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What are glacier surges?[1]

Mark F. Meier and Austin Post

Water Resources Division, U.S. Geological Survey, Tacoma, Washington, U.S.A. 98402

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A total of 204 surging glaciers has been identified in western North America. These glaciers surge repeatedly and probably with uniform periods (from about 15 to greater than 100 years). Ice flow rates during the active phase may range from about 150 m/year to > 6 km/year, and horizontal displacements may range from < 1 to > 11 km. Ice reservoir and ice receiving areas can be defined for surging glaciers, and the reservoir area does not necessarily coincide with the accumulation area. Glaciers of all shapes, sizes, and longitudinal profiles can surge, and no unusual "ice dams" or bedrock constrictions are evident. Surges occur in many different climatic, tectonic, and geologic environments, but only in certain limited areas (mainly in the Alaska, eastern Wrangell, and St. Elias mountains). Three types of surging glaciers are defined: (I) large to moderate-sized glaciers with large displacements and very fast flow, (II) large to moderate glaciers with moderate displacements and flow rates, and (III) small glaciers with small displacements and moderate to fast flow rates. All three types involve an inherent instability which is self-triggered at regular intervals, but with Type I surges an additional (unknown) mechanism produces the very high flow rates.

Introduction

Glacier surges, also known as exceptional or catastrophic advances, galloping glaciers, or pulsatory glaciers, have been observed in many parts of the world. Although hundreds of glaciers are known to surge, and several have been studied in the height of their activity by glaciologists, insufficient quantitative information makes it difficult to define or even describe glacier surges properly. Most descriptions of surging glaciers mention or imply a sudden advance which does not seem to be related to a variation in climate, and (or) exceptionally high speeds of glacier flow (two orders of magnitude greater than expected), and (or) a regular periodicity of either sudden advances or fast movements. Obviously, the concept of a surge is not well defined.

Some fundamental questions need to be answered before the mechanics or causes of surges can be discussed: (1) can a glacier surge only once or are all surges periodic? (2) do very high ice velocities always occur during surges? (3) are surges triggered by external events, such as climatic fluctuations or earthquakes? (4) is there a distinct class of glaciers which surge, or is there a complete spectrum of activity from surges to ordinary advances? (5) what kinds of glaciers surge?

Glacier surges in western North America

Distribution

In the course of yearly aerial reconnaissance studies of glaciers in western North America, Post has observed and photographed thirty-five glaciers actively surging since 1960. Through a study of older aerial photographs he has identified forty-four other surges in progress. These glaciers are recognized by the characteristics most commonly associated with surges: chaotically crevassed surfaces; rapidly opening crevasses; sheared margins and sheared-off tributaries; bulging, overriding, advancing fronts; and large vertical and horizontal displacements of the ice. Some of these glaciers have been observed during two or more surges, and the surface features during the active phases have been found to be remarkably similar for each surge. These characteristics

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[1] Presented at the Seminar on the Causes and Mechanics of Glacier Surges, St. Hilaire, Quebec, September 10–11, 1968.

are so unusual that most surges can be distinguished from normal fast-moving or rapidly advancing glaciers without difficulty.

All of the larger and most of the smaller glaciers that have been observed to surge exhibit distinctive surface features during their less active or quiescent phase. Most conspicuous of these are repeated loops, folds, or irregularities in medial moraines, such as the famous contorted moraines of the Susitna Glacier in the central Alaska Range (Fig. 1). Other distinctive features include curious pits in the surface, distinctively contorted ice foliation, and the virtual stagnation of exceptionally large portions of the glaciers. Longitudinal profiles locally steeper than the profiles of adjacent lateral moraines or trimlines may be noticeable just before a surge. These features are also so unusual that most surging glaciers can usually be identified without difficulty even when quiescent. No major glacier in the study area that does not display some of these surface evidences of surge activity has any record of past surges. The validity of these indicators is also demonstrated by three spectacular, recent surges which were predicted by Post on the basis of such evidence—those of the Walsh, Steele, and Chitina Glaciers.

All of the larger glaciers and most of the smaller glaciers in western North America, from the Sierra Nevada in California and Wind River Range in Wyoming to the Brooks Range in Arctic Alaska, have been examined by aerial reconnaissance and studied by means of aerial photographs. Several tens of thousands of glaciers were examined, and only 204 show evidence of surge behavior (Post, in press). A number of small surging glaciers have doubtless not been identified and some small normal glaciers may have been classified incorrectly as surging glaciers, because small glaciers retain the least evidence of past surge activity. The observational data on a few larger glaciers are suggestive of surging but not conclusive. More data on certain questionable glaciers, a precise definition of surge, and especially a long, close watch on the small glaciers will be necessary in order to arrive at a more accurate determination of total number.

