remained in an upright position and they were re-occupied the second summer.

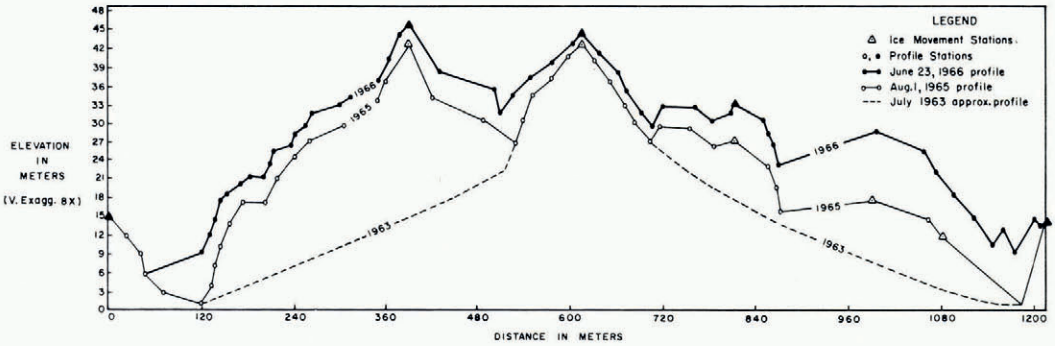


*Fig. 8. Transverse profiles of "Sioux Glacier" for 1963, 1965 and 1966. (See Figure 7 for location of stations 3, 4 and 5.)*

### *Profile stations*

In addition to the 13 ice-movement stations, two sets of profile stations were marked and occupied. The first set was transverse to the glacier (Fig. 8) and included ice-movement stations 3, 4 and 5 (Fig. 7). The bench marks shown on the 1966 profile in Figure 8 represent the ice-movement stations. The additional bench marks on the 1965 profile include the two stations lost through ablation. The profile points shown in Figure 8 were the turning points for the leveling survey and these were marked with a painted number and a circle. The same profile points were re-occupied the following year.

The second set of profile stations extended longitudinally from ice-movement station 1, near the terminus, to station 9, almost 2 km farther up-glacier (Fig. 7). The Kern theodolite was also used for the leveling survey.

## Results

### *Velocity measurements*

Triangulation of the ice-movement stations 1 year after the initial measurements revealed the existence of variations in the rates of flow of the surface ice. Figure 7 shows by a circle the location of each station at the time it was first established. The tip of the arrow leading from each circle represents the location of the station at the end of 1 year. The length of each arrow, therefore, is the distance that the station was displaced between the 1965 and 1966 summer seasons.

The data show a significant and expected decrease in velocity down-glacier, except between stations 6 and 7, where there is a slight increase. Attempts to identify velocity–distance curves with derived functions were frustrated by the lack of sufficient stations. Although the conclusions are tenuous, there appears to be a velocity decrease of 0.06 m/year for every meter distance down-glacier from station 10 to 7 and 0.05 m/year for every meter near the terminus (Table I). Between stations 6 and 7, there is a slight increase of 0.09 m/year per meter and between stations 5 and 3 the rate of decrease is five times the average rate of decrease of 0.06 m/year per meter.

Table I. Ice Movement and Elevation-change Data for "Sioux Glacier", 1965–66 (see Figure 7 for Location)

| *Ice-movement station* | *Velocity* m/year | *Distance from station 1* m | *Elevation change* m |
|---|---|---|---|
| 1 | 21 | 0 | * |
| 2 | 46 | 395 | +3.0 |
| 3 | 58 | 678 | +6.0 |
| 4 | 60 | 682 | +2.6 |
| 5 | 73 | 790 | +3.1 |
| 6 | 84 | 1 294 | −2.6 |
| 7 | 80 | 1 730 | −2.2 |
| 8 | 90 | 1 890 | −3.5 |
| 9 | 98 | 2 130 | −8.0 |
| 10 | 175 | 2 440 | * |

* Station not included in the longitudinal survey.

These rates appear to be valid in that operator errors were all but eliminated and instrument errors were corrected by standard surveying procedures. All measurements were made at least twice and by two different assistants. The instrument was shaded at all times and identical points on each station were confirmed during the surveying.

The sudden leveling off of the rate of decrease in ice velocity between stations 6 and 7, and the very rapid rate of decrease between stations 3 and 5 therefore appears to be a real and apparently significant change. This is presumed to be caused by a subglacier topographic control now effective as a result of thinning of the ice here.

