The Alaska Earthquake
March 27, 1964

Effects on Hydrologic Regimen

Glaciers

GEOLOGICAL SURVEY PROFESSIONAL PAPER 544-D

THE ALASKA EARTHQUAKE, MARCH 27, 1964:
EFFECTS ON THE HYDROLOGIC REGIMEN

Effects of the March 1964 Alaska Earthquake on Glaciers

By AUSTIN POST

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THE ALASKA EARTHQUAKE SERIES

The U.S. Geological Survey is publishing the results of investigations of the Alaska earthquake of March 27, 1964, in a series of six Professional Papers. Professional Paper 544 describes the effect on hydrology. Other Professional Papers, some already published and some still in preparation, describe the effects of the earthquake on communities; the regional effects of the earthquakes; the effects on transportation, communications, and utilities; and the history of the field investigations and reconstruction effort.

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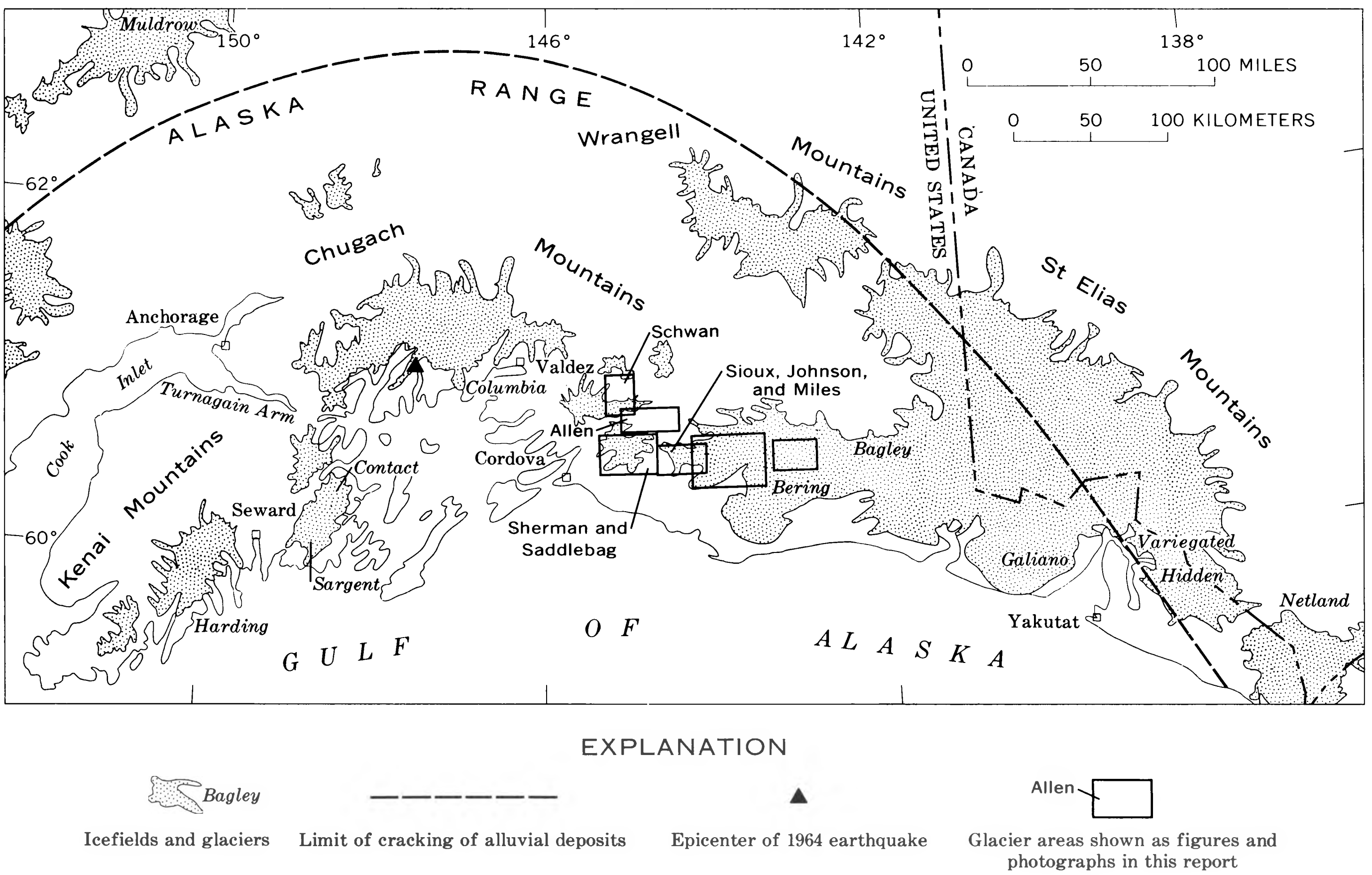

Figure 1.—Map of south-central Alaska showing the major glaciers and icefields and the epicenter of the March 27 earthquake.

EFFECTS OF THE MARCH 1964 ALASKA EARTHQUAKE ON GLACIERS

By Austin Post

ABSTRACT

The 1964 Alaska earthquake occurred in a region where there are many hundreds of glaciers, large and small. Aerial photographic investigations indicate that no snow and ice avalanches of large size occurred on glaciers despite the violent shaking. Rockslide avalanches extended onto the glaciers in many localities, seven very large ones occurring in the Copper River region 160 kilometers east of the epicenter. Some of these avalanches traveled several kilometers at low gradients; compressed air may have provided a lubricating layer. If long-term changes in glaciers due to tectonic changes in altitude and slope occur, they will probably be very small. No evidence of large-scale dynamic response of any glacier to earthquake shaking or avalanche loading was found in either the Chugach or Kenai Mountains 16 months after the 1964 earthquake, nor was there any evidence of surges (rapid advances) as postulated by the Earthquake-Advance Theory of Tarr and Martin.

INTRODUCTION

Alaskan glaciers are of such size and number that they influence the climate, streamflow, and works of man in many parts of the State. Their influence is especially important in the region most strongly affected by the Alaska earthquake of March 27, 1964, where about 20 percent of the land area is covered by ice (fig. 1). North, east, and west of the epicenter, the Chugach Mountains are covered with approximately 6,500 km² (square kilometer) of icefields and snow-filled valleys from which more than a dozen major and hundreds of smaller glaciers descend. Southwest of the epicenter the Sargent and Harding Icefields and other glaciers cover approximately 4,200 km² in the Kenai Mountains. East of the Copper River, the Bagley Icefield contains some 10,400 km² of glaciers.

Most rivers in this area derive a part of their flow from glaciers, and, for many major streams, such as the Matanuska and Copper Rivers, glacier melt provides a substantial part of their summer runoff. Although it is primarily the glacial rivers that affect works of man in the State, in a few places the glaciers themselves are near transportation routes or facilities. Changes in glaciers resulting from earthquakes thus may have economic as well as scientific interest.

The 1964 earthquake was one of the strongest ever recorded in North America. Tectonic displacements occurred over a larger area than has previously been observed (Plafker, 1965a; Plafker and Mayo, 1965). The area in which cracking occurred in alluvial deposits is considered the probable limit of the area where noticeable effects on glaciers might be expected (fig. 1).

The author conducted aerial-photographic investigations on glaciers in northwestern North America from 1960 to 1963 under grants from the National Science Foundation. This project was administered by the University of Washington, Seattle, P. E. Church being principal investigator. Practically all of the larger glaciers in Alaska were examined and their various features noted. More than 2,000 oblique and vertical photographs were taken each year. These observations and pictures provide detailed information about the glaciers before the earthquake occurred.

The U.S. Geological Survey continued these studies in 1964 and 1965 as part of a broader program of investigation of the relation of glaciers to climate and the role of glaciers in the hydrologic cycle. Mark F. Meier directed this program.

By comparing photographs taken before and after the earthquake, the immediate effects on glaciers can be analyzed. The data available make it possible to determine what changes have occurred in other years in the shaken area. Changes in regions where earthquake shaking did not take place were also analyzed. Studies were conducted in late August and in September, the time when the seasonal snow cover on glacier ice is at a minimum. High-resolution aerial cameras were used. The following glacier features were visually examined and photographed:

- Firn line and snow cover.
- Snow, ice, and rock avalanches.
- Extent of crevassing and evidence of changes in glacier thickness and rate of flow.
- Surface features including ogives, icefalls, medial moraines, superglacial streams and lakes.
- Glacier termini—position, configuration, and relative activity.
- Iceberg discharge of tidal glaciers.
- Outlet and marginal streams, and glacier-dammed lakes.
- Terminal and lateral moraines, trimlines, and barren zones.

In addition, a careful search was made during the 1964 and 1965 flights to find evidence of changes in glaciers attributable to the earthquake.

ACKNOWLEDGMENTS

This study was made possible by utilizing aerial photographs taken for the National Science Foundation in 1960, 1961, and 1963 under contract with the University of Washington, Seattle, Wash. Information and(or) photographs were furnished the author by George Plafker of the Geological Survey and Troy Péwé of the University of Alaska, John Sater of the Arctic Institute of North America, and W. O. Field of the American Geographical Society. John R. Reid of the University of North Dakota, Colin Bull of the Ohio State University, Institute of Polar Studies, Samuel Tuthill of Muskingum College, Ohio, furnished information regarding studies of Sherman and Martin Rivers Glaciers. Mark Meier of the Geological Survey discussed the probable effects on glaciers of avalanches and tectonic displacements. W. R. Fairchild, Don Sheldon, and Jack Wilson provided skilled piloting on aerial photographic missions. D. R. Crandell of the Geological Survey and W. O. Field critically reviewed the manuscript.

POSSIBLE EFFECTS OF EARTHQUAKES ON GLACIERS

Earthquakes and changes in the surface of the earth related to earthquakes can affect glaciers in many ways. The glaciers can be made thicker or thinner, the land surface can be so deformed as to cause changes in net mass budget (difference between accumulation and ablation of snow and ice) or in the slope of the glaciers, glaciers which calve off into water can be affected by shaking or by changes in the water body, and the glacier ice may be directly affected by shaking. Seven possible changes are:

1. Increased ice thickness resulting from:
   a. Extensive avalanching of ice and (or) snow from adjacent slopes onto glaciers.
   b. Rockfalls and rockslide avalanches from adjacent slopes onto glaciers.
   c. Decreased melting due to insulation of ice provided by heavy accumulations of dust or rock debris on glaciers.
   d. Decreased melting due to increased albedo (solar radiation reflectivity of the surface), caused by accumulation of clean avalanche snow and ice over dirty ice.

Increased ice thickness on glaciers results in accelerated glacier motion (Nye, 1952; Weertman, 1957) and a possible advance of the terminus. Sudden spectacular glacier advances after the severe 1899 earthquake were reported by Tarr and Martin (1914); they attributed the advances to extensive earthquake-induced avalanching of snow and ice onto the glaciers. Less spectacular effects of increased ice thickness might be a slowing of the glacier retreat, stability, or a slow advance of the terminus.

2. Decreased ice thickness resulting from accelerated melting due to decreased albedo, caused by a thin surface layer of dust and rock debris. Reduced ice flow, slowing of advance, stagnation or retreat of the terminus, or even complete

disappearance of the glacier are possible effects of thinning.

3. Disruption of glacier-fed rivers by:
   a. Glacier advance, blocking the normal course of streams or rivers and forming lakes, which may be followed by a sudden release of water when such glacier dams burst or are overtopped and rapidly disintegrate.
   b. Closing or opening of englacial or marginal channels resulting in the impoundment or release of runoff.

Highways parallel the Matanuska and Copper Rivers, and transportation routes follow rivers in the Kenai Mountains. In addition, major ports, such as Seward and Valdez, are near the mouths of glacier-fed rivers. Severe damage could result from flooding if these streams were affected by earthquake-induced changes in glaciers.

4. Change in flow characteristics of glaciers due to shaking. Sudden advances of glaciers have been reported where no snow and ice avalanching have been observed. The possibility that earthquake shaking of unstable glaciers directly results in such advances has been considered (Post, 1960). Such advances might result from:
   a. Changes within the structure of the glacier ice that alter its flow-law properties and, in consequence, the speed of internal deformation of the glacier.
   b. Changes in the properties of the boundary layer between the glacier and its bed that alter the rate at which the glacier slides.

The author knows of no physical mechanism which would permit shaking to cause appreciable changes in glacier flow rates by either of these phenomena. Inasmuch as no observational data on either mechanism are available, these phenomena are considered purely hypothetical and are not discussed further in this report.

5. Breakup of the terminus of tidewater glaciers due to shaking. Accelerated discharge of icebergs and possible retreat of the glacier might result.

6. Changes in the terminus of tidewater glaciers due to vertical movement of the land. Advance of raised glaciers and retreat of lowered glaciers are possibilities.

7. Long-term changes in mass or flow characteristics of glaciers or both, due to change in altitude or slope caused by tectonic displacement. Effects may be greater or less, depending upon the magnitude of the changes.

SNOW AVALANCHING

The 1964 earthquake occurred at a time of year when large quantities of snow were present on glaciers, and avalanche hazard was high in some areas. E. R. LaChapelle, snow avalanche specialist with the U.S. Forest Service, stated (oral commun., 1966):

> The Good Friday earthquake occurred during a period of known natural avalanche hazard in the Chugach Mountains in the vicinity of Anchorage and Turnagain Arm. The snow cover at this time was recorded as unstable. For this reason, the Forest Service ranger on duty at Alyeska Ski area closed parts of that area to public use a few hours prior to the earthquake. The subsequent occurrence of avalanches in this and other nearby areas indicates that the hazard prediction was correct.

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Because of the unstable snow conditions mentioned by LaChapelle, major avalanching onto the glaciers might have been expected during the earthquake. However, George Plafker (written commun., 1964) found little evidence of snow avalanches on the glaciers during flights made March 29 and April 6, 1964. He wrote:

> My general impression gained from the reconnaissance flying is that the volume of snow shaken down by the earthquake is infinitely small relative to the size of the drainage basins of the coastal glaciers. I seriously doubt that the amount of snow observed in these avalanches could have a significant effect upon the regimen of any of the glaciers I saw * * *.

Ragle and others (1965a, p. 2) made reconnaissance flights between April 9–19 and September 4–24, 1964, and summarized their findings as follows:

> The scarcity of obvious change was surprising because the glaciers must have been shaken violently by the earthquake. There were few snow avalanches or snow slides in the glacier basins and none of them appeared to have added enough substance to affect glacier regimen appreciably * * *. With a few exceptions, hanging glaciers did not appear to have been affected and there was no unusual calving of glacier termini into tidewater.

Photographs taken April 1, 1964, by T. L. Péwé show the termini of Meares, Yale, Harvard, and Columbia Glaciers. No evidence of avalanching is shown.

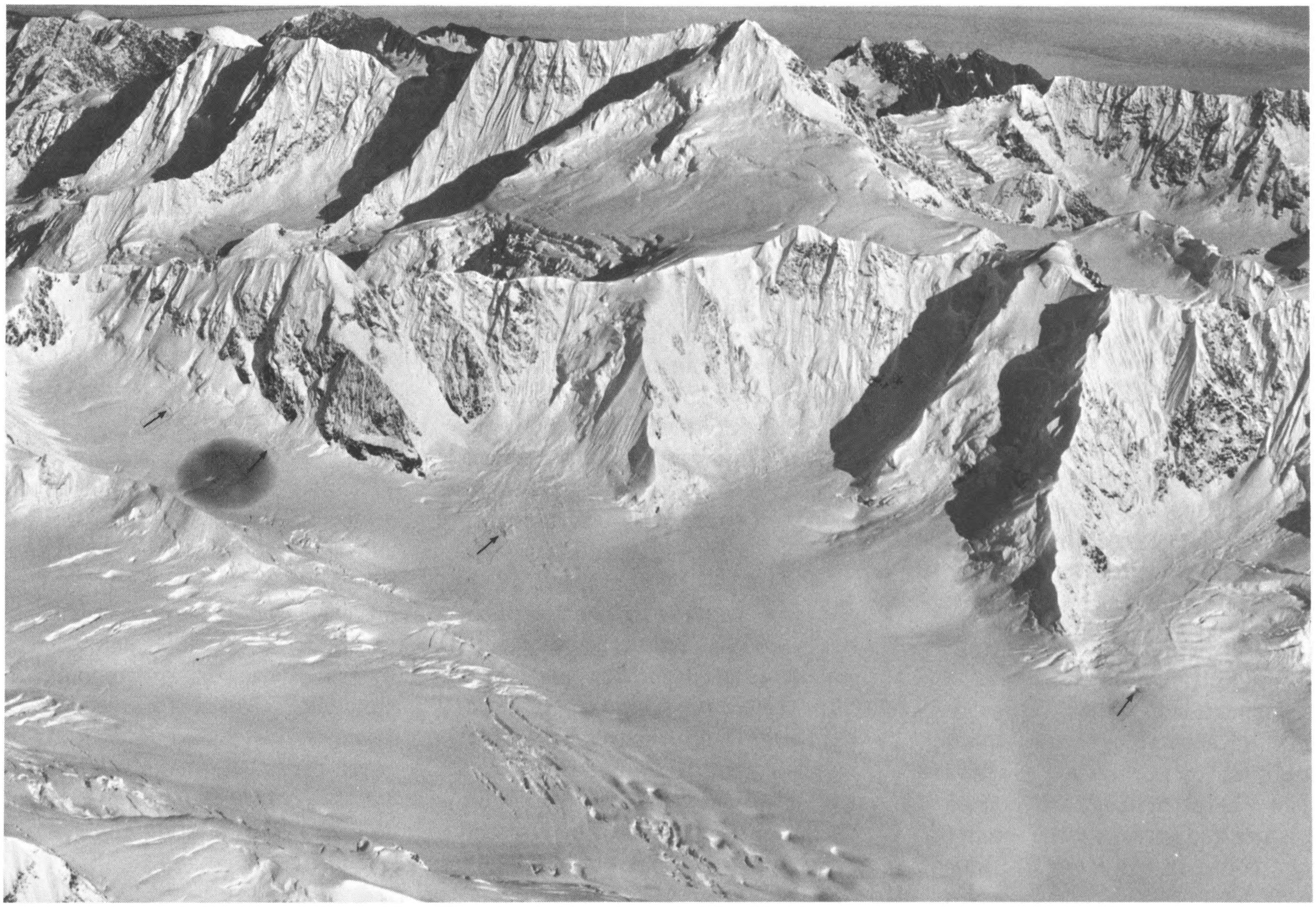


FIGURE 2.—Head of Meares Glacier, August 24, 1964. The snow avalanches, which may have resulted from the March 27 earthquake, are shown by arrows.