The 204 glaciers which show the characteristics of surge behavior occur in the Alaska Range, the Chigmit, eastern Wrangell, eastern Chugach, and St. Elias mountains of south-central Alaska, and in the St. Elias mountains in southwestern Yukon Territory and northwestern British Columbia. No surging glaciers have yet been identified in any other area in western North America.

General Characteristics

From yearly aerial photographs it is possible to deduce changes in crevassing, surface level, moraine patterns, and extent of these surging glaciers. By plotting these data on maps, yearly displacements of surface features on individual glaciers can be measured (Fig. 2), the geometry of moraine folding can be worked out, and other quantitative data obtained (Post 1960, 1966). From these studies we deduce the following general characteristics of surges in western North America.

(1) All surging glaciers surge repeatedly. All large surging glaciers show at least three old moraine loops marking earlier surges, some show ten or more loops. This means that a history of surging is known for hundreds of years into the past. Smaller glaciers, especially those which lack medial moraines, show less surface evidence of surges, and this evidence is often destroyed by ablation after a relatively few decades. However, no example of a single surge interrupting a past history of normal behavior has yet been found.

(2) Most surges for which we have information on timing are uniformly periodic, and the length of cycle appears to be rather constant for a single glacier, as deduced both from long records of observed surges (e.g., for Variegated, Tyeen Glaciers) or from studies of the uniform deformation and looping of moraines (e.g., of Susitna Glacier, Fig. 1).[2] Thus these surges are not triggered directly by any known external events, such as earthquakes or climatic fluctuations.

(3) All active surges take place in a relatively short period of time (<1 to ~6 years, most commonly 2–3 years), after which the glacier lapses into a quiescent phase lasting for a much longer time (~15 to >100 years, commonly 20–30 years).

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[2] However, smaller scale surges have been observed on a few large glaciers (e.g., Steele Glacier in 1946); whether these upset the regular periodicity of major surges is not known.

