THE CONTACT OF THE ROSS ICE SHELF WITH THE CONTINENTAL ICE SHEET, ANTARCTICA

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Abstract. A profile of ice thickness along the 647 mile trail from Little America V to Byrd Station has been obtained from altimetric, seismic, and gravity measurements, and detailed studies made at the junction of the Ross Ice Shelf and the Marie Byrd Land plateau. The surface elevation profile clearly shows the depression characteristic of this contact. The thickness of the floating ice shelf has been determined from the elevations assuming hydrostatic equilibrium; for this purpose the accurately known density-depth relationship obtained from a deep borehole at Little America V was employed. The buried rock topography at the contact has been deduced from a seismic sounding and variations in the gravity anomaly. Movement studies over a 22 month period are presented, and the crevasse pattern of the contact is analyzed in terms of ice movement. Suggestions are given for traversing the region by vehicle.

Résumé. Les épaisseurs de la glace le long d'un profil de 1041 km depuis Little America V jusqu'à Byrd Station ont été obtenues par des mesures altimétriques, sismiques et gravimétriques, et par des études détaillées à la jonction du Ross Ice Shelf et du plateau de Marie Byrd Land. Le profil des altitudes montre clairement la dépression qui caractérise cette jonction. L'épaisseur de l'ice-shelf a été calculée à partir des altitudes en supposant celui-ci en équilibre hydrostatique; pour ce calcul, on a utilisé la fonction de la densité avec la profondeur, connue avec précision à la suite d'un forage profond effectué à Little America V. On en a déduit la topographie du socle rocheux sous-glaciaire au point de jonction en se fondant sur les sondages sismiques et les variations de l'anomalie de la pesanteur. La détermination des vitesses superficielles a été effectuée pendant 22 mois, et le tracé des crevasses à la jonction est analysé en fonction du mouvement de la glace. Les routes les plus sûres pour les véhicules traversant cette région sont déduites de cette étude.

Zusammenfassung. Ein Profil der Eisdichte entlang der 1041 km langen Fährte von Little America V bis Byrd Station wurde auf Grund seismischer sowohl Höhen- und Schweremessungen aufgenommen, und eingehende Untersuchungen am Berührungsgebiet des Ross Schelfeises und des Marie Byrd Landplateaus durchgeführt. Das Oberflächenstandrissprofil zeigt in klarer Weise die für diese Berührung charakteristische Senkung. Unter Voraussetzung hydrostatischen Gleichgewichts wurde die Dichte des schwimmenden Schelfeises auf Grund der Standrisse berechnet; zu diesem Zweck wurde das genau bekannte Dichte-Tiefe-Verhältnis, das sich aus einem tiefen Bohrloch bei Little America V ergab, benutzt. Die Topographie der unten liegenden Felsen im Berührungsgebiet wurde aus einer seismischen Lotung und Schwankungen in der Schwereanomalie abgeleitet. Bewegungsbeobachtungen im Laufe einer Zeitspanne von 22 Monaten werden vorgelegt, und das Rissbild des Berührungsgebietes wird in Form von Eisbewegung dargelegt. Ratschläge für das Überqueren der Region mit dem Wagen werden gegeben.

Introduction

During October-November 1956 an Army-Navy team of oversnow transportation specialists established a 647 mile (1,041 km.) trail connecting the United States I.G.Y. Antarctic stations of Little America V (lat. 78° 11·9′ S., long. 162° 16·0′ W.) and Byrd Station (lat. 79° 59·2′ S., long. 120° 01·0′ W.).[1] At lat. 79° 30′ S., long 150° 05′ W. this trail passed over the junction of the floating Ross Ice Shelf and the grounded ice sheet (Fig. 1). This section of the trail, from mile 183·5 to 190·9 (measured in statute miles from Little America V), went through a heavily crevassed zone and was designated "Fashion Lane". The trail party spent several weeks working on this stretch of trail, blasting and filling crevasses to provide a safe route for heavy tractor and sledge traffic. At this time the area was mapped by both surveying and aerial reconnaissance methods. The results of this work have been published by the U.S. Navy Hydrographic Office as maps H.O. 16384-9 (scale, 1 : 196,400) and H.O. 16384-8 (scale, 1 : 15,840) and serve as the base maps for the studies here reported (Figs. 2 and 3).