Furthermore, no evidence of significant avalanching of ice or snow was found during the author's investigations in August 1964. Traces of large winter or spring snow avalanches can usually be detected on glaciers as late as August because of differing snow texture, streaks of fine debris, or the obscuring of glacial structures. All of the larger glaciers in the Chugach Mountains were observed. Detailed oblique photographs were taken of the precipitous slopes adjacent to the Columbia, Meares, Yale, and Harvard Glaciers, all of which are near the epicenter (fig. 1). The areas of these glaciers and the areas of earthquake-induced avalanches of snow found on these glaciers are summarized in table 1.

TABLE 1.—*Snow avalanches on large glaciers near the epicenter of the 1964 earthquake*

Glacier	Distance from epicenter		Area of glacier (km^2)	Approximate area of snow avalanches (km^2)
	Km	Direction		
Columbia	25	NE	1, 370	5
Meares	23	NNE	135	5
Yale	26	N	225	0
Harvard	35	N	505	25

On the Columbia Glacier, evidence of snow avalanching was so minor that no more avalanches were noted than are shown in photographs taken in other years. A few small snow avalanches occurred near the head of Meares Glacier (fig. 2).

Evidence of snow avalanching has been found each year the glaciers have been examined. The amount of avalanching in 1964 was not, in general, more than that usually detected. All observers' reports and the evidence seen in August 1964 indicate that snow avalanching resulting from the earthquake was not great enough to materially affect any glacier's regime.

ICE AVALANCHING

Large-scale avalanching of ice from hanging glaciers and ice-veneered cliffs adjacent to large glaciers could materially affect a few glacier regimes. The glaciers were carefully scrutinized in August 1964 to determine if ice avalanching had taken place.

The ice-sheathed cliffs near the head of Harvard Glacier are among the most extensive and steepest in the Chugach Mountains. Many small avalanches occurred on the south side of the glacier (fig. 3), but only two were large enough to leave conspicuous deposits. No evidence of extensive ice avalanching was noted adjacent to the Yale Glacier.

Although some steep ice on slopes had an unusually shattered appearance after the earthquake (Nielsen, 1965), no ice avalanches were found that were large enough to materially affect any glacier's regime.

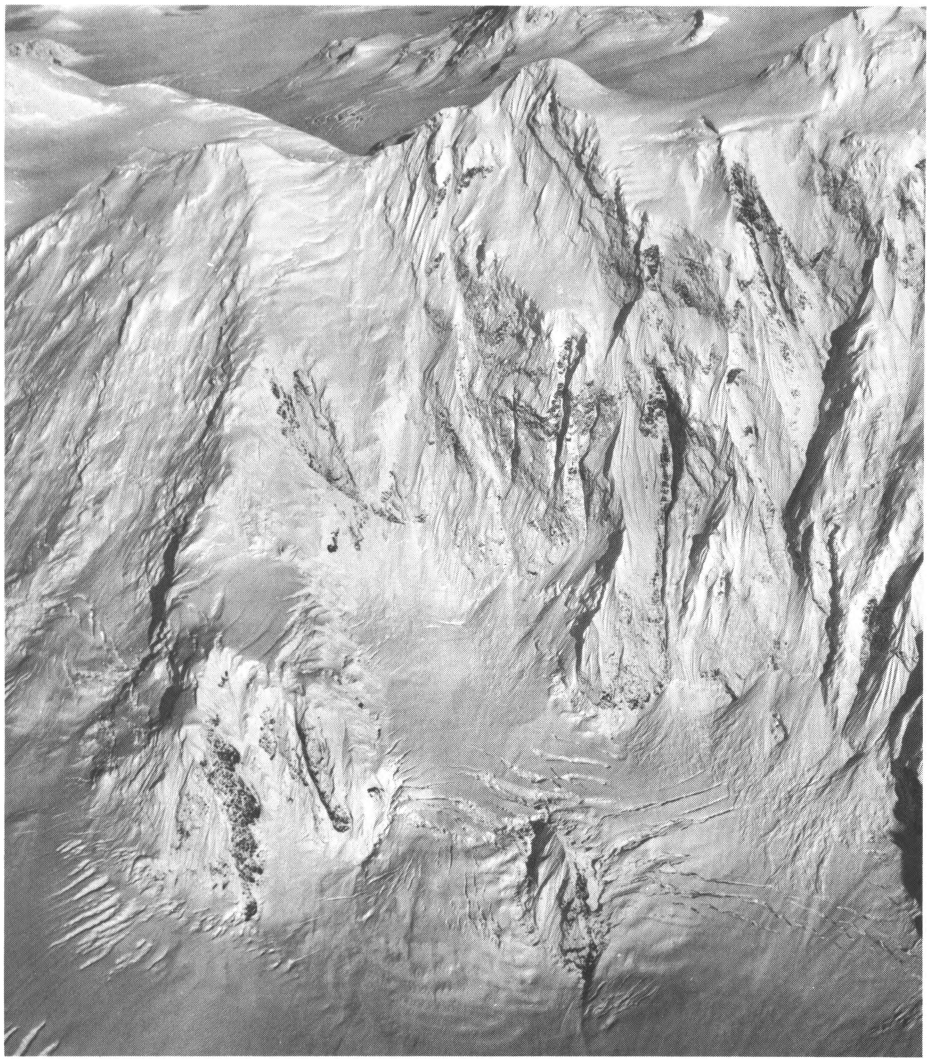


FIGURE 3.—Cliffs on south side of Harvard Glacier, August 24, 1964. Sliding of snow has taken place on these slopes, as shown by the avalanche paths and filled crevasses on the left and by the avalanche debris at the foot of the cliffs in the center of photograph. However, hanging glaciers on these cliffs apparently were little affected by the earthquake.

EARTHQUAKE-INDUCED ROCKSLIDE AVALANCHES ON GLACIERS

Apparently the most important effect of the 1964 earthquake on glaciers has been the change in their regime resulting from rockslide avalanches. Rockfalls occurred over a very broad area as a result of the earthquake. This distribution is not a simple function of distance from the epicenter, but is related to local structure and weakness in bedrock. Direction of avalanche movement apparently was controlled by local topography, no particular direction of movement predominating. Most of these rockfalls and rockslide avalanches were minor in both size and importance.

Rockslide avalanches which occurred between August 1963 and August 1964 that were observed by the author are listed in table 2. The location and area of the glaciers and of all rockslide avalanches of more than 0.5 km², together with the general direction of movement of the avalanche, are listed.

Several very large rockslide avalanches occurred at the time of the earthquake. Profiles of these avalanches are shown on figure 4. Individual rockslides are described below.

TABLE 2.—*Earthquake-induced rockslide avalanches*

[Slide area: more important slides in italic]

Glacier		Avalanche						
					Slides			
Name	Area (km²)	No.	Latitude	Longitude	No.	Area (km²)	Length (km)	Direction traveled
			° ′	° ′				
Sherman	57	1	60 33	145 10	1	*8.5*	6	NW.
		2	33	06	1	1.5	2.5	N.
		3	31	08	1	1.5	3	N.
		4	32	10	1	.5	1.5	NE.
Schwan	140	1	60 53	145 11	1	*9*	6	NNW.
		2	57	08	1	.5	1.5	W.
Martin River	290	1	60 36	143 36	1	*5*	3	NNW.
		2	36	38	2	*11.5*	4	NW.
		3	38	35	2	6.5	5	S, SSE.
		4	37	39	1	[1] 8.5	5	SSE.
		5	34	38	1	1.5	3.5	SW.
		6	33	44	1	1	2.5	S.
Bering	5,830	1	60 32	143 17	1	3	5	S.
		2	30	10	1	2.5	6.5	S.
		3	29	06	1	2.5	5	S.
		4	29	04	1	1	1.5	SSE.
		5	28	142 27	1	1.5	2.5	N.
Steller	Branch of Bering Glacier.	1	60 35	143 17	1	*7.5*	6.5	N.
		2	33	31	1	1	2.5	SE.
		3	33	32	1	.5	2.5	SSE.
		4	32	34	1	1	4	SSW.
		5	32	39	1	1	2.5	S.
Sioux	------	1	60 32	144 19	1	*3*	4.5	S.
		2	34	18	5	1	1	1 NW, 3 SW, 1 SE.
		3	32	18	1	1	1	NW.
Johnson	26	------	60 34	144 21	4	2.5	2.5	1 W, 3 NW.
Unnamed	8	------	60 36	144 21	2	1.5	1.5	N, SE.
Van Cleve	62	------	60 42	144 13	2	1	1	N.
Saddlebag	10	------	60 31	145 06	4	2.5	2.5	1 SSE, 2 SW, 1 NE.
Fickett	3	------	60 33	145 01	1	1	3	NNE.
Allen	230	1	60 46	144 50	1	2	3	N.
		2	45	45	1	1	2.5	NW.
		3	47	55	1	1	1.5	N.
Scott	155	------	60 43	145 08	3	1.5	1	SE.
Rude	26	1	60 47	145 11	1	2	5	NW.
		2	47	08	1	1	2	NW.
Tasnuna	31	------	61 02	145 27	1	1.5	2.5	WNW.
Columbia	1,370	1	61 13	147 14	1	1	1.5	SW.
		2	13	16	2	1	1.5	ESE.
Ranney	4	------	61 11	147 34	1	1	2	SE.
Serpentine	26	------	61 09	148 16	1	.5	2.5	S.
			06	18	1	.5	2	E.
Surprise	70	------	61 02	148 31	2	3	3	ESE.
Harriman	49	------	60 56	148 28	2	1	2.5	N.
Pigot	16	------	60 54	148 30	1	.5	4	E.
Twentymile	49	1	60 57	148 38	1	2	2.5	W.
		2	56	38	3	1.5	1.5	1 W, 2 NW.
Contact	10	------	60 28	148 28	4	3	1.5	NE.
Unnamed	11	------	59 48	149 57	3	1.5	1.5	W.
Do	4	------	59 42	150 03	2	2.5	1.5	W, SW.
Do	4	------	59 44	150 15	1	.5	1.5	E.

[1] Dust.

SHERMAN GLACIER

The Sherman Glacier (figs. 4*A*, 5) received one very large rockslide avalanche and several smaller ones at the time of the earthquake. The largest of these, which covers about 50 percent of the ablation area of the glacier, is 5.6 km long, as much as 4 km wide, and has an average thickness of 5 m (figs. 6, 7, 8). It has been computed by George Plafker (1965b) to contain about

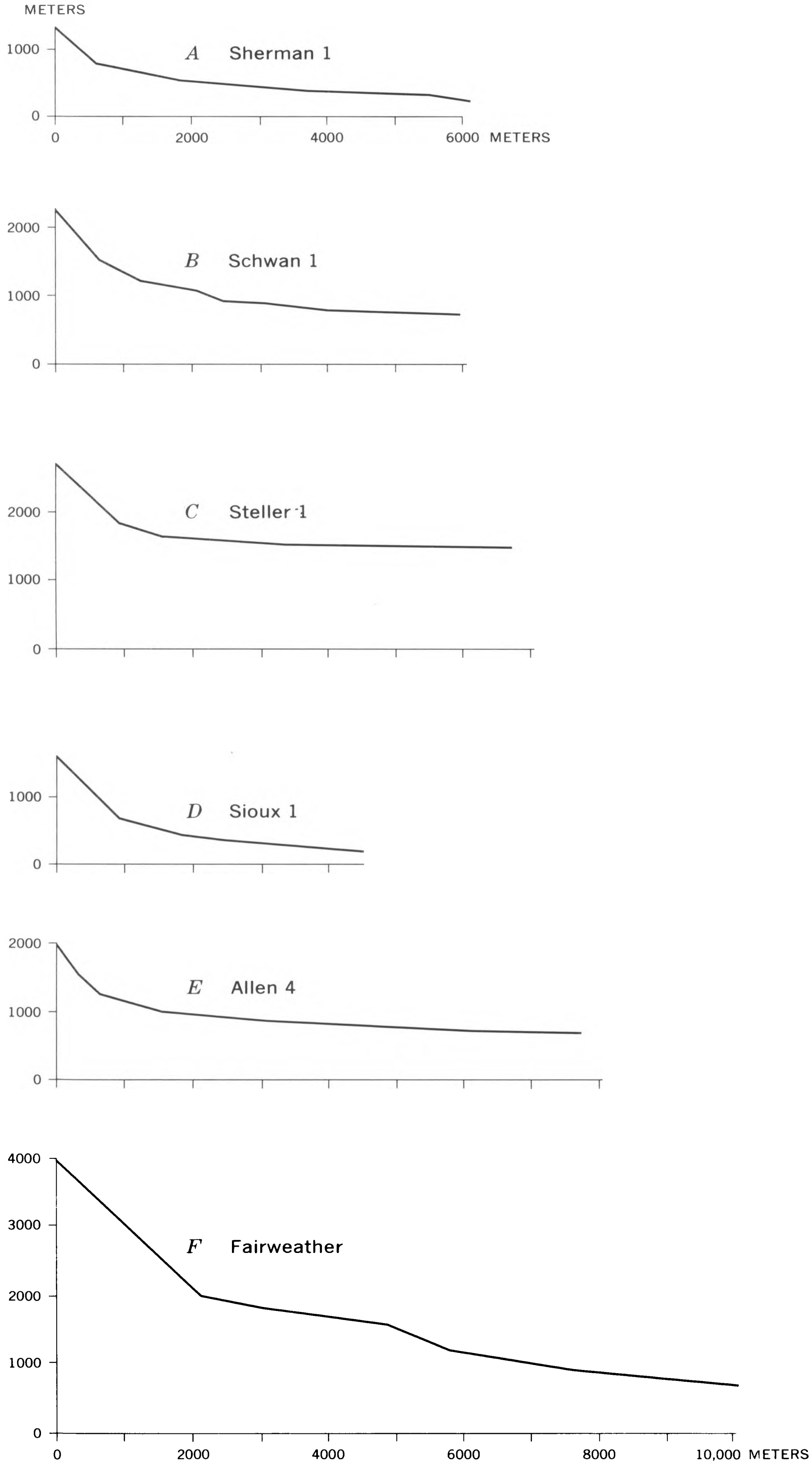
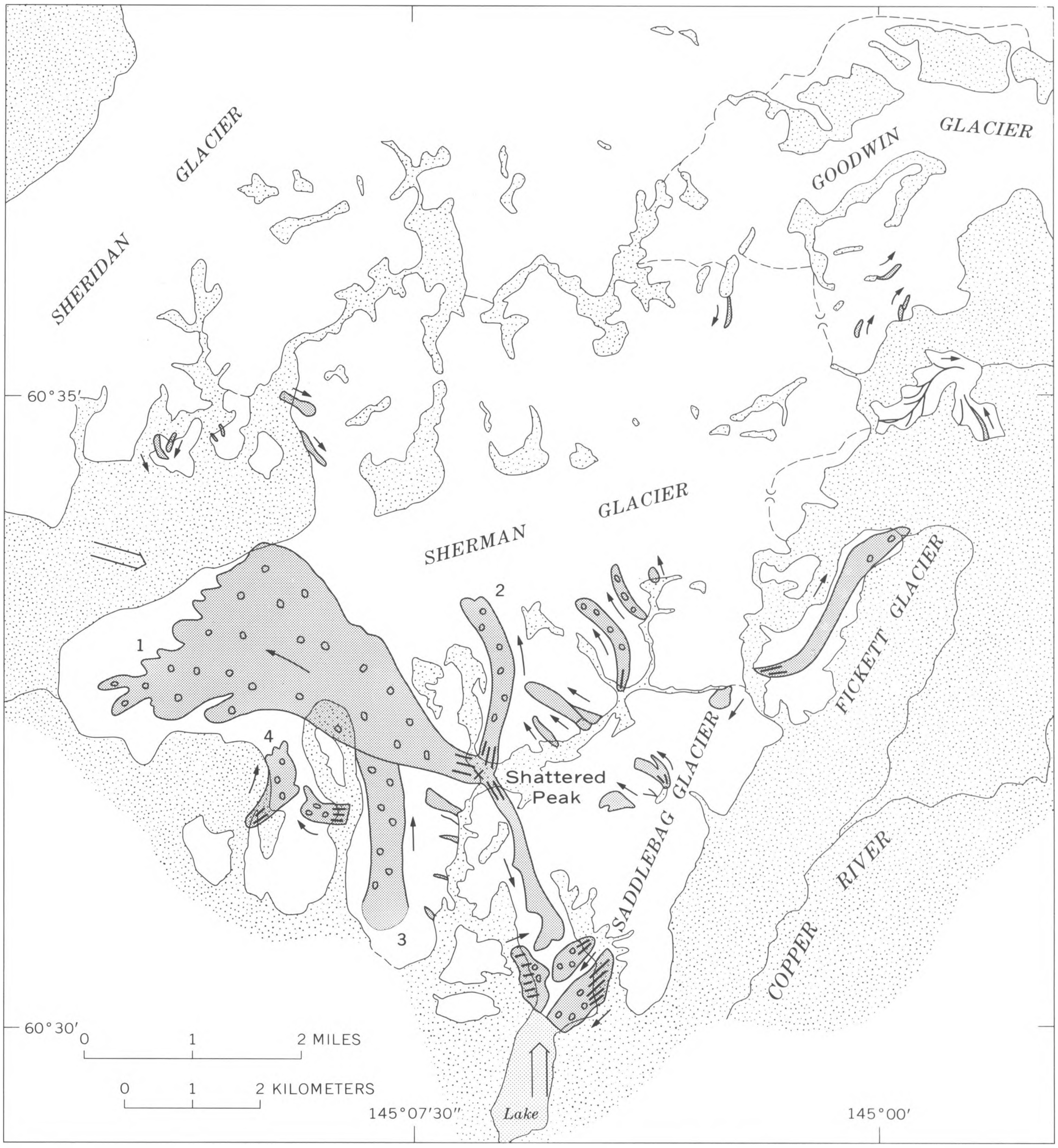


FIGURE 4.—Horizontal profiles of rockslide avalanches on glaciers. Datum is mean sea level.