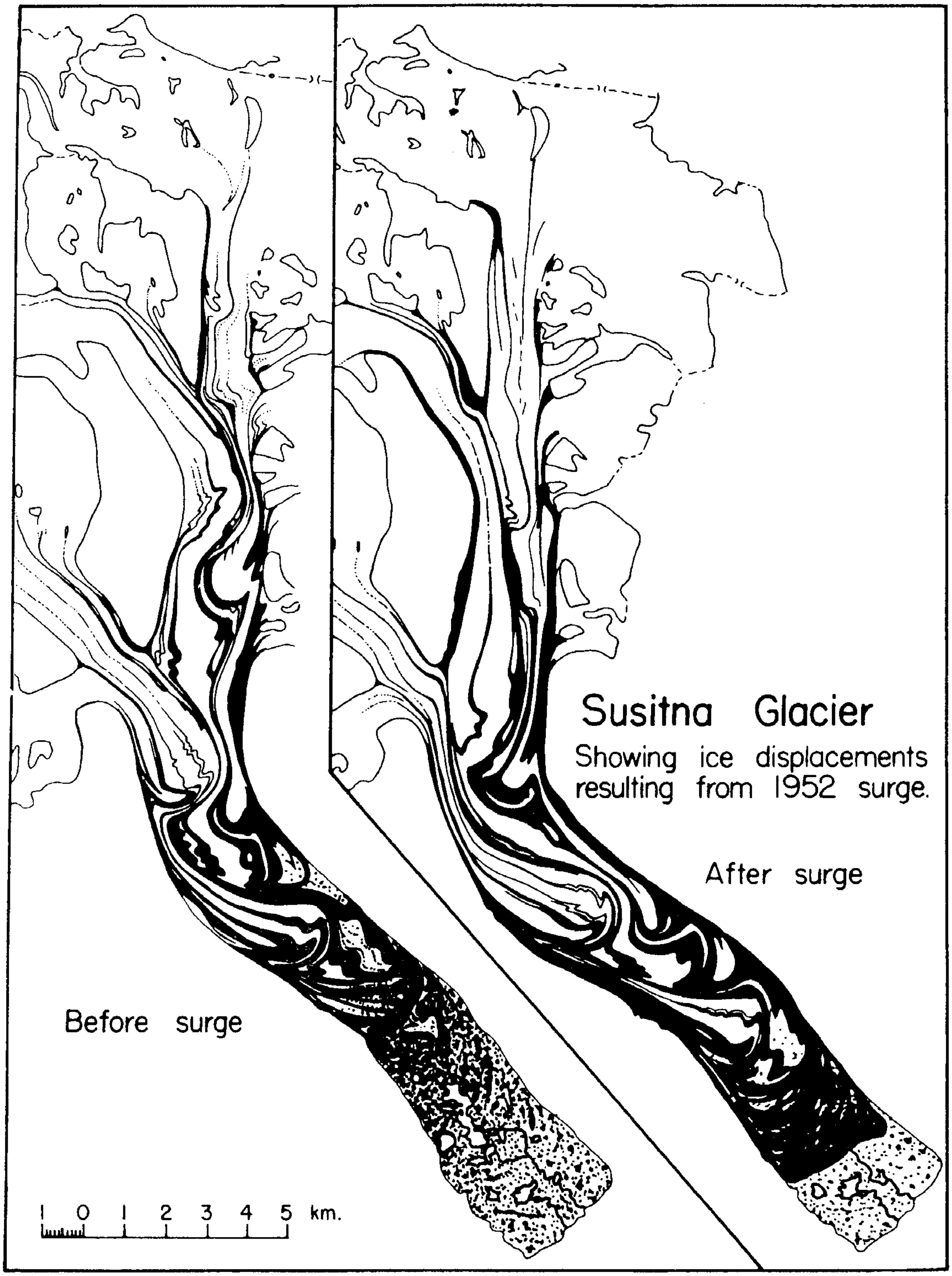

FIG. 1. Maps of Susitna Glacier, Alaska, just before and just after the 1952 surge, showing changes in contorted medial moraines.

(4) The time for a complete cyle, or for the active phase, has no simple relation to the length, area, or speed of the glacier. Periods longer than 30 or 40 years are associated only with some large glaciers, but other large glaciers cycle at intervals of about 20 years, which is a common period for small glaciers. Probably the period is, in general, a complex function of the total ice displacement during the surge and the net balance rate during quiescence.

