The Amery Ice Shelf*

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Abstract

The results of measurements from 3 visits over successive summers to the Amery Ice Shelf are presented. These results illustrate the pattern of accumulation over the ice shelf, how the accumulation rate has varied over recent years, the velocity and strain rate distributions over the ice shelf, the elevation profile, the surface temperature profile, and the pattern of change in the position of the ice front.

The values of accumulation and ice movement are used to evaluate a mass budget of the Amery Ice Shelf and Lambert Glacier drainage system of the Antarctic Ice Cap. The results suggest a high ratio of gain to loss.

I. Introduction

The Amery Ice Shelf is a highly dynamic region of the Antarctic. That is to say, if we consider that the flow of the Antarctic ice is everywhere orthogonal to the surface contours then it appears that the drainage basin of the Lambert Glacier Amery Ice Shelf system is a huge area of about 1/8 of the area of Antarctica. This region is shown in Fig. 1, adapted from Giovinetto (1964). Since this flow must pass through just 1/60 of the Antarctic coastline we might expect the rate of loss of ice at the margin to be much greater than the average coastal flow, or that the average accumulation rate is much lower than the average if balance is to be maintained.

Because of this apparently important role of the Amery Ice Shelf in the Antarctic mass balance, the Australian National Antarctic Research Expeditions (A.N.A.R.E.) in collaboration with the Department of Meteorology of the University of Melbourne, have made several summer expeditions to the ice shelf to initiate a major long term program of study. Unfortunately the ice shelf is not readily accessible from Mawson and some 400 km of high plateau have to be crossed to reach it. Furthermore the edges of the ice shelf are quite heavily crevassed and only light vehicles can cross to the centre with safety.

Figure 2 shows the routes travelled by three expeditions (1962, 1963, 1964) to carry out the first exploratory investigations and measurements. A three year program of glaciological research was drawn up at the Department of Meteorology and carried out by the A.N.A.R.E. glaciologists: I. Landon Smith 1962, E. Wishart 1963, W. Budd 1964. An outline of the work done by these parties has been described by Landon Smith (1963) and Budd (1965).

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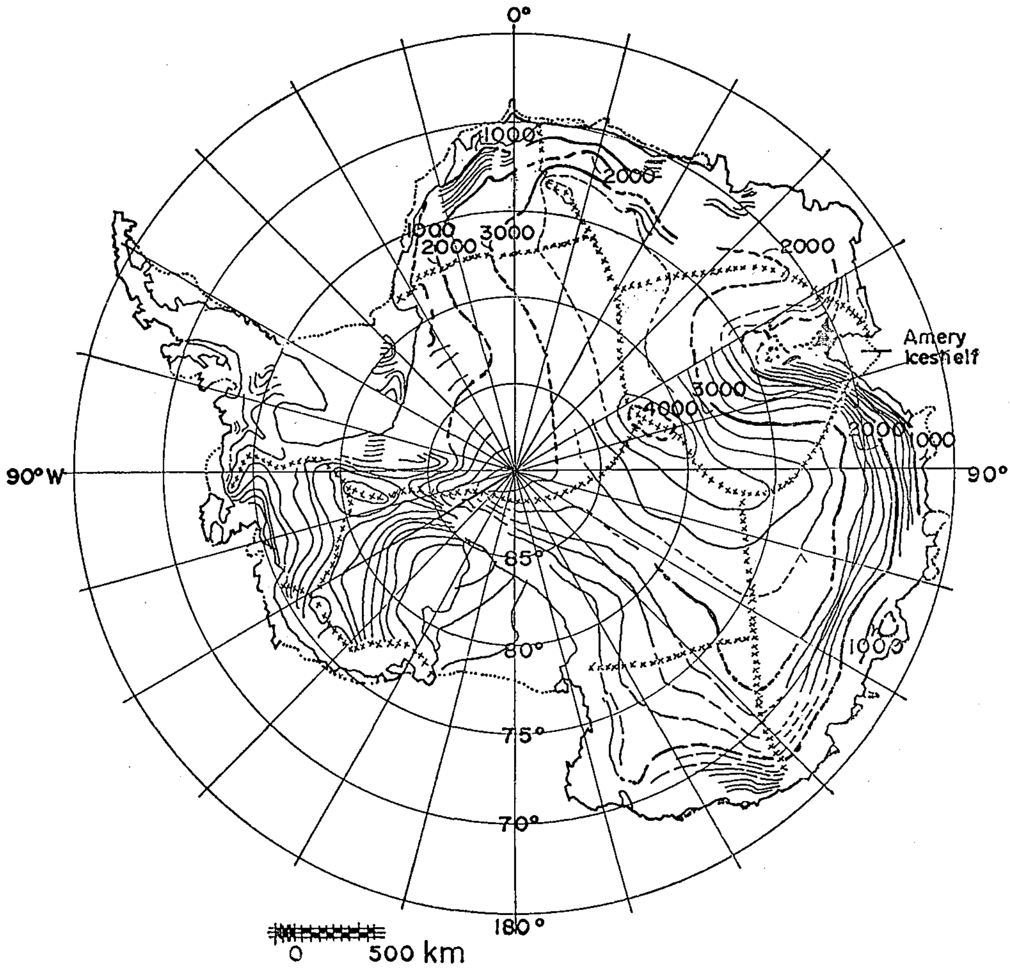

Fig. 1. The Antarctic drainage basins (from Giovinetto, 1964) showing the large area drained by the Lambert Glacier and Amery Ice Shelf in proportion to the coastline length. Elevations in metres

A study of the dynamics of the shelf, Budd (1966), discusses the velocity and strain distributions over the ice shelf and their relation to theoretical flow laws. As a consequence of the velocity and accumulation distributions over the ice shelf a study is made of the change in form of the ice shelf. The conclusion reached is that the ice shelf appears not to be in a steady state but may be thinning at the front and thickening at the rear.

A more complete detailed report of the combined results of the three year's work is in preparation. The purpose of this paper is to present an outline of the basic results and examine their import with specific reference to (i) the mass balance of the Amery Ice Shelf and (ii) the balance of the Amery Ice Shelf Lambert Glacier drainage basin. Finally an outline of the projected program for the next phase of the study will be presented.