Two months later, the Byrd oversnow traverse party passed over this trail on their way to Byrd Station conducting a seismic, gravity, magnetic, and glaciological program *en route* as well as a continuous altimetric survey. The seismic soundings and gravity readings [2, 3, 4] enabled a profile to be constructed along the trail which is included in Figure 1.

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On 30 November 1958 additional studies were made at "Fashion Lane" by the authors as part of an I.G.Y. airlifted geophysical program. While the ski-equipped DC-3 aircraft landed at one end of "Fashion Lane" for surveying and ice-movement studies, two men traversed the crevassed region on skis to make closely spaced altimetric and gravity measurements. The elevation profile, ice-thickness determinations, rock topography, movement studies, and crevasse pattern are discussed respectively in the following sections.

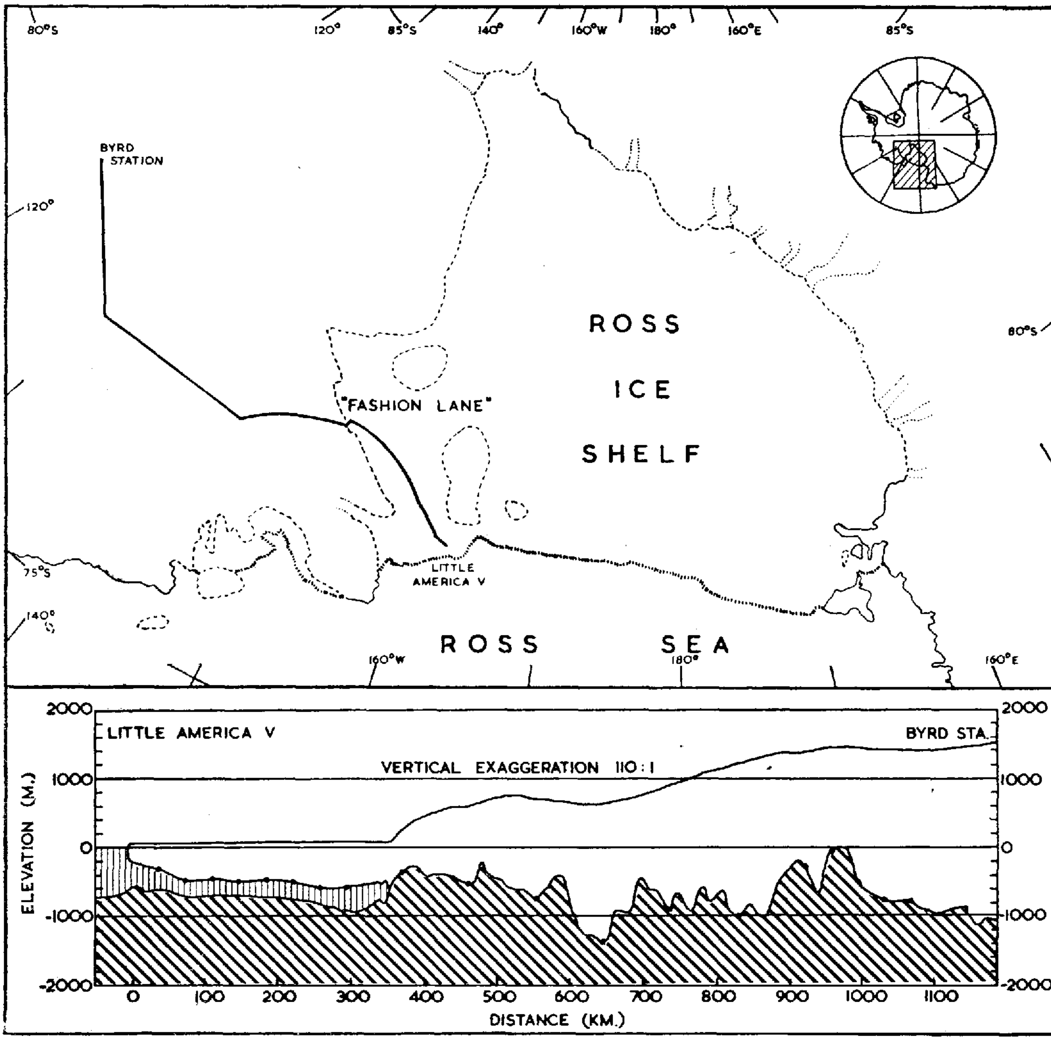

Fig. 1. Profile of ice thickness and bedrock topography along Army-Navy trail from Little America V to Byrd Station

Elevation Profile

Independent altimetric determinations of elevation along portions of the trail from Little America to Byrd have been made by the United States Naval Support Force,[1] an oversnow traverse party led by C. R. Bentley,[5] and a second oversnow traverse party led by A. P. Crary.[2] The elevation of 80 m. adopted for mile 183·5 is a weighted mean from this work. The detailed altimetric leveling along "Fashion Lane" by the 1958 airlifted party was then

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tied to this benchmark. The elevation profile is presented in Figure 3 with a vertical exaggeration of 50 to 1.

The most noteworthy features of this profile are (i) the abrupt increase in elevation as one goes from the ice shelf onto the continental ice sheet and (ii) the depression associated with the juncture of the ice shelf and ice sheet. Light conditions permitting, this valley can be distinctly seen from the ground or air running along the periphery of the ice sheet.

On the other side of the continent, the Ellsworth oversnow traverse crossed the junction of the Filchner Ice Shelf and grounded ice at eight places during the 1957-58 field season. These elevation profiles also show a valley at the junction of grounded and floating ice. The profiles indicate the depth of the valley to be proportional to the slope of the ice descending