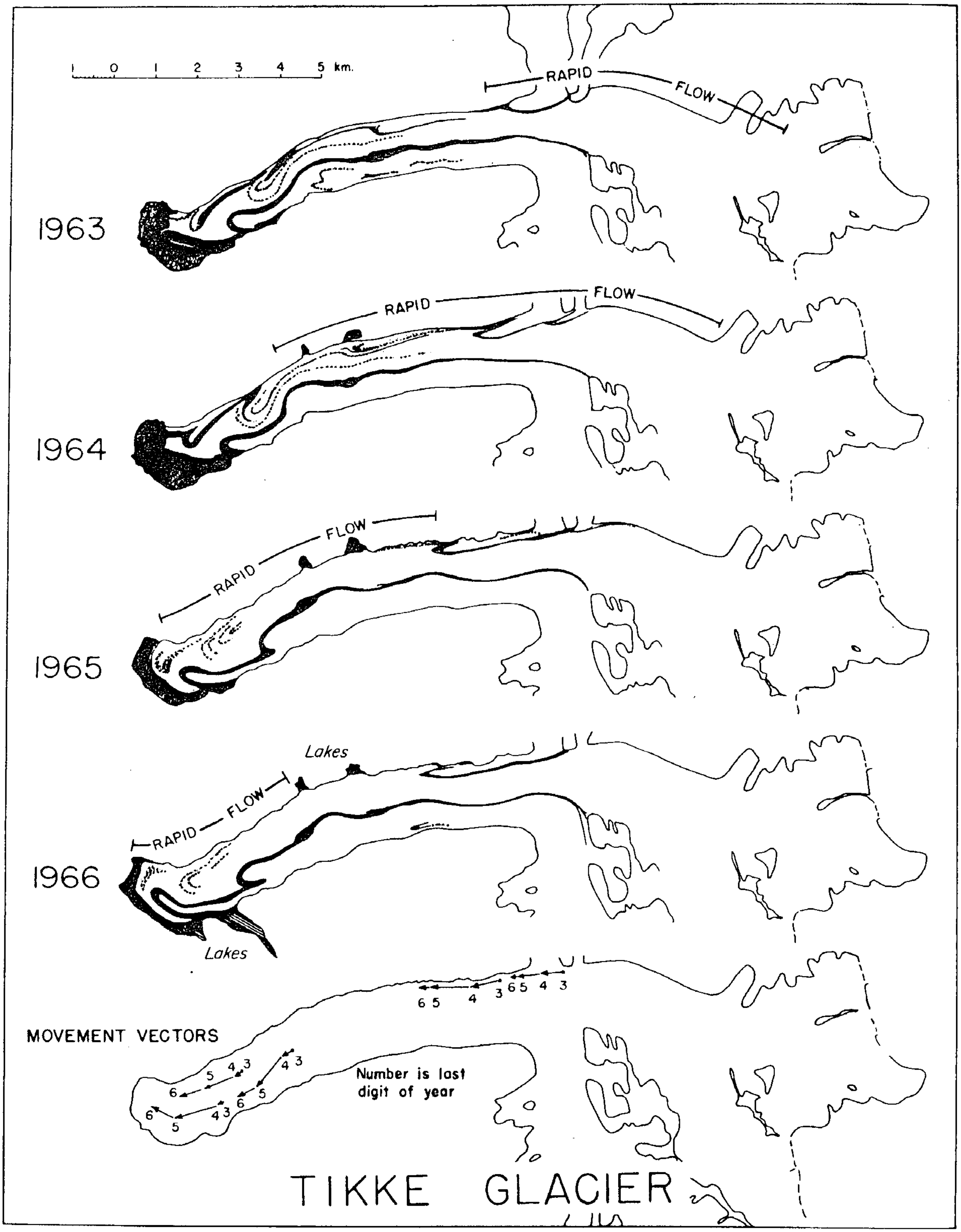

FIG. 2. Maps of Tikke Glacier, British Columbia, during the 1963–66 surge showing changes in medial moraines, movement vectors, and the zone of most rapid flow.

(5) Speeds of ice flow during the active phase are always much faster, perhaps at least an order of magnitude faster, than flow rates at similar locations on the same glacier during the quiescent phase. Flow rates during surges can be as high as 5 m/hour for short intervals of time, and can average more than 6 km/year at a fixed location for periods of a year or more. However, flow speeds much lower than this have been observed during undoubted surges (e.g., 150–1000 m/year, averaged over a year).

(6) Total horizontal displacements of ice during the active phase are typically measured as a few kilometers (11.5 km was observed on Walsh Glacier (Post 1967*a*)) but can be less than 1 km. Total displacements during the quiescent phase are typically 1/100th to 1/10th that which occur during the active phase at equivalent locations in the portion of the glacier which shows surge activity. The fastest speeds are associated with large displacements, but fairly rapid flow has been seen in some small glaciers with relatively little total displacement.

(7) Because surges occur repeatedly and the glaciers do not continuously grow longer, most surges do *not* result in advances of the terminus.

(8) It is possible to define an ice reservoir area and an ice receiving area for all surges. The ice reservoir is not identical with the accumulation zone; the reservoir can be entirely within the ablation zone. During the quiescent phase the reservoir thickens and the longitudinal profile in the lower part of the reservoir area continuously steepens. The active phase usually appears to begin with rapid movement where this steepening has occurred. The rapid movement propagates quickly up glacier to include all the ice reservoir area and down glacier into the receiving area. The rapid flow removes ice from the reservoir area causing vertical lowering of the surface in the order of tens or hundreds of meters, and adds ice to the receiving area causing a similar or greater amount of thickening there. As the surge proceeds, the zones of lowering and thickening may move down glacier, so that in some areas the ice surface first rises and later falls (Fig. 3). In some cases the surge extends to the very head of the glacier, but in other cases only the lower half of the glacier surges (Fig. 4).

(9) No abrupt bedrock sills or depressions are suggested by the profiles of most surging glaciers (Fig. 4). "Ice dams" which might weaken to trigger a surge are not evident in most surging glaciers. In fact, in some cases a surge in one branch of a glacier may override a second branch, and this may then be followed by a surge of the second branch suggesting that the extra load contributed to (or triggered) the second branch's surge (Fig. 3).

(10) Practically all kinds and sizes of glaciers surge, and glacier surges occur in almost all climatic environments. In western North America surging glaciers as small in length as 2 km and as large as 200 km have been observed to surge. Cirque glaciers, valley glaciers, piedmont glaciers, and more complicated types have been observed to surge. Marine, temperate glaciers in areas of high accumulation and ablation activity as well as subpolar glaciers in continental, cold areas can surge. Surging glaciers can have steep or gentle, smooth or irregular longitudinal profiles (Fig. 4). The transition area between ice reservoir and receiving areas can have a convex, concave, or smooth profile. Thicknesses and basal shear stresses are, as far as we know, not unusual (Table I).

(11) Surging glaciers occur only in certain restricted areas in western North America. The reason for this is not yet evident because these surging glaciers occur in such differing climatic environments, are situated on various bedrock types, and show no clear relation to any known, definable environmental characteristic, including tectonism (Post 1965; 1967*b*). There is a remarkable association of glaciers with at least one major fault valley, the Denali fault in Alaska, but many other major fault zones and areas of active tectonism do not contain any surging glaciers (Post, in press). Almost nothing is known about subglacial rock permeabilities, bed roughness, or heat flow conditions under glaciers; these might determine the necessary (if not sufficient) boundary conditions for a surge.

(12) Although it is difficult to classify surging glaciers with the meager existing data, most of the surges in western North America can be divided into three major categories (see Table I).