EXPLANATION

AVALANCHE DEBRIS

Probably 1 meter or more thick containing rock fragments 3 meters or more long

Small volume of dust and fine rock debris

Source area of avalanche

Direction of view shown in accompanying photograph

Direction of movement

1
Number of avalanche listed in an accompanying table

Ice-covered divide

Figure 5.—Map of rockslide avalanches in the Sherman and Saddlebag Glaciers area.

FIGURE 6.—Rockslide avalanche on Sherman Glacier. The source was from the area marked by the fresh scar on Shattered Peak in middle distance. The debris displays flowlines and terminal digitate lobes. No marginal dust layer is present. The steep margin, about 20 m above the clear ice, is due to more rapid melting of the exposed glacier than the ice protected by the debris (see figs. 4A, 5, 7, 8). Photograph taken on August 25, 1965.

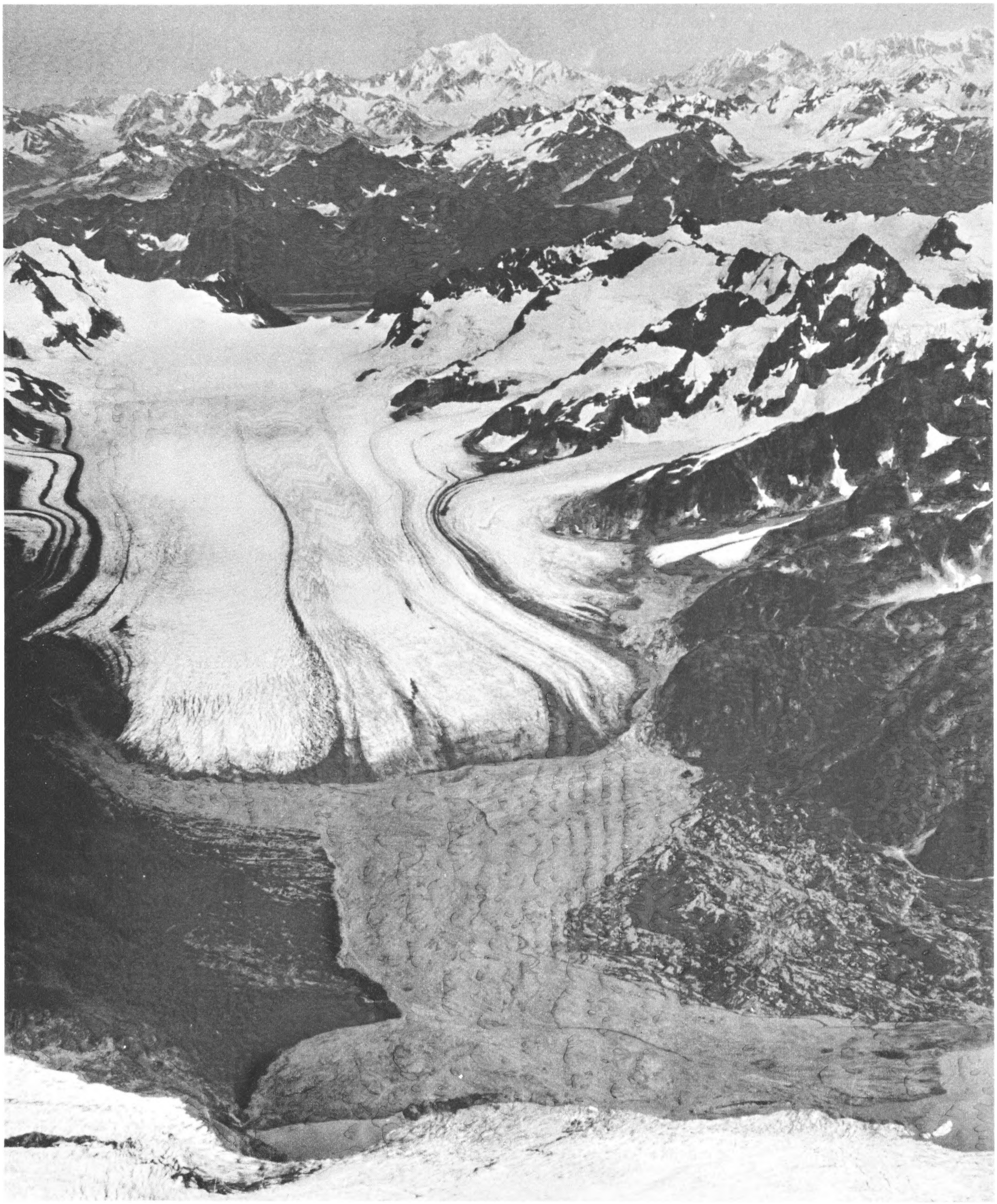


FIGURE 7.—Sherman Glacier on August 26, 1963, showing conditions before the earthquake; compare with figure 8.

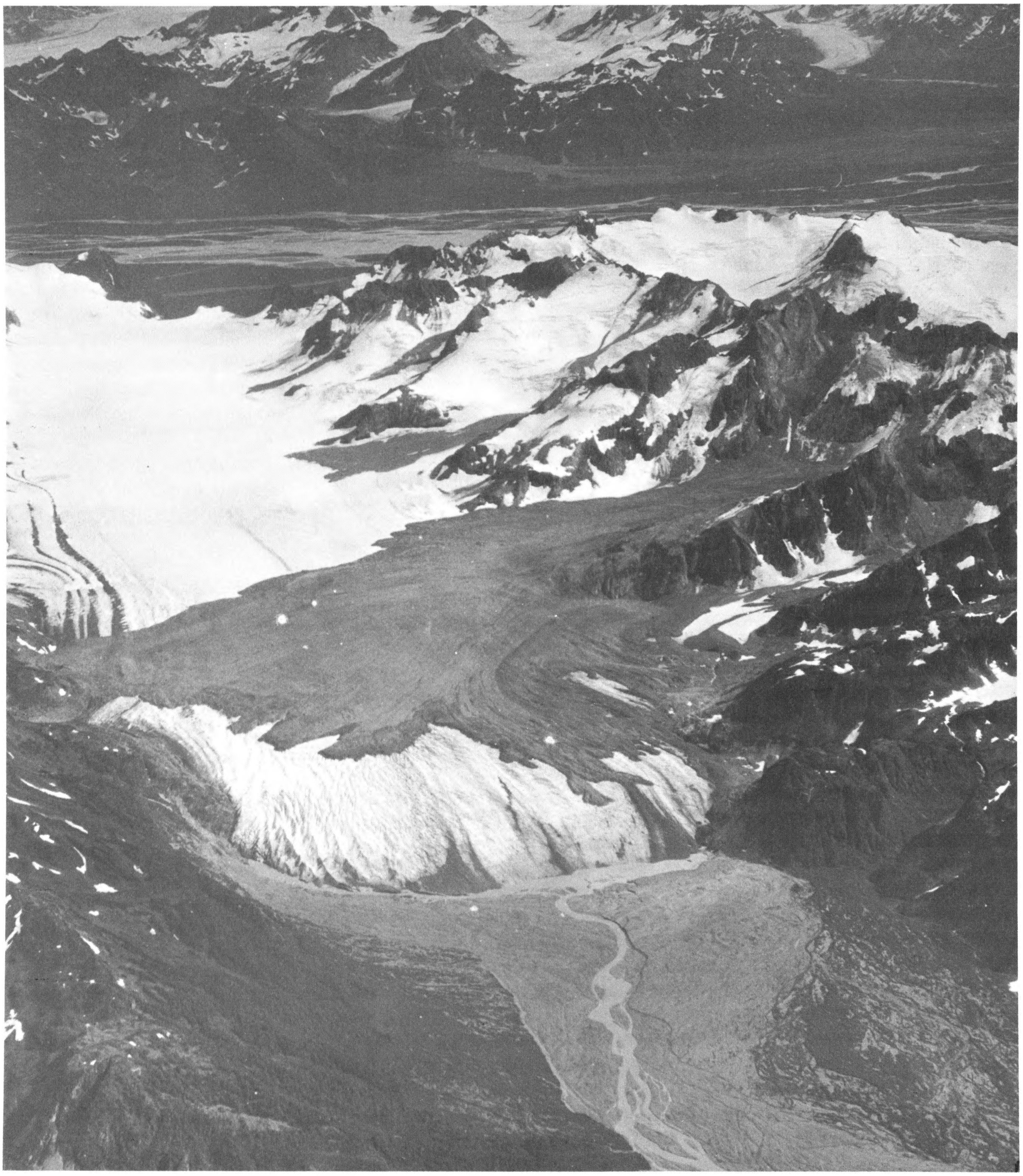
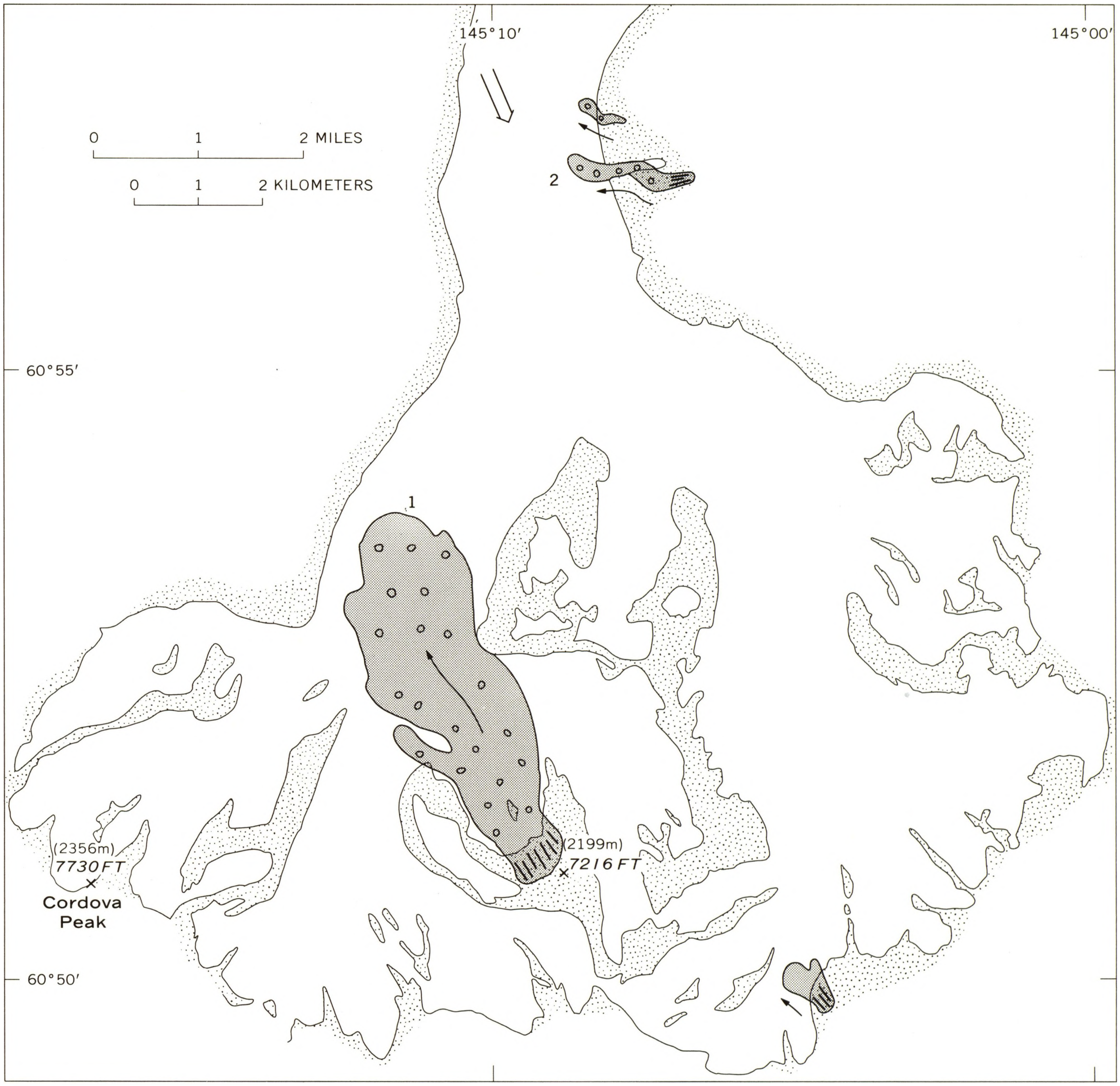


FIGURE 8.—Rockslide avalanche on Sherman Glacier. The avalanche was formed by the collapse of Shattered Peak in the middle distance. The debris shows flowlines and terminal digitate lobes. No marginal dust layer is present. View looking southeast. Photograph taken August 24, 1964.



EXPLANATION

AVALANCHE DEBRIS

Probably 1 meter or more thick containing rock fragments 3 meters or more long

Small volume of dust and fine rock debris

Source area of avalanche

Direction of movement

Direction of view shown in accompanying photograph

1

Number of avalanche listed in an accompanying table

FIGURE 9.—Map of rockslide avalanche on Schwan Glacier.

25 million m³ (cubic meters) of shattered rock debris and minor amounts of admixed ice and snow. Practically all of this material came to rest on the glacier below the firn line. No marginal dust layer is present. Possible effects of the avalanches on the glacier include reduced ablation, increased flow, and advance of the main glacier.

W. O. Field of the American Geographical Society (written commun., 1966) has commented: "The Sherman Glacier has retreated about 800 meters previous to 1950, from forest trimlines. From August 5, 1950, to June 1965, recession at the outermost part of the terminus in the middle of the valley totaled 375 meters, representing an annual average of 25 meters." However, by late summer 1965, an advance of as much as 6 m in some parts of the terminus may have occurred (M. T. Millett, oral commun.). A push moraine about 5 m high had formed (W. O. Field, oral commun.). Aerial photographs taken of the terminus in 1963 and 1964 show a small retreat between those dates; little further change in the terminal position of the glacier was noted in 1965.

The effect of the avalanche deposit on the behavior of the glacier and the mode of deposition of the avalanche debris are being investigated by Colin Bull of the Ohio State University Institute of Polar Studies (written commun., 1966).

SCHWAN GLACIER

Although the rockslide avalanche (figs. 4*B*, 9) on Schwan Glacier is one of the largest resulting from the 1964 earthquake, it covers only about 15 percent of the ablation area of this large glacier. Its effect on the glacier's regime therefore should be relatively small. Photographs taken in 1963, 1964, and 1965 show no apparent dynamic change in the glacier between these dates (figs. 10, 11).

BERING AND STELLER GLACIERS

With its major branch, the Steller Glacier, the Bering Glacier covers an area of about 5,800 km². Four rockslide avalanches more than 5 km in length and several smaller ones originated on Waxell Ridge. The largest avalanche (Steller 1) is 6.5 km in length, has a maximum width of 2 km, and probably contains at least 10 million m³ of rock. Because it lies well above the snowline and is therefore largely snow covered in all photographs, few details are known. From a maximum source altitude of nearly 3,000 m, the rock debris descended slopes of about 43° for 600 m. On reaching the nearly level glacier, the material swept out with a gradient decreasing to less than 2° in the last 3 km (fig. 4*C*). Snow on the upper parts of the other rockslide avalanches on Waxell Ridge obscures source areas (fig. 12). Four small avalanches occurred on the western part of the Steller Glacier (fig. 13).

No dynamic response to avalanche loading has been noted in any of the branches of Bering and Steller Glaciers where avalanches occurred. Long-term effects of the avalanche debris will be to reduce ice melt somewhat, but, relative to the size of these large glaciers, this effect will be insignificant.

MARTIN RIVER GLACIER

The Martin River Glacier (fig. 13) is fed by three major tributaries, the most northerly of which received three major avalanches (Tuthill, 1966). Together these probably contain about 24 million m³ of broken rock. Three other avalanches on this branch appear to be little more than thin layers of dust. The avalanches on this branch of the glacier are so large that some dynamic response to the loading would seem likely. About 5 percent of the glacier surface was covered with rock debris. As this material moves into the ablation area, its effect will be to reduce ice melt. A medial moraine near the center of the main tributary of the glacier moved down valley about 240 m between August 1964 and August 1965.

SIOUX GLACIER

The Sioux Glacier (unofficial name, Tuthill and others, 1964; Tuthill, 1966. Figs. 4*D*, 14) received the greatest number of rockslide avalanches, for its size, of any valley glacier (fig. 15). As a result, easily detectable changes in the glacier's regime are anticipated. Long-term effects of the debris will be to reduce ice melt, which will favor rejuvenation of the relatively inactive terminal ice and may eventually result in advance. Various features of the glacier are listed below.

Feature	*Size (km²)*
Accumulation area	12
Area covered by debris	2
Ablation area	5
Area covered by debris before earthquake	1
Area covered by debris after earthquake	4.5

About 17 percent of the accumulation area of the Sioux Glacier was covered by rockslide debris. Little dynamic response to this loading could be found in a comparison of vertical photo-

FIGURE 10.—Schwan Glacier on August 26, 1963, showing conditions before the earthquake; compare with figure 11.

FIGURE 11.—Rockslide avalanche on Schwan Glacier. The source of the avalanche is the mountain peak behind and to the left of the debris. A broad layer of dust surrounds the deposit. View looking southwest. Photograph taken August 25, 1964.