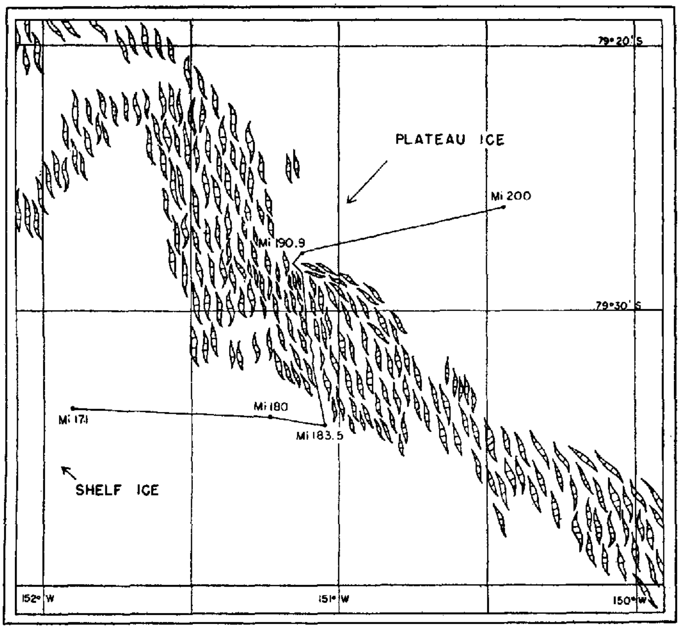

Fig. 2. Approaches to "Fashion Lane". Arrows indicate direction of ice movement

from the continent. Figure 4 is the cross-section obtained on one of the crossings. The bottom surface of the shelf is drawn assuming (i) complete and local hydrostatic equilibrium (solid line) and (ii) a uniform shelf thickness (dashed line). The former picture, showing a necking of the ice, may be more nearly correct if the valley is the result of constant bending in response to tides, similar to the thinning which takes place when bending a strip of metal in order to break it, as suggested by Robin.