Correspondence and criticism - Glacier thinning during deglaciation (Flint, Demorest, and Max). 1942

Thwaites, F. T. (Fredrik Turville), 1883-1961
[s.l.]: [s.n.], 1942

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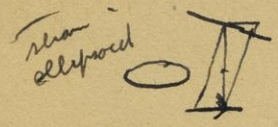
Flint, R. F., and Demorest, Max, Glacier thinning during deglaciation: Am. Jour. Sic., vol. 240, pp. 29-66, 113-136, 1942

The paper by Flint and Demorest ~~cited above~~ entitled Glacier thinning during deglaciation is in two parts, the first by the junior author. In this part the mechanics of glacial flow are analized and certain conclusions reached which differ sharply from those of Thwaites (1) as well as from those of students of rock flowage.

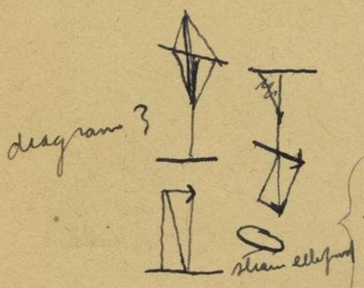
diff frac & flow cleavage

Thwaites, F. T., Outline of Glacial Geology, pp. 17-18, 1941

It is here assumed that deformation is by fracture cleavage not flow cleavage

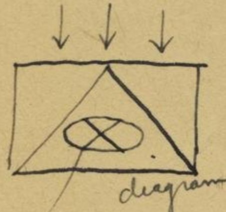


On p. 32 it is assumed that a bottom slope is essential to "gravity flow". Such is not the case for in any mass of plastic material which is unsupported along ~~one~~ the sides the form of either top or bottom is relatively immaterial. On p. 35 it is stated that the conditions which bring about "extrusion flow" require a sloping top. From the standpoint of mechanics both ~~conditions~~ a sloping base and a sloping top have ~~are~~ essentially similar differential stresses.

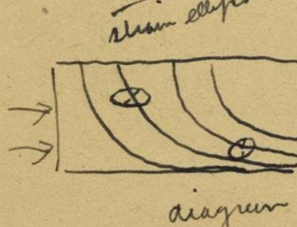


in stating that it is prop to cos

Another error is that stress is proportional to the sine of the angle measured from vertical times the cosine of the angle ~~from the vertical~~ to direction of pressure. is a matter of fact stress ~~It~~ reaches a maximum at 45 degrees. Speed of motion on an inclined plane is not an index to the stress existing along the surface before motion starts. It is the result of acceleration caused by a component of the force of gravity. (~~figure 1~~)(figure 1)



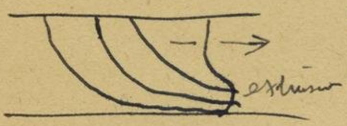
On p. 34 the author implies that the layers of ice on which shearing takes place are parallel to the inclined floor of the glacier. This is not to be expected. unless it is actually flow cleavage to which the crystal system of ice is not well adapted Within the flow the maximum shear is at an angle of 45 degrees and the ice tends to shear along this plane. However, near the bottom of the ice this tendency is complicated by an additional factor, the friction of the bottom against the basement rock. The resultant is a curved surface of shear dipping at 45 degrees in the upper part of the ice and flattening off to (figure 2) when a change in axes of strain ellipsoid parallelism with the bottom. This is exactly the same as "fracture cleavage" in rocks. Whether or not there will be a film of ice at the



bottom which is motionless depends upon ~~whether or not~~ the shearing strength of the ice is in proportion to ~~greater or less than~~ as compared with the friction between the ice and the basement on which it rests. It might be expected that friction would be less than shearing strength and that the ice would slide if the slope ~~was~~ were steep enough. However, if the slope ~~is~~ were very flat then shear might occur.

see first diagram

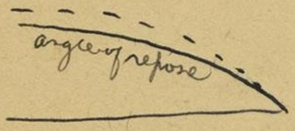
The author's distinction between "gravity flow" and "extrusion flow" is not warranted by either fact or theory. The forces are exactly the same in both cases, i.e. a sloping basement ~~and~~ or a sloping top. ~~As a matter of fact neither is important.~~ Now it is stated on p. 35 that the less plastic ice of the top of a glacier is carried on top of the ~~f~~ ice below so that the entire top part participates in the movement of "gravity flow". Why is this not true with "extrusion flow?" The only possible way to hold the ice motionless above an underlying zone of flow ~~below~~ is for it to possess enough tensile strength to resist breaking along crevasses. If flow extends throughout the entire mass of a continental ice sheet why are crevasses confined to the margins? Or are those of the center kept continually covered with snow?



see first diagram

It is true that the differential pressure due to a sloping top does slightly alter the picture. Stress due to this factor alone would have one of the planes of maximum shear in a horizontal position, as Demorest holds. But it is combined with stress due to weight. ~~alone.~~ In this case, the lines of shear will ~~curve off~~ dip at some angle between 45 degrees and horizontal, again curving off to parallelism with the floor. (figure 2)

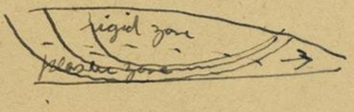
¶ Another point on which there may well be difference of opinion is the statement on p. 39 that ice would ultimately flow to a level surface provided the edges were enclosed. This denies the existence of a minimum slope ~~below~~ on the margin of the ice sheet ~~belowxwhich~~ sufficenent to overcome internal resistance ~~a~~ to flow, that is what Thwaites terms an "angle of repose". Now all substances ~~contain~~ demand a minimum amount of stress before flow is possible. This must vary in ice with the temperature but time alone will not overcome the demand~~s~~ for energy. Unless the margin of an ice sheet is replenished with snow motion must cease from outflow but thinning is not a necessary consequence back of this marginal zone. (figure 3)



Another point made by Thwaites is the fact that motion of a continental glacier is largely ~~or~~ if not wholly confined to the marginal zone of maximum surface slope. Under the views of Demorest this could not be true, but if we recognize the steeply dipping planes of shear then such a view seems inescapable. Certainly the base of a large ice sheet must be essentially motionless over a large area near the center. (figure 2)

see figure before

As for "obstructed flow" it is undobtedly correct to conclude that resistance to movement decreases with depth from the surface, that is with increase of weight and temperature. Beyond question basal flow is retarded by friction as outlined above. But glacial polishing and striation~~s~~ prove motion at the very bottom of the ice. At the thin edges of an ice sheet internal resistance to flow or shear is undoubtedly higher than under deep ice. The result must depend upon which way relief is easier, by bodily shoving of the rigid thin ice margin over the basement or by internal shear ~~or~~ (thrust faulting). ~~Here~~ It is an observed fact that the planes of shear do curve upward toward the margin of the ice. But the method of relief must depend wholly on local conditions. Such being the case why use the term "obstructed"?



p. 32. The author confuses force and stress.

Force is a vector quantity but stress is scalar.
(See R.V.Southwell:An Introduction to the theory of Elasticity, Oxford, 1936)

Stress is not proportional to the cosine of the angle but to the product of the sine x the cosine, a quantity which rea~~s~~ches a maximum at 45 degrees.

Therefore the stress on y is not greater but less than that at x. Speed of motion on an inclined plane is not an index to the stress existing along the surface before motion starts. It is the result of acceleration caused by a component of the force of gravity.

It is nevertheless true that stress at z is less than stress at y.

p. 34.

The author implies that the layers of ice on which shearing takes place are parallel to the inclined floor of the glacier. This is not to be expected. Within the flow the maximum shear stress is at an angle of 45 degrees with the vertical and the ice tends to shear along this plane. However near the bottom this tendency is complicated by an additional factor, viz the friction of the bottom of the glacier. This tends to produce a shear stress parallel to the bottom. The resultant is a curved surface of shear dipping at 45 degrees in the upper part of the ice and flattening off to parallelism witn the bottom. The stresses are not easy to analyze but they must be somewhat like those within a mass of clay pressed between two parallel plates, bearing in mind that the upper plate is missing a vertical pressure is supplied by gravity. See Nadai, Plasticity, p. 223.

Whether or not there will be a film of ice at the bottom which is motionless depends on whether ~~the~~ or not th shearing strength of the ice is greater or less than the friction between the ice and the bottom. It might be expected that friction would be less than shearing strength and that the ice would slide if the slope was steep, but that on flatter slopes the ice would shear. However, if the layer is of "theoretically infinitesimal thickness"we need not quihble over this point.

p. 35

In the case of extrusion flow it would seem that the stress within the ice would be similar to that just discussed.

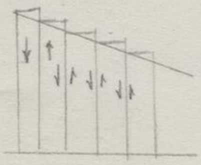
A sloping top surface is not necessary. On a level sheet of ice the vertical force of gravity would produce a family (2.) of surfaces of maximum shear stress and cause extrusion at the end of the sheet.

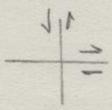
The sloping surface introduces a factor of differertial (3) pressure. The stress due to this factor alone would, it is true, have one of its planes of maximum shear in the horizontal position. But this acts in conjunction with the 45 degree (theoretical) shears. The combined stress (4) would be inclined at some angle between 45 degrees and horizontal, again curving off to parallelism with the floor. (5)

Admitting that the plasticity would be greatest near the bottom of the ice-sheet and that the lower layers would flow, is it not true that the upper part of the sheet would ride on them? The only thing to prevent this is the tensile strength of the upper layers. Would not the upper layers fail along tension cracks (crevasses) just as the upper surface of a landslide breaks off and rides on the lower shear plane? (6)

(2.)

(3)





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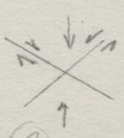

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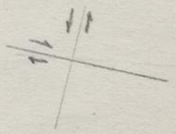

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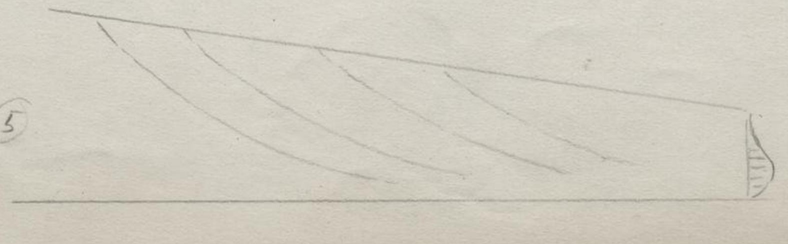

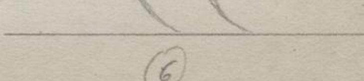

(6)

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Flint, R. F., and Demorest, Max, Glacial thinning during deglaciation:
Am. Jour. Sci., vol. 240, pp. 29-66, 1942

So far as I can see there is no valid reason for distinction between "gravity flow" and "extrustion flow." The mechanics of pressure upon any given particle in a vertical section are exactly the same. The only possible difference lies in the position of the component which causes movement in the direction of easiest flow. In the case of a sloping basement the direction of flow will be downhill and movement would be possible with a flat surface (0 slope). But with a horizontal base flow is possible only with a slanting top.

Now it is admitted, and observation demonstrates, that movement of the ice at depth in the case of gravity flow carries with it all ice above. Why is this not also true with "extrusion flow"! I certainly can find no reason for any difference despite the diagrams. If this point be admitted not only is the distinction much less marked but the diagrams are distinctly misleading.

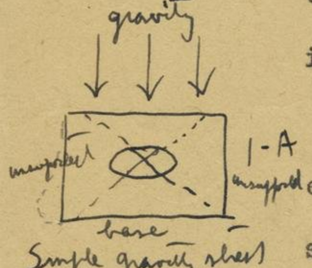
As for "obstructed flow" it is undoubtedly correct to conclude that resistance to movement decreases with depth from the surface, that is with increase of weight. Basal flow is retarded by friction beyond question, but it certainly is not prevented even at the very bottom of the ice. Observation proves this or we would not have glacial erosion. Again the diagrams are misleading. At the thin edges of the ice cap internal resistance to flow is certainly higher than under thicker ice. The result on movement must depend upon which way relief is easier, by bodily shoving the rigid ice against bottom friction or by shear (thrust faulting) within the ice. Observation seems to suggest that the method of relief depends upon local conditions. Such being the case I fail to see the necessity of calling this "obstruction".