### *Profile measurements*

*Transverse profile.* Figures 8 and 9, respectively, show the transverse and longitudinal profiles of "Sioux Glacier" as measured in the summer of 1965 and then again in 1966. The transverse section was measured to determine the importance of the slide debris on the rate of ablation. The control area was the part of the medial moraine which was not covered by the slide debris. If no significant changes in elevation occurred on the medial moraine, it could be assumed that the change in the elevations of the adjacent slide debris cover are primarily the result of the more effective insulation. Figure 8 shows that, although the greatest increase in elevation does in fact occur in the slide areas (of the pre-earthquake profile), even station 4 at the crest of the old medial moraine is higher by almost 3 m. Table I lists the changes in elevation for each of the stations intersected by the profile.

It is concluded that the medial moraine has been affected by a change in the regimen of the glacier. The change may be either the result of more effective insulation afforded by the slide debris farther up-glacier or a long-term change in the regimen related to normal ablation/accumulation ratios.

Beneath the slide debris, however, the elevation of the glacier surface increased as much as 12 m between 1965 and 1966. The profile of this part of the glacier for the summer preceding the 1964 earthquake was estimated from available photographs. Although this particular profile is highly subjective, it is believed to be a good approximation. As can be seen by comparing this profile with the 1965 one, the major effect of the ablation must have occurred within 1 year after the earthquake. At station 5 (Fig. 8) the surface was raised approximately 28 m, presumably as a result of the debris insulating the underlying ice from

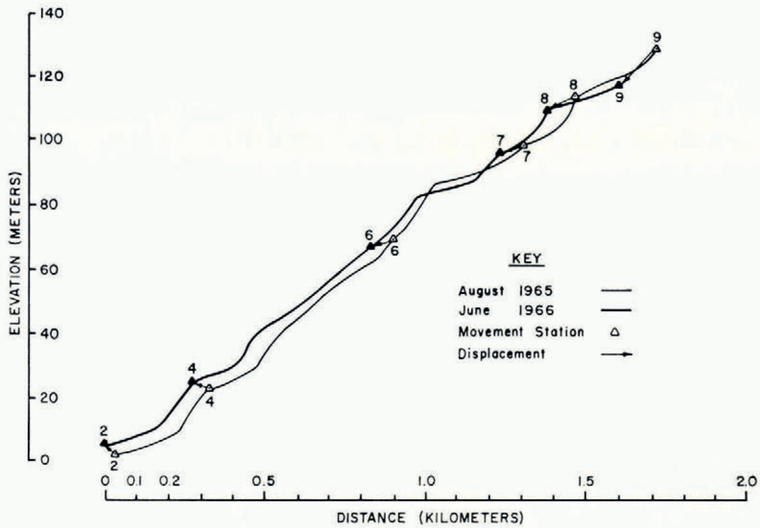


*Fig. 9. Longitudinal profile of "Sioux Glacier" for 1965 and 1966. (See Figure 7 for location of stations.)*

the otherwise rapid ablation. There are, however, several other possible explanations for this rise. Since this area is in the zone of net ablation, a point on the surface which is moving with the glacier should normally move into an area of lower elevation. An exception to this would be the case where the ice is undergoing compressive flow to the extent that the forward and upward flow of the ice also causes the surface to rise. In other words, the post-earthquake profiles may reflect the fact that the points along the profile traverse may have flowed into a part of the glacier that is and has been moving up-hill. If this were true, a longitudinal profile would show this rise. However, Figure 9 reveals that this is not the case.

Another explanation for the 28-m rise of the glacier surface at station 5 is therefore necessary because the addition of a debris cover should merely cause the ablation rate to slow down, not cause it to cease altogether. A pre-earthquake transverse profile of the lower part of "Sioux Glacier" is approximated by the profile shown on Figure 8. During the ensuing winter, snow and ice accumulated and buried this surface to some unknown depth. When the slide debris from the earthquake spread over the surface of "Sioux Glacier" it, in turn, buried

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this winter accumulation. The ablation that summer was inhibited by the presence of the insulating cover; the selected profile stations at the close of the ablation season not only had moved down-glacier but were also higher than the equivalent surface at the close of the ablation season the year before. The increase amounted to the part of the 1963–64 winter accumulation that had escaped ablation during the 1964 summer because of the slide-debris cover. In any event, this amount was undoubtedly less than the total accumulation because the slide cover merely inhibited the rate of ablation.