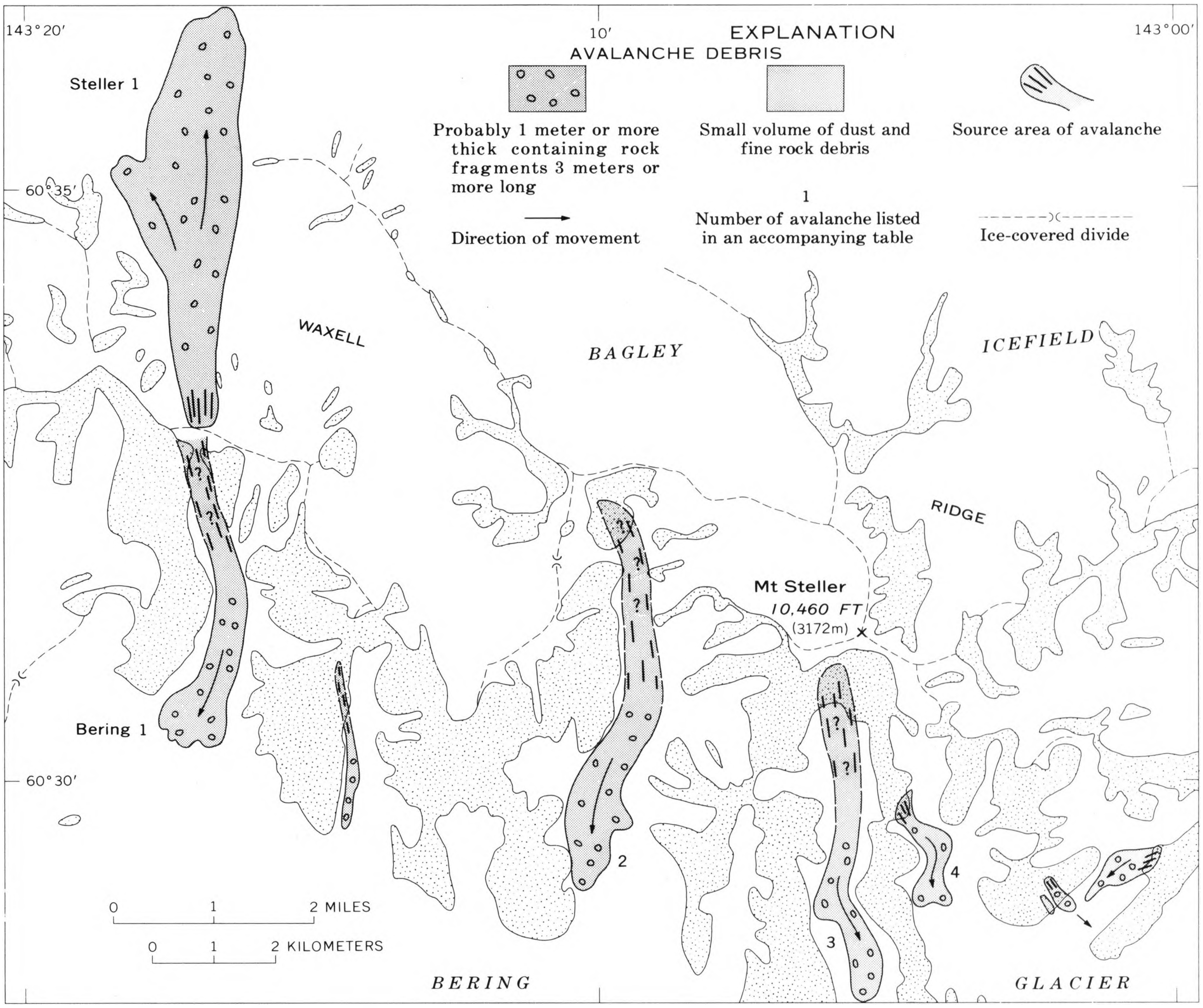


Figure 12.—Map of rockslide avalanches in the Waxell Ridge region, Bering and Steller Glaciers.

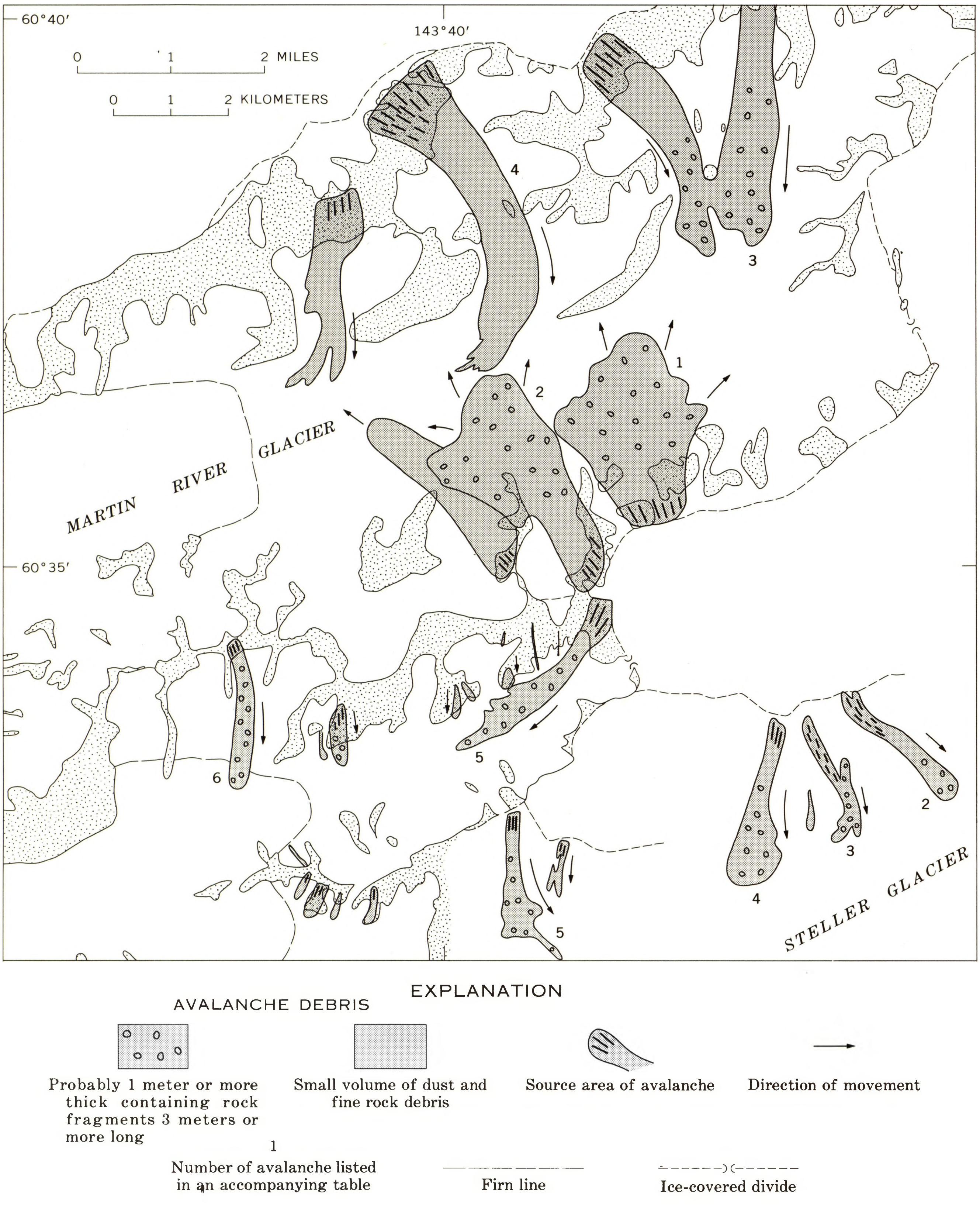
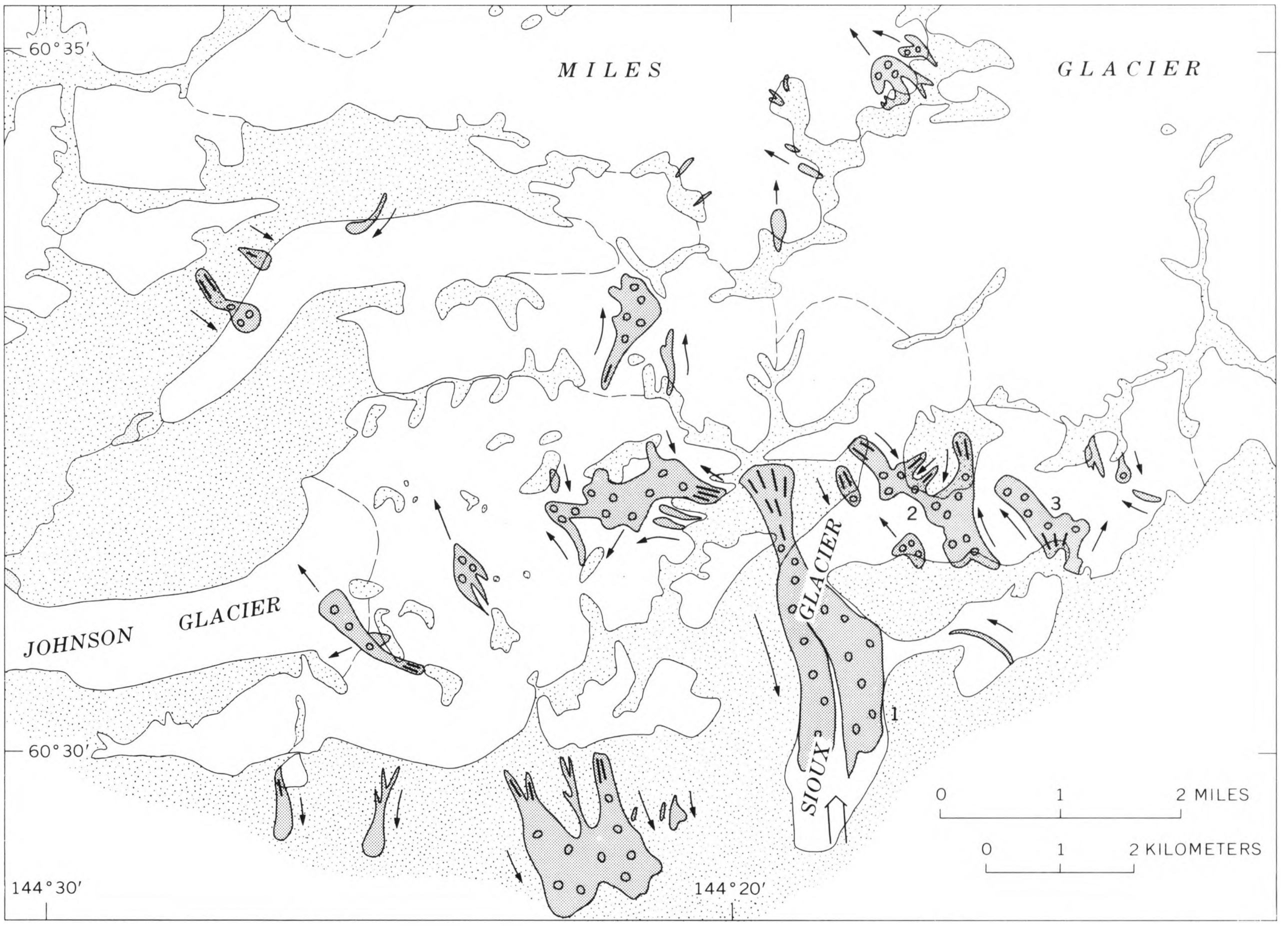


FIGURE 13.—Map of rockslide avalanches on the Martin River and western Steller Glaciers.



EXPLANATION

AVALANCHE DEBRIS

Probably 1 meter or more thick containing rock fragments 3 meters or more long

Small volume of dust and fine rock debris

Source area of avalanche

Direction of movement

Direction of view shown in accompanying photograph

1 Number of avalanche listed in an accompanying table

Firn line

Ice-covered divide

FIGURE 14.—Map of rockslide avalanches in the region of Sioux, Johnson, and Miles Glaciers.

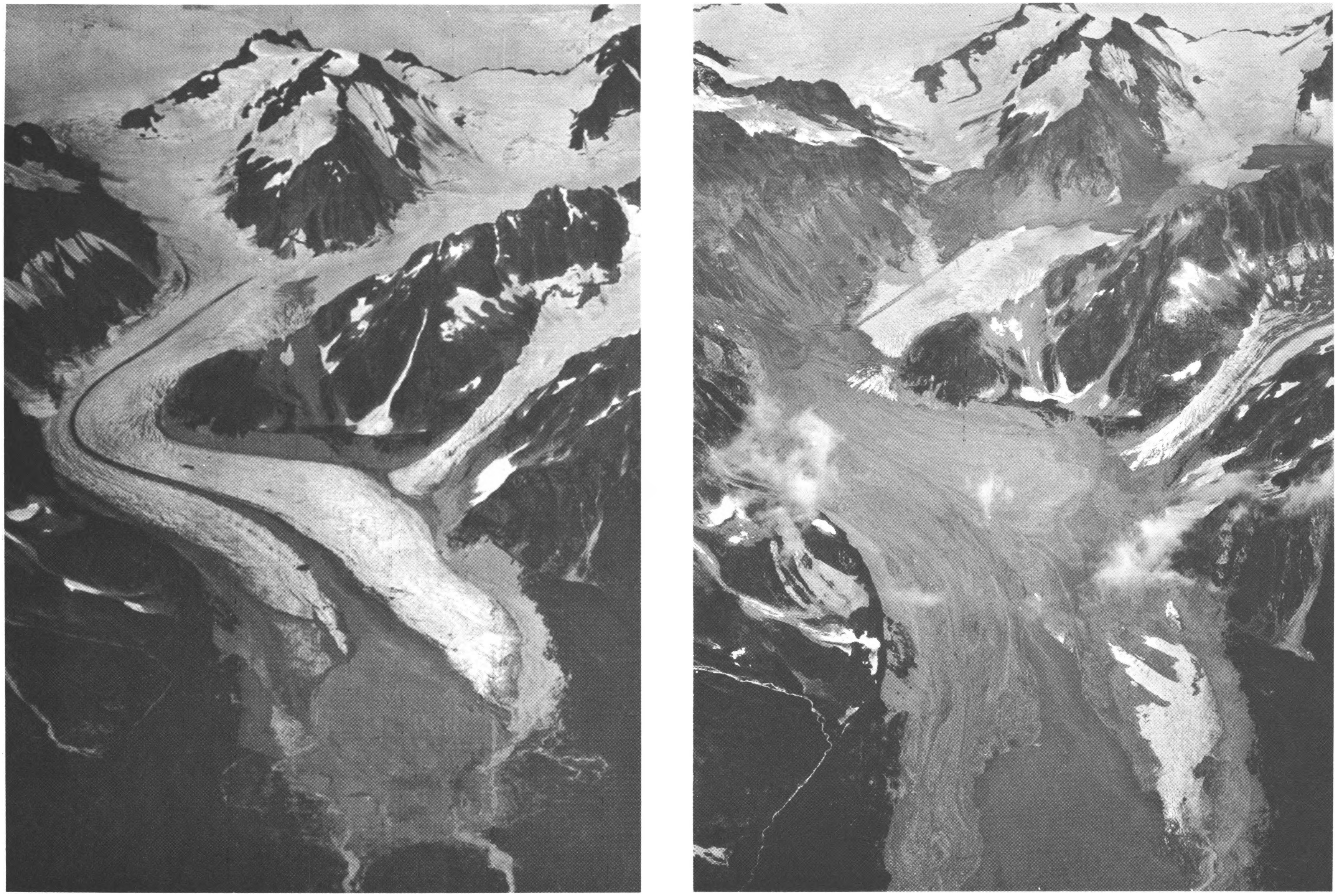


FIGURE 15.—Sioux Glacier on August 26, 1963 (left) and August 24, 1964 (right). **Nearly all of the ablation area** of this glacier was covered by debris from large rockslide avalanches orginating on the peak on the left. Other smaller rockslides occurred at many places in the accumulation area (see fig. 14). Views looking northwest.

FIGURE 16.—Saddlebag Glacier on August 26, 1963, showing conditions before the earthquake (above) and on August 25, 1965, showing conditions after the earthquake (below). Note the change in Shattered Peak. View looking north.

graphs taken in August 1964 and August 1965. Some slight increase in crevassing in the area of the firn line may have taken place.

After the earthquake, nearly 90 percent of the ablation area of this glacier was covered with debris. Tuthill (1966) estimated the avalanche debris at 8,400,000 m^3. According to the observations of J. R. Reid (University of North Dakota) on August 1, 1965 (written commun.), "This [avalanche debris] is already seen to be an important factor in the regimen of this glacier as the cover has already relatively raised the surface approximately 50 feet above the bare ice adjacent to it."

SMALLER AVALANCHES

In addition to the large avalanches described above, several smaller ones occurred which have features of interest as noted below.

SADDLEBAG GLACIER

Saddlebag Glacier (fig. 5) is quite similar to the Sioux in size and configuration. Approximately 50 percent of its ablation area was covered with debris from many small rockslides. The glacier terminates in a lake, which is more than 1.5 km long and was formed largely during the retreat of the glacier since 1948. No appreciable change in the glacier terminus was noted between August 1963 and August 1965 (fig. 16). A small advance or an increase in the rate of ice discharge into the lake is likely because of the decreased melting resulting from the avalanche debris.

ALLEN GLACIER

Three rockslide avalanches were noted in 1964 on Allen Glacier (fig. 17). The digitate margin of the largest avalanche deposit and the paths followed by various parts of the debris clearly indicate that several rockfalls must have occurred from the same general source area. No marginal dust area is present.

No dynamic effects of the avalanches on the glacier have been noted. The fact that the ice in the area where the largest 1964 avalanche (fig. 18) came to rest has remained almost unchanged from 1964 to 1965 suggests that there has been no significant increase in the amount of ice flowing from this part of the glacier.