The matter of ice cap stagnation has been discussed by me on pages 17-18 of the "Outline of glacial geology" and so far I see no reason for changing the views there set forth and not mentioned in the paper As around 800 copies of this book are in circulation in all parts of the world it might be cited.

Flint, R. F., and Demorest, Max, Glacier thinning during deglaciation:
Am. Jour. Sci., vol. 240, pp. 29-66, 113-136, 1942

¶ The paper by Flint and Demorest on "Glacier thinning during deglaciation" consists of two parts, the first of them by the junior author. In this part the mechanics of glacier flow are analized. Conclusions reached differ sharply not only from those heretofore announced the writer (1), but also from the fundamental priciples of structural geology which have been expounded by ~~many~~ writers. The writer acknowledges aid from Professors ~~Hugh~~ E. McKinstry and S. A. Tyler in the preparation of the following criticism.

¶ although Demorest is reported to have made many experiments of ice flowage ~~yet~~ he nowhere states whether the deformation here described is ~~classed as~~ "fracture cleavage" or ~~as~~ "flow cleavage." Theoretical considerations favor the former. ~~Under light load~~ Ice is relatively brittle and under a light load must be deformed by fracture. Furthermore, ice does not crystallize in forms which have cleavage which compares in perfection with that of mica, hornblende, etc which occur in rocks which display ~~altered by~~ flow cleavage. Lake ice || xls



Simple gravity stress

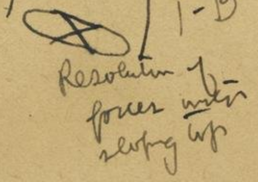
The simplest case is deformation of a block of ice with unsupported ends and a level top. (Fig. 1, A.) In this case the long axis of the strain ellipsoid is horizontal (~~and fracture follows the unchanged~~ diameters of the original circle) thus forming fractures inclined at (theoretically) 45 degrees from the horizontal. In flow of this type the form of either top or bottom of the plastic mass is relatively immaterial It is also evident that a certain portion of the bottom under the center of the mass is unaffected by motion.

{according to max strain theory which has been rejected by [illegible])

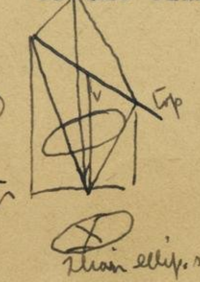
Now if ~~the~~ we resolve the forces acting upon a point ~~with either~~ under a sloping top ~~or a sloping basement~~ we find that the resultant is not ~~longer~~ vertical (Fig. 1, B) but is inclined slightly in the direction of slope. This causes the long axis of the ellipsoid to tilt slightly away from the horizontal position, up toward the direction of ~~slope~~ relief, making the dip of one ~~the~~ shear planes ~~[illegible]~~ less than 45 degrees. Then: ~~The other plane would dip more than 45° and become~~ crevasses Fig 1, C

stet

(Or are crevasses tension cracks



Resolution of forces under sloping top

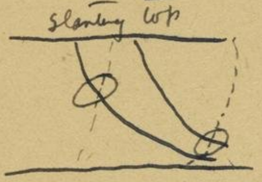


Strain ellipsoid

Now the slope of the bottom has very little influence excepting that it permits of somewhat easier movement. From the foregoing analysis the ~~baix~~ basis upon which "extrusion flow" ~~with~~ under a sloping top is ~~separated~~ discriminated from "gravity flow" on an inclined base ~~is evidently~~ appears unsound and unecessary.

[illegible]

Another factor is the effect of basal friction on the direction of shear. ~~This factor~~ Friction causes a tilt of the long axis of the strain ellipsoid up toward the edge of the ice thus causing the planes of shear to flatten out at the bottom. The analogy to S-shaped cleavage developed in a thin plastic bed between competent layers given is evident. ~~The other lines of shear, which correspond to the other unchanged axis of the ellip-osid, are doubtless the cause of crevassing. (figure 1, C)~~



1 - C
Relation of strain ellipsoid to flow

no ¶ Whether or not there will be any film of motionless ice at the bottom of the glacier depends upon the shearing strength of the ice as compared with the friction between the ice and the underlying basement. It might be expected that friction would normally be the lesser of these two quanities and that the ice would slide upon the rock. ~~unless the slope was~~ ~~stsspssssssghxss~~ so ~~gentle that shear, might occur.~~ ~~enough to count~~

Demorest's statement that "extrustion flow" occurs only at depth and does not carry with it the overlying ice contradicts his statements in regard to "gravity flow". The only possible way to keep this surficial ice from being carried along on top of moving ice would be a sufficient tensile strength to resist friction. ~~Knowing~~ The fact that ~~lightly loaded~~ ice breaks readily under tension demonstrates that such a relation is ~~seen to be~~ impossible. ~~But~~ Observation discloses few crevasses on the tops of existing continental glaciers unless it be that they are kept always filled with snow, ~~In this case~~ May it not be that the writer's ~~x~~ contention that the central parts of ice sheets are essentially motionless from top to bottom be correct? In such case noticable flow is confined to areas of sufficient surface slope where differential pressure is added to simple gravity strain.

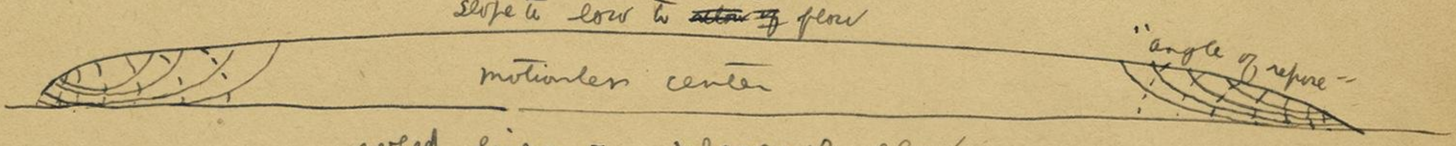
Fig 2

Demorest states on page 39 that if ice were placed in a basin it would ultimately reach a flat surface. This view neglects the fact that any and all deformation ~~absorbs~~ demands energy. Below a certain mimumum of stress, which will naturally vary in absolute amount with temperature and other factors, no flow is possible. There must certainly be a ~~certain~~ minumum slope ~~maintained~~ or "angle of repose" ~~which must be surpassed~~ on the edge of an ice cap which must be exceeded to cause appreciable flow. If this slope is not maintained by snowfall then motion must cease throughout the entire glacier regardless of size.

~~Fig. 2~~

The designation "obstructed flow" for the effect of The rigidity of thin ice ~~with less plasticity~~ near the margins of an ice sheet is open to difference of opinion. At these thin edges resistance to shear is undoubtedly greater than under thick ice. On the other hand friction is less because of the decrease in weight. It would appear likely that, except where a rough basement raises the value of friction and compells internal shear on planes which rise toward the margin, the rigid edge of the ice will be shoved bodily over the underlying material. Is not this the explantion of glacial abrasion and plucking? If so, why use the term "obstructed"?

F. T. Thwaites University of Wisconsin
March 17, 1942



solid lines = planes of flow
dotted lines = crevasses

Fig 2
cross section of a continental glacier

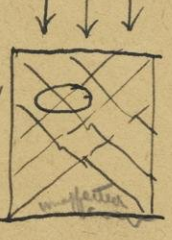
~~version of March 20, 42~~ !

Flint, R. F., and Demorest, Max, Glacier thinning during deglaciation:
Am. Jour. Sci., vol. 240, pp. 29-66, 113-136, 1942

The paper by Flint and Demorest on "Glacier thinning during deglaciation" consists of two parts, ~~the first of which is by the junior author~~. In the ~~first~~ part, by the junior author, the mechanics of glacier flow are analyzed. sp? The conclusions there reached differ sharply not only from those heretofore announced by the ~~writer~~ writer (1) but also from the fundamental principles of structural geology which have been expounded by many writers. In the preparation of the following criticism the writer was greatly aided by Professors H. E. McKinstry and S. A. Tyler.

Flow takes place both by recrystalization and by shear

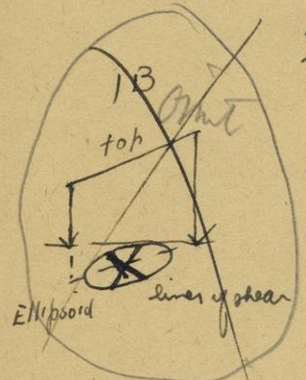
~~Although it is reported that Demorest has made many experiments on ice flowage he does not seem to recognize the difference between "fracture cleavage" and "flow cleavage".~~ Ice crystallizes in the hexagonal system which ~~in general~~ does not lend itself very well to the formation of cleavage such as occurs with minerals like mica and hornblende. Natural lake ice has the long axes of the crystals ~~with the long axes~~ parallel and vertical. ~~and~~ Such ice displays a moderate degree of cleavage ~~in all~~ along vertical planes, a fact taken advantage of in putting up natural ice. Ice at ~~ordinary~~ temperatures not far below freezing and under light load is notably brittle. ~~It seems likely, therefore, that~~ glacial ice ~~in a glacier where there is much included~~ is weakened by inclusion of air and dirt ~~is~~ and therefore is more likely to be deformed ~~only~~ by fracture. Therefore the following discussion is based on this assumption. Demorest seems to assume that deformation is by shear which is essentially the same idea


Ellipsoid!

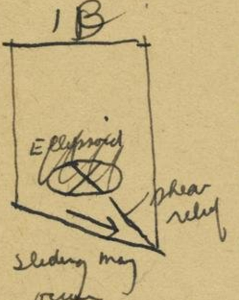
1A

Figure 1, A, shows the simplest case of ice deformation, that of a block of ice with level top and two unsupported sides. In this case the long axis of the strain ellipsoid is horizontal and the planes of shear dip approximately 45 degrees. The triangluar section beneath the planes which reach the bottoms of the open sides is essentially unaffected.

We can alter this picture by increasing the ~~dept~~ height of the column of ice until the bottom is rendered plastic by reason of pressure, aided in an actual glacier by increased temperature due to the internal heat of the earth. In this case the phenomenon termed "extrusion flow" by Demorest would cause the bottoms of the open sides to begin to bulge out. But ~~it~~ they could not ex~~tend~~pand an appreciable amount without carrying with ~~it~~ them the superimcumbent ~~rg~~ rigid ice. Ice has too low tensile strength to resist the strain set up by "extrusion", and must be moved, throughout the mass. The shear planes would be the same.

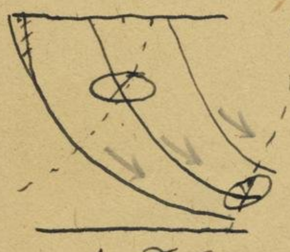


Now let us consider the case of an inclined top ~~to~~ on the column. ~~Figure 1, B shows that the resultant of the forces acting on a particle is inclined from the vertical thus al~~ This condition is not readily analized but so changes the position of the strain ellipsoid by tilting it down parallel with the slope. With the known low inclination of glacier surfaces this ~~change~~ effect is not important and ~~is~~ must be a ~~very~~ minor factor in deformation.



Next let us consider the effect of an inclined basement under the column. With this condition the friction between ice and rock may be low enough to permit ~~th~~ sliding ~~xxx~~ of the ice instead of shearing. This is what Demorest terms "gravity flow" but the foregoing analysis shows that it is essentially similar to his "extrusion flow" except that it ~~is~~ may be more rapid as shown in Fig. 1, B.