This debris along the slowly moving profile line was buried beneath more snow and ice that winter and then, during the summer of 1965, this cover was entirely removed through ablation along with some of the underlying older ice presumably resulting in a slightly lower surface than the immediate post-earthquake surface. This is the 1965 profile shown on Figure 8. The same process of snow and ice accumulation repeated itself that following winter and when the 1966 profile was measured again the ablation season was at its peak. The resulting profile, however, was not slightly lower than the year before but significantly higher.

Station 4 at the crest of the medial moraine was 2.6 m higher than the previous summer. Because the profile from which data were obtained was measured relative to fixed points along either side of the glacier, this rise is absolute in respect to the valley wall. But, during the intervening year between measurements the station moved down-glacier, and also down-slope, about 68 m. The surface slope here is about 2.5 m drop in those 68 m of horizontal distance. The station, therefore, actually should have been 2.5 m lower. The difference is a net increase in thickness of 5.1 m (2.6 m+2.5 m) from what it had been in 1965. If all points along the profile were corrected to a straight line across the glacier, the rise of 5.1 m would be seen. Since only three control points (stations 3, 4 and 5) on each of the profiles were included in the base-line triangulation survey, any attempt to make the correction for the remainder of the profile would be invalid.

It could be assumed that no ice is being added to this glacier at the area of the transverse profile; all snow and ice that accumulate during the winter ablate completely during the next summer. Some of the older ice is also removed as well. But with the addition of an insulating blanket the old ice is no longer removed as rapidly. Under these circumstances the new ice surface will always be lower than the year before. However, it will not be as low as it would have been if the debris cover were not there.

Since the 1966 surface is actually higher, it must be concluded that ice is under compressive flow here. The source of this ice is presumed to be farther up-glacier and the mechanism of transfer to the lower part of the glacier must be related to the thrust planes found here (Fig. 4; p. 357). The upward component of the ice flow here apparently is the factor causing the surface to be higher rather than lower.

*Longitudinal profile.* The longitudinal profile shows additional variations. Down-glacier from station 6 the surface was raised from the 1965 level. This has already been explained by observations of the transverse profile. Up-glacier from this station, however, the glacier surface is higher at some stations and lower at others. Station 9, for example, is 8 m lower (Table I). As can be seen from Figure 7, every station along this profile is on debris-covered ice and presence or absence of a cover, therefore, is not the reason for the difference between the two ends of the profile. One striking difference, though, is that this upper zone is much more crevassed than the lower one. Station 10 could not be reached on foot during the 1966 investigations; it was located in a maze of crevasses that had not been visible the previous summer. It is believed that this would be a significant cause for more rapid ablation here, if it is more rapid. As the crevasses opened much of the superglacial debris slid into them, exposing the underlying ice to more rapid ablation. As a matter of fact, the rate of ablation here may be greater than it was prior to the earthquake. The bare ice is now coated with a veneer of dust and other fine-grained sediment left when the rest of the debris slid into the crevasses. The increased absorption of radiation undoubtedly augments the ablation rate.

Another more likely explanation for the lowering of this part of the glacier is that a kinematic wave recently passed through. Post (1966, 1967) has reviewed the characteristics of surging glaciers and has cited some of the glaciers that have been identified as having surged. Post (1967, p. D38–39) stated that:

"An abrupt kinematic wave of ice in the upper glacier begins moving very rapidly down valley. This movement results in a rapid transfer of ice from the upper regions toward the terminus, and the surface of the glacier is chaotically broken. The ice discharge may lower the surface as much as 150 m in the upper part of the glacier. . . . The volume of ice loss in the upper part and gain by the lower part of the glacier appears to be the same."

Nisqually Glacier on the slopes of Mount Rainier, Washington, has also experienced what are recognized as kinematic waves (Meier, 1963). Of particular significance to this paper is the similarity between this and "Sioux Glacier" (Table II). A common explanation for the

TABLE II. COMPARISON OF NISQUALLY AND "SIOUX" GLACIERS (DATA FOR NISQUALLY GLACIER FROM JOHNSON (1960))

| | *Nisqually Glacier* | *"Sioux" Glacier* |
|---|---|---|
| Area ($km^2$) | 5.7 | 17 |
| Length (km) | 7.4 | 10 |
| Width (km) | <1 | 1 |
| Vertical extent (m) | 3 048 | 1 150 |
| Velocity (m/year) | | |
| (2.7 km from terminus) | 76 (1944–45) | 110 (1965–66) |
| (1.6 km from terminus) | 18 (1944–45) | 80 (1965–66) |