[6] The latter picture implies a rigidity sufficient to account for the lack of local hydrostatic equilibrium. Because of the small density differential between ice and water, and because of the abrupt changes in rock topography at this point, the gravity method cannot distinguish between the two alternatives; seismic measurements with sufficient detail have not as yet been made.

Ice Thickness Determinations

If the surface elevation E and the density ρ_i as a function of depth are known for a floating ice shelf, the thickness T may be obtained by solving numerically the equation

$$(T-E)\,\rho_w = \int_0^T \rho_i \, dt.$$

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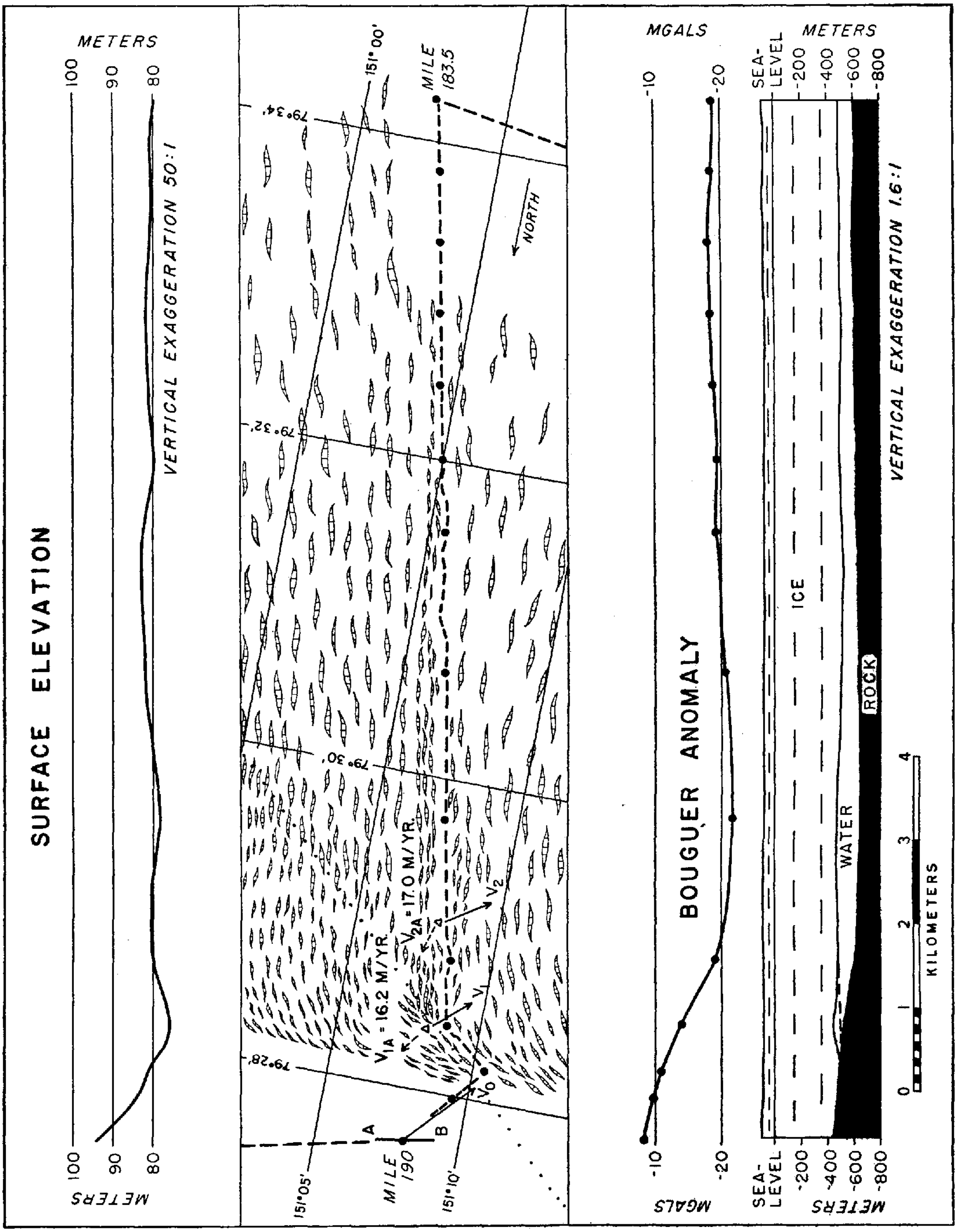