As soon as flow commences, the factor of basal friction must be considered. Figure 1, ~~B~~ C, shows that this force results in a tipping of the strain ellipsoid so that the planes of shear along which motion takes place flatten out with depth. This is exactly the same as the S-shaped cleavage which develops in a layer of plastic rock between two more rigid layers.



1-~~B~~ C.

The other possible plane of shear. may cause crevassing.

The final change in the postulated conditions is to increase the width of the column in proportion to its height as shown in figure 2. Let us suppose for illustration that the mass was orginally of uniform thickness. Then ~~It~~ it will spread out along shear planes, such as those shown ~~by dotted lines~~, until the slope of the sides will be so gentle that the available force is insuffici~~t~~ent to overcome the internal reistance to deformation. It must be realized that

~~all~~ deformation requires a certain minimum amount of energy and ~~U~~unless this motive power is available there can be no movement no matter how long the time. If~~, however,~~ the accumulation reaches an unstable size ~~where~~ so that power is available, it will settle to a stable form with a certain "angle of repose" or "profile of equilibrium" for the sides which would vary in ~~degree~~ ~~amount~~ slope with temperature and rigidity of the ice. ~~Movement~~ flow could only be maintained by addition of sufficient new snow to keep the profile above this minimum or by wastage of the thin ~~[illegible]~~ margin. barring any change in climate, If the thickness of the ice sheet was ~~so~~ too great in proportion to ~~t~~ its horizontal extent settling of the center with consequent outward movement would also occur. Such "extrusion flow" would be along ~~step~~ shear planes inclined about 45 degrees in the upper part of the ice and would be recorded at the surface by crevasses throughout the entire ice sheet. Along the margins slumping ~~along~~ on similar inclined shear planes would proceed toward the ~~a~~ point of equilibrium. If that were attained, ~~then~~ The entire mass would ~~then~~ be stagnant. Snowfall plus wastage would prevent permanent stagnation

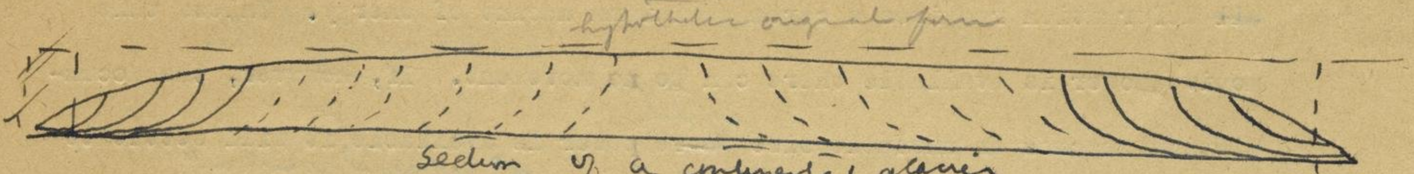
During ~~the~~ movement of the ice sheet the thin margins would, as Demorest correctly states, be more rigid than the ~~bottom~~ lower part of the thicker ice. He calls this condition "obstructed" ~~flow~~. However, ~~I~~it is not certain that relief in this marginal zone would always occur by shearing along planes which rise toward the ice edge. It might well be that the friction of the thin ice on the basement would be less of an obst~~ical~~acle to movement than would be shearing. Then the marginal ice would be shoved bodily over the material below causing glacial erosion.

If the continental glaciers had transverse sections at all like those ~~of the proportions~~ of existing ice sheets, then the contention of the present writer that movement was essentially confined to the sloping margins appears sound. Motion could, ~~then~~ be maintained only (a) by new snow on these margins, ~~where it~~ (b) melting of edges ~~Stuck~~ Snow was ~~formed~~ contributed partly by impinging masses of warm moist air and was ~~partly~~ in part transported by ~~radiating~~ winds ~~blowing out~~ which radiated ~~from~~ from the center. Both these factors would cause more accretion on the margins than on the center of an ice sheet thus maintaining a condition of stagnation in the ~~center~~ middle. So far as the writer knows crevasses are not ~~recorded~~ ~~present~~ in the center of existing continental glaciers.

F. T. Thwaites University of Wisconsin. March 20, 1942

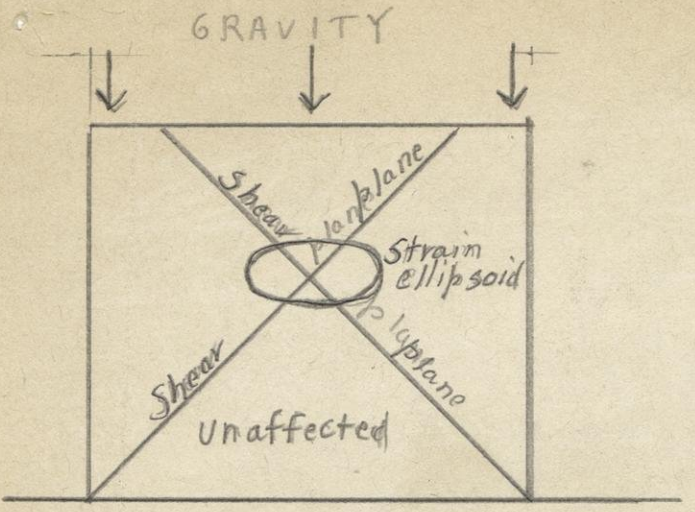
fig 2 over

Figure 2

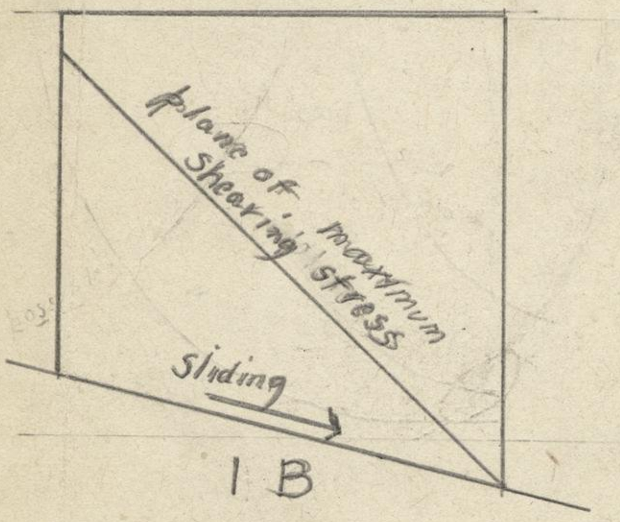


Section of a continental glacier

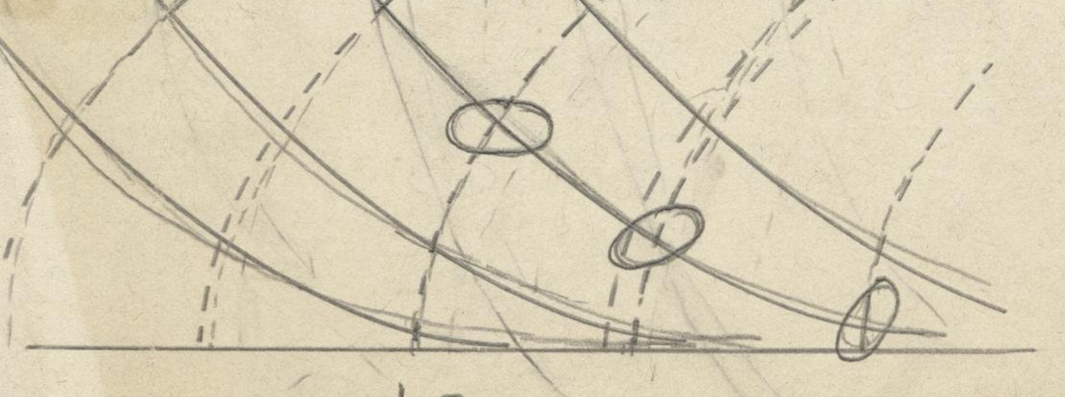
Dotted lines show shears due to thinning by settling of top
Solid lines show shear planes in margins.
No flow is possible except insofar as snowfall maintains an unstable form which rises above a "profile of equilibrium"


GRAVITY
Shear plane
Strain ellipsoid
Shear plane
Unaffected

1A


plane of maximum shearing stress
sliding

1B



1C


Zone of flow
2
"original" surface
Zone of immobility
Zone of flow

Flint, R. F., and Demorest, Max, Glacier thinning during deglaciation: Am. Jour. Sci., vol. 240, pp. 29-66, 113-136, 1942

The paper by Flint and Demorest on "Glacier thinning during deglaciation" consists of two parts. In the part by the junior author the mechanics of glacier flow are analyzed. The conclusions there reached differ sharply not only from those heretofore announced by the writer (1) but also from the fundamental principles of structural geology which have been expounded by many writers. In the preparation of the following criticism the writer was greatly aided by Professors H. E. McKinstry and S. A. Tyler.

Flow takes place both by recrystallization and by shear. Ice crystallizes in the hexagonal system which does not lend itself very well to the formation of cleavage such as occurs with minerals like mica and hornblende. Natural lake ice has the long axes of the crystals parallel and vertical. Such ice displays a moderate degree of cleavage along vertical planes, a fact taken advantage of in putting up natural ice. Ice at temperatures not far below freezing and under light load is notably brittle. Glacial ice is weakened by inclusion of air and dirt and therefore is more likely to be deformed by fracture. Demorest seems to assume that deformation is by shear which is essentially the same idea. Therefore, the following discussion is based on this assumption.

Figure 1, A, shows the simplest case of ice deformation,

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(1) Thwaites, F. T., Outline of glacial geology, pp. 17-18, 1941

that of a block of ice with level top and two unsupported sides. In this case the long axis of the strain ellipsoid is horizontal and the planes of shear dip approximately 45 degrees. The triangular section beneath the planes which reach the bottoms of the open sides is essentially unaffected.

We can alter this picture by increasing the height of the column of ice until the bottom is rendered plastic by reason of pressure, aided in an actual glacier by increased temperature due to the internal heat of the earth. In this case the phenomenon termed "extrusion flow" by Demorest would cause the bottoms of the open sides to begin to bulge out. But they could not expand an appreciable amount without carrying with them the superimcumbent rigid ice. Ice has too low tensile strength to resist the strain set up by "extrusion" and must be moved throughout the mass. The shear planes would be the same.

Now let us consider the case of an inclined top on the column. This condition is not readily analyzed but changes the position of the strain ellipsoid by tilting it down parallel with the slope. With the known low inclination of glacier surfaces this effect is not important and must be a minor factor in deformation.

Next let us consider the effect of an inclined basement under the column. With this condition the friction between ice and rock may be low enough to permit sliding of the ice instead of shearing. This is what Demorest terms "gravity flow" but the foregoing analysis shows that it is essentially similar to his "extrusion flow" except that it may be more rapid as shown in figure 1, B.

As soon as flow commences, the factor of basal friction must be considered. Figure 1, C, shows that this force results in a tipping of the strain ellipsoid so that the planes of shear along which motion takes place flatten out with depth. This is exactly the same as the S-shaped cleavage which develops in a layer of plastic rock between two more rigid layers. The other possible plane of shear may cause crevassing.

The final change in the postulated conditions is to increase the width of the column in proportion to its height as shown in figure 2. Let us suppose for illustration that the mass was originally of uniform thickness. Then it will spread out along shear planes, such as those shown, until the slope of the sides will be so gentle that the available force is insufficient to overcome the internal resistance to deformation. It must be realized that deformation requires a certain minimum amount of energy and unless this motive power is available there can be no movement no matter how long the time. If the accumulation reaches an unstable size so that power is available, it will settle to a stable form with a certain "angle of repose" or "profile of equilibrium" for the sides which would vary in slope with temperature and rigidity of the ice. Barring any change in climate, flow could only be maintained by addition of sufficient new snow to keep the profile above this minimum or by wastage of the thin margin. If the thickness of the ice sheet was too great in proportion to its horizontal extent settling of the center with consequent outward movement would also occur. Such "extrusion flow" would be along shear planes inclined about

45 degrees in the upper part of the ice and would be recorded at the surface by crevasses throughout the entire ice sheet. Along the margins slumping on similar inclined shear planes would proceed toward the point of equilibrium. If that were attained, the entire mass would be stagnant. Snowfall plus wastage would prevent permanent stagnation.