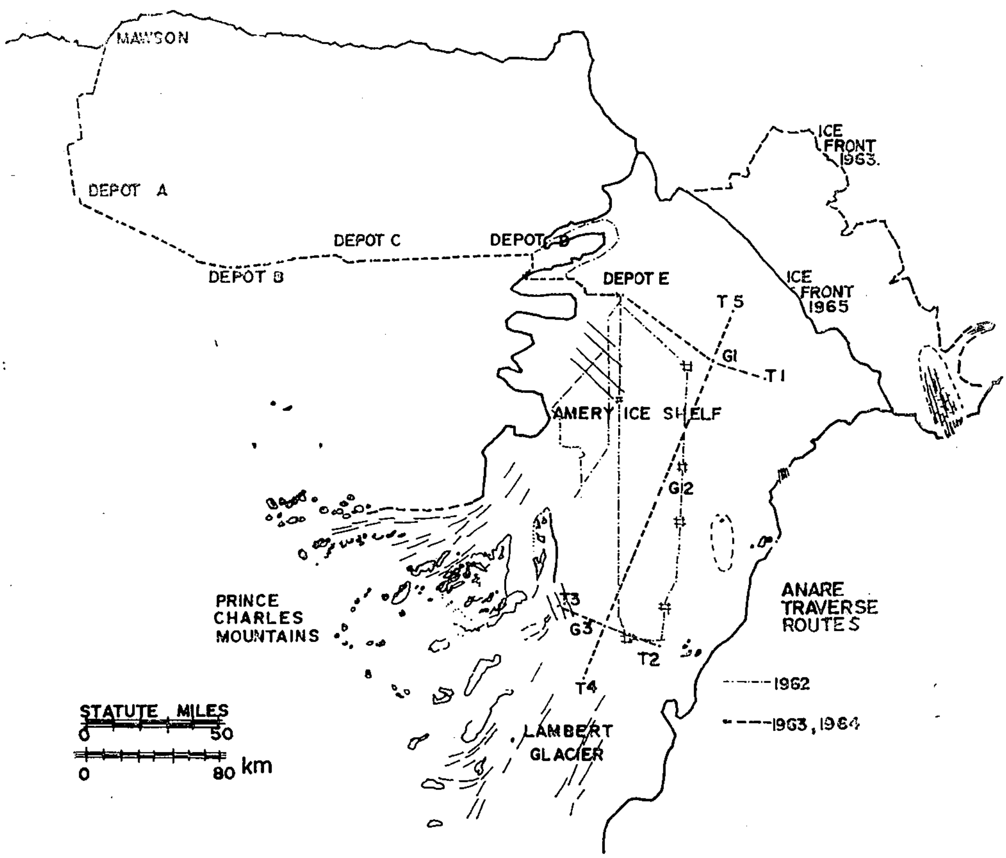

Fig. 2. Amery Ice Shelf traverse routes by A.N.A.R.E. 1962, 1963, 1964 from Mawson

II. Outline of Work Carried Out

II. 1. *1962.* The ice shelf was reached with dogsleds and D 4 tractors and snowtracs from the western margin to establish a depot, E, which was then maintained for about one month. Here a pit was excavated to 4 m depth to study the stratigraphy in detail. An 8-stake strain grid was set up and surveyed twice during the period. A detailed astrofix was carried out. Surface meteorological observations were maintained. A snowtrac executed reconnaissance journeys along the western margin and into the centre, carrying out elevation measurements on route.

A dogsled party traversed a north-south route as far as Manning Nunataks. Pits were dug to 2 m depth to examine stratigraphy and firn temperatures. A movement line was established at latitude 71°S and accumulation stakes left here and at depot E.

On the return voyage in January 1963 the ice shelf front was recharted from the 'Thala Dan'. A landing was made on the front and an astrofix carried out. Elevations of the ice shelf were measured going inland from the front, and a further pit excavated to determine the accumulation rate.

II. 2. *1963.* Again the major work was performed using 2 dog-teams with tractor support.

From depot D to E, G 1, T 1, G 2, G 3, T 2, T 3, T 4 (as shown in Fig. 2) stakes were placed 3.2 km apart. Pits were excavated along the route and temperatures were measured in boreholes to 10 m depth. Strain grids with diagonal 1.5 km were set out at G 1, G 2, G 3 and astrofixes carried out at these points, in addition to depot E, T 1, T 2, T 3, T 4.

II. 3. *1964.* Tractors were driven to depot D, carrying two weasles and a motor-toboggan. From here the weasles and toboggan followed the same route as for 1963, with the addition of T 5.

The accumulation stakes were remeasured, further pits dug, temperatures measured in boreholes, stations re-astrofixed, elevations measured barometrically, and the strain grids resurveyed.

In January 1965 the position of the Amery ice front was replotted by radar from the 'Nella Dan'.

III. Discussion of Results

III. 1. *Elevations and ice thickness profile.* From the elevation profile measured along the centre line of the ice shelf a corresponding ice thickness profile has been cal-

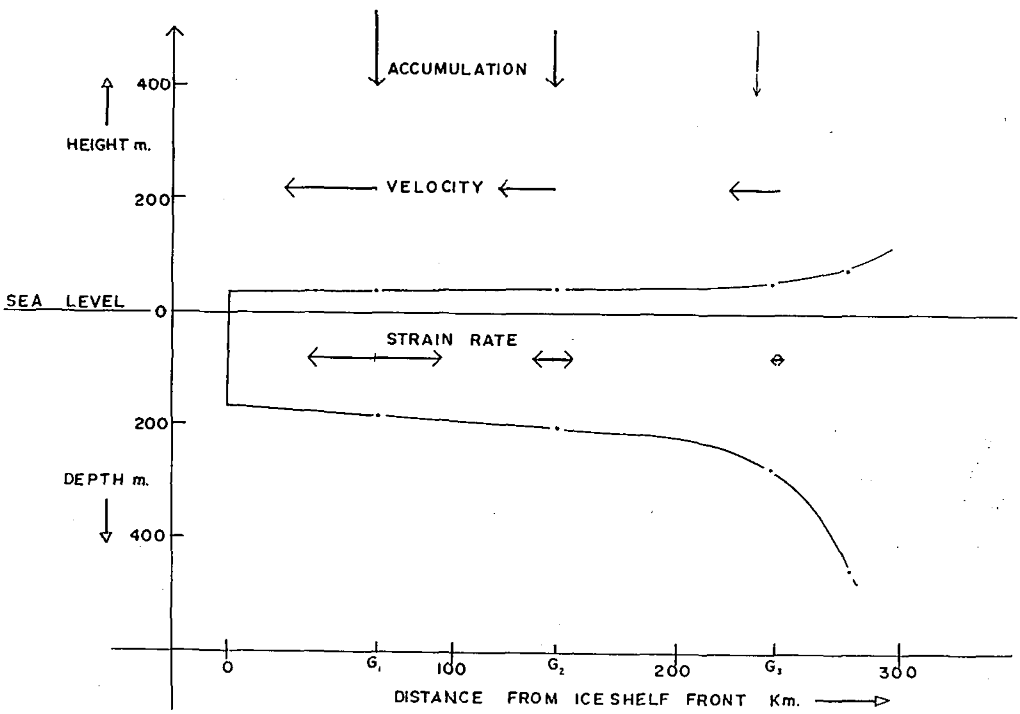

Fig. 3. From the measured elevation profile from T 5 to T 4, and Crary *et al.*'s (1962) ice thickness-elevation results for the Ross Ice Shelf, a thickness profile has been calculated for the Amery Ice Shelf. Velocity, longitudinal strain rate, and accumulation rate along the ice shelf are shown schematically to scale

