

THE CONSTITUTION OF VALLEY GLACIERS*

By ROBERT P. SHARP

(California Institute of Technology, Pasadena, Cal., U.S.A.)

ABSTRACT. Ice streams composing a compound valley glacier may be juxtaposed, inset or superimposed, and Demorest's concepts of ice flowage provide a plausible explanation for these relations. If valley floors are accordant, juxtaposition results because the waxing force of gravity and obstructed gravity flow in the tributary glacier overcomes the waning force of obstructed extrusion flow from the trunk glacier enabling the tributary to force its way into a juxtaposed position with the trunk glacier in the main valley. If discordance in valley floors is less than the thickness of the trunk glacier, an inset position develops by the same mechanism. If the discordance is greater than the thickness of the trunk glacier, superimposition results. Locally, superimposed or inset relations may be established by exceptionally rapid advances, even with accordant valley floors, but any superimposed ice stream shortly becomes inset by sinking into the underlying ice, at least in temperate glaciers.

ZUSAMMENFASSUNG. In einem zusammengesetzten Talgletscher liegen die Eisströme in folgender Anordnung vor:

- (1) Zwei oder mehr Ströme können nebeneinander in einem gemeinsamen Bett fließen (nebeneinandergestellt).
- (2) Ein Strom kann einen Kanal in einen anderen geschnitten haben (eingesetzt).
- (3) Ein Strom kann vollkommen auf der Oberfläche des anderen ruhen (übergeschoben).

Demorest's Begriff der Eisströmung gibt eine einleuchtende Erklärung dieser Verhältnisse wieder. Wenn zwei Gletscherbetten auf demselben Niveau stehen so erfolgt Nebeneinanderstellung. Wenn zwei Gletscherbetten auf verschiedenem Niveau stehen, und der Unterschied geringer als die Dicke des Hauptgletschers ist, so entsteht durch denselben Mechanismus eine eingesetzte Lage. Wenn der Unterschied grösser als die Dicke des Hauptgletschers ist, so erfolgt Überschiebung. Lokal können selbst bei ausgeglichener Talboden durch aussergewöhnlich schnelles Vorrücken übergeschobene oder eingesetzte Verhältnisse entstehen, aber jeder übergeschobene Eisstrom wird bald zum eingesetzten Eisstrom dadurch dass er in das unterliegende Eis einsinkt, dies gilt zum mindesten für Gletscher in gemässigten Klimas.

INTRODUCTION

In a compound valley glacier¹ fed by several tributaries, the individual ice streams clearly maintain their identity as they flow side by side down the trunk valley. This is strikingly illustrated by Washburn's superb photograph of the Barnard Glacier in Alaska (Fig. 1, p. 174). Glaciologists have also long realized that medial moraines are the surficial traces of steeply inclined septa of debris-rich ice lying between the individual ice streams. These observations lead easily to a three-dimensional picture of valley glaciers in which the individual ice streams extend in each instance from the surface to the floor (Fig. 2, p. 183). For convenience, this can be termed the "juxtaposed" position. Since the days of Louis Agassiz it has seemingly been accepted as the principal, if not the only, arrangement of ice streams in a compound valley glacier, and a recent text-book of glacial geology² reaffirms this concept.

A juxtaposed position probably exists in many valley glaciers, and it may be the usual arrangement, but as far back as 1932 Visser³ described glaciers in the Karakoram clearly composed in part of "inset" (or inlaid) and "superimposed" ice streams (Fig. 2). Furthermore, Visser's discovery had been anticipated by descriptions of glacier overriding by Garwood and Gregory⁴ in 1898, Novarese⁵ in 1911, Workman⁶ in 1913 and in even earlier instances cited by Odell⁶ extending back to Kornerup in 1879. The concept of superimposed and inset ice streams has been further clarified and developed by Odell⁶ and von Klebelsberg,⁷ so that it is now well founded and deserves full recognition by glaciologists. Visser³ considers the inset and superimposed arrangements to be the rule rather than the exception.