During movement of the ice sheet the thin margins would, as Demorest correctly states, be more rigid than the lower part of the thicker ice. He calls this condition "obstructed". It is not certain, however, that relief in this marginal zone would always occur by shearing along planes which rise toward the ice edge. It might well be that the friction of the thin ice on the basement would be less of an obstacle to movement than would be shearing. Then the marginal ice would be shoved bodily over the material below causing glacial erosion.

If the continental glaciers had transverse sections at all like those of existing ice sheets, then the contention of the present writer that movement was essentially confined to the sloping margins appears sound. Motion could be maintained only (a) by new snow on these margins or (b) melting of edges. Snow was contributed partly by impinging masses of warm moist air and was transported by winds which radiated from the center. Both these factors would cause more accretion on the margins than on the center of an ice sheet thus maintaining a condition of stagnation in the middle. So far as the writer knows crevasses are not present in the centers of existing continental glaciers.

F. T. Thwaites, University of Wisconsin, March 20, 1942

628 East Second Street
Flint, Michigan.

May 27, 1942.

Professor F. T. Thwaites
Department of Geology
University of Wisconsin
Madison, Wisconsin.

Dear Professor Thwaites:

Flint has forwarded to me a copy of your discussion of my latest efforts. I am glad to have it and to benefit by your criticisms, for it is apparent that I have failed to make my thesis thoroughly understood.

It would seem that we are quite at odds; yet I am in hopes that clarification of our ideas may show that we can meet on common ground, for several of the implications found in your discussion are quite in agreement with thoughts of my own. I am particularly impressed by your idea that erosion by ice sheets is largely confined to the marginal and near-marginal parts, though my reasons for believing so are somewhat different than yours. I also like the idea of ice movement as you describe it, but I believe that its application is more limited than you indicate. At the heads of the outlet glaciers that flow through valleys transecting the barrier of coastal mountains in western Greenland, movement of the sort you describe is certainly in progress. It is made apparent by the existence of "landslide" terraces with backward sloping surfaces that contain shallow lakes during the summer months of excessive ablation. I should like to have discussed these features in the recent paper by Flint and myself; however, it seemed best to restrict our discussion to those principles that apply particularly to glacier thinning. Consequently I have now prepared a second paper in which the analyses of flow-producing stresses are reviewed and their applications to general ice-sheet problems are discussed. I have touched upon problems of growth, shrinkage, configuration, and erosion, and have described the ice movement at the heads of the Greenland outlets.

I wish circumstances had been such that I might have sent this second MS to you. However, I am now on the way into the Army where I will be occupied for the duration. I therefore hastened the preparation of the MS and sent it off so that it might be in the works before I leave this country. I hope that when you have read this second paper you will find less occasion for disagreement with me--or it may be that you will have even more criticisms to make. In any case may I suggest that you withhold publication of the present discussion until you have seen the coming paper. Aside from my hopes that you may find areement with me, there is another reason why I would ask you to suspend judgment at the present time. It seems to me that problems of ice movement and flowage have too long been subject to confusion through controversey, and that avoidance of further controversey in print will aid us in the clarification of the subject. When the war is over I am in hopes that I will be able to meet the few such men as yourself who are genuinely and intellegently interested in these problems. I am sure that we can meet on the common ground of a mutual interest in learning and expounding the truth rather than in perpetuating controversey.

To be more specific in answer to your criticisms, I would point out what seems to be an error in the last few sentences of the last full paragraph on page 1. From those sentences I take it that you consider the "shear" I have ~~di~~ discussed to be of a rigid, discontinuous sort related to fracture. I am sorry I did not make myself clear on this point, for the contrary is true. I use the word shear as it applies to flow of any fluid. The term is used by physicists to mean differential motion within any flowing substance whether it be a gas, a liquid, or a plasticly flowing solid. This, of course, leads to the question of whether or not ice flows--that is, whether or not it moves in obedience to the laws of fluid mechanics. Personally I feel confident that it does. And as I remember it, you also speak of flowage in your "Outline" though you deny true plasticity because of the weakness of ice under tensional stresses. Perhaps this difference of opinion is founded on a difference in our definitions of terms. No one can deny the fact of tensional fracturing in glaciers; yet there is no reason to think that ice fails by fracture when subject to high confining pressures at depth within a glacier. I think I am right in saying that the higher the confining pressure and the higher the temperature, the greater the range of stress at which ice will flow plasticly. At atmospheric pressure ice is plastic to only very small stresses (to "long-time" stresses as they are sometimes called). Higher stresses cause failure by fracture--tensional fracture--or compressional shearing. Thus ice at the surface of a glacier is subject to both flow and fracture. At depth, hewever, increased confining pressure results in an increas~~ing~~ed range of plastic behavior--that is, it takes more stress to cause failure by fracture. Consequently flow becomes more dominant at depth and crevassing dies out. The depth at which crevassing dies out must thus depend upon the magnitude of stresses applied. Where maximum stresses are low, crevasses must be shallow or, as is the case in parts of many glaciers, crevasses may be entirely absent. On the other hand, where maximum stresses are high, crevasses may reach to great depths. At first sight this may seem contrary to the behavior of plastic solids as ordinarily demonstrated by the conventional stress-strain diagram. However, when it is realized that "creep" is slow flowage under small stresses operating for a long time (hence the term "long-time" stresses) we can appreciate the fact that the conventional stress-strain diagram established by short-time procedures is not a good clue to the behavior of glaciers where stresses, however small, are operative over very long periods of time.

These ideas on ice strength and plasticity have been strongly brought home to me through the past three years during which I have been conducting experimental work on ice behavior under various conditions of confining pressure, temperature, and deformational stress; and I think they are fairly well established. Unfortunately I am not yet ready to publish on this work and will now be delayed for the duration of the war.

In defending the idea of ice flowage it is also pertinent to mention another result of the recent experimental work. this is the concept of "instantaneous recrystallization" which may help us to explain the manner in which solid ice is able, in its slow way, to flow in obedience to the laws of fluid mechanics--the laws that govern the movements of all streamline flow. Unquestionably slip on basal pinacoids, regelation, "foam cell" melting and rotation of grains are also important--in many cases of greatest importance--but the process of instantaneous recrystallization may explain how individual grains are continually subject to flowage at times and in places where other processes may not be favored.

It may be argued that these are not processes of flow in so much as their application to any single grain of ice does not cause flow within that single grain. Speaking of individual grains we can only say: this grain of ice is now suffering regelation, or this grain is now undergoing internal deformation that may lead to instantaneous recrystallization, or this grain is rotating within a foam cell, or is rotating by regelation, or this grain is being sliced along its basal slip planes. Yet when aggregates of grains are considered, the sum of movements allowed by these various processes and caused by the flow-producing stresses are truly movements of plastic flow. In fact, plastic flow may, for our purposes, be defined as the sum of inter-granular and intragranular motions by which a solid aggregate of crystalline grains undergoes differential movement in obedience to the laws of fluid mechanics. The important thing is that fluid mechanics applies to the sum of movements even though it does not apply to the deformation and motion of any single grain. In a way the same idea applies to a liquid wherein the individual motions of thermally agitated molecules are not considered in the analysis of fluid mechanics that applies to the sum of differential motions within the aggregate of molecules.

With these ideas in mind I do not feel that my ideas, as expressed in the recent paper, "differ sharply . . . from the fundamental principles of structural geology," for the principles you cite are those that apply to the deformation and failure of rigid and near-rigid materials--principles that do not apply to the deformation of a flowing substance. Would you ask Professors McKinstry and Tyler to reconsider my concepts with this point of view in mind?

As I remember it you wrote me a few years ago commenting favorably on my discussion of the striae found on the abandonned bed of the Clements Glacier in Glacier Park. Those striae appeal to me as being among the most convincing evidences we have in support of the idea of truly plastic ice behavior within glaciers. Do you now find disagreement with those ideas; and if so, why?

Inshort, I would ask: (1) What is wrong with the idea of ice flow in obedience to the laws of fluid mechanics? (2) If you grant that ice does move in obedience to those laws, what is wrong with the mechanics of the flow-producing stresses as I have presented them?

It seems to me that these are the fundamental questions we must answer. If my ideas are demonstrably wrong, I would like to know it, and I would like to know why. However, I feel that any discussion which only asserts they are in error without demonstrating what the error is,can only bring confusion to the subject--especially in the mind of the non-specialist who may be unable to make a personal appraisal of the issue.

I hope to be in the country for another month or more and should be very glad for your personal answer to these comments. In any case accept my best regards. I hope the war will short enough that I may soon be able to meet you for a discussion of these interesting problems.

Very sincerly yours,
Max Demorest
Max Demorest

Copies to:

Flint
McKinstry and Tyler

June 4, 1942

Mr. Max Demorest,
628 East Second St.,
Flint, Michigan

Dear Mr. Demorest:

Thank you very much for you long letter of May 27 in reply to my criticisms. I am afraid that there is little chance for any full discussion now. Tyler was called out some time ago by W OPM to manage a mine in New York. McKinstrey has just left for the Economic Warfare outfit in Washington. This leaves me without my advisers so I feel that the whole matter must be postponed "for the duration."

I will say, however, that so far as I can tell ice is deformed like rock but will yield to pressure of less magnitude. I also feel that there is a certain minimum amount of available energy which must be exceeded to cause deformation.

A point I could not see is that there is any essential difference betweengravity and extrusion flow. Surely the latter would have to carry along ice above the "bulge".

But I must stop. So far I have had no chance to go to the war. But after getting my three young boys to bed I sometimes think I would like to go for a rest!

Best regards,

Sincerely

628 East Second Street
Flint Michigan

June 9, 1942.

Professor F. T. Thwaites
Department of Geology
University of Wisconsin
Madison Wisconsin

Dear Professor Thwaites:

I am very glad to have your letter of the 4th in reply to which I would say:

You are, I believe, correct in your statement that "ice is deformed like rock but will yield to pressure of less magnitude." And you are also correct in thinking that there is a minimum amount of stress required to cause deformation. Technically the difference between a viscous and a plastic substance lies in the requirement of the plastic substance for a certain minimum stress to cause deformation by flowage. Theoretically a viscous substance will flow under any stress however small. Of course these differences are brought about by differences in molecular structure; however, once flowage is in progress differences in molecular structure make no fundamental differences in the mechanics of the flow. Hence a plastic substance, when in the right environment, may be deformed in obedience to the laws of fluid mechanics in exactly the same way as a fluid.

The fact that ice ic deformed like a rock might better be stated: Ice is a rock, a rock whose plastic range is greater than that of any other rock. Hence when we consider the deformation of ice we are most concerned with plastic deformation. When we consider the deformation of other rocks (gypsum and rock salt perhaps excluded) we are most concerned with non-plasic deformation , especially at shallow depths. At great depths fluid mechanics may apply equally to all types of rock though structural inhomogenieties would create a very complicated stress distribution beside which the stress distribution within glaciers would appear to be very simple.

As for the difference between gravity and extrusion flow, that is perhaps too long a subject for the present. Essentially the difference is this: Gravity flow is similar to the sliding of a book from a tilted table whereas extrusion flow is similar to the squeezing-out of toothpaste from a tube. In terms of a continental glacier this is perhaps better visualized by thinking of a harizonatal layer of putty under a flat-lying board. If the board is pushed down vertically the putty must be extruded laterally from all sides. The extrusion of ice from ~~below the~~ the lower parts of a glacier is similar except that no overlying board is being pushed down. Rather differential pressure caused by the surface slope of the glacier is responsible for the extrusion. Ice overlying the "bulge" is not carried forward because differential movements of flow allow the more plastic ice at depth to be forced out laterally while the less plastic ice near the surface resists deformation. There is of course a very gradual change in plasticity with depth with the result that flow simply dies out toward the surface. There is, however, a vertical settling of the surface because of the removal by extrusion of the lower ice.