The relation of glacier regime to earthquake effects is complicated by the fact that the Allen Glacier has shown evidence of increased flow in the terminal area each year since 1961. The nearby Childs Glacier, which is similar to the Allen in many respects, also clearly shows evidence of rejuvenation and some advance in the terminal area (figs. 19, 20). The cause of the advance is unknown, but these glaciers probably are responding normally to climatic fluctuations. About half of the terminal area of Allen Glacier is covered with ablation moraine and has remained stagnant. The section where ice is exposed appeared smooth and almost inactive in 1961; there were more crevasses in 1963. The 1964 observations disclosed an advance of about 300 m during the previous year; in 1965 an advance of an additional 300 m had occurred, and both an increase in thickness and more crevassing were discernible in nearly all of the lower parts of the glacier. It seems likely that neither the shaking nor avalanche loading is responsible for the present advance of Allen Glacier, for the advance was already under way prior to the earthquake in 1964.

FICKETT GLACIER

A rockslide avalanche originated on a peak at the head of the small Fickett Glacier (fig. 5) and swept down the center, coming to rest in the terminal area. Although nearly 40 percent of the glacier surface received some rock debris from this rockslide, the volume of the material was relatively small. Some decrease in ice melt will probably result.

UNNAMED GLACIER NEAR PAGUNA BAY

Small rockslides from at least five sources avalanched onto a small unnamed glacier in the Kenai Mountains at lat 59°42′, long 150°03′. About 50 percent of its surface was covered with rock debris. Decreased melting and possible future advance of this glacier may result.

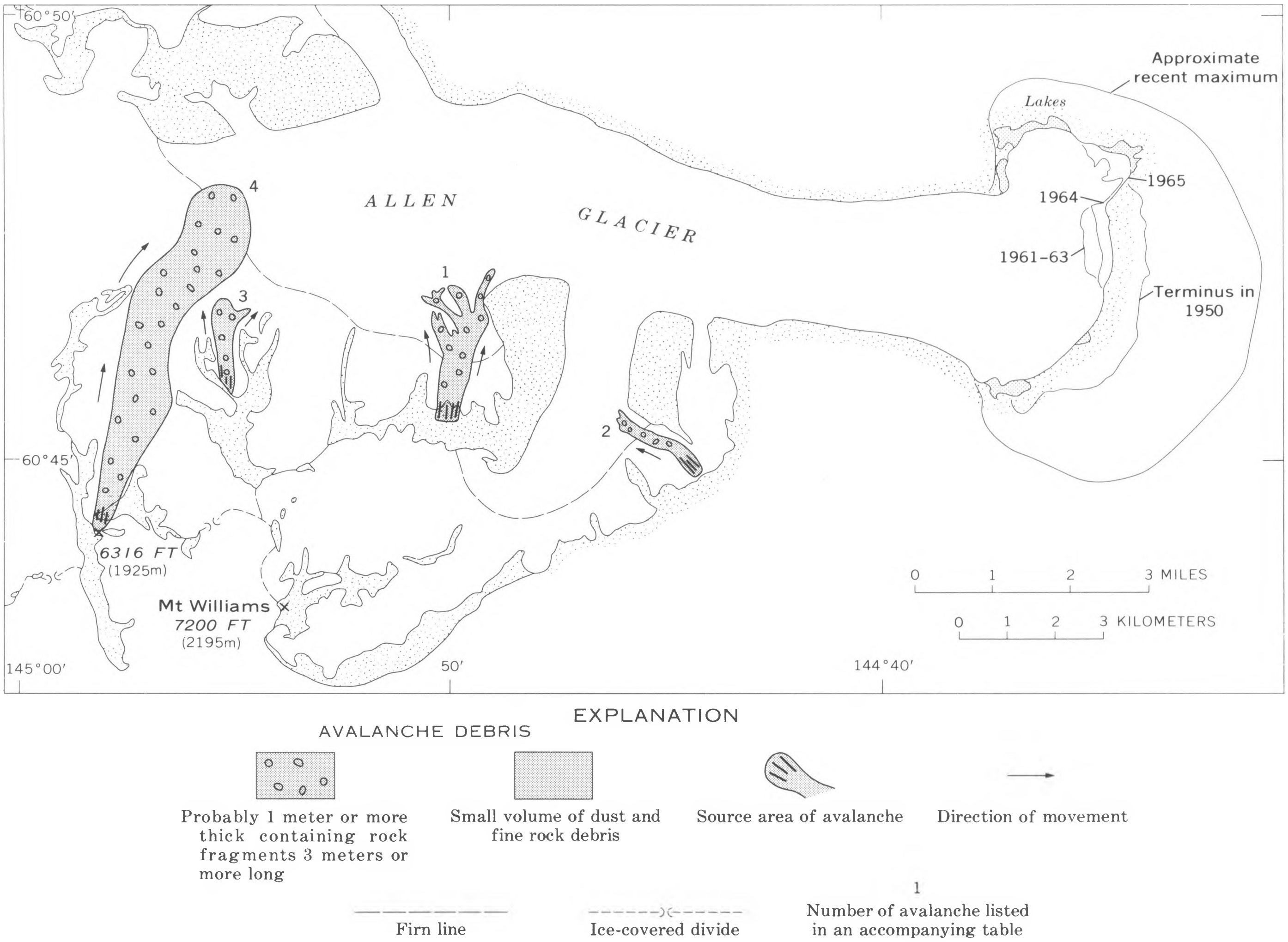


FIGURE 17.—Map of rockslide avalanches on Allen Glacier.

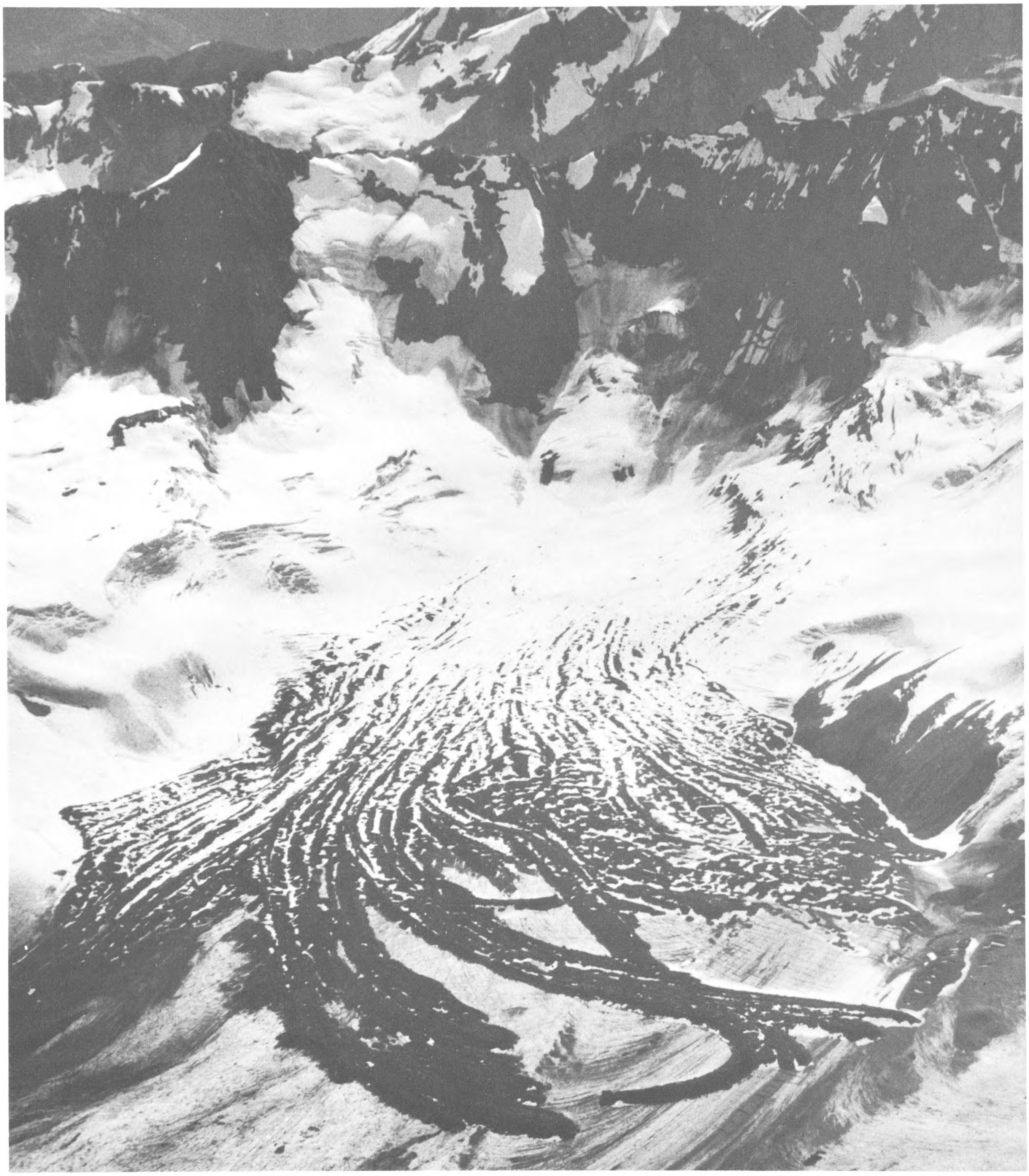


FIGURE 18.—Allen Glacier rockslide avalanche 1 (see fig. 17). The digitate margin of this avalanche deposit and the paths followed by various parts of the debris, some of which override others, clearly indicate that several rockfalls must have occurred from the same general source area. No marginal dust layer is present. Photograph taken on August 25, 1965.

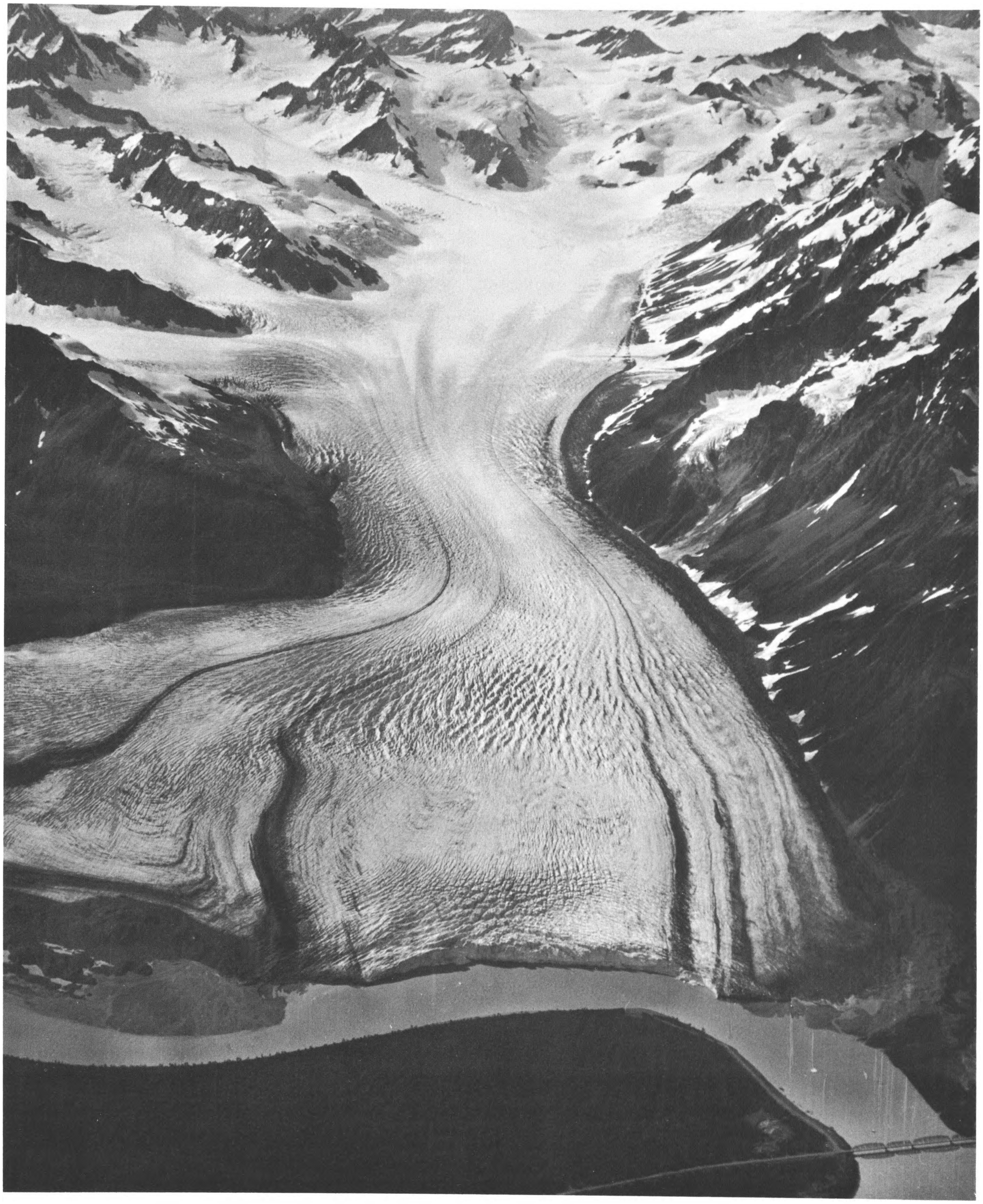


FIGURE 19.—Childs Glacier, August 26, 1963, showing conditions before the earthquake; compare with figure 20.

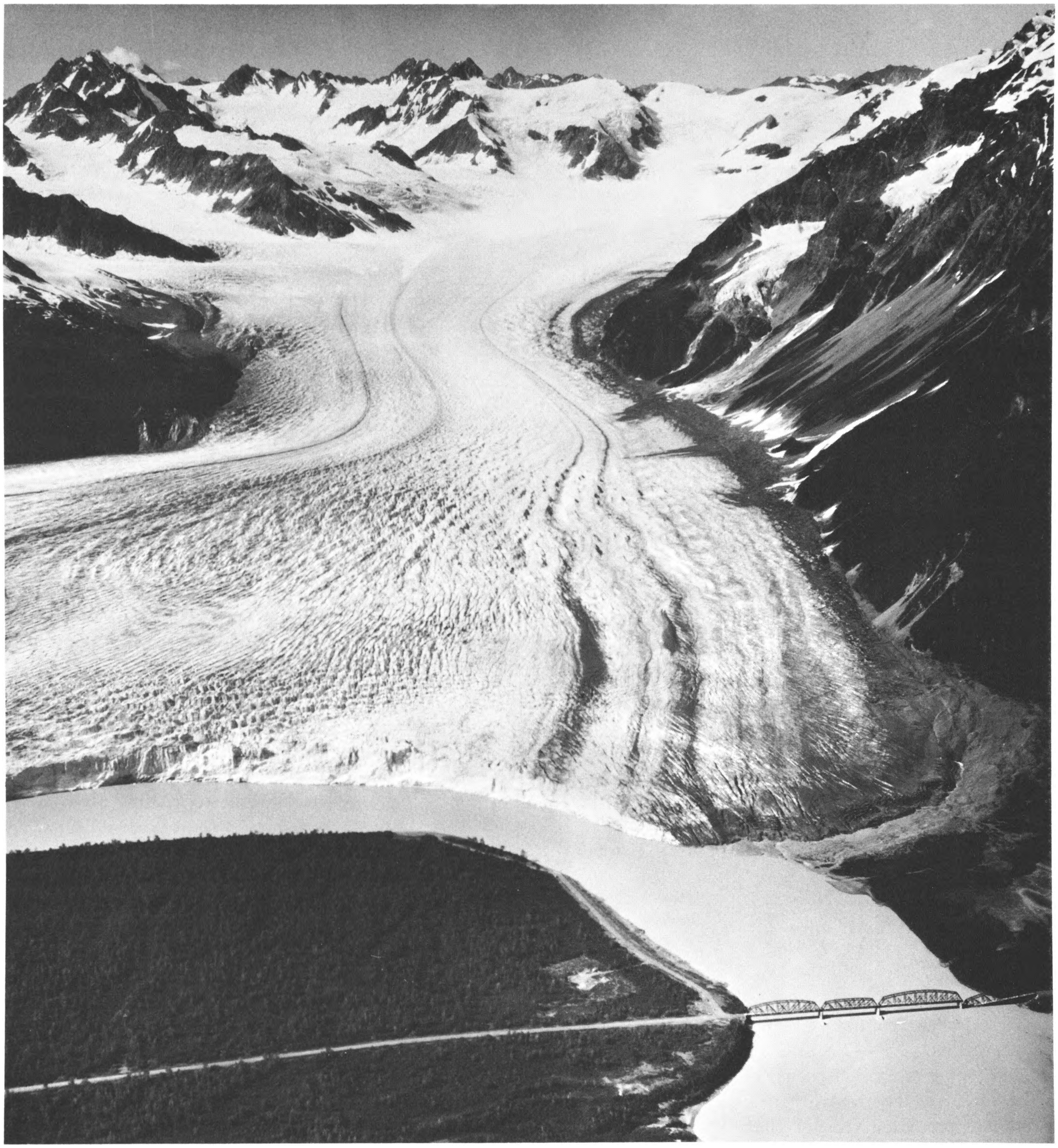


FIGURE 20.—Childs Glacier, August 25, 1965, showing conditions after the earthquake. The size and distribution of the small rockslides on the glacier are fairly typical of the slides in many areas in the Chugach and Kenai Mountains. No dynamic response of the glacier to these avalanches has been noted, nor, in view of the small volume of the rockslides, is a response probable. Since 1960, this glacier has thickened and advanced in the terminal area. Note the change in the glacier on the right; the small marginal lakes visible in the 1963 view are almost completely covered by the advancing glacier in 1965. The Million Dollar Bridge, a span of which was shaken down by the earthquake, crosses the Copper River (lower right of the photograph).