Fig. 3. Geophysical studies at "Fashion Lane": (a) elevation profile; (b) crevasse pattern; (c) movement studies; (d) ice thickness determinations; (e) rock topography

At Little America V the ice density as a function of depth is accurately known from a Snow, Ice, and Permafrost Research Establishment deep drilling project. Ice cores were recovered from the surface to a depth of 255 m. The shelf thickness at this location was estimated by the glaciologists to be 259 m. on the basis of an extrapolation of the temperature-depth curve. This estimate is in perfect agreement with the thickness determined by seismic measurements at the drill site prior to completion of the drilling program. The surface elevation at the drill site was obtained by transit leveling from sea ice about two miles (3 km.) away.

Adopting a value of 1·0278 g. cm.$^{-3}$ for the density of sea-water based on oceanographic soundings near the ice front [7] and the values of density as a function of depth obtained by the SIPRE deep drilling project,[8] the relationship between T and E is readily computed (Fig. 5). This relationship was then used to determine the thickness of the floating ice along "Fashion Lane" from the observed surface elevations.

Rock Topography

The ocean bottom elevation is known at mile 160 as a result of a seismic sounding.[2] The rock elevation at mile 183·5 was then determined by comparing the free air gravity anomalies at the two locations.[4] An anomaly of one milligal will be produced by an infinite slab 23·9 m. thick when the density differential between this slab and the overlying sea-water is 1 g. cm.$^{-3}$. In the present case no rock outcrops occur in the surrounding region, and it is necessary to obtain a value for rock density by indirect means. The difference in rock elevation (in meters) between mile 160 and mile 183·5 is then

$$\text{(Difference in free air anomaly)} \times \frac{23 \cdot 9}{\Delta \rho}.$$

where $\Delta\rho$ is the density of the rock minus the density of sea-water.

Seismic refraction studies by Crary at Little America V have given the thicknesses and seismic velocities of the underlying rock.[9] Empirical curves relating seismic velocity and density have recently been prepared by Nafe and Drake [10] and by Woollard.[11] The mean of the density values obtained from these curves for the seismic velocity determined by Crary is 1·97 g. cm.$^{-3}$. Subtracting from this the density of sea-water, $\Delta\rho$ becomes 0·94 g. cm.$^{-3}$. Thus one milligal change in gravity theoretically reflects a 25·4 m. change in rock elevation. In this manner the rock surface at mile 183·5 is found to be 607 m. below sea-level. The detailed topography beneath "Fashion Lane" was then computed in a similar manner at the fourteen points where gravity measurements had been made. The results are presented in Figure 3.

Movement Studies

When the Byrd oversnow traverse party crossed "Fashion Lane" on 1 February 1957, they established a 690 m. baseline through mile 190·9 overlooking "Fashion Lane". From this baseline four movement flags placed approximately 1, 2, 3 and 4 miles distant were located by triangulation using a Kern DKM 2 theodolite.