I hope that these comments may clarify the questions somewhat, though I fear that I am not being very lucid. I will look forward to a time after the war when we can get together for some oral discussion.

With best regards,

Yours very sincerely,

Max Demorest

Max Demorest.

~~Figure it out some time and you will find that putty in such a circumstance will flow outward from beneath the board at a rate that is dependent upon the~~

Excuse the economy on paper!

M.D.

Beaudry Just Latest in Great Cavalcade of Arctic Courage

(Continued from Page 5)

verde and picked him up along with six other men. Then they returned to the sled camp.

A few days later Capt. Balchen landed on the snow cap, his third such landing, bundled the survivors, the rescuers and dogs into his big plane, and flew out.

Radioman Honored

The rescue came after Capt. Monteverde and six of his men had been on the icecap five months! The captain paid tribute both to his men and the rescuers, but especially to Corp. Howarth, who had repaired the radio to bring help, and who then had perished at his moment of apparent rescue.

"We all owe him our lives," Monteverde said.

Later Capt. Monteverde, Lt. Spencer and Sgt. Tetley were received by President Roosevelt.

Experiences of members of the Nobile expedition were equally harrowing. Gen. Nobile, explorer and dirigible builder, first tasted arctic adventure in 1926 when he and Roald Amundsen, famous Scandinavian explorer, flew over the north pole in the dirigible Norge, which Nobile had built and piloted.

A Petty Angle

Their feat was later marred by a dispute between the two for honors and glory. Nobile claimed that he was the leader of the epic flight and that Amundsen was a passenger. Amundsen labeled Nobile as merely a hired hand.

But later, in spite of the feud, Amundsen showed heroic greatness.

In 1928 Gen. Nobile headed again for the north pole in the dirigible Italia, carrying 16 crew members and scientists. On May 24, the Italia crossed the pole. Then no word was heard for 47 hours. Within that time tragedy had intervened.

On May 25 the big dirigible, swept by titanic winds, crashed on icy wastes, 18 miles north of the eastern extremity of North East Land, and about 15 1/2 miles from Foyn Island, the nearest land, north of Spitzbergen.

Five Countries Help

The gondola and main cabin were smashed. Seven members were carried away with the balloon, and lost.

Faint radio signals from the Italia soon started rescue operations. Five nations ultimately participated. Meantime, the survivors split into two groups.

Late in June, a month later, first rescues were effected, and first saved was Gen. Nobile himself. His leg was broken. His mascot dog also was saved.

The rescue was remarkable. The general and six men were sighted on ice floes. Capt. Tornburg, a Swedish flyer, braved death by landing his little plane amid tossing ice cakes. The seven men fought their way across the dangerous ice to the plane, and Gen. Nobile was caught in the heaving ice mass. His left leg was broken, and he suffered other injuries. Because of this, he was rescued first. The pilot returned, and saved another man, and later the others were picked up.

Swedish Scientist Dies

Meantime, the second group, consisting of Dr. Finn Malmgren, Swedish scientist, and Capts. Albert Mariano and Filippo Zappi, still were missing.

Not until days later was any trace of them found, but only Mariano and Zappi were alive. They were saved. Malmgren, they reported, had died of exposure. He was still living when they last saw him but near death. On his insistence, they said, they left him.

And meantime, the great Roald Amundsen had set out from Tromsoe, Norway, with two companions, Rene Guilbaud and Lt. Leif Dietrichsen in a search for Nobile—Amundsen's old friend and later enemy.

It was one of the most unselfish acts in mankind.

Roald Amundsen never did come back. He perished with his companions in the arctic wastes!

Trouble for Nobile

Nobile and his fellow survivors soon returned home as heroes. But Gen. Nobile's hero role did not endure long. An Italian commission held him responsible, as leader, for the wreck of the Italia, and forced him to retire from the army. At the same time Nobile was being criticized for permitting himself to be rescued first.

Nor did Capts. Zappi and Mariano escape onus. Charges were made that they had resorted to cannibalism—with Dr. Malmgren the victim, to keep alive. This they denied. No proof was given to support this dreadful accusation, and Malmgren's mother formally absolved the two. Capt. Mariano's memento of the disastrous flight was the loss of one leg, frozen and later amputated.

Cannibalism Before

Once before cannibalism has been alleged in arctic exploration, this in connection with the ill fated Greely expedition.

In 1881, Maj. Gen. A. W. Greely, United States army, started out with 26 men to explore the northern coast of Greenland. There, at Camp Sabine, 450 miles south of the north pole, they made winter quarters.

It was expected that relief ships would reach them in 1882. But none did. The year passed, and so did the year 1883. Finally, on June 22, 1884, Capt. Winfield S. Scott (later admiral), reached the camp. He found only seven survivors, Gen. Greely among them, half crazed, virtually starved, kept alive only by moss.

Of the 19 men who perished, six were allegedly eaten by their comrades. Greely retorted that the charges were false, but the rumors have continued thru the years.

Many Lesser Cases

These—the recent rescue, the Monteverde rescue, the Nobile rescue and the Greely rescue—were epic instances in artic history, but in between were many others.

During the early war years when hundreds of bombers and fighters were crossing the Atlantic, some lost course and crashed on the Greenland icecap. In the first two years alone 25 planes went down. Only one completely disappeared, and presumably crashed thru a huge crevasse. Rescues were effected in the 24 others by the Arctic search and rescue units stationed at the various Greenland bases. In these 24 cases, 90 per cent of personnel was saved.

Two of the more famous rescues were the work of Lt. Howard Wurtz of South Pasadena, Cal., and Capt. Joseph Burns, of Sierra Madre, Cal.

Dangerous Alternatives

On Oct. 7, 1943, a C-47 developed motor trouble above the icecap. Four men bailed out, but three others crashed with the plane. One was killed, and two seriously burned.

Next day Lt. Wurtz started out on a search and rescue mission. He sighted the wreckage, and a message written by foot in the snow saying: "Man dying." Wurtz hurried back to his base, Bluie West 1.

He and Capt. Burns debated possible action—land a navy PBY plane, with floating wings to a lake 20 miles from the crash scene and bring the men in by dog sled; send a dog team from Camp Adalaer 70 miles distant, or attempt a plane landing.

Tries It With Wheels

This last was chosen, but it seemed almost certainly fatal, for the camp there had no plane equipped with skis, and no plane yet had been known to land successfully on the ice cap on wheels. Col. Balchen had made three landings a few months earlier, but with a navy plane with boat pontoons serving as runners.

Lt. Wurtz made the flight—and he landed on wheels.

But the young lieutenant quickly found himself in a dangerous predicament. His wheel gear had frozen and sunk deep into the snow. He could not take off. Capt. Burns, notified by radio, parachuted ski equipment. It took five hours to attach.

Meantime, an AT6 advanced training plane was equipped with skis and wheels at the base, and made three trips, bringing back one man each time.

Brains Save The Day

Then Lt. Wurtz took off with the survivors. The skis worked beautifully on the take-off, and he headed back to base.

But—a new problem developed. Just as one could not normally safely land on wheels on the ice, one could not land on skis on a concrete runway. What did this resourceful young flyer do? He radioed ahead to spread natural gravel along the shoulders of the runway.

Then he landed his ski equipped plane on a shoulder of the runway. Why? Because the hard gravel, actually little pebbles, served in the same manner as ball bearings, enabling him to roll along to a safe landing!

Capt. Burns some time earlier saved single handed an entire Flying Fortress crew who had made a forced landing on a fjord 170 miles from base. Bad weather "socked in," hampering rescue work.

Unaware Of Danger

The young airmen apparently did not realize their peril. They radioed requests for supplies, including whisky, which is used in the arctic along with other rescue aids. When five bottles were dropped to them they chirped back cheerily, "Where's the soda?" It was doubtful whether any had ever before drunk liquor.

Capt. Burns reached them with a Norseman plane, equipped with skis and wheels. He made two round trips, totaling in actual flight some 900 miles, all in severe weather.

No, Greenland is no place in which to be stranded. It offers no life, only death.

Wholesale Killer

Dated records since 1553 show that 754 men lost their lives up to 1909 in explorations there or in related arctic areas. In 1553 70 men of the Willoughby and Chancellor expedition died. The Munk exploration in 1619 cost 62 lives and the disastrous Franklin expedition of 1845 took 135. Other explorations recorded tolls from 1 to 53. The most recent major loss was that of the Charcot expedition of 1936 when 60 men perished in a gale off Iceland.

These men who died since 1553 were English, French, Dutch, Scandinavian, Italian, Russian, American. Most of them sought the unknown north pole and glory. But for them the price was death.

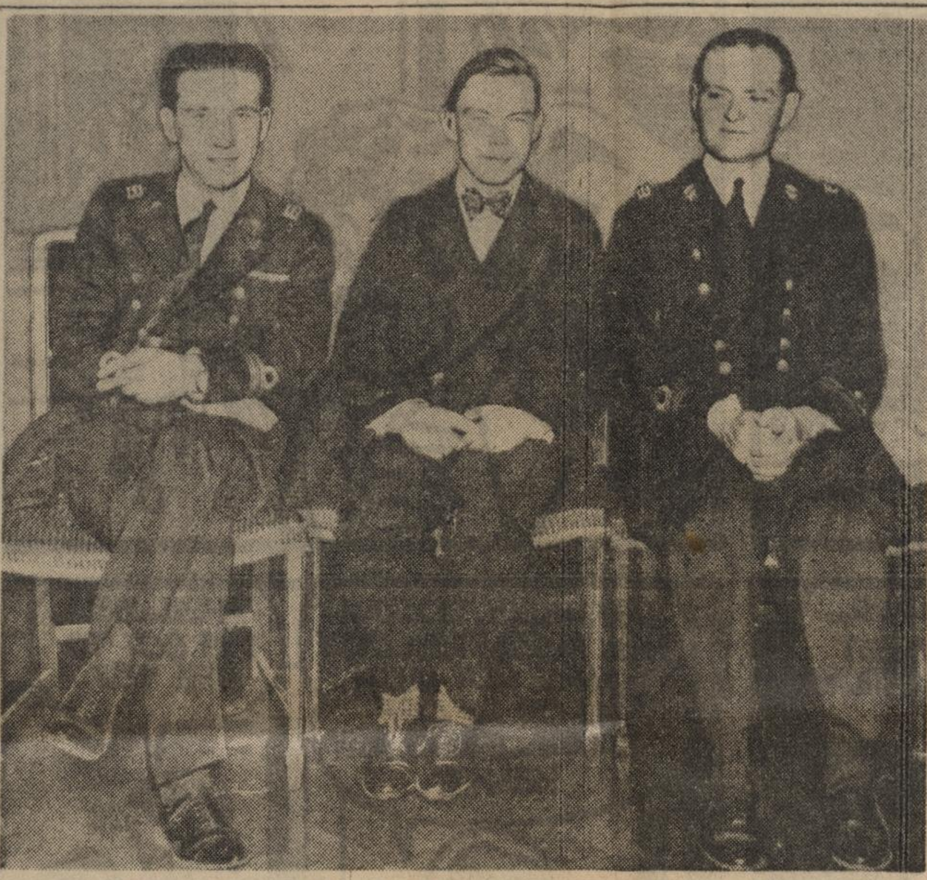
Greenland's frigid icecap and other arctic regions can be cheated once in a while; but the odds are against it!