THE EVIDENCE FOR JUXTAPOSED, INSET AND SUPERIMPOSED ICE STREAMS

✓ The superimposed position needs no defence, for it has been independently confirmed by the

* Division of Geological Sciences, California Institute of Technology, Contribution Number 429.

field observations of Visser,³ Washburn,⁸ Odell,⁶ and Heim and Gansser.⁹ Washburn⁸ describes what he terms a "superimposed" glacier in the terminal cliff of the Crillon Glacier in Alaska, but his description indicates that the ice stream occupies an inset position according to the terminology previously established by Visser.³ Frequently the juxtaposed and inset arrangements cannot be observed directly and must be inferred from surface relations. In this regard transverse moraines are by far the most significant feature. They are accumulations of superglacial debris which occupy a transverse position on a valley glacier and form a connecting loop between two medial moraines or a medial and a lateral moraine. They have been termed "cross or oblique",³ "horse-shoe,"⁶ "melt,"⁷ and "pseudo-terminal moraines,"¹⁰ but should not be confused with Forbes' dirt bands, which are wholly surficial and occur below ice falls. At least two types of transverse superglacial accumulations are recognized: (1) those composed of debris carried up into the ice along scoop-shaped transverse shear planes,¹⁰ which may be termed "transverse moraine bands,"* and (2) those marking the ends of inset ice streams which are named "transverse moraines."

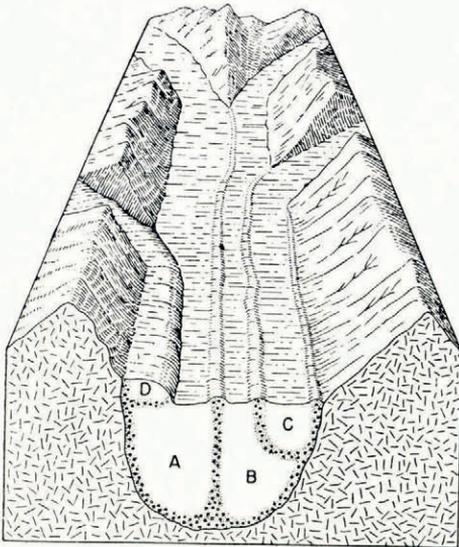


Fig. 2. Juxtaposed (A and B), inset (C) and superimposed (D) ice streams in a trunk glacier

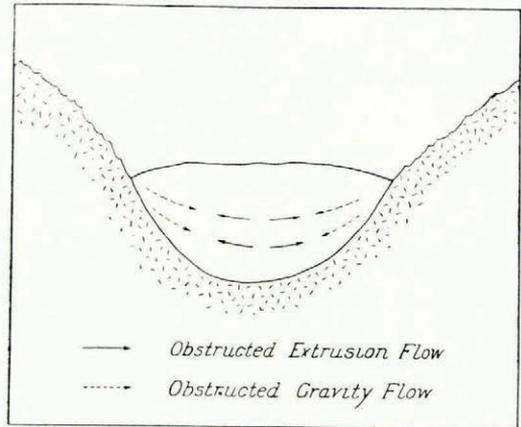


Fig. 6. Transverse section of a valley glacier showing balance between inward obstructed gravity flow and outward obstructed extrusion flow

Inasmuch as lateral or medial moraines on a glacier are the outcropping edges of a continuous hull of debris-laden ice which extends beneath the glacier for its entire length, it is readily apparent that a transverse moraine is simply the outcrop of this same debris-rich hull at the terminus of an inset ice stream. Transverse moraines can usually be distinguished from transverse moraine bands by the fact that they contain more debris, do not extend completely across the trunk glacier, are clearly related to one particular ice stream and are found at its terminus (Fig. 3, p. 175). As so distinguished, the transverse moraine provides good evidence of the inset position and is the principal means of recognizing that arrangement.