waves on the two glaciers is inviting. It can be seen from the table that Nisqually Glacier is smaller but considerably steeper than "Sioux Glacier". Despite this fact, the terminus velocity of Nisqually Glacier is much less than the velocity at a similar distance from the terminus of "Sioux Glacier". Johnson (1960, p. 60) observed that, when a kinematic wave passed through this part of the glacier, the surface velocity increased to more than 100 m/year. This particular wave was well-documented by Johnson from his annual measurements of four transverse profiles located 0.8, 1.6, 2.2 and 2.7 km from the 1956 terminus. The kinematic wave traveled from the upper to the second lowest profile at an average rate of about 275 m/year between 1945 and 1949. The velocity from there to the lowest profile was only 135 m/year (Johnson, 1960, p. 59). Meanwhile, the surface velocity of the glacier at the upper profile was about 76 m/year and only 15–18 m/year at the second lowest profile.

"When the wave first became evident at profile no. 2, the maximum annual movement was about 50 to 60 feet [15 to 18 m] per year. The wave, however, had moved from profile no. 3 [upper profile] to no. 2 [second lowest] at a rate of almost 900 feet [274 m] per year. It is evident that the wave moves along the glacier at a much faster rate than the ice." (Johnson, 1960, p. 60)

The effect of this wave on Nisqually Glacier, therefore, was to increase both the velocity of the glacier and the amount of surface crevassing.

The intense crevassing and the accompanying lowering of the surface of "Sioux Glacier" by 8 m is rather convincing evidence that a kinematic wave did, in fact, move through this glacier. However, the result was not a surge, because just as in the case of Nisqually Glacier the volume of the glacier was insufficient to cause the mass transfer necessary to create a surge at the terminus.

There was unmistakable accompanying activity at the terminus. In numerous places along the western margin, especially opposite stations 1 and 2 (Fig. 7), the outwash sediments and till were shoved vertically as well as laterally sometime between 1965 and 1966. The absolute amount could not be determined, but some of these sediments were about 15 m higher and 30–40 m farther to the east than they had been 1 year earlier. The shoving probably occurred when the kinematic wave reached the terminus.

The wave on Nisqually Glacier took approximately 9 years to travel 2.2 km. It is believed that the wave on "Sioux Glacier" traveled at a much higher velocity. The significantly lower and highly crevassed surface along the upper part of the longitudinal profile (Fig. 9) and the increased elevation and thrusting of the lower part suggest that the wave has already moved to the terminal area. Because there was very little crevassing of the upper area 1 year earlier (1965), it is concluded that the wave had not yet reached this area at that time. The wave, therefore, traveled at a minimum rate of about 2 km/year. The origin of the wave may have been associated with the increase in thickness of the glacier at the head of the debris slide but there is no way of confirming this. In any event, the present longitudinal profile is largely the result of energy associated with a kinematic wave. Future measurements should support this conclusion.

## Summary

The Alaska earthquake of 27 March 1964 triggered a debris slide which buried one-third of "Sioux Glacier". The primary effect of this cover has been to inhibit ablation. Transverse profiles of the glacier near the terminus show the 1966 surface is as much as 28 m higher than the approximated profile for 1963. Most of this is due to the insulation afforded by the debris cover. But that part of the glacier which has been covered by debris, at least since 1938, and which was not directly affected by the slide debris, also increased in height. This was confirmed by the data obtained from the longitudinal profiles, which show that the lower part of the glacier was raised over 5 m in the interval between 1965 and 1966. The upper half, on the other hand, dropped as much as 8 m in that same interval.

The only plausible explanation for the rise of the lower part of this glacier is that ice has been transferred within the system. A kinematic wave is believed to have moved through this glacier sometime between 1965 and 1966 causing crevassing and lowering of the surface in the upper part of this glacier, and thrusting and raising of the lower part of the glacier. Mass transfer of ice is the reason for the changes in ice thickness as indicated by changes in surface elevation along the length of the glacier.

Ice-movement analysis reveals a down-glacier decrease in flow velocity from 175 m/year at the upper margin of the slide cover to 21 m/year near the terminus and along the crest of the old debris-veneered medial moraine. The rate of down-glacier decrease varies from 0.05 or 0.06 m/year per meter horizontal distance to 0.1 m/year per meter. However, one area shows a slight increase in velocity, and this coincides with the lower zone of that part of the glacier characterized by a lowered surface. This phenomenon probably reflects a subglacial topographic control that has become more effective as a result of thinning of the glacier here.

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