Type I—Large (>30 km long) to moderate (5–30 km long) valley glaciers which flow at very high speeds (>15 m/day averaged over a year, or >50 m/day for short periods) with

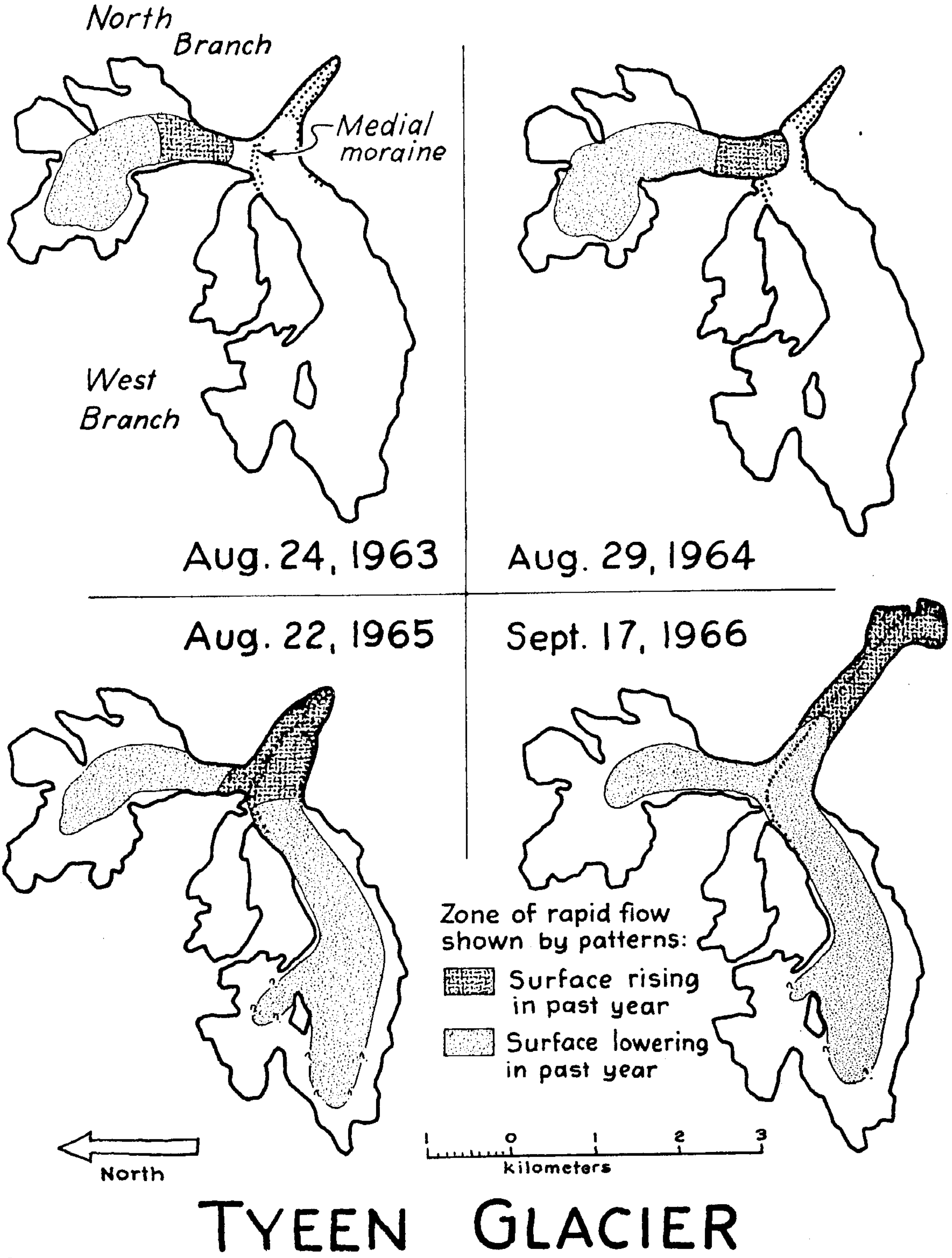

FIG. 3. Maps of Tyeen Glacier, Alaska, during the 1963–66 surge, showing changes in the zone of most rapid flow.

large resulting displacements (>5 km), and, in most cases, large-scale lowering (>50 m) of the ice reservoir. During the quiescent interval the receiving area becomes virtually stagnant, and the terminus may retreat several kilometers if this ice is not covered by moraine. Type example: Muldrow Glacier, Alaska Range, Alaska (Post 1960). Basal shear stresses during quiescence may be appreciably lower than for the other types of surging glaciers (Table I).