The juxtaposed position, the one usually postulated and perhaps the most common, is the

* A term suggested by Francois E. Matthes in a letter dated 7 February 1948.

most difficult to demonstrate. However, if an ice stream extends all the way to the terminus of the trunk glacier, chances are good that it is juxtaposed, for thinning by ablation near the snout of a glacier terminating on land is so great that most ice streams reaching the snout extend to the floor of the glacier. This criterion is not entirely dependable, for Visser³ and Washburn⁸ describe inset ice streams visible in the terminal cliffs of several glaciers. In a limited view, such as that of the Barnard Glacier (Fig. 1), it is not possible to distinguish juxtaposed from inset ice streams with certainty, but surficial relations suggest that some of the seemingly juxtaposed ice streams in the Barnard Glacier are actually inset. A down-valley view might show transverse moraines and thus confirm the inset arrangement, but if all the ice streams disappear under a heavy cover of ablation debris near the terminus, the true relations will be difficult to ascertain.

Relatively complex relations are to be expected among ice streams in a compound valley glacier composed of tributaries of various sizes and degrees of activity coming from valleys with

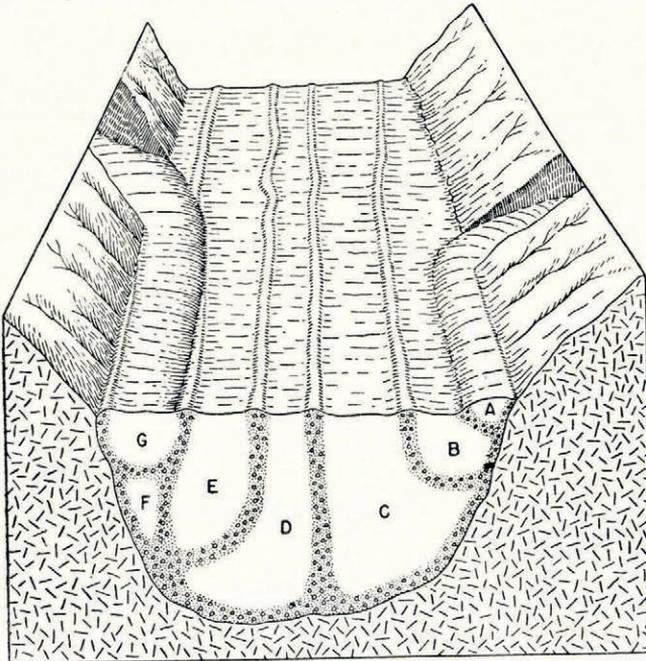


Fig. 4. The internal structure of a compound valley glacier. A is superimposed on B which is inset in C lying in juxtaposed arrangement with D. The juxtaposed ice streams E and F are inset in D, and G has settled to an inset position from an initial condition of superimposition

different amounts of discordance. Large tributary glaciers composed of two or three inset or juxtaposed ice streams may become inset within other ice streams of similar arrangement. It is not beyond expectation that a large compound valley glacier may have an internal constitution equalling or exceeding in complexity that suggested in Fig. 4.

ORIGIN OF THE JUXTAPOSED, INSET AND SUPERIMPOSED POSITIONS

Concepts of glacier flow recently developed by Demorest¹¹ provide a plausible explanation of ways in which these positions are developed. Indeed, the juxtaposed, inset and superimposed relations may well provide independent support for his reasoning. Demorest recognized four types of ice flowage: extrusion flow, obstructed extrusion flow, gravity flow and obstructed gravity flow. Extrusion flow and obstructed extrusion flow are pressure-controlled and take place chiefly in ice masses resting on essentially horizontal floors or floors sloping in opposition to the direction

of flow. The pressure is developed by differences in ice thickness and produces a squeezing out of plastic ice from the deeper part of the glacier. If this movement is opposed by a topographic barrier or by less plastic ice, obstructed extrusion flow results. Gravity and obstructed gravity flow occur in glaciers resting on floors inclined in the direction of flow, and the movement is caused by a component of gravity. Both types of obstructed flow are directed towards the surface of the glacier and thus provide mechanisms for thickening the ice. In obstructed extrusion flow the movement is along lines directed forward and upward and in obstructed gravity flow along lines directed forward and downward. In the latter, the surface slope of the glacier, according to Demorest, must be steeper than the lines of flow. In the arguments which follow, Demorest's concepts are assumed only as a working hypothesis, for his deductive analysis is yet to be tested by field studies.