New Swim Suit

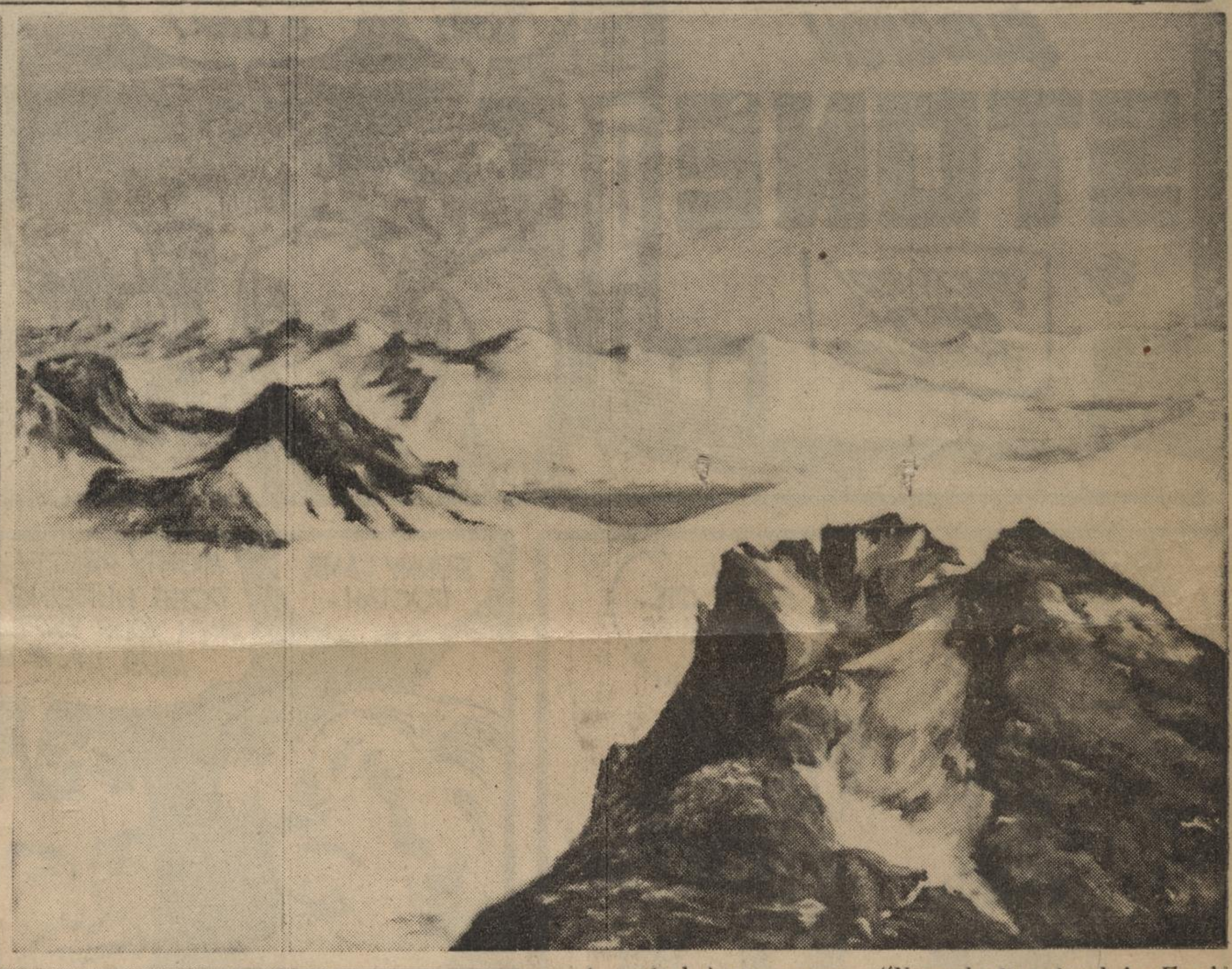
Actress Diana Lynn models a swim suit she will wear in a new picture now in production in Hollywood. (Wide World Photo)

Greenland Icecap Believed Fatal to 1000 Adventurers in 400 Years

Beaudry Just Latest in Great Cavalcade of Arctic Courage

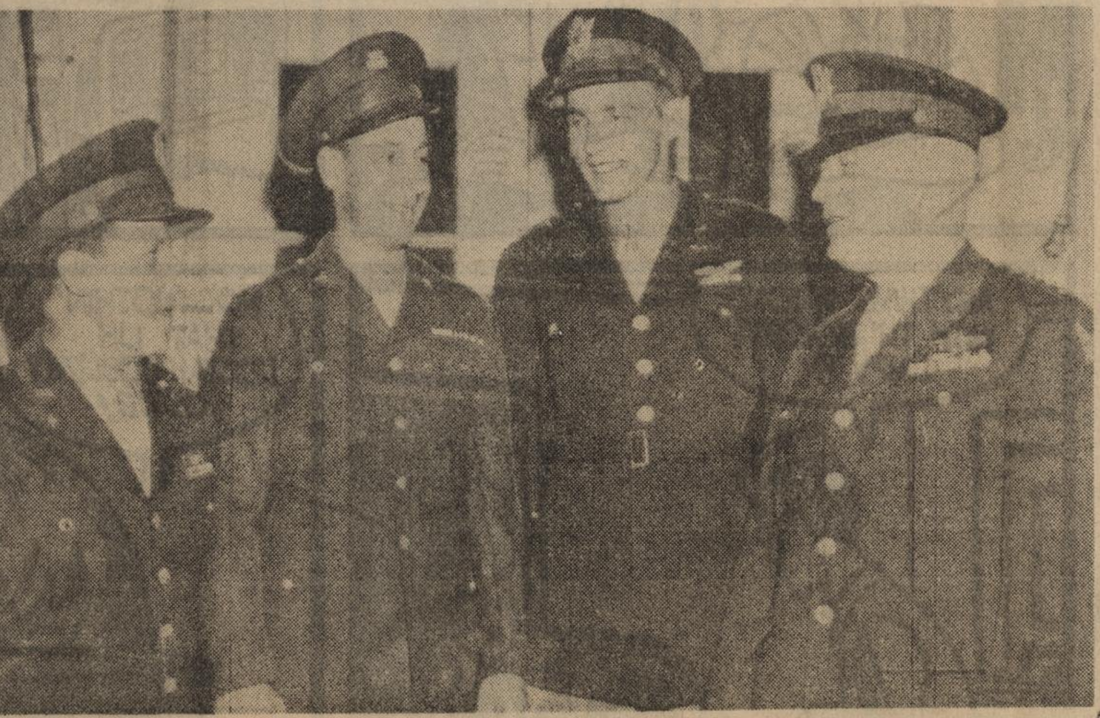


Capt. Filippo Zappi (left), Prof. Finn Malmgren, and Capt. Albert Mariano of Gen. Nobile's 1928 exploration. Malmgren, Swedish scientist, died after the airship Italia crashed. Malmgren's mother had to silence charges that the captains ate her son.



A typical icecap scene, "Nunataks," painted by Frank Cipriani of THE TRIBUNE, author of this article, after an aerial reporting assignment to Greenland. A nunatak is a mountain whose peak rises above the icecap. A glacial lake is seen. "Beautiful, awesome," says Cipriani.

Gen. Umberto Nobile, Italian explorer balloonist, who lost his reputation and almost his life on icecap when the dirigible Italia crashed.



Capt. Armand L. Monteverde (left), Sgt. Don T. Tetley, Lt. Harry E. Spencer, and Gen. H. H. Arnold in Washington in 1943 when Monteverde and his two young crewmen were congratulated by President Roosevelt after they survived five months on the icecap north of Bluie West 1.

Bluie West 8 on west coast of Greenland, from which Lt. Col. Emil J. Beaudry took off in a plane equipped with jets and skis to rescue dozen men stranded on icecap over Christmas.

(Continued from Page 1)

estimated 827,275 square miles. Except for some 18,000 persons, largely Eskimos, who live along its coasts, it is lifeless. Some moss it grows, but that is all.

And That Ice Cap!

Most foreboding of its features is its icecap—a vast expanse of snow and ice. Its area is not known; estimates range from 500,000 to 721,000 square miles—greater than the combined areas of Pennsylvania, California, New York, Indiana, Iowa, Michigan, Illinois and Texas.

Along this frozen icecap sweep the arctic furies, hurricane winds above 100 miles an hour, temperatures down to 60 and perhaps more below zero, and blizzards.

There is nothing there for men, except glory in attempts to reach the north magnetic pole. Even the Eskimos shun the cap. In addition to the normal hazzards of arctic winters, there is the terrible one of crevasses. These are long slits in the cap, hidden to sight by thin layers of ice. Men—many men—have fallen thru them and been lost to sight in their seemingly bottomless pits. Some are known to be over one mile deep.

New Interest Born

Until World War II., Greenland was left strictly to explorers. Then it was realized that this frozen land provided a short cut to the orient, Europe and the Americas by way of the top of the world. The airplane did it.

America undertook Greenland's defense, establishing air bases amid snow, rock and ice in a miracle of engineering and effort.

The bases still are being maintained, and that is why the 12 army airmen happened to be marooned.

The story goes back to Dec. 9 when seven men based at BW 1 station, commonly known as Bluie West 1, in the southern tip of Greenland, made a forced landing in a C-47 transport on the icecap about 110 miles from their base.

A Skilful Landing

The seven were: Lt. James B. Prevost, Knoxville, Tenn.; Lt. Robert J. McDonald, Bridgeport, W. Va.; Capt. Edwin W. Thompson, Milford, Conn.; Sgt. Francis J. Summers, Manayunk, Penn.; Sgt. Francis J. Duffy, Windsor, Conn. Warrant Officer Posy L. Holcomb, Gainesville, Ga., and Capt. Walter F. Speakman, Drumwright, Okla.

The landing was well done, the simple proof being that none of the seven was injured. As they stepped from their big plane the snow swirled about them. Nearer were mountain tops, called nunataks, their snow covered crags seemingly brilliant pink and purple in the morning sun peeping just above the southern horizon. In winter the sun never rises more than a few degrees above the horizon because of Greenland's northern latitude, and is on a blinding level with the eyes.

Ice Piles Up Higher

Actually the stranded airmen were on a plateau some 7,600 feet above sea level—a plateau perhaps of ice and snow a mile thick. Nobody knows the thickness of the snow cap. Some estimates give it as 5,000 feet, some 10,000, but each year it grows higher as succeeding layers of snow pile one upon the other. There are no balancing thaws on the icecap.

The officers and men of the landed C-47 wasted no time in fretting. They knew that you have to act quickly in Greenland, or any other areas of the frozen arctic. They carried some emergency equipment, but not much, and could not survive long without fast help.

Their most valuable possession now was their radio. Slightly damaged, and without generating power, it was weak. They also had to contend with the constant workings of northern magnetic influences, which so often made radio useless.

Predicament Is Known

But, fortunately, their radio worked, weakly it is true, and shortly their base, BW 1, learned of their dangerous predicament.

Fellow airmen soon winged toward them, and parachuted emergency supplies, warmer clothing, food, medicines, little stoves, and material from which huts could be built. They also dropped a small generator to boost their radio power—and a bit of Christmas cheer.

Meantime, army men in Greenland, Labrador, Newfoundland, Washington, D. C., and even Alaska, planned the rescue.

On the fourth day, Lt. Charles L. Ferguson, of Sturgeon Bay, Wis., and Technical Sgt. Louis A. Lane, of Willow, N. Y., started out in a B-17 for the rescue. They circled overhead, and landed in a clean looking stretch of snow near the marooned men.

Further Misadventure

But the big Flying Fortress nosed over into a snowbank, and Ferguson and Lane also became stranded.

That made two planes down and nine men marooned.

While further rescue steps were planned, the weather grew worse. Winds howled in from the north, snow fell, and the temperature dropped. But more supplies were parachuted, and the nine men dug in, building igloos and a snow hut. Once a polar bear approached within 80 feet but nobody moved, and the burly creature, one of the most savage on earth, stumbled away, soon disappearing from sight as its white fur blended with the white snowy background.