ROCKSLIDE AVALANCHES NOT ASSOCIATED WITH THE 1964 EARTHQUAKE

AVALANCHES BEFORE THE 1964 EARTHQUAKE

Large avalanches on several glaciers in Alaska occurred in the two decades before the 1964 earthquake. Prominent older undated deposits are located on the Chistochina Glacier in the Alaska Range and on Casement Glacier in Glacier Bay. Rockslides have avalanched repeatedly on Margerie Glacier near Glacier Bay, the most recent in 1961.

Some especially conspicuous avalanches on glaciers that were noted before the 1964 earthquake are listed in table 3. In the Chugach Mountains the 1960 avalanche on Barry Glacier and the 1963 avalanche on Surprise Glacier occurred about 38 and 55 km, respectively, west of the 1964 earthquake epicenter. A rockslide avalanche from the same source as the 1963 avalanche covered part of the Surprise Glacier at the time of the 1964 earthquake.

TABLE 3.—*Rockslide avalanche deposits on glaciers since 1945 and prior to 1964 earthquake*

Glacier		Avalanche					
Name	Area (km²)	Year	Latitude	Longitude	Area (km²)	Length (km)	Direction traveled
			° ′	° ′			
Casement	181	1945?	59 07	135 47	3	2.5	SE
Johns Hopkins	310	1961?	58 47	137 10	2	2	NE
Margerie	130	1961	58 56	137 13	2.5	3	SE
Netland	39	1952?	59 26	137 54	2.5	2.5	NW
Smith	18	1955?	61 16	147 48	.5	1.5	E
Bryn Mawr	23	1960?	61 15	147 52	1	3	ESE
Vassar	13	1958?	61 13	147 53	1	1.5	ESE
Barry	78	1960	61 11	148 07	4	3.5	SE
Serpentine	16	1963?	61 07	148 16	.5	2.5	W
Surprise	57	1963	61 02	148 31	.5	1.5	SE
Pigot	21	1945?	60 54	148 29	1	3	E

ROCKSLIDE AVALANCHES SINCE AUGUST 1964

Two very large rockslide avalanches occurred in south-central Alaska between August 24, 1964, and August 22, 1965. One of these (Allen Glacier 4, fig. 21) occurred in the vicinity of three rockslide avalanches on Allen Glacier that had probably been caused by the 1964 earthquake. It is larger and has a lower gradient than any of the rockslide avalanches that occurred at the time of the earthquake (fig. 4*E*).

A rockslide avalanche on Fairweather Glacier (fig. 22), which probably occurred during the summer of 1965, is the longest of any of those observed. Its overall gradient is also much the steepest, in that the material was derived from as high as 4,050 m on the mountain whereas the toe of the debris is at only 700 m (figs. 4*F*, 23). The Fairweather Glacier avalanche is 600 km east-southeast of the 1964 earthquake but near the Fairweather fault along which movement occurred during the 1958 earthquake. This latter earthquake, which registered more than 8 on the Richter Scale, caused a major rockslide avalanche into Lituya Bay some 30 km south. The location, area, and length of the Allen 4 and Fairweather Glacier avalanches as well as other recent smaller rock avalanches are listed in table 4. These avalanches do not differ significantly from those which occurred at the time of the earthquake.

A rockfall avalanche, more than 6 km in length, occurred on Emmons Glacier on Mount Rainier, Wash., in 1963 (Crandell and Fahnestock, 1965). No earthquakes of notable magnitude had occurred in the region between 1948 and 1964, and no earthquake was recorded at the time of the initial rockfall. This evidence indicates that large and potentially destructive rockslide avalanches, although more likely to occur during violent earthquakes, do occur at other times.

TABLE 4.—*Rockslide avalanches more recent than 1964 earthquake*

Glacier		Avalanche					
Name	Area (km²)	Year	Latitude	Longitude	Area (km²)	Length (km)	Direction traveled
			° ′	° ′			
Allen (avalanche 4)	230	1965?	60 47	144 56	7.5	7.5	NNE
Fairweather	260	1965?	58 53	137 40	8.5	10.5	WSW
Blossom	8	1965	60 03	140 05	1.5	1.5	E
Marvine	310	1965	60 06	140 07	1	3	W

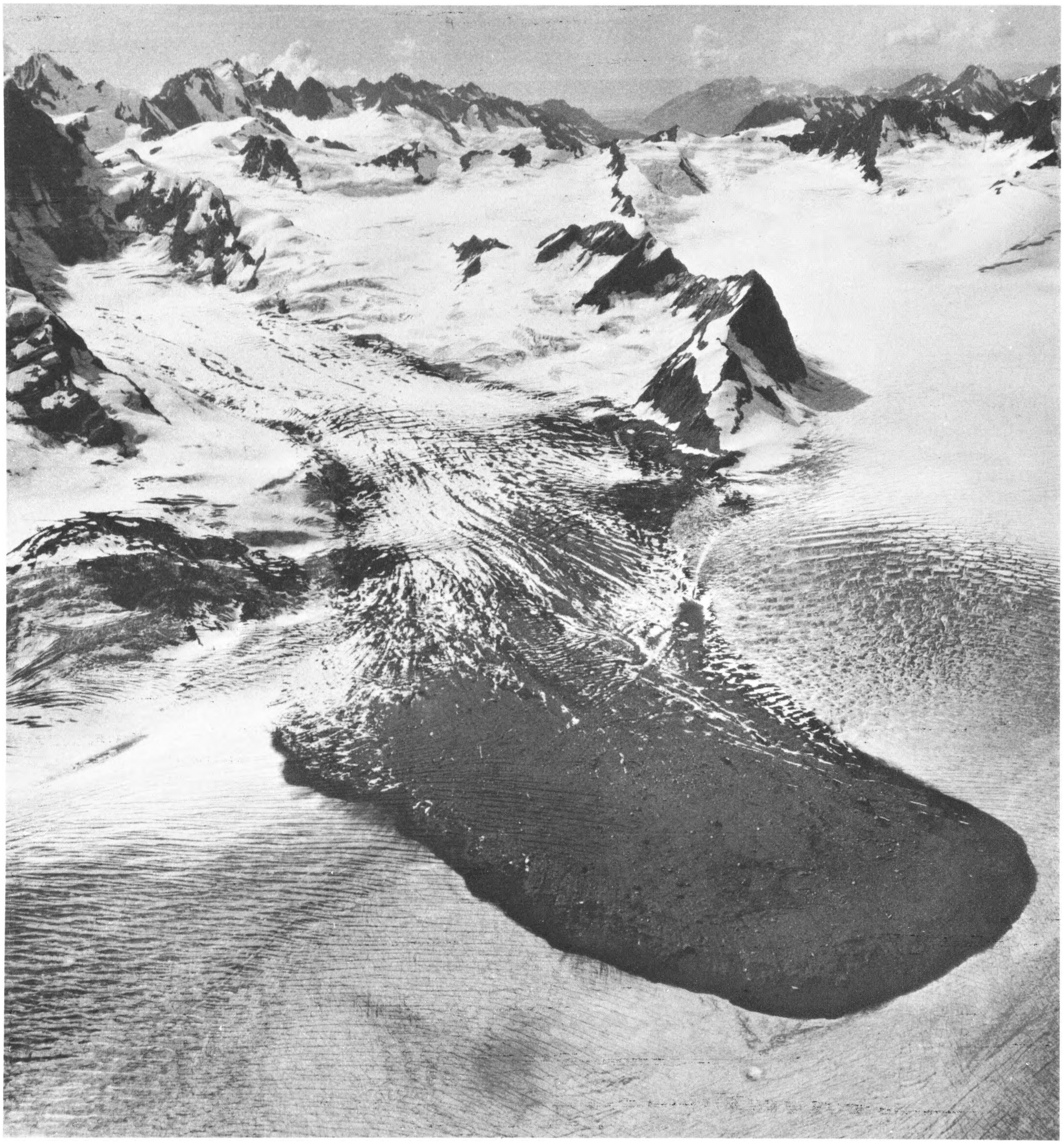


FIGURE 21.—Allen rockslide avalanche 4, view looking southwest. This avalanche was not present on August 24, 1964. The source area was the black cliff at the head of the tributary branch of Allen Glacier. This avalanche traveled 7.5 km and has a maximum width of 1.5 km (figs. 4*E*, 17). Many large rock fragments are included in the debris and a thin layer of dirt and dust borders the edge of the deposit. A much smaller avalanche, Allen 3 (table 2), which occurred in 1964, can be seen to the left of the 1965 debris. Photograph taken on August 25, 1965.

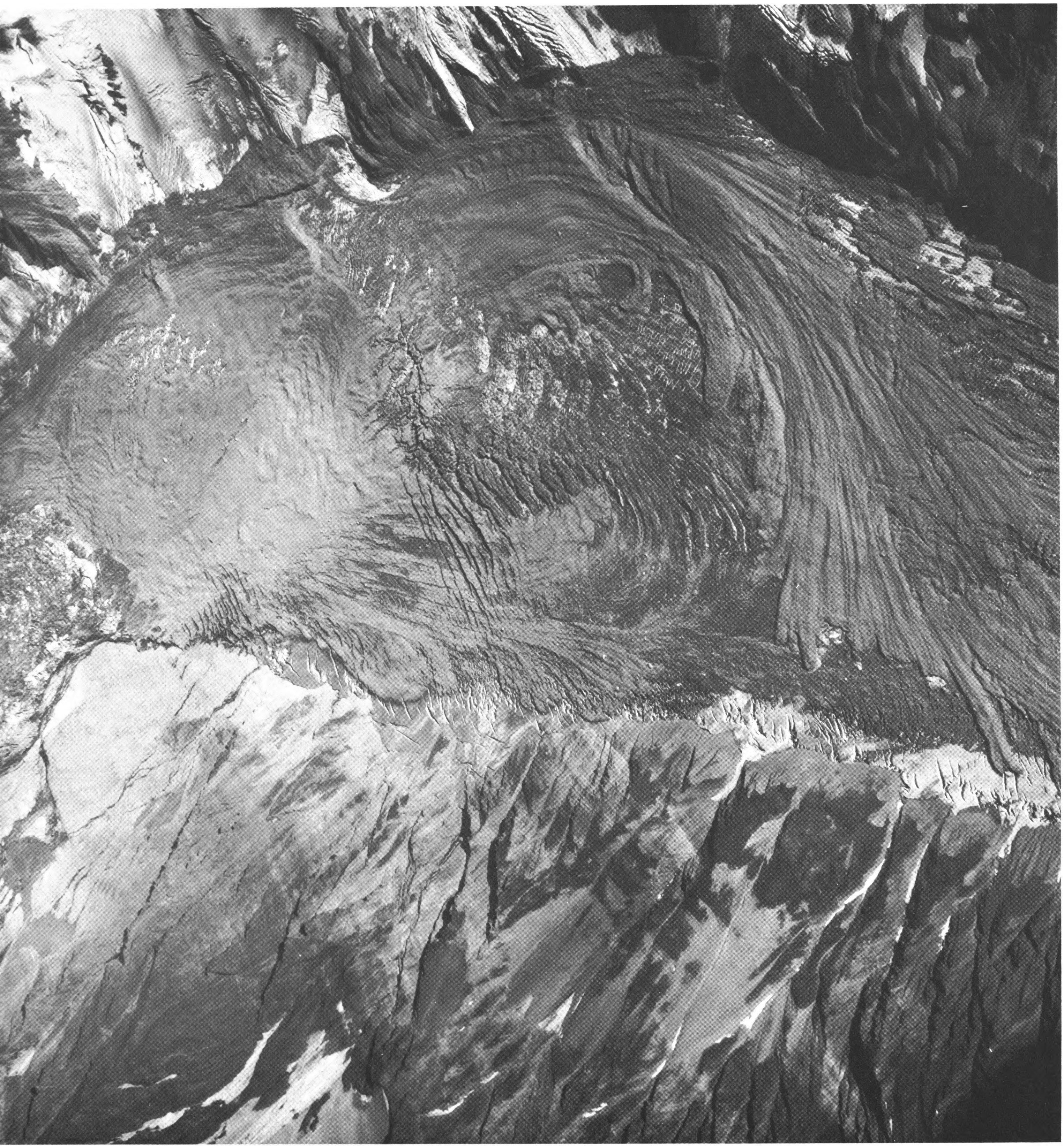


FIGURE 22.—Rockslide avalanche on Fairweather Glacier August 22, 1965; view looking east. The avalanche scar on Mount Fairweather was not present in August 1964. Dust clouds attest to the continued fall of debris from the source area. The avalanche traveled 10.5 km and had a maximum vertical descent of 3,350 m (fig. 4F).

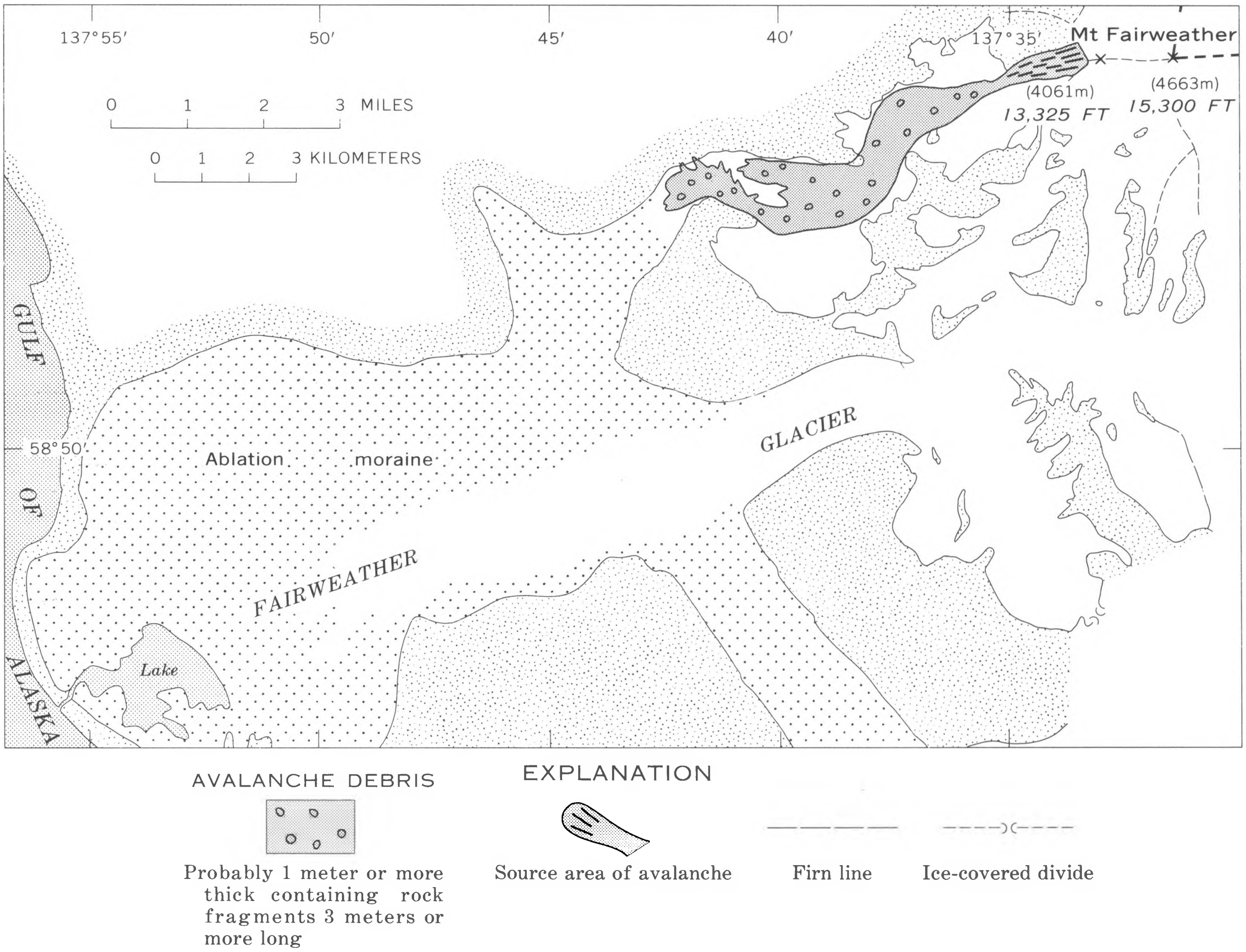


FIGURE 23.—Map of rockslide avalanche on Fairweather Glacier.

GENERAL CHARACTERISTICS OF THE LARGER ROCKSLIDE AVALANCHES

Sherman 1, Schwan 1, Steller 1, Sioux 1, Allen 4, and the Fairweather Glacier avalanches display several common characteristics: (a) the source area was a cliff currently undergoing glacial erosion; (b) the volume of the material moved was probably at least 400,000 m^3; (c) the avalanche initially descended very steep slopes for at least 600 m and gained very high velocity; (d) on reaching the glacier, the rock debris swept over surficial features, such as medial moraines, without greatly modifying them; (e) the gradient of the avalanche on the glacier surface was often less than 5°; (f) the distance traveled by the avalanches at low gradient was several kilometers. Profiles of these avalanches are shown in figure 4.

The distances traveled by the largest Sherman, Schwan, Allen, Steller, and Fairweather rockslide avalanches at low gradients suggest that the friction of the debris on the glacier surface was remarkably small. This prompted one observer to comment that glaciers must be "slick as ice." Shreve (1966) suggested that compressed air may have constituted an easily sheared lubricating layer for the Sherman avalanche.

The avalanches exhibit variations in the size of the fragments and the density of material. Most of the larger avalanches contain blocks exceeding 3 m in greatest dimension. The bulk of the material consists of fairly small fragments either scattered uniformly over the deposit or concentrated in irregular hummocks or windrows. Clearly defined banding or flow lines in the direction of movement is shown by only one avalanche (fig. 6). The margins of several deposits terminate in fairly smooth, rounded outlines (fig. 21); others are moderately irregular with digitate margins (fig. 6). Smaller avalanches were highly irregular (fig. 18).