Type II—Large (>30 km long) to moderate (5–30 km long) valley glaciers which show

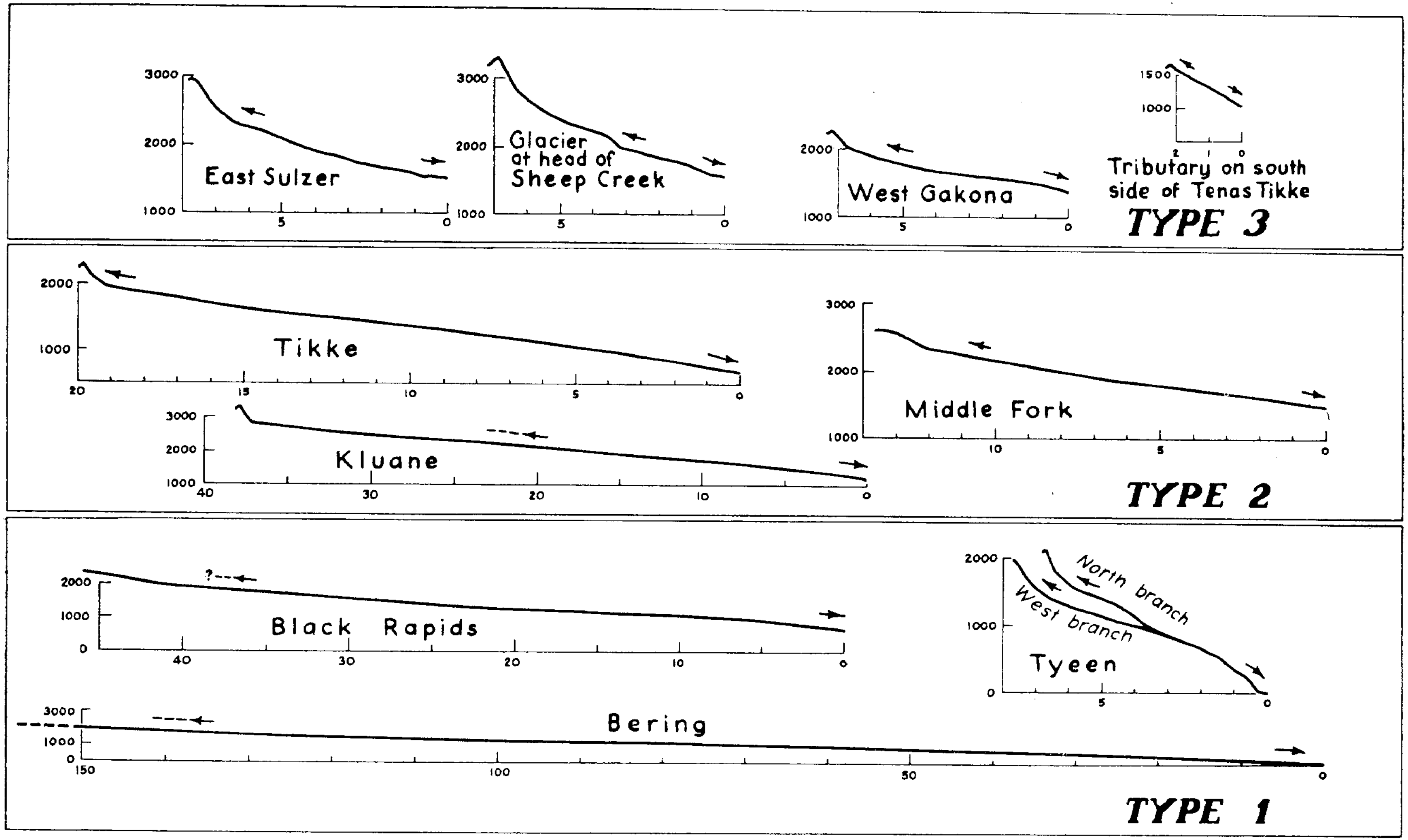

FIG. 4. Longitudinal profiles of ten typical surging glaciers. The three types of glaciers are defined in the section on general characteristics. Vertical exaggeration is 2:1. Distances from terminus are in kilometers, altitudes in meters. Arrows indicate limits of observable rapid flow during surges; dashed extensions to arrows indicate that rapid flow diminishes gradually above this point.