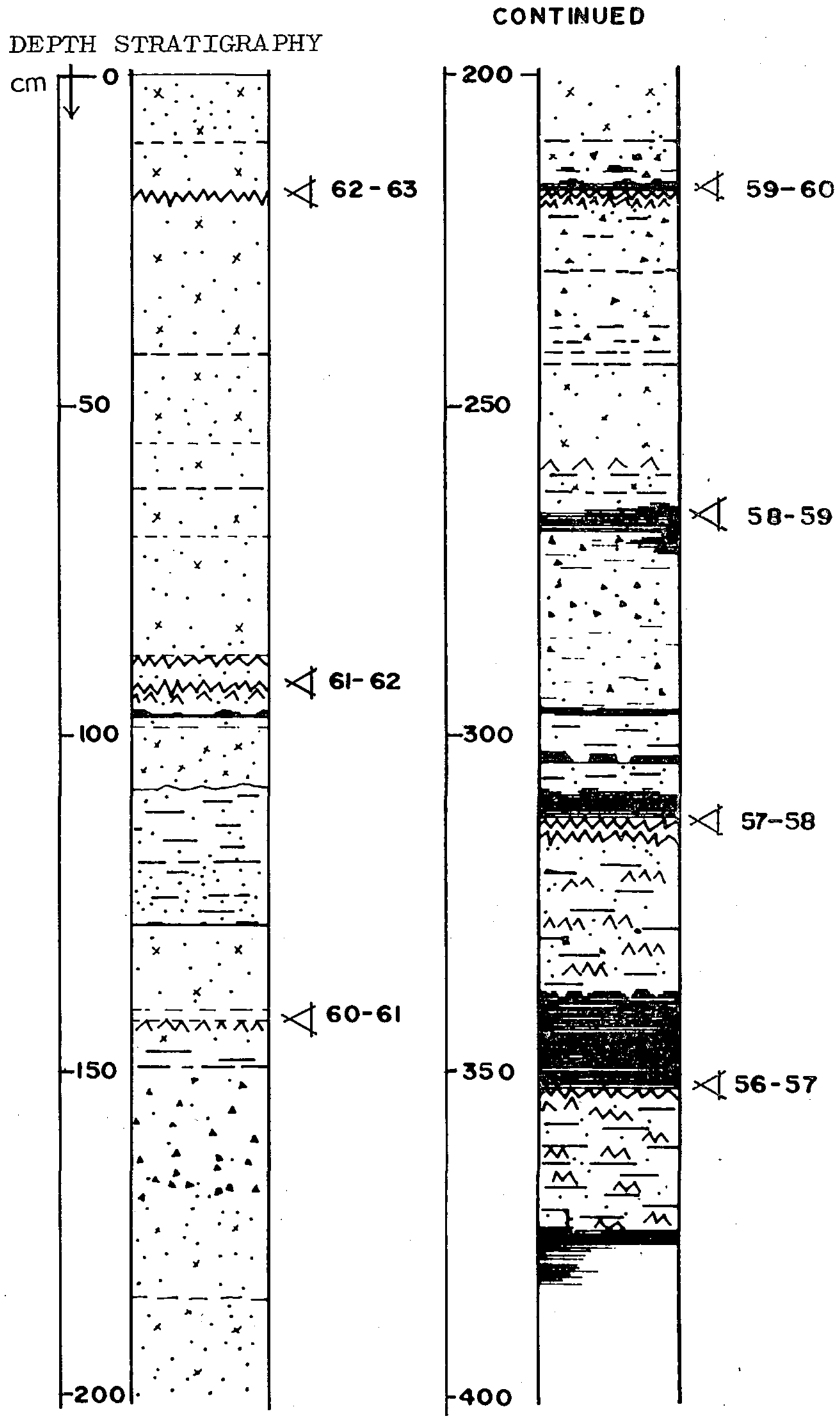

Fig. 4. Pit stratification data obtained by Landon Smith at depot E showing the annual layers identified by summer ice layers and sublimation crystals. Pit No. 10, 69°09'S, 70°09'E, 21 XII 1962