On 30 November 1958, the airlifted traverse party resurveyed the two nearer movement stakes. Unfortunately the use of "Fashion Lane" by tractor trains during the intervening time had destroyed the mile 3 movement marker, and poor atmospheric conditions at the time of the second survey did not permit the accurate location of the mile 4 marker.

The apparent movements of the two innermost markers are converted to an annual rate and indicated by broken arrows in Figure 3. At first sight it appears that the markers have moved north-east toward a stationary baseline. Actually, both baseline and markers are

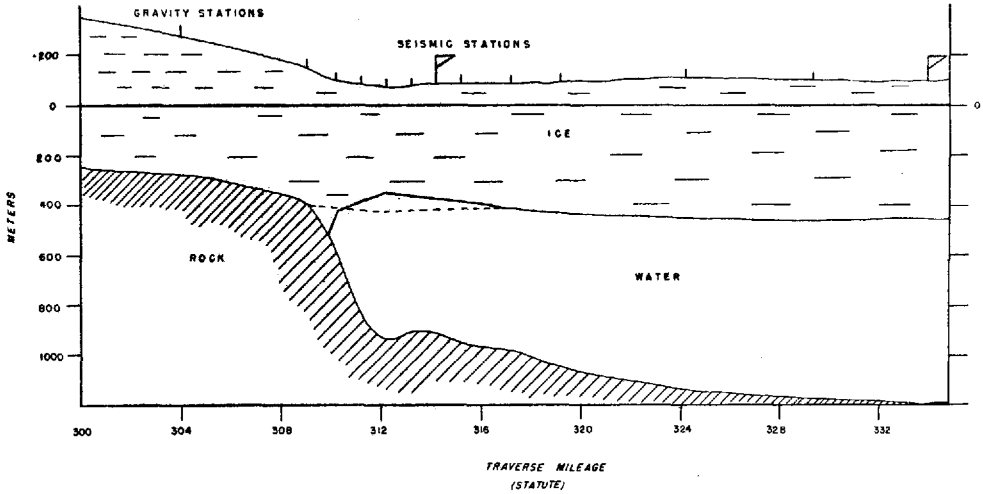

Fig. 4. Contact of Filchner Ice Shelf and grounded ice at lat. 80° 36·4′ S., long. 46° 59·0′ W. The bottom of the shelf near the contact is drawn (1) assuming complete and local hydrostatic equilibrium and (2) a uniform shelf thickness