E. R. LaChapelle (written commun., 1966) comments:

The digitate lobes exhibited by the Allen 1 and Fairweather rockslide avalanches [figs. 18, 22] are characteristic of wet-snow avalanches. The 'wheeling' and erratic crossflow shown in figure 18 are often seen in large wet-snow avalanches which run out onto nearly level terrain. It appears that the same flow mechanism must be at work in both wet-snow and rock avalanches. The presence of water in the latter is to be suspected. Dry-snow avalanches do not exhibit these peculiar flow patterns.

Rockslides on glaciers resulting from the earthquake appear to be generally composed of coarse materials or are thick enough to reduce rather than increase melting of the underlying ice. Thus, after a few years' ablation, avalanches below the firn line tend to become platforms whose surfaces stand considerably above the surrounding ice. A good example of such effects after several years' ablation is a large deposit on Netland Glacier in the Alsek River valley which resulted from a rockslide avalanche occurring some time after 1951 (fig. 24).

W. O. Field (written commun. 1966) states, "At the lower end of the Sherman slide, the debris was already on a well-formed platform on October 1, 1964, after only one ablation season. In July 1965 the top of the debris at the lower end of he slide, which was about 5 feet thick, was already about 30 feet above the surrounding clear ice surface."

Figures 11 and 21 show a continuous dust layer 30 m or more in width around the margins of the Schwan and Allen 4 avalanches. If these avalanches traveled on cushions of compressed air, this dust may have been expelled from beneath the debris as the avalanche came to rest (Crandell and Fahnestock, 1965, p. A10). Dust bands are not present adjacent to most smaller avalanche deposits, or where the avalanche deposit has a digitate margin (Allen 1, Sherman 1, and Fairweather). A layer of dust around the margin of a small rockfall on Scott Glacier is separated from the coarse debris by 30 m or more of clean snow. Some smaller avalanches seem to consist largely of dust and fine rock debris.

FIGURE 24.—Rockslide avalanche on Netland Glacier (location shown on fig. 1). This avalanche occurred sometime between 1951 and 1961. Note the height of the "table," estimated to be 30 m or more, formed by the debris which has retarded the melting of the underlying ice. Photograph taken August 29, 1964.

CHANGES IN DRAINAGE AND FLOW OF GLACIALLY FED RIVERS DUE TO THE 1964 EARTHQUAKE

Reports that the discharge of the Copper River was greatly reduced temporarily after the earthquake led to some speculation that changes in glaciers near the river might have been the cause. No major changes were found in large glaciers which border the river.

Several glaciers in the area affected by the earthquake block side valleys and form lakes (Stone, 1963). Most of these lakes drain under or alongside the glaciers during the summer months. Ragle, Sater, and Field (1965b) observed several of these lakes in April 1964, but, because of the presence of snow and because of the dearth of observations made in former years for comparison, they were unable to draw any firm conclusions as to the effect of the earthquake on these lakes. The author's photographs of many of these lakes taken in 1960, 1961, 1963, 1964, and 1965 provide evidence that conditions observed in late August 1964 were typical of other years.

A large lake on the west side of Columbia Glacier (lat 61°02′, long 147°08′) was considered by G. Swinzow to have been lowered by the earthquake (cited by Ragle and others, 1965a, p. 20). No evidence supporting this lowering was found in a photograph of the lake taken by T. L. Péwé on April 1, 1964. If recent lowering of the lake had taken place, snowfall since the earthquake had concealed all evidence along the shorelines of any former level of the water.

The late August levels of most of the larger glacier-dammed lakes in the Chugach Kenai Mountains are listed in table 5. Although

TABLE 5.—*Late August levels of glacier-dammed lakes in the Chugach and Kenai Mountains, 1960–65*

[D, drained practically dry; H, high; In, intermediate level; L, low]

Lake	Glacier	Latitude	Longitude	Length (km)	1960	1961	1963	1964	1965	Remarks
		° ′	° ′							
Unnamed	Bering	60 20	142 56	2	-----	-----	H	-----	-----	Marginal, near McIntosh Peak; probably does not drain.
Do	do	17	143 01	1	-----	L	-----	-----	-----	Near head of Kosakuts River.
Hana	do	15	07	5	L	L	L	L	L	In Grindle Hills. Lowered to lateral moraine about 1959 by glacier recession.
Unnamed	do	17	16	2	L	H	D	H	-----	Marginal embayment, northwest side of Grindle Nunatak.
Do	do	23	30	5	H	H	H	H	H	In Khitrof Hills between Bering and Steller Glaciers; drains rarely if at all.
Do	do	24	32	2	H	H	H	-----	H	In Khitrof Hills, Steller Glacier side; generally ice filled.
Do	do	23	44	2	L	-----	H	L	-----	Southeast of present Berg Lake.
Berg	do	25	47	8	H	H	H	H	H	Formed owing to glacier recession by joining of 5 former marginal lakes. Present outlet on bedrock. Apparently drains rarely if at all.
Barkley	Tana	44	142 37	2	L	L	L	L	L	Formerly as much as 11 km long in Granite Creek valley. Outlet is along margin of Tana Glacier.
Unnamed	do	47	57	6	-----	-----	-----	H	-----	Altitude 957 m; outlet under Tana Glacier.
Do	Unnamed	47	143 44	2	-----	-----	H	L	-----	Altitude 1,250 m; between two glaciers; ice on three sides.
Canyon	Martin River	30	54	1	D	-----	-----	D	-----	Formerly up to 3 km long; drains under glacier.
Unnamed	do	31	144 12	2	L	L	L	L	L	Side valley, outlet over lateral moraine to glacier; not recently filled.
Van Cleve	Miles	42	144 22	6	H	In	L	L	L	Between Miles and Van Cleve Glaciers; probably drains annually.
Unnamed	do	42	29	1	L	-----	-----	H	-----	Lateral, probably drains annually.
Do	McPherson	35	37	2	-----	-----	H	-----	L	Drainage caused washout of part of Copper River Highway in 1965.
Do	Unnamed	49	32	3	-----	-----	-----	-----	-----	Glacier blocks main valley; between two glaciers, West Branch Rude River.
Trap	Tsina	61 14	145 55	2	-----	-----	L	-----	-----	Between two glaciers; probably does not drain.
Unnamed	Valdez	13	146 07	1	H	-----	-----	H	-----	Between two glaciers formerly joined.
Iceberg	Tazlina	36	28	3	-----	-----	-----	-----	-----	In side valley, east side of glacier; probably drains annually.
Unnamed	do	38	38	6	-----	H	-----	H	-----	In side valley, west side of glacier between glaciers. May lower annually.
Do	Nelcina	39	52	3	-----	-----	-----	-----	-----	South lake of two lakes on east side of glacier.
Do	do	42	55	2	-----	-----	-----	-----	-----	North lake of two lakes on east side of glacier.
Number One	Columbia	08	48	2	H	H	H	H	H	Between Columbia and Anderson Glaciers. Seldom if ever drains.
Unnamed	do	07	53	2	H	H	H	H	H	In side valley southwest of lake Number One. Seldom if ever drains.
Do	do	06	54	2	L	In	-----	In	D	West of Clear Creek. Generally ice filled.

data are not complete, the indications are that 1964 conditions followed normal patterns and that the 1964 earthquake had little, if any, effect on the formation and drainage of these lakes.

Careful observations were made in 1964 and 1965 to determine if there had been changes in surficial or englacial drainage systems, but no evidence of such changes was found. A few minor changes in stream channels near glaciers resulting from alluvial cracking were noted. Some minor stream diversion was found where water from Sherman Glacier crossed alluvial outwash. There was no evidence of any permanent changes in stream channels.

TABLE 5.—*Late August levels of glacier-dammed lakes in the Chugach and Kenai Mountains, 1960–65*—Continued

Lake	Glacier	Latitude	Longitude	Length (km)	1960	1961	1963	1964	1965	Remarks
		° ′	° ′							
Unnamed	Columbia	02	147 08	5	L	H	H	L	L	In lateral valley, northwest of terminus; probably lowers annually.
Billys Hole	do	06	12	5	H	H	H	H	H	In lateral valley; seldom if ever drains.
George	Knik	17	148 35	21	L	-----	-----	L	L	Usually drains annually.
Unnamed	Unnamed	60 29	55	2	-----	-----	H	-----	-----	In lateral embayment, generally ice filled.
Do	Excelsior	02	42	3	-----	H	-----	H	-----	In lateral valley on east side. Probably drains annually.
Do	Ellsworth	07	149 01	2	-----	-----	-----	-----	-----	In lateral valley, west side, formerly over 3 km long, lowered by glacier recession.
Do	Bear	60 00	34	3	D	D	D	D	D	In lateral valley near terminus; probably has not filled for several years.
Do	do	04	36	2	-----	-----	-----	H	H	In lateral valley, altitude 400 m; mostly ice filled.
Do	Skilak	12	56	1	H	H	-----	-----	-----	In embayment on east side of glacier, altitude 890 m.
Do	Tustamena	02	150 27	2	H	-----	H	-----	H	Blocked by lateral lobe of glacier; outlet over bedrock; probably does not drain.
Do	Yalik	59 31	44	1	-----	-----	-----	-----	-----	In lateral valley on east side, altitude 400 m.
Do	Petrof	24	47	1	-----	-----	-----	-----	-----	In lateral valley on east side, altitude 150 m.

EFFECTS OF THE 1964 TECTONIC DISPLACEMENT ON GLACIERS

A subsidence in the central-western Chugach and Kenai Mountains as a result of the earthquake has been reported by Plafker (1965a, p. 1677). It would appear that in almost all places the accumulation areas of the icefields in these mountains were lowered 1–2 m. The axis of greatest subsidence was near the crest of the main icefields. In the vicinity of Cordova an uplift of nearly 2 m took place. The relationship of such changes to glaciers is shown on figure 25.

Where the land is raised with respect to the sea, the area above the snowline on glaciers is increased and the area below the snowline is decreased. A change of altitude of 2 m, which is about the maximum believed to have taken place during the earthquake, would have but a tiny effect, because the changes in area above and below the snowline of most glaciers would be less than 1 percent of their total area. Any immediate changes are doubtless too small to be detected, owing to the masking effect of greater variations in the volume of snow accumulation and ablation resulting from variable and unmeasured climatic factors. However, immediate slight changes would be followed by continuing changes, and a new surface altitude would be reached gradually. The total additional change in thickness after a long period of time for a 15-mm net mass budget perturbation would be of the order of magnitude of 1 m (assuming a typical ice extension rate of 1.5 percent per year) according to the theory proposed by Nye (1960, p. 568). In all probability this change could not be detected.

In several areas, glaciers flow in the direction the land was tilted by the earthquake. The slopes of at least 15 small glaciers (none longer than 8 km) flowing northwestward toward Nellie Juan River and Kings Bay from the Sargent Icefield were increased by about 0.1 m per km. However, the surfaces of these glaciers slope about 100–300 m per km, so the percentage of increase due to the earthquake was inconsequential.

A few major glaciers flow in a direction opposite to the way the land was tilted. The gradients of both the Chenega (Sargent Icefield) and the lower Columbia Glacier (Northern Prince William Sound)—approximately 75 and 25 m per km, respectively—were lowered by about 0.1 m per km. Although the speed of glacier flow is sensitive to changes in slope,

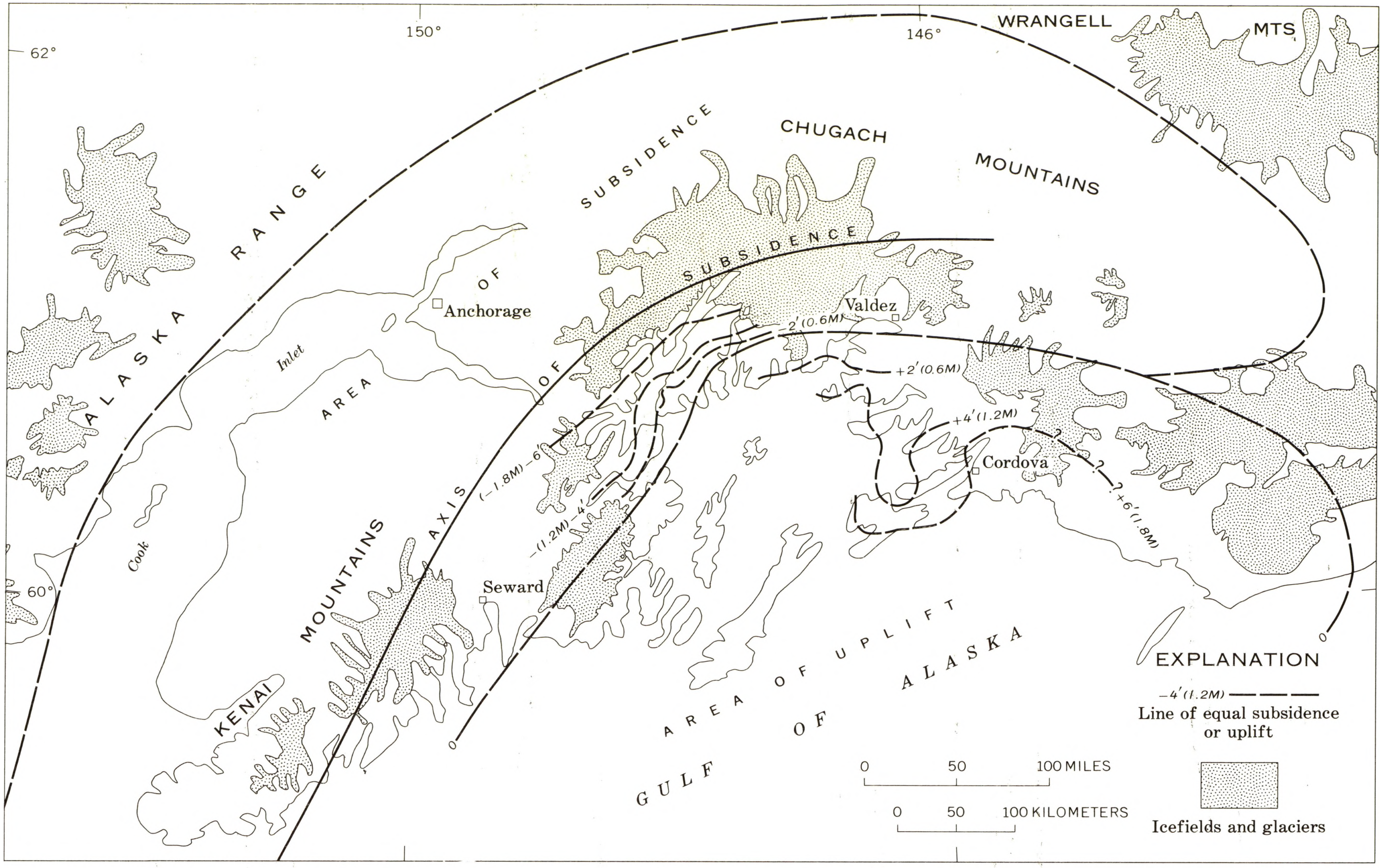


FIGURE 25.—Map showing relation of earthquake subsidence and uplift to glaciers. Data from Plafker and Mayo (1965).

these changes appear to be too small to detect. Most other major glaciers were not tilted appreciably, or were tilted transversely.

Small changes at the terminus caused by uplift or subsidence of the land have taken place on glaciers that end in tidewater. Table 6 lists some of these effects. The Columbia Glacier was raised about 1 m and the Surprise, Harriman, and some other glaciers on the western side of Prince William Sound were lowered about 2 m. No changes in Columbia Glacier that can be attributed to the uplift are yet apparent. In areas where the land subsided, some glaciers show evidence of increased tidewater erosion. Embayments in the terminal ice cliffs of Serpentine and Harriman Glaciers have formed since 1963. The embayments appear to be due to the lowering of these glaciers which has allowed the sea to attack the ice more vigorously than when the glaciers ended in very shallow water.

TABLE 6.—*Changes in termini of tidewater glaciers in the Chugach and Kenai Mountains, 1960–65*

["Minor" indicates small changes along the glacier termini which do not represent any appreciable net advance or retreat. "Slight" indicates a net change of 50 m or less over the glacier terminus]

Glacier	Changes during—	
	1960–63	1963–65
Columbia	Minor	Minor.
Meares	Slight advance.	100 m advance.
Yale	300 m retreat.	350 m retreat.
Harvard	Slight advance.	Slight advance.
Smith	Minor	Do.
Bryn Mawr	Slight retreat.	Minor.
Wellesley	Minor	Slight advance.
Coxe	do	Minor.
Barry	do	Slight advance.
Cascade	do	Minor.
Serpentine	do	100 m retreat.
Surprise	150 m retreat.	Slight retreat.
Harriman	Minor	Do.
Blackstone	do	Minor.
Beloit	do	Do.
Chenega	do	Do.
Bainbridge	Slight retreat.	Do.
Aialik	Minor	Do.
Holgate	do	Do.
Northwestern.	Slight retreat.	Slight retreat.
McCarthy	Minor	Minor.
Dinglestadt.	do	Do.

DIRECT EFFECTS OF THE 1964 EARTHQUAKE ON TIDAL GLACIERS

Twelve glaciers in the Chugach and 13 in the Kenai Mountains end in tidewater, usually at the heads of steep-walled fiords. The ice cliffs, rising 30 m or more above the water surface, appear highly unstable, and catastrophic collapse during the earthquake, resulting in rapid retreat of the glacier, might have been expected.

Photographs taken in former years show that all these glaciers are intricately crevassed. Transport of debris on the lower Columbia Glacier, the largest tidewater glacier in the region, indicates that the average rate of ice movement near the center of the valley has been about 460 m per year since 1960. No clear evidence of increased rate of flow of any of these glaciers has been noted since the earthquake.

Icebergs were reported by Troy Péwé (cited by Ragle and others, 1965a, p. 7) in College Fiord on April 1, 1964, in unusual quantities. Later photographs of the fiord indicate that a rapid retreat, which has characterized Yale Glacier in recent years, has continued. This glacier is considered to be the main source of the floating ice.