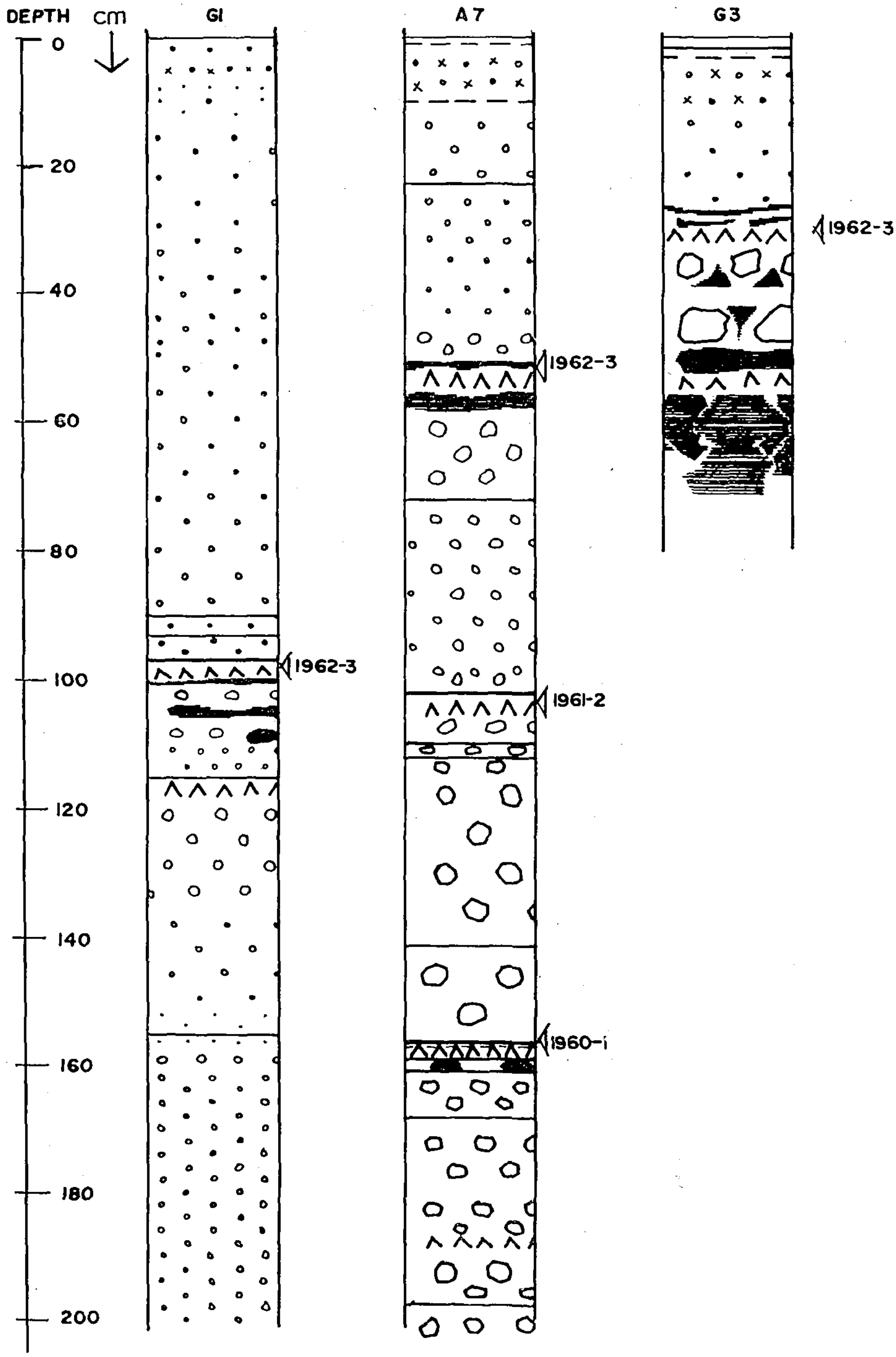

Fig. 5. Variation in snow strata down the Amery Ice Shelf centre from the pits of Wishart in 1963

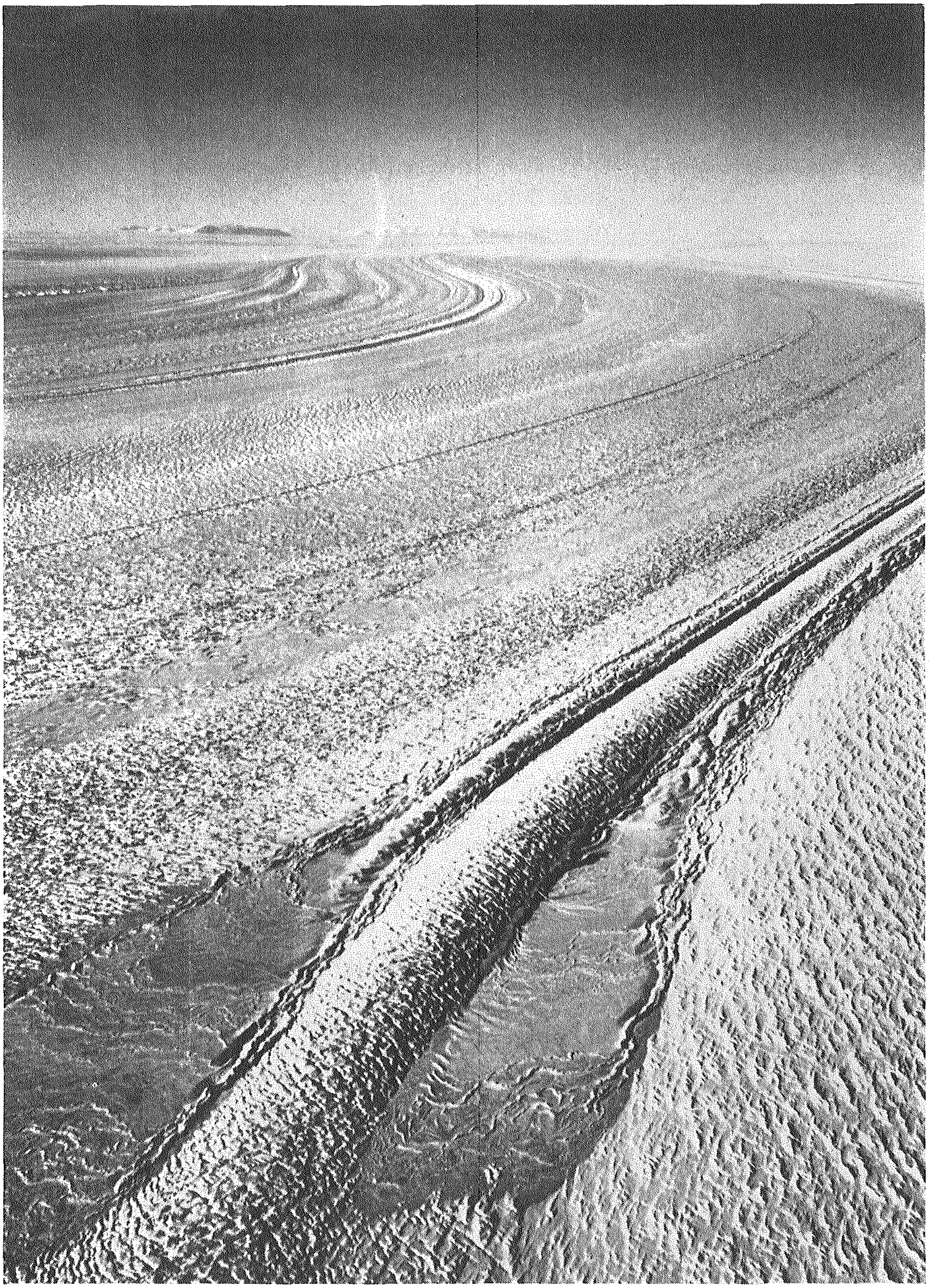

Fig. 6. Looking south along the Lambert Glacier from a height of 3 000 m above the surface (A.N.A.R.E. photograph)

culated. In order to do this the ratios of elevation to ice thickness for various elevations, as determined by Crary *et al.* (1962, p. 62) for the Ross Ice Shelf have been assumed to apply to the Amery Ice Shelf. The resultant profiles are illustrated in Fig. 3. The Amery Ice Shelf is relatively flat in the front section—similar to the central section of the Ross Ice Shelf, with slope 0.3×10^{-4}. This slope gradually increases to 1.2×10^{-4} by G 3, and becomes even greater further south—presumably marking the entry of the Lambert Glacier. The ice thickness follows the same pattern, increasing from 200 m at the front to 330 m at G 3. Further south the ice is probably grounded.