TABLE I

Characteristics of some typical surging glaciers

Glacier	Mountain range; state, territory, or province	Type	Area, total (km^2)	Length		Average slope, surging part (°)	Cycling period (years)	Duration of active phase (years)	Maximum observed annual velocity (km/year)	Maximum observed displacement (km)	Estimated thickness* (m)	Estimated shear stress* (bars)
				Total (km)	Surging part (km)							
Bering	Chugach–St. Elias, Alaska	1	5800	200	>153	0.7	30 ± 15	3	?	9.7	480	0.4
Klutlan	Icefield, Y.T.	1	1072	55	40	1.3	30 ± 10	3	>3.2	6.5	—	—
Walsh	St. Elias, Alaska–Y.T.	1	830	89	86	1.0	50 ± 10	4	>5.6	11.5	220	0.4
Muldrow	Alaska, Alaska	1	393	63	46	2.2	50 ± 10	2	6.6	6.6	290	0.9
Variegated	St. Elias, Alaska	1	49	20	19	4.2	20 ± 0.5	2	>5	>5	—	—
Tyeen	Fairweather, Alaska	1?	11	7	7	13.6	20 ± 1	3	>1.5	>2.4	—	—
Kluane	Icefield, Y.T.	2	352	38	20	2.6	19 ± 1	?	?	2	—	—
Tikke	Alsek, B.C.	2	75	19	18	3.6	20 ± 1	3	1.0	2.0	250	1.4
Middle Fork	Wrangell, Alaska	2	34	14	11	4.1	?	1?	?	1.4	—	—
Glacier at head of Sheep Creek	St. Elias, Alaska	3	5	7	3	7.2	?	2	?	1.2	—	—
Tributary on South side of Tenas Tikke Glacier	Alsek, B.C.	3	1	2	2	16	20 ± 1	3	0.15	>0.5	75	1.9
Small glacier west of Steele Glacier†	Icefield, Y.T.	3?	3	3	2	11.9	?	>6	0.1	>0.3	—	—

*Calculated before surging at cross section between ice reservoir and ice receiving areas, based on volume continuity using measured width, area, and horizontal ice displacement, and estimated thickening in ice reservoir area; shear stress calculated for $\rho g h \sin \alpha$ component only.

†Unofficially designated "Jackal Glacier" by Icefield Ranges Research Project, Arctic Institute of North America.

much smaller displacements (2–5 km) with moderate lowering (10–30 m) of ice reservoir. Flow speeds are largely unknown, but may range from only 2 m/day to about 8 m/day. Slow flow may occur in the receiving area during quiescence, but terminal retreat and (or) surface lowering occur. Type example: Tikke Glacier, Alsek Range, British Columbia.

Type III—Small (2–10 km long), steep glaciers which show small displacements which are, however, large relative to the glacier's size (10–30%), little observable depression of ice reservoir (but great extension with an appreciable part of glacier surface riven with gaping crevasses above it). The rates of flow are almost completely unknown but may range from <1 m/day to perhaps 8 m/day. Almost complete stagnation usually occurs in the receiving area during quiescence, resulting in marked recession of the terminus. Type example: tributary on south side of Tenas Tikke Glacier, Alsek Range, British Columbia.

(13) Whether there is a complete transition of behavior from surges to normal glacier activity is a question we cannot answer at this time. Some of the small Type 3 glaciers which advance relatively slowly, such as the small glacier west of Steele Glacier (Table I), may not be properly classed as surging glaciers but may be a transitional form between surging and normal glaciers. Some large glaciers, such as the Capps and Tokasitna in the Alaska Range, apparently experience periodic small-scale pulses of activity cycling in 10 years or less. Some other glaciers, such as Nisqually on Mount Rainier, have changed their flow regime so markedly in apparent response to climatic fluctuations that their behavior shows some characteristics of a surge regime (Meier 1968). Also we have observed several small, very steep glaciers, such as the Spillway Glacier in the North Cascades Range of Washington State, which periodically breaks apart and advances almost as an ice avalanche. (The Allalin Glacier in Switzerland may be a similar example.) We do not consider the Capps, Tokasitna, Nisqually, or Spillway types of behavior to be surges, but they may involve some aspects of the unstable flow mode common to true surge behavior.

Conclusions

These observations on glaciers in western North America indicate that surging glaciers comprise an unique class of glaciers which can be defined in a general way. However, the precise boundaries of this class are hard to set. We believe that the single distinguishing characteristic is the regular, periodic alternation of slow and fast flow regimes. These observations suggest the following conclusions pertinent to the mechanism of surging.

(1) The periodic activity indicates that the longitudinal profile of the glacier is not stable. During the quiescent phase, the ice reservoir thickens. When the glacier becomes sufficiently thick and steep at the lower part of the reservoir, the component of basal shear stress $\rho g h \sin \alpha$ apparently reaches a critical value and the surge begins.[3]

(2) Once the surge begins, the condition of rapid flow propagates very quickly both up and down glacier, even though in the ice reservoir area the stress component $\rho g h \sin \alpha$ is now decreasing. However, the total shear stress on the bed may still be increasing owing to the very large longitudinal stresses. This rapid flow condition indicates a remarkable decoupling of the ice from the bed.

(3) The active phase of the surge appears to end when the stress component $\rho g h \sin \alpha$, or the total bed shear stress, reaches a certain low value. This low value may be due to a low thickness in the reservoir area and a low slope in the receiving area.

(4) The instability must be due to some as yet undetermined subglacial boundary condition related to specific properties of the bed. The peculiar distribution pattern of surging glaciers indicates that it cannot be entirely due to a specific type or shape of glacier, nor can it be due to a specific climatic environment.