One of the principal factors determining the position taken by a tributary ice stream upon joining a trunk glacier is the accordance or discordance of the valley floors,⁸ although relative size,

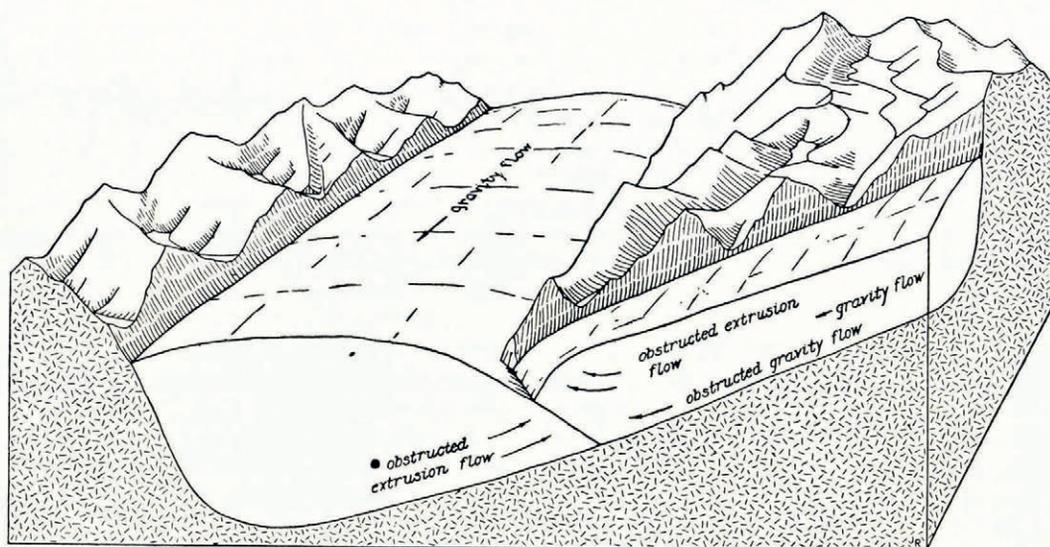


Fig. 5. Diagrammatic representation of the relations between types of flow at the junction of a trunk and tributary glacier

vigor, time of initial arrival at the junction, and physical condition of the ice may occasionally exert a controlling influence. Analysis by means of Demorest's modes of flow shows that a juxtaposed position results if the valley floors are accordant.

For example, assume that the trunk glacier reaches an accordant junction first, forming a barrier across the tributary valley and sending a branch lobe a short distance up it. The flowage in this short and rapidly thinning lobe is uphill and can be produced only by differential pressure, so it must be of the obstructed extrusion type. In the meantime the tributary glacier moves down its valley and upon reaching the junction overrides the lower part of the barrier formed by the steeply sloping face of the branch lobe. At first this overriding is by gravity and obstructed gravity flow, but eventually it is caused at least in part by obstructed extrusion flow (Fig. 5, above). As ice continues to move down the tributary valley the tributary thickens itself by obstructed gravity flow, and this increasing thickness allows it to encroach further and further on to the branch lobe from the trunk glacier. The part of the branch lobe overridden by the tributary becomes part of

its gravity-flow system, and with each additional encroachment the power of extrusion flow from the trunk glacier decreases. If ice continues to move down the tributary valley gravity flow inevitably becomes the more powerful, and the tributary glacier forces its way into the main valley and takes up a juxtaposed position with the trunk ice stream. The overridden ice of the barrier probably functions as part of the tributary glacier in this operation.