III. 2. *Accumulation measurements.* The analysis of the snow stratigraphy from pits and cores has been very successful on the Amery Ice Shelf for determining the annual snow accumulation rates. The annual mean temperature was found to decrease from −20.9°C at G 1 (lat. 69°40′S) to −23.5°C at G 3 (lat. 71°S). In summer the air temperature reaches above freezing and melting occurs with consequent ice layers forming in the surface snow. Below this ice layer frequently large depth hoar sublimation crystals form in a large cavity. Collapse of this cavity often gives rise to the phenomenon "firnstoss"—a loud rumbling sound associated with the collapse.

Figure 4 shows the firn stratigraphy to 4 m depth determined at depot E in 1962 by Landon Smith. Seven layers are discerned, going back as far as 1956. Landon Smith found that the mean variability from one year to another in accumulation was 11%. Also it can be seen from Fig. 4 that the degree of melting appears to have been greater in the earlier years (viz. 1956–59).

The variation in accumulation rate along the ice shelf centre is illustrated in Fig. 5, showing the stratigraphy of 3 pits examined by Wishart from G 1 to G 3. The snow accumulation decreased from 100 cm·yr^{-1} to 23 cm·yr^{-1}. At G 3 only 2 annual layers

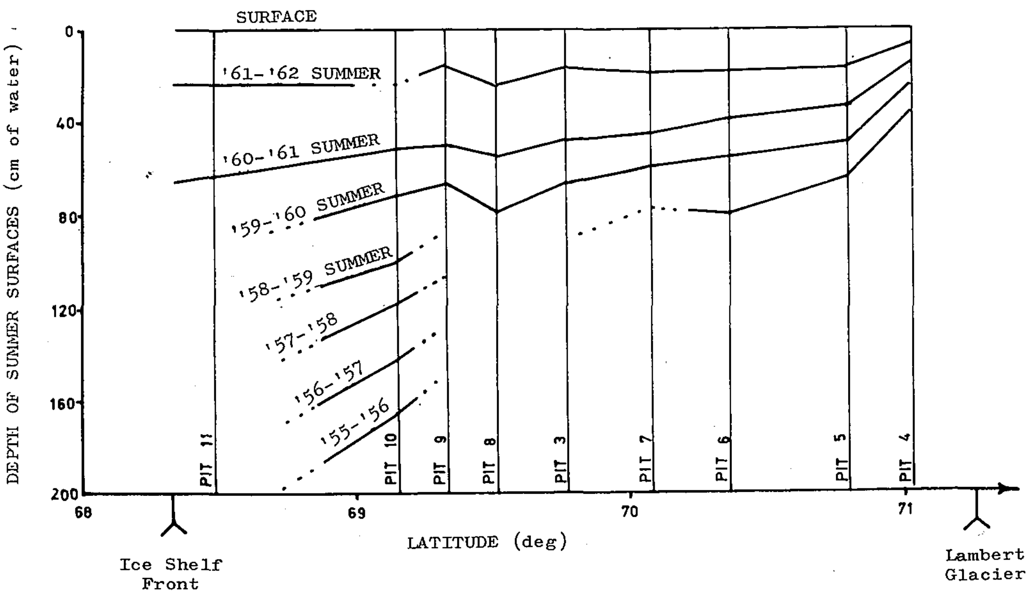

Fig 7. Variation in accumulation rate with latitude and distance inland from the coast obtained from the pit data of Landon Smith in 1962

were found above solid ice of over several metres depth. Thirty-two kilometres further south this ice prevailed with just slight patches of snow on the surface. The photograph of Fig. 6 shows the Lambert Glacier south of this region.

Figure 7 constructed from the results of all the pits dug by Landon Smith, shows the variation of accumulation rate along the ice shelf for the different years covered by the depth of the pits. His resultant decrease of accumulation rate away from the ice front

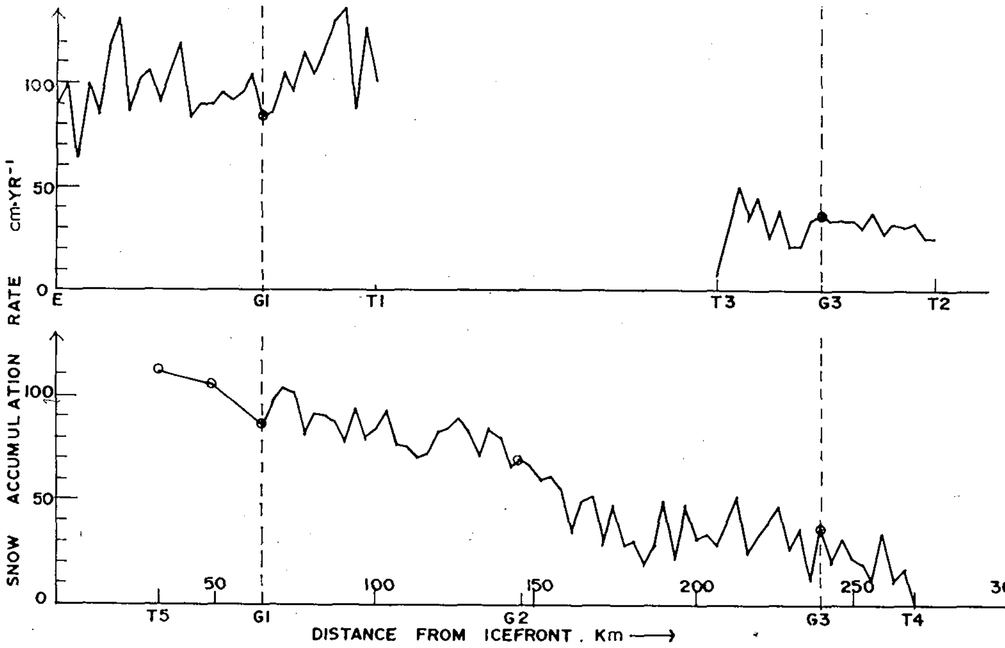

Fig. 8. Snow accumulation rates over the Amery Ice Shelf as determined by measurements on stakes 3.2 km apart over 1964