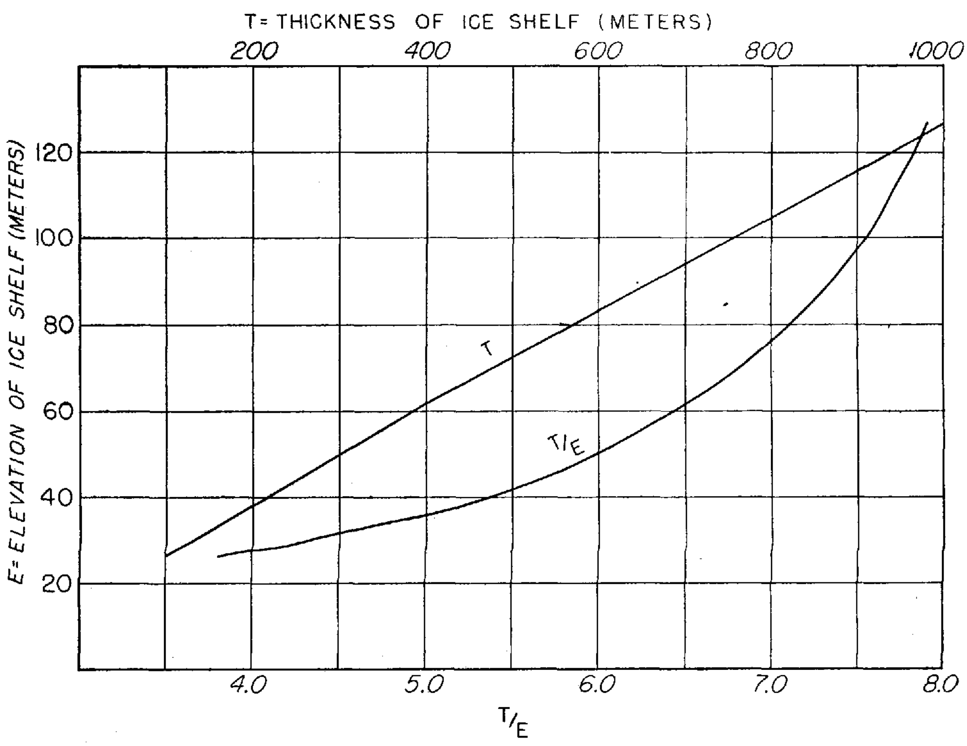

Fig. 5. Relationship of surface elevation and ice thickness for a floating ice shelf based on the density-depth data from the SIPRE deep bore-hole at Little America V

moving, and the observed apparent movement indicates the difference in true movement rates in accord with the vector equation

$$\mathbf{V}_0 + \mathbf{V}_{2a} = \mathbf{V}_2$$

where $\mathbf{V}_0$ = velocity of baseline,
$\mathbf{V}_2$ = velocity of mile 2 movement marker,
$\mathbf{V}_{2a}$ = apparent velocity of mile 2 movement marker.

Without having any fixed point (for example, a mountain peak) as reference, $\mathbf{V}_0$ and $\mathbf{V}_2$ cannot be determined. However, the normal components of these vectors can be determined by assuming the conservation of mass across the line of grounding. We have the two equations

$$V_{0n} + V_{2an} = V_{2n}$$
$$V_{0n}H_0 = V_{2n}H_2$$

where H_0 = thickness of ice beneath baseline,
H_2 = thickness of ice beneath mile 2 movement marker,
and n indicates component normal to line of grounding

from which we obtain
$$V_{0n} = \frac{V_{2an}H_2}{H_0 - H_2}$$

When the thicknesses of the floating and grounded ice are nearly the same, as in the present case, small errors in the depth determinations will produce large errors in the calculated velocities. At "Fashion Lane" an additional complication exists. The local line of grounding, as indicated by the crevasse pattern of Figure 3, has a different strike from the more regional line of grounding evident on the smaller scale map of Figure 2. The strike of the regional line of grounding is indicated by dots in Figure 3.

Because of these complications, quantitative results for true movement rates are not presented. However, certain qualitative results are evident. First, since the apparent movement vectors are directed toward the grounded ice, the floating ice must be slightly thicker than the grounded ice, in conformity with the profile in Figure 3. Second, since the apparent movement vectors rotate counterclockwise as one moves outward from the grounded ice, the true movement vectors must rotate clockwise indicating increased seaward component of motion. These results are indicated schematically in Figure 3.

Movement studies might provide the best means for determining whether the ice shelf thins beneath the valley near the contact. Consider the two markers of the present survey, number 1 located in the valley and number 2 located beyond it. If $H_1 = H_2$, then $V_{1n} \sim V_{2n}$. If $H_1 < H_2$, then $V_{1n} > V_{2n}$. Unfortunately, because of uncertainty as to the line of grounding, a definite conclusion cannot be obtained from the present work.

Using the seismic information at mile 200 and Nye's original theory of glacier flow (which assumes perfect plasticity),[12] it is possible to obtain an estimate of the shear stress at the base of the ice. For this purpose, the physical conditions in the vicinity of "Fashion Lane" are preferable to those of a mountain glacier because in the present case there is no frictional resistance contributed by the valley walls. If

τ = shear stress at base of ice,
ρ = density of ice = 0·90 g. cm.$^{-3}$,
g = acceleration of gravity = 983 cm.sec.$^{-2}$,
h = ice thickness at mile 200 = 630 m.,
$\sin\alpha$ = surface slope = 1/52,

then $$\tau = \rho g h \sin\alpha = 1{\cdot}07 \text{ bars.}$$

This agrees well with the estimate of τ = 1 bar for most glaciers which Nye gave in his original publication.