The trunk glacier makes room for the tributary in the following manner. In the transverse section of a valley glacier obstructed extrusion flow directed outward toward the sides is balanced by obstructed gravity flow directed inward toward the center (Fig. 6, p. 183). Extrusion flow arises from the difference in thickness of ice between the center and the edges, and gravity flow arises from the inward slope of the valley floor. The push exerted by the advancing tributary tips the balance in favour of obstructed gravity flow, which causes the marginal ice of the trunk glacier to move inward and at the same time produces an increase in thickness as the trunk glacier is squeezed into a narrower channel. Obstructed gravity flow occurs only where the valley floor slopes inward. At the point where the floor becomes flat or slopes inward from the opposite side, obstructed extrusion flow, generated by the differential increase in thickness of ice, takes over and continues the adjustment across the glacier. The total increase in thickness need not be as great as might be imagined, since an attending increase in down-valley velocity within the trunk glacier disposes of much of the additional ice.¹¹

An adjustment in the trunk glacier above the junction is also required, as it is now partly obstructed by the entering tributary. An increase in thickness by obstructed gravity flow takes place immediately above the junction in that part of the trunk glacier dammed by the projecting tributary. This increased thickness gives rise to obstructed gravity and obstructed extrusion flow directed transversely across the valley in the manner outlined above.

Increase in thickness of the trunk glacier down-valley from the junction takes place by obstructed gravity and obstructed extrusion flow. Adjustments within the brittle surficial ice hull, 100 to 150 ft. (30-45 m.) thick, are perhaps more by fracture than flowage.

If we return to the original premise of accordant valleys but assume that the tributary reaches the junction first, a juxtaposed position is again the ultimate result. The tributary may erect a barrier across the trunk valley, but gravity flow now favours the trunk glacier, which overwhelms this barrier and forces the tributary to take up a juxtaposed position at the side of the valley. It is true that a relation of superimposition exists between the trunk glacier and the part of the tributary that it overwhelms, but this is a local arrangement which moves down to ultimate destruction by melting at the terminus of the glacier. The more permanent relation is one of juxtaposition, and it is developed as a result of the conflict between gravity and extrusion flowage outlined above.

Visser³ believes that a juxtaposed position develops only between ice streams exactly equal in volume, velocity, density, compaction and structure, and flowing from accordant valleys. He maintains that valley accordance or discordance is outweighed by size, velocity and physical condition of the ice in determining relations between ice streams, and he cites field evidence of overriding glaciers coming from accordant valleys. Initial overriding is to be expected, but if the analysis presented in the preceding paragraphs is sound and Demorest's concepts of glacier flow correct, then the initial condition of overriding should be replaced by the juxtaposed arrangement when the adjustment between ice streams flowing from accordant valleys is completed.

If the valley floors are initially discordant and the trunk glacier is thick enough to raise a barrier across the tributary valley, an inset relation develops by the interplay between gravity and pressure flow already outlined. No mechanism is apparent by which a juxtaposed position could develop under these conditions, even though the tributary reaches the junction first. As the inset condition is established, an upper layer of the trunk glacier equal in thickness to the tributary must be squeezed into a narrower stream. This adjustment takes place by the workings

of transverse obstructed gravity and obstructed extrusion flow already detailed in the instance of juxtaposed ice streams.

Field observations¹² and study of photographs like that of the Susitna Glacier, Alaska (Fig. 3, p. 175), show that some glaciers experience repeated surge-like advances at relatively high velocities. The mechanism and effects of these surges are far from completely understood, and only brief speculative treatment is offered here.

It would seem that the high velocity of a surge-like advance must endow the ice stream concerned with a momentum which enables it to shoot a lobe or tongue out into the trunk valley far beyond its normal marginal position (Fig. 3). In this process the trunk glacier is pushed aside and medial moraines are deformed.⁸ Some overriding probably occurs, but excess ice thickness so developed is disposed of by obstructed extrusion flow at depth. The projecting ice tongue moves forward by virtue of its own momentum and not by gravity or pressure flowage in the usual sense. The effects resemble those of gravity flow, for the movement at the surface is as great or greater than the movement at depth. The trunk glacier is squeezed into a narrower channel and yields by pressure-controlled extrusion flowage in all directions, except downward, in a plane at right angles to the push exerted by the momentum-driven ice. The resistance of the trunk glacier to this push produces some obstructed flowage within the momentum-driven ice lobe which causes deformation of medial moraines within the projecting lobe. Deformation of medial moraines in that part of the trunk glacier dammed by the projecting tributary lobe is also attributed to obstructed types of flow within the trunk glacier.