Rescuers wanted desperately not merely to save the men but to save them in time for Christmas. Five, incidentally, had their families at Air Base BW1.

Another Plan Tried

On Dec. 17, First Lt. Allerd M. Medvall, of Seattle, Wash., and First Lt. James C. Buerke, of Tampa, Fla., went aloft in a glider towed by a big plane, and glided down to the beleagured men.

The plan—a daring one that had been successfully tried only a short time before in the Alaska wastelands—was to load the stranded men in the glider, then hook on to a strong tow line as it dangled from a low flying plane overhead.

The plane flew low. The men piled into the glider—eleven of them this time. The tow line was grabbed and locked to the glider.

The plane flew on. The glider moved. In seconds it was airborne, some 50 feet from the ground. Then the tow line snapped. By all odds, the glider should have crashed killing some if not all of its occupants. But by expert handling from the abnormally low altitude, the airmen landed the glider safely.

Now three aircraft were down and 11 men in all stranded, but rescuers refused to lose heart. On Dec. 22, First Lieut. Howard L. Halstead, of Greenville, S. C., reached the men in a second glider. Again a plane flew overhead. Again the men—now 12 in all—piled into the glider.

Again the tow line was hooked to the glider and a take-off attempted—but again the tow line snapped. Now four aircraft were down, and 12 men in all stranded.

Maj. Gen. A. W. Greely, who lost 19 men in 1881-1884 in Greenland. Seven survivors were accused of cannibalism.

Concern Spreads Apace

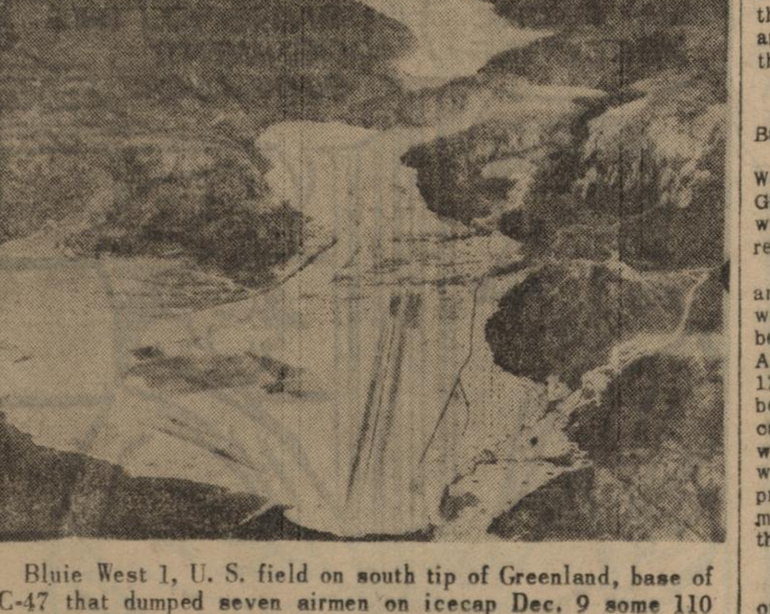
World interest centered on the little group. In Washington, navy officials offered help, and in faraway Alaska, Col. Bernt Balchen, noted arctic flyer who had performed many far north rescues, took off in a C-54 for Greenland to lend his knowledge to the rescue effort.

On Christmas day the navy's big carrier, the Saipan, with 1,200 men aboard—all gave up their holiday leaves for this mercy mission—sailed from Norfolk, Va. Aboard were five helicopters. The strategy was to ride close to the Greenland coast, not too far from the airmen, and pick them up by helicopter.

The Going Is Rough

By now the weather was really bad. No area is worse in winter than the North Atlantic. Mountainous waves rolled the Saipan until one-third of her crew were seasick. Snow obscured vision. Ahead was even worse weather with possible icebergs as added menace. Capt. Joseph L. Kane was forced to reduce speed from 25 knots to 15 and then to 10.

On the icecap the men huddled together. The temperature had sunk to 40 below zero. Winds lashed them at 100 miles an hour. The outlook was bleak, indeed. But behind them lay all the resources of the United States and thousands of determined men. All around were men poised to offer their own lives in the effort.



Bluie West 1, U. S. field on south tip of Greenland, base of C-47 that dumped seven airmen on icecap Dec. 9 some 110 miles from home.

Rescuers Converge

The Saipan plowed on. Col. Balchen with eight men flew on.

And at BW 8, known as Bluie West 8, on the west coast of Greenland, some 260 miles northwest of the stranded men, other rescuers also were working.

Rescue efforts were intense—and not the least of the tenseness was created by traditional rivalry between the army and the navy. All equally wanted to save the 12 men, but the army wanted to beat the navy to the punch, because after all, the men down were of their own service. And it would not have harmed naval prestige to have rescued the army men, and be able to say, "It took the navy to do it."

Unnoticed Endeavor

While all attention was focused on the dramatic run of the Saipan and Col. Balchen's dash from Alaska, hardly anybody noticed activies at Bluie 8.

Yet, since Dec. 15, they had been busy up there, with a rescue mission in charge of young Lt. Col. Emil J. Beaudry, 32 of South Hadley Falls, Mass.

Col Beaudry, a bomber pilot during World War II., with a record of 26 missions and 200 combat hours, is considered one of the air force's leading jato (jet-assisted take-off) pilots.

Moreover he became only a year ago a hero in a "top of the world" rescue. It was on Dec. 26, 1947, that Beaudry landed his plane on isolated Dyke lake in Labrador, and rescued nine men who three days earlier had made a forced landing in a B-17. The air force scoured more than 100,000 square miles of scrub wilderness before finding trace of the men. That was on Christmas day of 1947. Beaudry then was doing experimental flying in Greenland. Next day, using a jato C-47 he effected the rescue.

Beaudry To The Rescue

This then, was the man chosen to make a daring rescue—and at the same time beat the navy and preserve the army's record.

On Dec. 28 the young colonel and his crew took off from Bluie West 8, on the west coast of Greenland. They speeded swiftly to the marooned men. Beaudry's plane was equipped with skis for landing and take-off, and also with four jet units, providing a 4,000 pound lift for the take-off.

The purpose of the jet aid was to accelerate the take-off, eliminating the long runs normally necessary to make a plane airborne. A plane of Beaudry's type usually needs a 4,500 foot runway, but this obviously was impossible on the icecap. In tests it was possible for a C-47 to take off in 600 feet with only two jet propulsions.

In severe cold jets are impractical. Thus the jet tanks were kept inside the plane to keep them warm en route to the rescue scene. Speed was imperative, and speed was achieved.

Comes The Big Test!

Beaudry landed near the 12 stranded airmen in the forenoon. While the happy airmen climbed into the plane, Beaudry's crew attached the jet apparatus.

Thirty-eight minutes from the moment of landing, Col. Beaudry was ready. Would the jets work? Would the plane run smoothly enough on skis on the ice?

The answer soon came. The propellers roared, the jets roared, and the big plane shot forward like an arrow.

Seconds later it was airborne!

And soon the rescued and rescuers were safe in Bluie West 1.

Just as simple as that—after days of suffering, trial, accident and near tragedy—was the rescue completed.

The word flashed quickly to the world. Messages went also to the big carrier Saipan, still 1,300 miles from her Greenland destination. Capt. Kane expressed happiness that the men had been saved, and turned his ship southward toward Norfolk.

Everybody was happy—the men who were saved, their relatives, and air force, the navy, and Col. Beaudry's wife.

"I knew he could do it," she said. "I feel as if I'm walking on air, I'm so happy."

The cost of the rescue was, fortunately, only in money, time, effort, and material, and not lives. In round dollars, the over-all cost of the several rescue missions was computed at $500,000.

Other Notable Rescues

In recent years there have been numerous rescues from the arctic, but this was one of the most spectacular.

Well remembered are those of Capt. A. L. Monteverde, who was marooned on Greenland's icecap for 148 days, and of Gen. Umberto Nobile, Italian polar explorer.

One of the heroes in the Monteverde rescue was Col. Balchen, who was poised to save the men recently marooned before Col. Beaudry stepped in.

The story of Capt. Monteverde, whose home is in Anaheim, Cal., begins in November, 1942, when he was ferrying a Flying Fortress across the stormy North Atlantic to England.

Monteverde was far eastward over the ocean when he received radio orders to search for a plane downed on the Greenland icecap.

One Crewman Hurt

North of Bluie West 1, Capt. Monteverde's plane crashed upon the icecap. Only one of the crew, Sgt. Paul J. Spina, of Frankford, N. Y., was injured. He suffered an arm fracture.

Capt. Monteverde's first act was to order the aft section of the broken fuselage used as a shelter against the cold winds. His next was to direct Corp. Loren H. Howarth, of La Crosse, Wis., to get the radio in operation. But the radio was virtually broken.

Then upon the young Wisconsin corporal fell the most important and most trying ordeal of all—to repair the radio in the intense cold. Beating his hands together frequently to keep them from freezing, he undertook the task. Upon him depended the lives of all the men.

The Corporal Succeeds

For eight days Howarth labored, then success. On the eighth day the stranded men sent out their first SOS, giving their approximate position.

Five days after the first signals help came. A plane from Bluie West 1 dropped warm clothing, food and other supplies, and in succeeding days other planes also parachuted supplies.

The war was on then, and utmost secrecy had to prevail, for the allies did not want the Germans to know American air positions in Greenland.

Nevertheless, rescue efforts were concentrated. Ironically, a group of American weather observers were only a few miles away, actually within sight of Monteverde and his men, but as far away as the moon so far as they were concerned, for the cap between them was covered with hidden crevases and sloping inclines.

A Frightful Incident

The crevasses were the worst, as the stranded men soon learned. Lt. Harry E. Spencer, of Dallas, Tex., co-pilot, innocently wandered too far from the wrecked plane—and went thru a fissure. He miraculously landed without injury on a ledge 100 feet below. Below that was the icy darkness of a bottomless pit. With the aid of a 50 foot rope tied to lengths of parachute shroud lines, he was finally pulled up. It was a shuddering experience.

Out from the near-by weather station set out Staff Sgt. Don T. Tetley, of Fort Sam Houston, Tex., and Lt. Max H. Demorest, of Flint, Mich., their vehicles two powerful motor sleds. At about the same time Col. Balchen was flying over Monteverde and his men, dropping supplies.

Lt. Demorest and Sgt. Tetley went as far as they could on sleds, then continued ahead on foot. They reached Capt. Monteverde and his crew, then started back on foot to get their sleds in hope of transporting the men to the weather station.

Death To A Helper

Here tragedy first struck—in the form of a crevasse.

Less than 100 yards from the Monteverde group, Lt. Demorest and his sled disappeared thru a slit in the ice!

Shortly afterward, Lt. John A. Pritchard Jr., of Burbank, Cal., a coast guard flyer, flew in a Grumman plane from the coast guard cutter Northland, and landed near the wrecked plane.

Pritchard took off Sgt. Alexander F. Tucciarone, of New York City, and Staff Sgt. Lloyd Puryear, of Lebanon, Ky., and delivered them safely to the Northland.

Brave young Lt. Pritchard immediately flew back to the wreck scene, but fog suddenly began closing in and he was ordered to take off at once. He took aboard Corp. Howarth and Radioman Benjamin A. Bottoms, of Salem, Mass.

Another Crackup

The plane would hold no more, and it was indeed, fortunate in this instance, for the young coast guardman's plane crashed in the take-off. All aboard—Pritchard, hero of one rescue; Howarth, the man who repaired the Monteverde radio, and Bottoms—were killed!

Meantime, the feet of Lt. William F. O'Hara, of Scranton, Pa., had frozen and become gangrenous. Capt. Monteverde ordered him taken by Sgt. Tetley's sled to the weather station. Accompanying Tetley were Lt. Spencer, and Pvt. Clarence Wedel, of Canton, Kan.