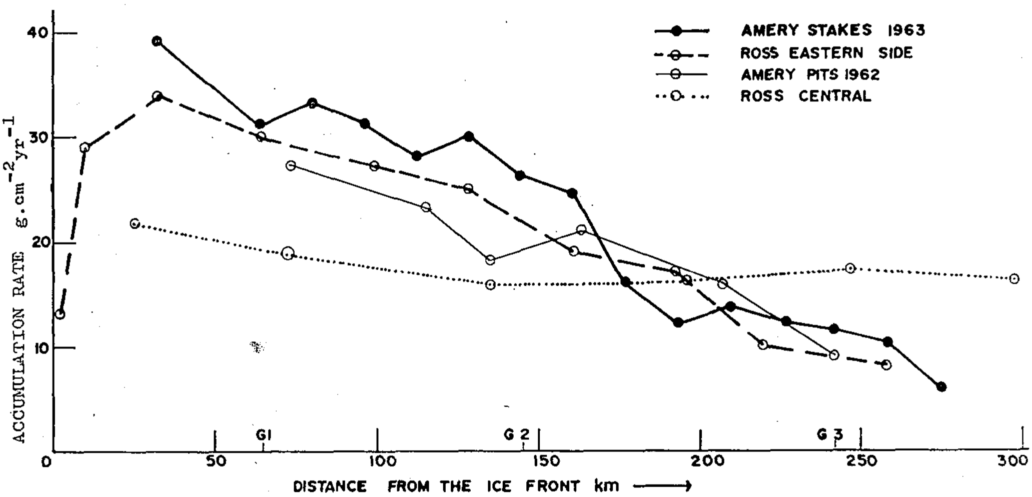

Fig. 9. Comparison of accumulation rates on the Amery and Ross Ice Shelves

was confirmed in 1964 by the remeasurement of the 1963 stakes. These results are shown in Fig. 8. The variation in accumulation rate across the ice shelf is small in comparison with the decrease going inland. The variability over shorter distances appears to increase towards the southern end. This is believed to be associated with small amplitude waves of several km wavelength, and whose amplitude increases as the Lambert Glacier is approached.

Figure 9 shows the comparison between accumulation rates on the Amery Ice Shelf and on the Ross Ice Shelf (from Crary *et al.*, 1962, p. 93). A striking similarity is seen

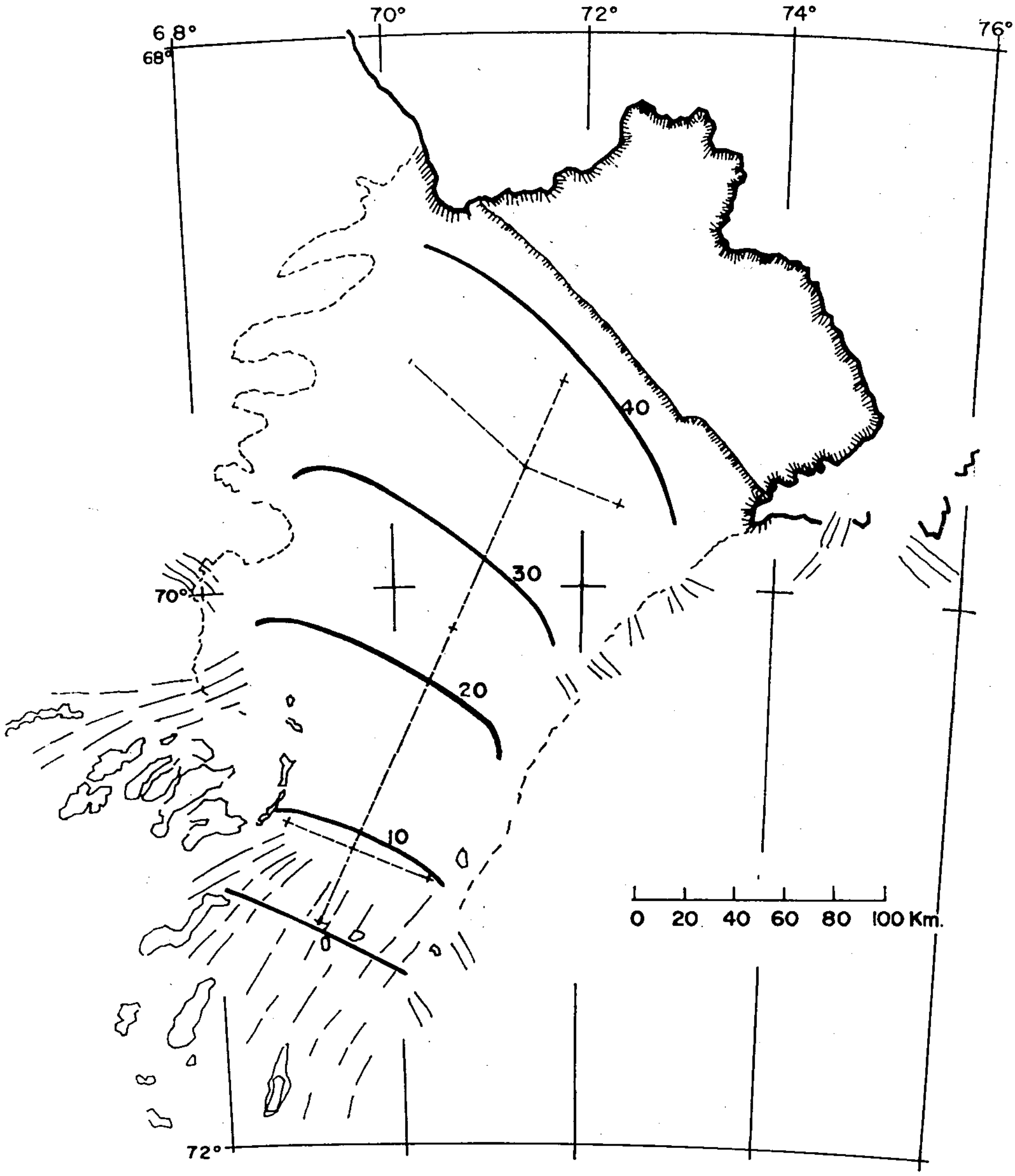

Fig. 10. Amery Ice Shelf accumulation contours constructed from the results of the stake measurements over 1964 ($g \cdot cm^{-2} \cdot yr^{-1}$)

between the accumulation rate over the Ross Ice Shelf to the east of Roosevelt Island and the Amery Ice Shelf. The accumulation rate in the centre of the Ross Ice Shelf is lower at the front but remains much more constant with distance inland.

The difference between pit measurements during 1962 and the accumulation measured from stakes over 1964 is largely accounted for by the 60 km change in position of the ice front.