An observer looking at the Susitna Glacier (Fig. 3) might conclude that even the surficial ice yielded to squeezing by the projecting tributary in a plastic or almost plastic manner. However, he should realize that the ice now composing the surface was at an unknown depth when deformation occurred. It has been exposed by subsequent lowering of the glacier's surface through ablation. The behavior of surficial ice during such deformation remains a matter of speculation, although at least some adjustment by slip along a number of discrete fracture planes appears a likely possibility.

The alternation of surges from different tributaries, shown in Fig. 3, probably arises from a difference in time required for an advance, originating from a common cause, to travel down the various tributaries. Local inset relations may be established by such surges even though the valley floors are accordant and the relations between ice streams established during periods of normal flow are those of juxtaposition.

If the discordance between valley floors is so great that no barrier is formed by the trunk glaciers, a wholly superimposed relation results at the junction, for the tributary flows or cascades on to the surface of the trunk glacier. It is also conceivable that a tributary glacier advancing with extreme rapidity may become superimposed on a trunk glacier by obstructed flowage regardless of the nature of the junction. This seems a likely possibility because some glaciers become superimposed upon themselves (Fig. 7, p. 188) by obstructed types of flow probably originating in a greatly increased rate of movement, coupled with an obstruction in the glacier's course. This process might properly be called "autosuperimposition."

A wholly superimposed position in temperate glaciers is usually short-lived, no matter what its origin, for the locally increased thickness of ice gives rise to obstructed extrusion flow both transversely and longitudinally. This permits the superimposed glacier to sink relatively quickly to an inset position. Cold Polar glaciers, which are below the pressure-melting temperature to considerable depth, may be rigid enough to support a superimposed ice stream for a much longer time, as noted by Odell.⁶ Visser³ also describes instances in which the overriding ice stream completely buries the overridden glacier and therefore does not develop an inset position.

Thus, the inset relation may be established by pushing from the side or by sinking in from

above. An inset position established by pushing can be identified by the fact that ice streams composing the trunk glacier move over to make room for the tributary. By contrast, ice streams of the trunk glacier disappear beneath the tributary inset from a superimposed position. Photographs suggest that the inset position established by pushing is the more common in Alaskan glaciers.

In some instances a small juxtaposed ice stream may lack sufficient nourishment to carry all the way to the terminus of the trunk glacier. It thins by ablation, and this thinning gives rise to transverse obstructed extrusion flow from adjoining ice streams, which squeezes the under-nourished tributary into an ever-narrowing channel. Eventually it may be completely pinched out^{7, 8, 13} or it may become inset upon ice squeezed beneath from neighbouring ice streams.