A mile and a half away, death again struck. Pvt. Wedel dropped into a crevasse, and never was seen again.

Lt. O'Hara, Sgt. Tetley and Lt. Spencer dared not forge ahead, and now became stranded.

Rescuers now had two separate groups to save, doubling the difficulty of their task. But planes soon located the Tetley party, and dropped supplies.

These various dramatic events covered a period of weeks, and then months. Capt. Monteverde and his men had crashed early in November of 1942. November had passed, then December, and the new year of 1943 had begun. In January Monteverde still was stranded.

In February, Col. Balchen landed a navy flying boat near the Tetley sled camp, and picked up Tetley, Spencer, and O'Hara. The pontoons served as skis.

Then, suddenly, further rescue efforts were halted by furious arctic weather, snow, subzero temperatures, and icy, blasting winds.

Dogs and Mushers

February passed, and March passed, and still Monteverde and several of his men were still stranded. Early in April, Balchen landed at the old sled camp, a mile and a half from the Monteverde group. This was necessary because the landing opportunities were better there. This time Col. Balchen landed a squad of men experienced in arctic work, and a dog team, and took off. Planes cannot linger long on the ice cap because of possible freezing of oil and various moving parts.

The men and dogs proceeded, under great difficulty, to Monte-

(Continued on Page 11)

June 17, 1942

Mr. Max Demorest,
628 East Second St.,
Flint, Michigan

Dear Mr. Demorest:

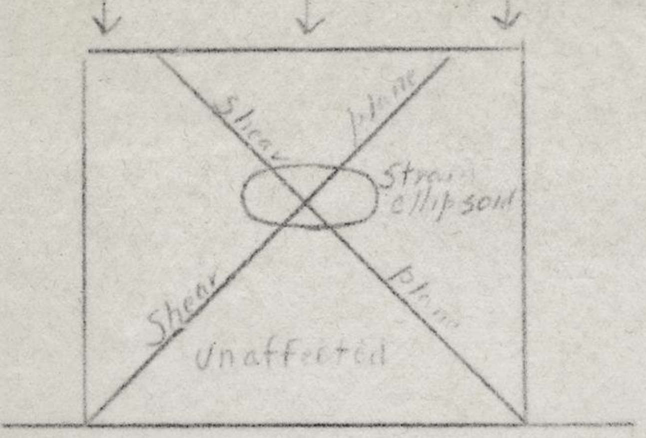
Your letter of the 9th has been in my file waiting answer so today I gave up trying to get around to it at home and took it back to the office where there is just now more peace and quietness.

I am inclined to think so of our differences are those of definition and not pri$\overset{n}{c}$iple However, I still do not get the difference between the two kinds of flow. True sliding is an accelerated movement like free fall. Such a movement is rare. I still feel that McKinstrey's idea that shear along the plane of easiest yielding is the explanation. That is the resistance to movement over the basement is less than that to movement within the ice. But as for extrusion flow I cannot follow your example. The bulging out of the putty under a board is not a good example. The board has high tensil strength compared to that of the putty. Now if a vertical stone retaining wall fails from bulging at the bottom the top of the wall is certainly carried along and also fails. Where the overlying material above the "bulge" is ice with very low tensile strength I should think it must also follow along as stated before . I cannot see that lack of plasticity could afford enough stregth to resist the force tending to move the overlying ice.

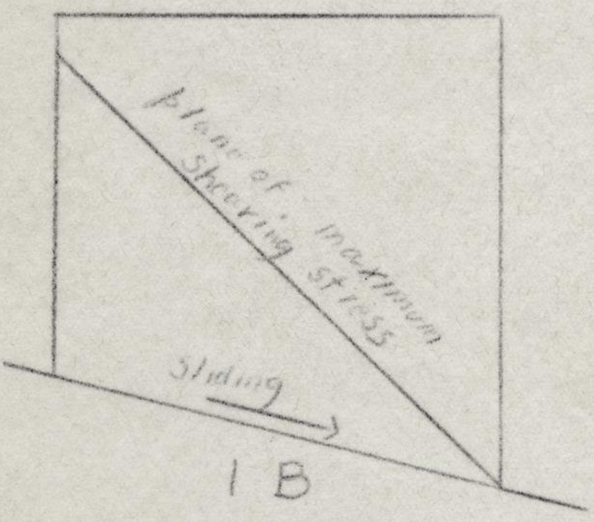
I am afraid we will have to drop the discussion, however, for the duration. I cannot publish a revision of the "Outline" under present conditions although if not called to some more pressing task I might get time to start on the preparation of a new text.

Just now I must catch up on well records which are now almost all from work directly due to the war. It does not look much like a substantial number of students in the fall but more may show up than we now expect.

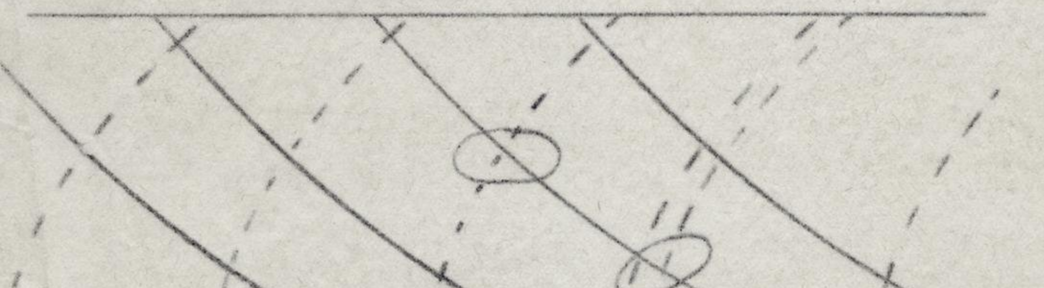
Sincerely,


Shear plane
Strain ellipsoid
Shear plane
Unaffected

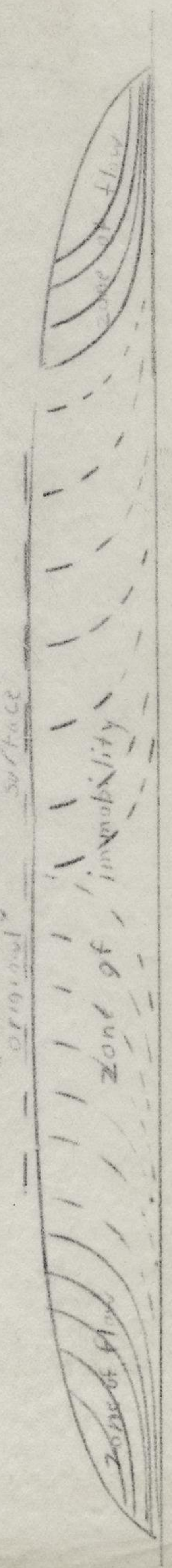
1A


plane of maximum Shearing stress
Sliding

1 B



1C


zone of flow
"original" surface
zone of immobility
zone of flow

2

Flint, R. F., and Demorest, Max, Glacier thinning during deglaciation: Am. Jour. Sci., vol. 240, pp. 29-66, 113-136, 1942

The paper by Flint and Demorest on "Glacier thinning during deglaciation" consists of two parts. In the part by the junior author the mechanics of glacier flow are analyzed. The conclusions there reached differ sharply not only from those heretofore announced by the writer (1) but also from the fundamental principles of structural geology which have been expounded by many writers. In the preparation of the following criticism the writer was greatly aided by Professors H. E. McKinstry and S. A. Tyler.

Flow takes place both by recrystallization and by shear. Ice crystallizes in the hexagonal system which does not lend itself very well to the formation of cleavage such as occurs with minerals like mica and hornblende. Natural lake ice has the long axes of the crystals parallel and vertical. Such ice displays a moderate degree of cleavage along vertical planes, a fact taken advantage of in putting up natural ice. Ice at temperatures not far below freezing and under light load is notably brittle. Glacial ice is weakened by inclusion of air and dirt and therefore is more likely to be deformed by fracture. Demorest seems to assume that deformation is by shear which is essentially the same idea. Therefore, the following discussion is based on this assumption.

Figure 1, A, shows the simplest case of ice deformation,

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(1) Thwaites, F. T., Outline of glacial geology, pp. 17-18, 1941

that of a block of ice with level top and two unsupported sides. In this case the long axis of the strain ellipsoid is horizontal and the planes of shear dip approximately 45 degrees. The triangular section beneath the planes which reach the bottoms of the open sides is essentially unaffected.

We can alter this picture by increasing the height of the column of ice until the bottom is rendered plastic by reason of pressure, aided in an actual glacier by increased temperature due to the internal heat of the earth. In this case the phenomenon termed "extrusion flow" by Demorest would cause the bottoms of the open sides to begin to bulge out. But they could not expand an appreciable amount without carrying with them the superimcumbent rigid ice. Ice has too low tensile strength to resist the strain set up by "extrusion" and must be moved throughout the mass. The shear planes would be the same.

Now let us consider the case of an inclined top on the column. This condition is not readily analyzed but changes the position of the strain ellipsoid by tilting it down parallel with the slope. With the known low inclination of glacier surfaces this effect is not important and must be a minor factor in deformation.

Next let us consider the effect of an inclined basement under the column. With this condition the friction between ice and rock may be low enough to permit sliding of the ice instead of shearing. This is what Demorest terms "gravity flow" but the foregoing analysis shows that it is essentially similar to his "extrusion flow" except that it may be more rapid as shown in figure 1, B.

As soon as flow commences, the factor of basal friction must be considered. Figure 1, C, shows that this force results in a tipping of the strain ellipsoid so that the planes of shear along which motion takes place flatten out with depth. This is exactly the same as the S-shaped cleavage which develops in a layer of plastic rock between two more rigid layers. The other possible plane of shear may cause crevassing.

The final change in the postulated conditions is to increase the width of the column in proportion to its height as shown in figure 2. Let us suppose for illustration that the mass was originally of uniform thickness. Then it will spread out along shear planes, such as those shown, until the slope of the sides will be so gentle that the available force is insufficient to overcome the internal resistance to deformation. It must be realized that deformation requires a certain minimum amount of energy and unless this motive power is available there can be no movement no matter how long the time. If the accumulation reaches an unstable size so that power is available it will settle to a stable form with a certain "angle of repose" or "profile of equilibrium" for the sides which would vary in slope with temperature and rigidity of the ice. Barring any change in climate, flow could only be maintained by addition of sufficient new snow to keep the profile above this minimum or by wastage of the thin margin. If the thickness of the ice sheet was too great in proportion to its horizontal extent settling of the center with consequent outward movement would also occur. Such "extrusion flow" would be along shear planes inclined about

45 degrees in the upper part of the ice and would be recorded at the surface by crevasses throughout the entire ice sheet. Along the margins slumping on similar inclined shear planes would proceed toward the point of equilibrium. If that were attained, the entire mass would be stagnant. Snowfall plus wastage would prevent permanent stagnation.

During movement of the ice sheet the thin margins would, as Demorest correctly states, be more rigid than the lower part of the thicker ice. He calls this condition "obstructed". It is not certain, however, that relief in this marginal zone would always occur by shearing along planes which rise toward the ice edge. It might well be that the friction of the thin ice on the basement would be less of an obstacle to movement than would be shearing. Then the marginal ice would be shoved bodily over the material below causing glacial erosion.

If the continental glaciers had transverse sections at all like those of existing ice sheets, then the contention of the present writer that movement was essentially confined to the sloping margins appears sound. Motion could be maintained only (a) by new snow on these margins or (b) melting of edges. Snow was contributed partly by impinging masses of warm moist air and was transported by winds which radiated from the center. Both these factors would cause more accretion on the margins than on the center of an ice sheet thus maintaining a condition of stagnation in the middle. So far as the writer knows crevasses are not present in the centers of existing continental glaciers.

F. T. Thwaites, University of Wisconsin, March 20, 1942