INTERPRETATION OF THE DATA

EFFECT OF AVALANCHE-CAUSED THICKENING ON FLOW OF GLACIERS

Most earthquake-caused snow and ice avalanches on glaciers were so small that no detectable changes in ice flow are to be expected. However, some rockfall avalanches, either through direct loading or the indirect effect of protecting the ice from melting, have caused parts of glaciers to be thickened by several meters. Insufficient data are available to calculate the changes in flow velocity of any specific glaciers affected by earthquake-related avalanches. However, the order of magnitude of these effects can be readily estimated. For a glacier whose flow is entirely due to internal deformation (the slip on the bed is zero), the surface ice velocity is proportional to the thickness raised to the power $(n+1)$, where n is an empirical constant (Nye, 1952, p. 84).

Field and laboratory results indicate that n equals approximately 3. Thus, if v is velocity and h is thickness, and the slope is not changed

$$dv/v = 4dh/h.$$

If, on the other hand, the glacier flows by slip on the bed (no internal deformation), according to the only existing theory (Weertman, 1957, p. 38), the velocity is proportional to the thickness raised to the power $\frac{1}{2}(n+1)$. Thus

$$dv/v = 2dh/h.$$

Unless some unusual and different flow mechanism is triggered, the immediate percentage increase in flow velocity will be 2–4 times the percentage increase in glacier thickness. Thus, a glacier 300 m thick which receives an avalanche equivalent in thickness to 1 m of ice over an appreciable part of its area may be expected to increase its flow velocity by only 0.7–1.3 percent. At the other extreme a glacier only 100 m thick, on which is deposited an extra load equivalent to 3 m of ice, might accelerate its flow by 6–12 percent.

The extra load might have a noticeable effect on the advance or retreat of certain glaciers. For a glacier in a steady-state condition with a simple wedge-shaped terminus of slope α lying on a horizontal bed, the net mass budget (a) at the terminus is related to the ice velocity by a simple geometric relation

$$v = -a \cot \alpha$$

Net mass budgets at the termini of glaciers in the earthquake area probably are of the order of magnitude of -8 m, and the slopes at the termini are rarely less than 10 percent. Thus, ice velocities right at the termini are generally less than 100 m per year. An earthquake-induced increase in ice velocity of 12 percent might produce an abnormal increase in advance of the terminus of as much as 10–12 m per year.

However, this increase is only the immediate increment in flow rate. The termini of glaciers (regions of compressing flow) are generally unstable (Nye, 1960, p. 563). The immediate thickening might trigger an instability which could continue to cause the glacier to thicken and the speed to increase for a number of succeeding years. This dynamic reaction is difficult to predict without knowledge of the kinematic wave properties of the particular glacier. Such information is available for only two small glaciers, neither of which is in Alaska (Nye, 1965). Furthermore, a layer of debris could cause an abrupt decrease in ice ablation. This decrease would result in a continuing increase in thickness until a new equilibrium condition is reached. Such effects are difficult to calculate, but it would not be unreasonable to find an advance of 10 m in 1 year followed by an increasing rate of advance of perhaps as much as 10 m per year, a tapering off to a constant slower rate of advance, and then a slow deceleration.

THE EARTHQUAKE-ADVANCE THEORY

Tarr and Martin (1914, p. 168–197) reported nine glaciers which made sudden short-lived movements ("advances") after the extremely severe earthquakes in 1899 near Yakutat Bay, Alaska. Changes from near stagnation to rapid movement occurred in the decade following the earthquake. To explain these unexpected large-scale changes, Tarr and Martin proposed the Earthquake-Advance Theory. This theory visualizes the following sequence of events:

1. Severe earthquake shaking causes large snow and ice avalanches to fall on the upper parts of glaciers from surrounding mountains.
2. This loading upsets the dynamic equilibrium of the affected glaciers and results in a rate of ice flow many times greater than normal.
3. The increased flow travels as a "glacier flood" which moves rapidly down glacier and causes a sudden short-lived advance of the glacier terminus (Tarr and Martin, 1914, p. 184–185).
4. The time delay between earthquake and terminal advance, as the "glacier flood" travels down glacier, is proportional to the length of the glacier. In the glaciers observed by Tarr and Martin, this delay ranged from less than 1 to 11 years.
5. After the stresses resulting from increased loading are dissipated, the glacier flow abruptly returns to its normal state.

This theory has since been generally accepted as a cause of sporadic or unusual glacier advances. It was expected that the 1964 Alaska earthquake would result in similar avalanches and glacier advances. Yet it is clear that snow and ice avalanching caused by the 1964 earthquake was insignificant in relation to the size of most glaciers and had little effect upon their regime.

Why did the very severe 1964 earthquake not cause more widespread snow avalanching on glaciers? One reason is that, as modern topographic maps show, few large glaciers in Alaska have areas nearby that are topographically suited to large-scale snow avalanching. Broad, relatively low gradient surfaces are typical of the valley glaciers. The glacially oversteepened cliffs of the surrounding mountains retain very little snow in any season, the greater part being removed by frequent minor avalanching as the snow accumulates. For these reasons, snow avalanching rarely can have an important effect on glacier regimes, regardless of the violence of an earthquake.

Ice avalanching on steep slopes was so minor during the 1964 earthquake as to suggest that these features are little affected by earthquake shaking. Areas where extensive ice avalanching can occur seem relatively limited in most glaciers. Thus, only very exceptionally does it appear likely that snow or ice avalanching on glaciers could be extensive enough during any earthquake to add sufficient material to a glacier to result in a rapid advance.

Rockslide avalanching on a few glaciers during the 1964 earthquake appeared extensive enough to upset the glaciers dynamically. The Martin River Glacier probably received the greatest loading with rockslide debris and appeared to be ideally suited to test the Tarr and Martin theory. In photographs taken in 1948, 1960, 1961, and 1963, the upper part of the glacier where the avalanches occurred was seen to be extensively crevassed. Whether crevassing in 1964 was greater than normal could not be determined with certainty. Vertical photographs were taken of the narrower parts of the glacier in 1964 and 1965 in order to determine down-valley movement of ice. In the area just below the firn line this movement amounted to about 260 m between August 1964 and August 1965. This amount is judged to be normal for a glacier of this size and configuration.

Sixteen months after the 1964 earthquake no evidence was found to suggest that a rapid advance was developing in any glacier in the Chugach or Kenai Mountains, nor was any evidence found of a "glacier flood" in transit. Because of the lack of snow and ice avalanching and the absence of any rapid advance in this region as a result of the 1964 earthquake rockslide avalanches, the Earthquake-Advance Theory was questioned, and the data presented by Tarr and Martin were carefully reviewed. Several points can be mentioned which suggest that the glacier movements they observed may not have been the result of earthquake-induced avalanching of snow, ice, or rock on glaciers.

Tarr and Martin did not actually observe evidence of earthquake-induced avalanches on the glaciers they described, except on the Galiano Glacier. Their descriptions of the changes which took place in the Galiano Glacier and in alluvial deposits as much as 8 km distant from its terminus indicate that very extensive slumping must have taken place along this part of the coastline of Yakutat Bay (Tarr and Martin, 1914, p. 82–86). The changes they noted are in some ways comparable to the slumping of alluvial deposits in the Turnagain Arm region during the 1964 earthquake. Alders 5–6 years old, growing on the slumped alluvium and the moraine-covered terminus of Galiano Glacier in 1905, indicate that the breakup of the glacier surface must have occurred about 1899, that is, at the time of the earthquake. Tarr and Martin did not report an actual advance of the terminus of Galiano Glacier. The changes they noted may have been caused by the slumping of the unconsolidated deposits on which the glacier terminates.

Hidden Glacier advanced 3 km about 1906–07 and this advance was by far the greatest described by Tarr and Martin. However, this glacier flows from an open snowfield where possible sources of significant avalanching are conspicuously absent.

It is pertinent to note that the three steep hanging glaciers on the mountain west of Disenchantment Bay were not shaken down by the 1899 earthquake although this area was severely shaken and the coastline raised 13 m. However, one of these glaciers was so unstable that 6 years later it avalanched into the bay when no earthquake occurred (Tarr and Martin, 1912, p. 49). This occurrence provides additional evidence that even very steeply pitched glaciers are not greatly affected by violent earthquakes.

On the basis of the maps then available, Tarr and Martin reported a rough correlation between glacier length and the time of terminal activity following the earthquake. Table 7 lists the lengths of the glaciers, as measured on accurate modern maps, and the period of terminal activity for the glaciers they observed. Inconsistencies are so large that the relationship seems unlikely.

GLACIER SURGES

Since Tarr and Martin's work, several sudden anomalous advances of glaciers have been reported. Hance (1937) and Moffit (1942) described the advance of the Black Rapids Glacier in central Alaska. The Muldrow, Susitna, and Yanert Glaciers at various times also made similar advances (Post, 1960).

Aerial investigations since 1960 in Alaska and Yukon Territory,

TABLE 7.—*Lengths and times of sudden movement of glaciers observed by Tarr and Martin after the 1899 earthquake*

[Length: As measured on accurate modern maps. Period of movement: As observed by Tarr and Martin; dates in parentheses were not observed but were inferred]

Glacier	Length (km)	Period of movement		Remarks
		Began	Ended	
Galiano	8	(1899)	(1900)	Slumping of coast of Yakutat Bay in this area probably resulted from 1899 earthquake. Changes in glacier may have resulted from slumping of underlying alluvial deposits. No advance reported.
Miller	5	(1899)	1901	Terminal advance, probably much less than the 1.5 km, shown by photographs; advance not observed.
Atrevida	13	1905	1906	Rapid movement of ice in valley and into terminal lobe 8 km from head of glacier; no terminal advance.
Haenke	14	1905	1906	Terminal advance of 1,370 m to sea plus unknown movement into sea.
Hidden	19	(1906)	(1907)	Terminus advanced 3 km. Position of medial moraines indicates steep tributaries on southwest side did not furnish more ice than normally.
Variegated	21	1905	1906	Rapid movement of ice in valley and terminal lobe; no terminal advance.
Lucia	24	(1908)	(1909)	Rapid movement of ice in valley and into terminal lobe 18 km from head of glacier; no terminal advance.
Nunatak	32	1909	1910	Small advance of terminus (as much as 300 m in 11 months). A slight further advance occurred in 1911 followed by retreat in 1912 of 0.4 km.
Marvine	48	1905	1906	Rapid movement of ice and slight advance of lobate part at least 40 km from head of glacier.

in addition to the studies mentioned above, have led to the identification of a type of glacier behavior, called a "surge," which can be clearly distinguished from normal, climatically induced advances (Post, 1965). A typical surge is described below.

After a relatively long interval (15–100 years) of virtual stagnation in the terminal area and slow increase in thickness in the upper part, the glacier is suddenly transformed. 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. A surface displacement of 4 km or more may take place in a single year at the peak of the movement. The ice discharge may lower the surface as much as 150 m in the upper part of the glacier. The transferred ice overrides and thrusts ahead the formerly stagnant ice in the lower valley, and here the thickness of the glacier often increases as much as 60 m. The volume of ice loss in the upper part and gain by the lower part of the glacier appears to be the same. Only rarely does the glacier advance beyond its terminal position before the surge. Apparently the active period of these surges does not exceed 3–4 years, regardless of the size of the glacier. Such surges may occur repeatedly in a single glacier; distinctive medial-moraine patterns frequently provide evidence of three or more former surges. Conterminous glaciers and even individual branches in a single large glacier may not surge at the same time. Surging glaciers are rare but have been reported in many parts of the world (see, for example, Sharp, 1954, Hattersley-Smith, 1964; Dolgushin and others, 1963; Post, 1960, 1965, 1966).

The "advances" of Tarr and Martin seem to have been surges of the same kind described above. The changes noted in the lower parts of the Lucia Glacier (Tarr and Martin, 1914, p. 64–69), Atrevida Glacier (1914, p. 69–79), and Variegated Glacier (1914, p. 115–126) are all typical of glacier surges. Even the "glacier flood" that Tarr and Martin described can be identified on surging glaciers. It is the kinematic wave mentioned above, and can be detected on the surface as a zone of intense crevassing which progresses rapidly down glacier.

Evidence of more than 27 glacier surges since 1936 has been recorded (fig. 26). At least three glaciers have made two or more recorded surges. The Variegated Glacier surged in 1905, about 1946, and again in 1964. The Kluane Glacier surged in 1941 and 1961. Tikke Glacier surged around 1946 and again in 1963. Practically all of the observed surging glaciers show evidence of having made three or more surges.

Correlation between glacier surges and earthquakes of Richter magnitude 7 or greater is lacking (fig. 26). No glacier surges have been recorded in the immediate vicinity of any strong earthquake since 1899, despite the fact that many glaciers are near several of the earthquake epicenters.

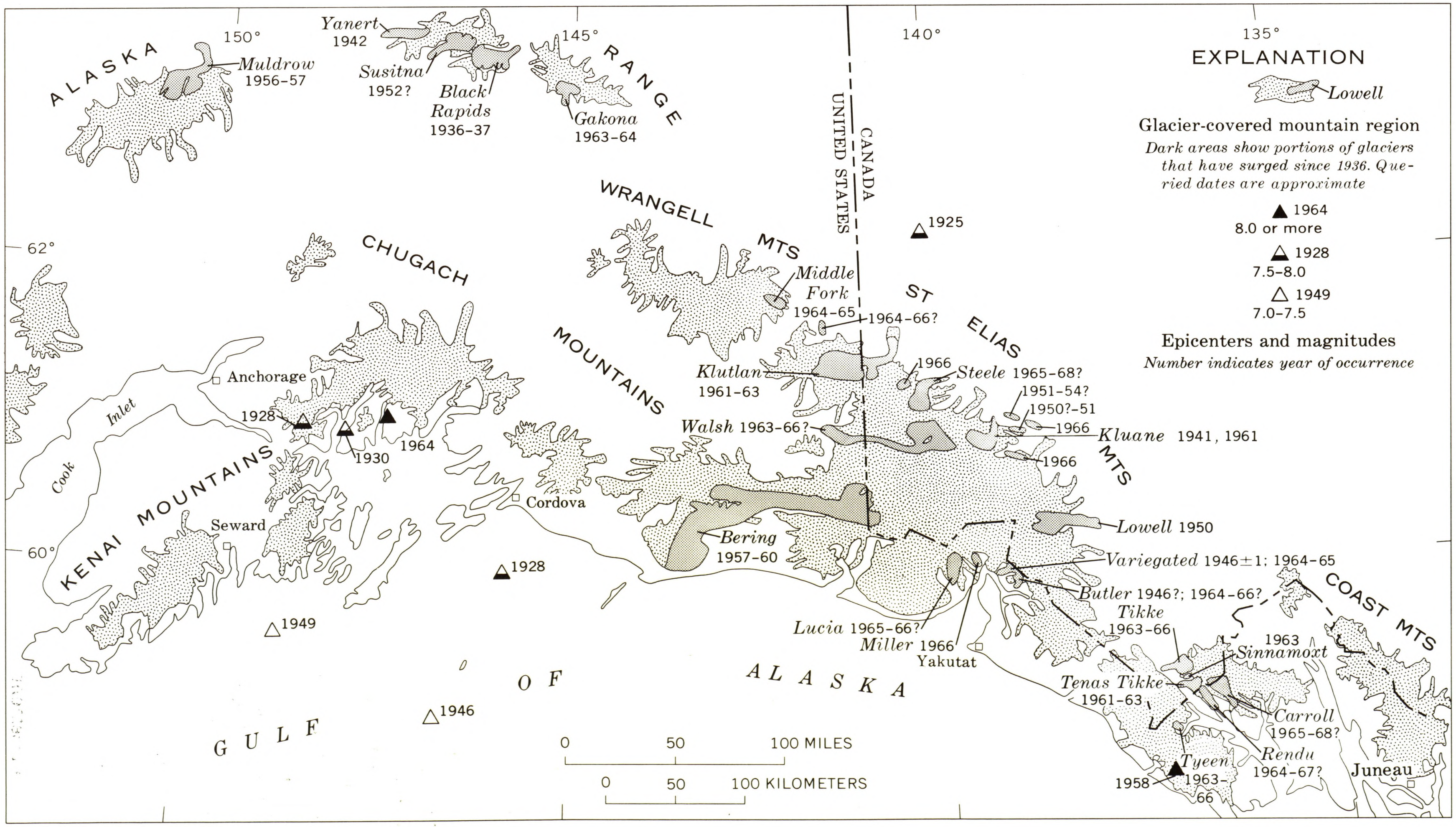


FIGURE 26.—Distribution of observed glacier surges since 1936 in Alaska and western Canada.

The Prince William Sound region of the Chugach Mountains where the 1964 earthquake occurred has received more earthquakes of Richter magnitude 7 or greater than any area in Alaska (fig. 26). Not one surging glacier or rapid advance has been reported in this area.

SUMMARY AND CONCLUSIONS

Aerial photographs show few snow and ice avalanches on glaciers as a result of the 1964 earthquake. Large and small rockslides avalanched onto glaciers at several localities. In August 1965 no clearly defined large-scale dynamic response to avalanche loading or other effects of earthquake shaking had been found in any glacier.

Large rockslide avalanches traveled several kilometers on glaciers at gradients of less than 5°. Two of these avalanches occurred many months after the earthquake. Compressed air may have provided an easily sheared lubricating layer. Rockslide avalanches are so extensive on the Sioux, Saddlebag, and Sherman Glaciers that the glacier regimes have been altered, principally because the debris insulates the ice and reduces melting. This effect favors future advances of these glaciers.

No apparent changes in ice-dammed lakes or glacier drainage resulted from the earthquake. Tidal glaciers show little immediate effects. Tectonic displacements affecting the altitude of glaciers are minor when compared to climatic influences. Changes in slopes of glaciers are probably too small to have observable effects.

No evidence supporting the Earthquake-Advance Theory has been found from investigations made since the 1964 Alaska earthquake. The nature of recent surges, the lack of correlation in time and space between them and recent earthquakes, and the probability that significant avalanching did not take place on at least one of the glaciers observed by Tarr and Martin all render the Earthquake-Advance Theory suspect.

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