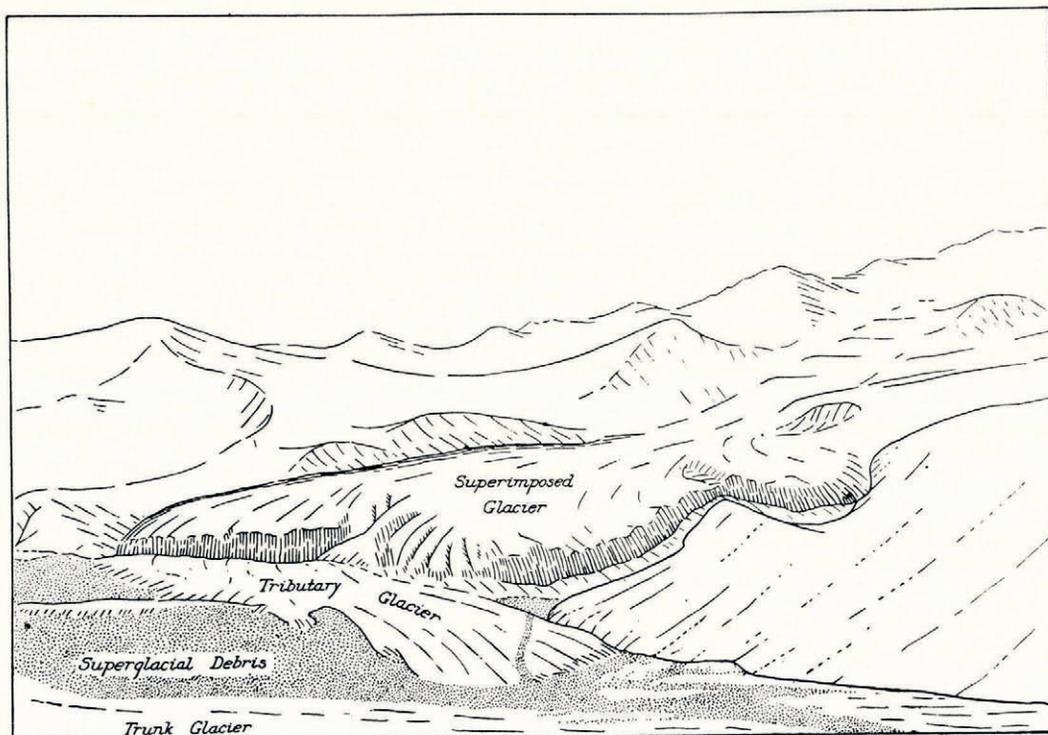


Fig. 7. Small, rapidly advancing glacier on east slope of Mt. Wood in the St. Elias Range, Canada. This glacier is superimposed upon itself and is beginning to override the trunk glacier in the foreground, Vertical ice front about 150 feet high

Discordant valley junctions are a recognized product of mountain glaciation, but it was assumed above that the valleys were already discordant when the glaciers arrived at the junction. Such discordance can be attributed to an earlier glaciation or to more rapid entrenchment of the master stream,¹⁴ but the effects of discordance developed while the valleys are filled with ice are worth examination.

Assume that a trunk and a branch glacier have taken up juxtaposed positions because of initial valley accordance, but assume further that the trunk glacier is deepening its valley and cutting back the walls so rapidly that the branch valley is eventually left in a hanging position. As this condition develops, the tributary ice stream begins to take up an inset position in the trunk glacier by means of the mechanism previously outlined. During evolution of the discordance,

therefore, the tributary will gain an inset position in the vicinity of the junction but retain a juxtaposed position further down-valley. Deepening of the trunk valley may continue to the point that the branch glacier becomes superimposed, but this superimposition, like all others, will not extend far down-valley for reasons already given.

At the initially accordant junction of two large and approximately equal branches of a glacier, the augmented ice stream may excavate so effectively that both branches are eventually left hanging. It is unlikely that this will alter the previously established juxtaposed arrangement, nor will the ice streams become autosuperimposed unless the amount of ice coming down the valleys increases greatly. Instead, the ice streams will cascade over the break in profile and continue to move out from its base in parallel position. It seems unlikely that the "plunge pool," if it may be called that, will be filled with stagnant ice, for the development and growth of the break in bedrock profile requires active ice at its base.

CONTORTED MORAINES

If adjustments in the thickness of valley glaciers are made by transverse obstructed gravity and obstructed extrusion flow, as proposed above, it would seem that the medial septa between individual ice streams must undergo deformation. Much of this deformation would occur in depth, where the ice is plastic, but it could be exposed subsequently in the lower reaches of a glacier where the surface has been lowered by ablation. Contortions in the medial moraines of some glaciers have probably been formed by adjustments in thickness through obstructed types of flow. But it seems unlikely that the extremely severe and complex distortions described and pictured by Washburn⁸ can be wholly of this origin.

Acknowledgment

Bradford Washburn's generosity in permitting reproduction of his photographs and the draftsmanship of David P. Willoughby and Joan T. Rounds are deeply appreciated. Profit has been derived from the critical comments of François E. Matthes and Richard H. Jahns.