From these profiles of accumulation rate, isopleths of annual mean accumulation over the Amery Ice Shelf have been constructed and are illustrated in Fig. 10. From

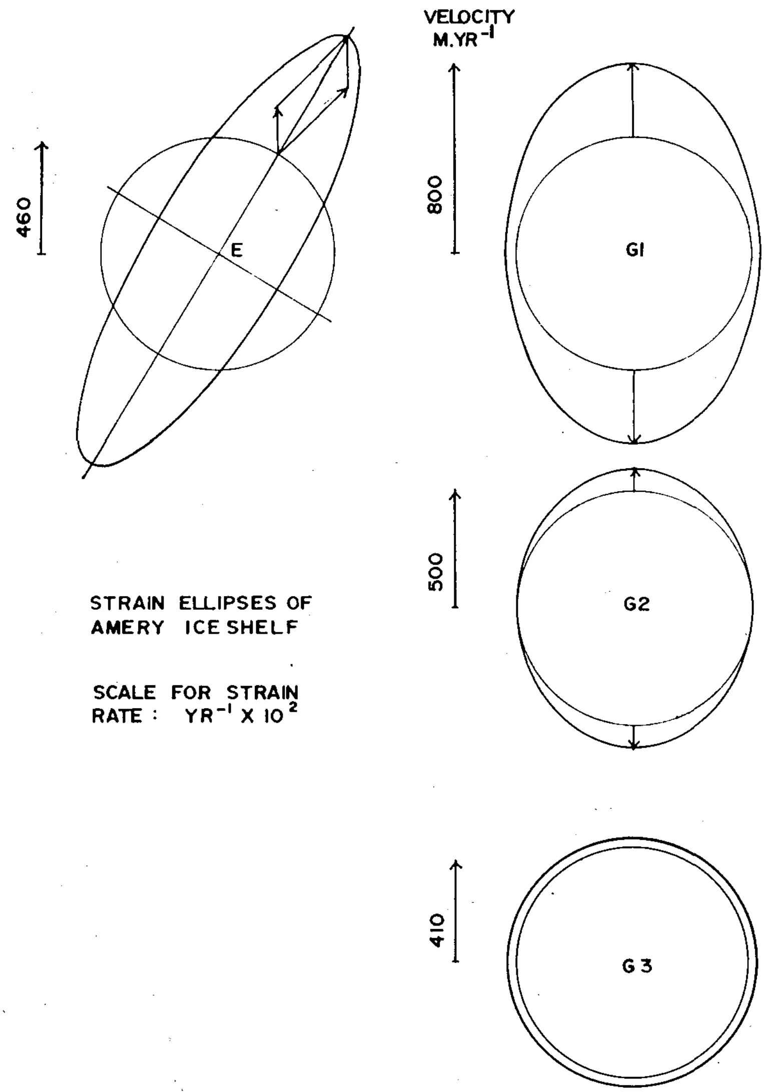

Fig. 11. Amery Ice Shelf strain ellipses drawn from the results of the strain grids at E, G 1, G 2, G 3. The central grids show a general expansion with the longitudinal strain increasing as the ice front is approached. The grid at E shows a pure shear due to the velocity gradient across the ice shelf superimposed upon a longitudinal expansion

this the total accumulation gain to the ice shelf has been calculated.

III. 3. *Velocity and strain distributions.* The strain ellipses obtained from the strain grids on the Amery Ice Shelf at E, G 1, G 2, and G 3 are shown in Fig. 11, together with the associated velocity. In each case a definite spreading of the ice shelf is observed. The velocity decreases going inland from the front from about 800 m·yr^{-1} at G 1 to

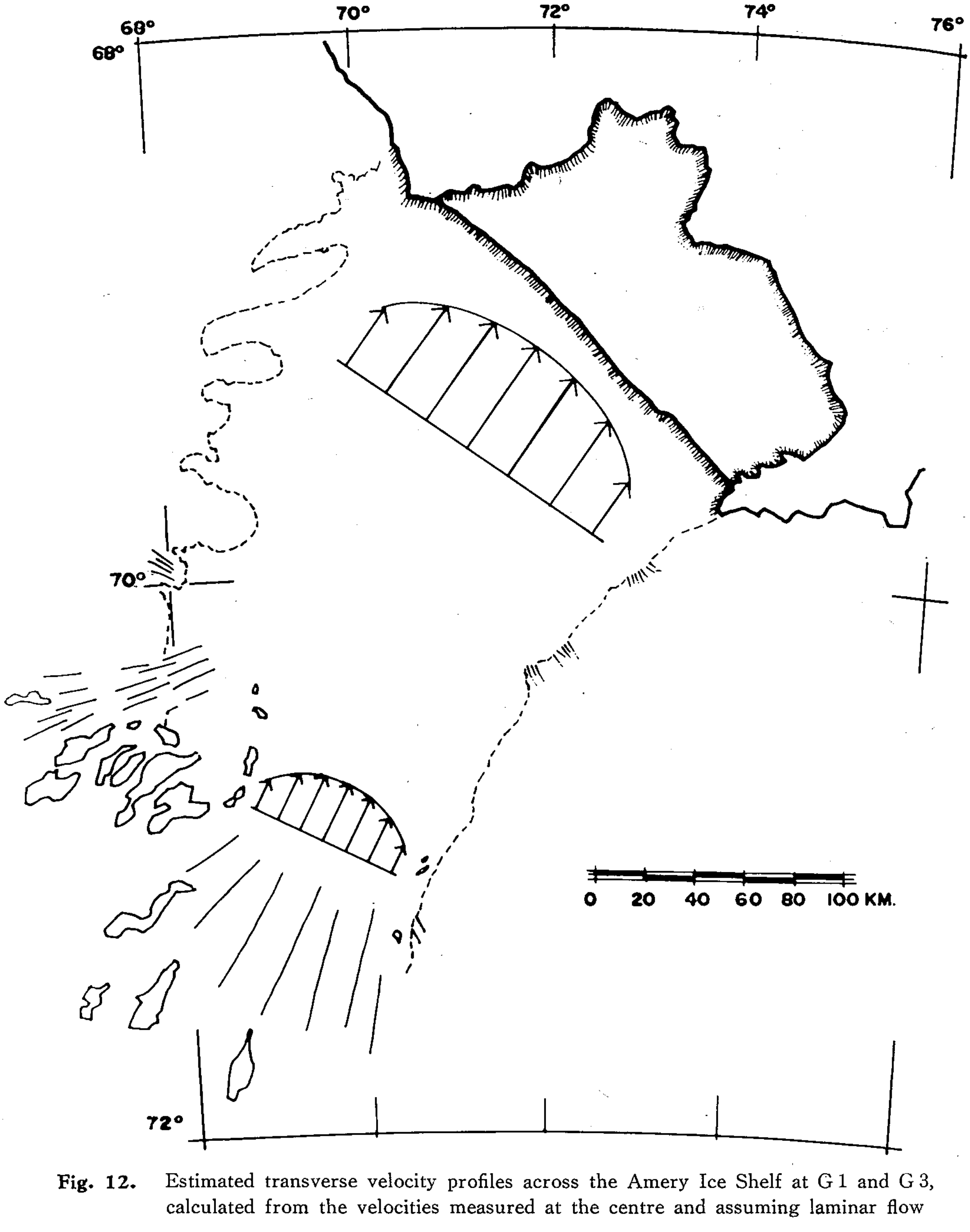

Fig. 12. Estimated transverse velocity profiles across the Amery Ice Shelf at G 1 and G 3, calculated from the velocities measured at the centre and assuming laminar flow