Crevasse Pattern

The crevasses of Figures 2 and 3 are schematic; nevertheless their orientation is correct. The same crevasse pattern was observed by the Ellsworth oversnow traverse. It is apparently characteristic of the contact between unobstructed plateau ice and floating ice shelf.

Figure 6 illustrates a possible qualitative explanation of the observed crevasse pattern. The circle near the contact is deformed to an ellipse as the ice moves outward. Crevasses develop perpendicular to the major axis of the ellipse as a result of tension. The tangents to a streamline (indicated by arrows in Figure 6) indicate the direction of movement at a given instant, in qualitative agreement with the results of the preceding section.

An alternate theory suggested to the authors is the following: As the ice descends the convex slope, the tensile strength at the surface is exceeded, and crevasses develop perpendicular to the direction of flow. Figure 7, from the Ellsworth oversnow traverse, illustrates this formation of crevasses on a steep slope. When the crevasses reach shelf level, they are rotated by the oceanward component of flow. The crevasses on the shelf originated on the slope; they have simply been transported to their present position.

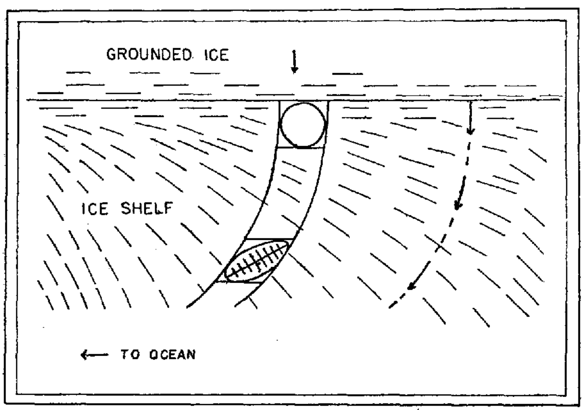

Fig. 6. Schematic diagram of the crevasse pattern characteristic of the contact of grounded ice and floating ice shelf

We find the latter theory unacceptable for the following reasons: (i) Rotation of ice has not been demonstrated; Figure 6 suggests that the ice may be strained and translated without appreciable rotation. (ii) The crevasses some distance out on the shelf appear as young and new as those near the foot of the slope. According to the theory, one should encounter successively older crevasses as one proceeds outward from the slope; such signs of age (for example, collapsed snow bridges) are not observed. (iii) There are many places where the slope is not steep enough to develop crevasses, and yet crevasses are observed on the shelf. This suggests that they are formed on the shelf, not on the slope.

If the crevasses are narrow, it is generally best for light vehicles to traverse the disturbed area at right angles to the strike of the individual crevasses. This concept was modified at "Fashion Lane"; here blasting and filling provided a safe route parallel to the crevasses on either side.

Where the slope of the descending plateau ice is steep, it may be impossible to travel directly up-slope because of crevassing. This was the situation encountered by the Ellsworth oversnow traverse. In this case drifting had resulted in a thick accumulation of snow between the axis of the valley and the steeper part of the slope. After crossing the crevassed ice shelf, the traverse party traveled safely for 12 miles (19 km.) at the foot of the slope until a point

Fig. 7. The Ellsworth oversnow traverse at the contact of the Filchner Ice Shelf and grounded ice at lat. 79° 29·3′ S. and long. 42° 52·0′ W. Note the tension crevasses developed on the slope. The lighted area behind the man on skis is the "snow apron" upon which it was possible to travel with safety until a crevasse-free slope was reached

was reached where the slope was free of crevasses, thus permitting ascent to the polar plateau. This "snow apron" is visible in Figure 7.

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