(5) The very rapid speeds attained by Type I surges are probably due to some additional mechanism, such as water flotation, which operates only in very special cases. It is emphasized that even during the peak of the active phase many surges move at rates which cannot be considered unusual for ordinary flow processes.

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[3] Where ρ is density, g gravity, h thickness, and α surface slope.

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Discussions and Replies

DISCUSSION BY DR. L. LLIBOUTRY

(1) Je crois que des précipitations plus fortes peuvent déclencher des crues. Cela serait prouvé par la relation qui semble exister entre le temps ecoulé depuis l'époque de fortes précipitations et la longueur des glaciers, aussi bien pour la Yakutat Bay que pour les Andes de Santiago.

REPLY BY DR. MEIER

Post has remeasured the Yakutat Bay glaciers using modern maps, and finds that the supposed linear relation between lengths and surge timings, as proposed by Tarr and Martin and later by Miller, breaks down completely.

DISCUSSION BY DR. LLIBOUTRY

(2) Je suggère que les régions où existent des "surging glaciers" sont celles où les précipitations varient beaucoup selon les années.

REPLY BY DR. MEIER

We have very few data on precipitation in the Alaskan mountains, certainly not enough to define regions of high or low variability.

DISCUSSION BY DR. LLIBOUTRY

(3) La caractéristique des "surging glaciers" me semble être l'existence de deux vitesses de glissement possibles. On peut alors compter parmi eux des glaciers tels que le Kongsbre (Spitsberg Ouest) qui, selon Voigt, avance beaucoup chaque été et est immobile en hiver.

DISCUSSION BY DR. W. F. WEEKS

Do you feel that the transition between your Type I and Type II glaciers in respect to velocity is discontinuous or continuous?

REPLY BY DR. MEIER

We cannot prove that the transition is either continuous or discontinuous; again, many more data are needed. Our interpretation of the meager data has led us to the tentative conclusion that there are relatively few glaciers which behave in a transitional way, so that there may be a real discontinuity in speed between Type I (superfast) and Type II (ordinary) surges. Thus we suggest that Type I surges might possibly involve an additional mechanism such as water buoyancy.

DISCUSSION BY DR. G. DE Q. ROBIN

Can the author distinguish between regular periodicity as characteristic of surging glaciers and the requirement that the reservoir must be completely refilled to trigger off a surge?

REPLY BY DR. MEIER

No, we cannot with the meagre evidence at hand. We lack sufficient data on surge timing, but even more important, we have few data on mass balance histories in areas where surging glaciers occur.

DISCUSSION BY DR. J. WEERTMAN

You have done a splendid job in giving us a clearer picture of just what are surging glaciers.

I am somewhat concerned that you may have done your job so well that the effect "If you can name a phenomenon you have understood that phenomenon" may take over in the literature. (An example is the wide acceptance of the discreet shear explanation of the formation of "shear moraines".) Thus your name "surging glaciers", which you have convinced the glaciological world to accept, has led you in your paper to ignore completely the very fast-moving outlet glaciers. Obviously they don't surge—by definition of that word. But the difference between them and surging glaciers may be only the trivial one that one type of glacier has an adequate ice supply to maintain a "surge" continuously whereas the other type "runs out of gas". I do hope that the outlet glacier problem will not be overlooked. At this time there is no reason for supposing that the triggering mechanism of a surge is more fundamental than the mechanism which maintains the surge.

The different categories of surges that you were able to propose has led you to the conclusion that fast surges arise from a different mechanism than slow surges. This conclusion may be correct. However, there is no reason why the mechanism that produces very fast velocities may not produce moderate velocities as well. The water-film mechanism that I have proposed can produce a continuous range of sliding velocities.

REPLY BY DR. MEIER

I agree with your hope that fast outlet glaciers not be overlooked. Certainly they pose an important problem which needs to be solved. I tend to look at the instability or triggering problem as more interesting because of its implications to the whole subject of glacier–climate interactions, and because we have such little understanding of how a flip-flop mechanism might be involved in glacier flow dynamics. In regard to the additional mechanism that might operate to produce superfast surges, I made this suggestion only because of an apparent, tentative observation that few transitional-speed surges exist. Only more and better data can answer this question.

DISCUSSION BY DR. W. BUDD

What is known about the temperatures of surging glaciers? For example, are surges found most often in temperate glaciers (at pressure melting everywhere), cold glaciers (below pressure melting everywhere), or glaciers with a temperate tongue and a cold accumulation region?

REPLY BY DR. MEIER

Very little is known. We know that surges may occur in temperate glaciers (if such a glacier exists); we know that some surging glaciers such as the Muldrow are at least subpolar in their accumulation zones but are probably temperate in their tongue areas; we know that subfreezing temperatures exist in the ablation areas of some small surging glaciers such as the Fox. However, we know almost nothing at all about temperatures at the bed of surging glaciers.