MS. received 5 April 1948

REFERENCES

1. Matthes, F. E. Glaciers. (In Meinzer, Oscar E., ed.) *Physics of the Earth—IX. Hydrology*. McGraw-Hill Book Co.: New York, 1942, Chapter 5, Fig. V-2, p. 152.
2. Flint, R. F. *Glacial Geology and the Pleistocene Epoch*. John Wiley & Sons, Inc.: New York, 1947, p. 74.
3. Visser, Ph. C. Gletscherüberschiebungen im Nubra- und Shyockgebiet des Karakorum. *Zeit. Gletscherkunde*, Bd. 20, 1932, p. 29-44.
4. Gletscherbeobachtungen im Karakorum, Scherflächen und Gletscherüberschiebungen. *Ibid.*, Bd. 22, 1935, p. 20-45.
5. Garwood, E. J. and Gregory, J. W. Contributions to the Glacial Geology of Spitsbergen. *Quart. Journ. Geol. Soc. London*, Vol. 54, 1898, p. 208-09.
6. Workman, W. H. Features of Karakorum Glaciers connected with Pressure, especially of Affluents. *Zeit. Gletscherkunde*, Bd. 7, 1913, p. 65-103.
7. Odell, N. E. The Glaciers and Morphology of the Franz Josef Fjord Region of North-East Greenland. *Geog. Journ.*, Vol. 90, 1937, p. 111-25.
8. Klebelsberg, R. von. Die Zusammensetzung der Talgletscher. *Zeit. Gletscherkunde*, Bd. 26, 1938, p. 22-43. Visser's Karakorum-Glaziologie. *Ibid.*, Bd. 26, 1939, p. 307-20.
9. Washburn, H. B. The Harvard-Dartmouth Alaskan Expeditions. *Geog. Journ.*, Vol. 87, 1936, p. 481-93.
10. Morainic Banding of Malaspina and Other Alaskan Glaciers. *Bull. Geol. Soc. Am.*, Vol. 46, 1935, p. 1879-90.
11. Heim, Arnold and Gansser, August. *The Throne of the Gods*. Macmillan: London, 1939, p. 68-69.
12. Chamberlain, T. C. and Salisbury, R. D. *Geology*. Henry Holt & Co.: New York. Vol. 1, 1909, p. 296-97.
13. Demorest, Max. Glacier Regimens and Ice Movement within Glaciers. *Am. Journ. Sci.*, Vol. 230, 1942, p. 31-66.
14. Ice Sheets. *Bull. Geol. Soc. Am.*, Vol. 54, 1943, p. 363-400.
15. Hance, J. H. The Recent Advance of Black Rapids Glacier, Alaska. *Journ. Geol.*, Vol. 45, 1937, p. 775-83.
16. Moffit, F. H. Black Rapids Glacier, Alaska. *U.S. Geol. Survey Bull.*, 926-B, 1942, p. 107-60.
17. Palmer, Howard. Observations on the Freshfield Glacier, Canadian Rockies. *Journ. Geol.*, Vol. 32, 1924, p. 432-41.
18. Matthes, F. E. Geologic History of the Yosemite Valley. *U.S. Geol. Survey, Professional Paper* 160, 1930, p. 33-39.



Fig. 1. Barnard Glacier, Alaska, near head of Chitina Valley in the St. Elias Range, looking north-east. Note adjustment in width of ice streams composing trunk glacier where joined by tributaries. Although these ice streams would appear to be in juxtaposed arrangement some may be inset. (See p. 182)

Photograph by Bradford Washburn



Fig. 3. Susitna Glacier in eastern Alaska Range, looking north-east. The complexity of the moraines is not completely understood but may be partly explained by surge-like advances of different branches and tributaries. These surges give sufficient momentum for an ice tongue to push far out into the trunk glacier, squeezing it into a narrow channel and producing severe deformation of medial moraines. (See p. 183)

Photograph by Robert P. Sharp