about 400 m·yr^{-1} at the southern end. Also the longitudinal creep rate, or velocity gradient, also decreases going inland, from 0.6% yr^{-1} at G 1 to 0.05% yr^{-1} at G 3. In "The dynamics of the Amery Ice Shelf", Budd (1966), an attempt is made to show how the variation in velocity and velocity gradient are related to the width of the ice shelf, the thickness gradient, and the ice flow law parameters.

The strain rate at E can be seen to be made up of a simple shear, due to the velocity gradient across the ice shelf, plus a longitudinal extension rate. The ratio of the longitudinal velocity gradient to the velocity for E and G 1 are about the same.

From these measured velocities, and velocity gradients, over the ice shelf estimated velocity profiles across the ice shelf at G 1 and at G 3 have been calculated. These profiles are illustrated in Fig. 12 and will be used to calculate the gain to, and the loss from, the ice shelf by ice flow.

IV. Mass Flux over the Amery Ice Shelf and Lambert Glacier Drainage Basin

IV. 1. *Budget of the amery ice shelf.* The ice mass flux, Φ say, across a section of width w, thickness H, and where the mean velocity is $\bar{V}$, is given by

$$\Phi = \rho H w \bar{V},$$

where ρ is the mean density of the ice over the thickness. From this relation the values of the ice shelf fluxes at G 1 and G 3 are calculated in Table 1.

Table 1. Ice shelf mass fluxes

		G 1		G 3		Ice front	
H	10^4 cm	2.2	±15%	3.3	±25%	2.0	±15%
w	10^7 cm	1.6		1.0		1.8	± 5%
$\bar{V}$	10^4 cm·yr^{-1}	$8.0\times\frac{3}{4}$	±15%	$4.1\times\frac{3}{4}$	±20%	$12.0\times\frac{3}{4}$	±15%
ρ	g·cm^{-3}	0.85		0.86		0.85	
Φ	10^{15} g·yr^{-1}	17.8	±30%	8.8	±45%	27	±35%

The errors are estimated probable errors and at this stage are very large. The assumption of a similar ice thickness—elevation relationship for the Amery Ice Shelf as for the Ross Ice Shelf may have resulted in an underestimation of the ice thickness at G 3, where the average ice density may be higher. Secondly because of the lower velocity at G 3 higher precision is required to keep the percentage error small.

The difference between the inward flow at G 3 and the outward flow at G 1 is made up from: inward flow from the boundaries plus accumulation over the surface, less loss by melting from below.

The gain from inward flow from the boundaries of the ice shelf is given by

$$F_b = 2lV_b H_b \rho_b,$$

where l is the boundary length of each side and the b subscript implies the average value of the variable along the boundary.

For the Amery Ice Shelf between G 1 and G 3 the following values are adopted:

$$\begin{aligned} l &\quad 160\,\mathrm{km}, \\ V_b &\quad 30\,\mathrm{m\cdot yr^{-1}} \pm 30\%, \\ H_b &\quad 200\,\mathrm{m} \pm 20\%, \\ \rho_b &\quad 0.85\,. \end{aligned}$$

Neither the ice thickness nor the velocity have been measured, but the values adopted are typical of the coastal ice flow in the Mawson region for ice 200 m thick. The elevation from D to G 1 indicated that the ice shelf is slightly higher in the centre ($\sim$5 m) than the edges. Hence the adopted ice thickness is expected to be close to the mean value along the boundary.

From the above values we obtain

$$F_b = 1.6 \times 10^{15}\,\mathrm{g\cdot yr^{-1}} \pm 40\%\,.$$

For the gain from surface accumulation we have

$$F_s = \bar{A} \times S\,,$$

where $\bar{A}$ is the mean accumulation rate over the area, and S the surface area. For the region between G 3 and G 1 we find $\bar{A} = 26\,\mathrm{g\cdot cm^{-2}\cdot yr^{-1}} \pm 10\%$ and $S = 2.4 \times 10^{14}\,\mathrm{cm^2} \pm 5\%$. Hence we obtain $F_s = 6.2 \times 10^{15}\,\mathrm{g\cdot yr^{-1}} \pm 15\%$. Neglecting melting or ice accretion at the base of the ice shelf for the moment we obtain for the total gain

$$\begin{aligned} F &= F_s + F_b \\ &= 7.8 \times 10^{15}\,\mathrm{g\cdot yr^{-1}} \pm 25\%. \end{aligned}$$

Comparing the total gain to the difference between inward and outward flux we find a net deficit of about 20% of the accumulation gain. This result is inside errors in the gain estimate and well within the high errors of the flux difference. Hence the precision of the measurements so far available allows us to only infer that the Amery Ice Shelf is possibly close to balance as a whole but may be thinning (in absence of ice accretion at the base) by about an average of $6\,\mathrm{cm\cdot yr^{-1}}$ (or $0.03\%\,\mathrm{yr^{-1}}$).

This conclusion is in agreement with the result presented by Budd (1966) which was obtained by considering the rates of change in thickness due to the strain, velocity, thickness gradient and accumulation at G 1, G 2 and G 3. The thinning was not uniform over the ice shelf but greatest at the front and even thickening at the rear. However, because of the still high errors at this stage only the trend can be considered as significant.

IV. 2. *The drainage basin budget.* We now consider the gain by net accumulation to the large drainage basin that appears to feed the Lambert Glacier system. A large part of this area is unknown, in so far as no accumulation measurements are yet available. Hence estimates of accumulation rates have to be extrapolated from the known results in neighbouring areas. The following sources have been consulted: Mellor (1959), Kotlyakov (1961), Dolgushin (1961), Rubin (1962), Losev (1963), Black and Budd (1964), Battye (unpublished), Giovinetto (1964, 1966), Bentley *et al.* (1964).

From these results annual net accumulation contours have been constructed over the area of the drainage basin and are illustrated in Fig. 13. These contours represent a conservative estimate of the accumulation and are somewhat lower than previous estimates.

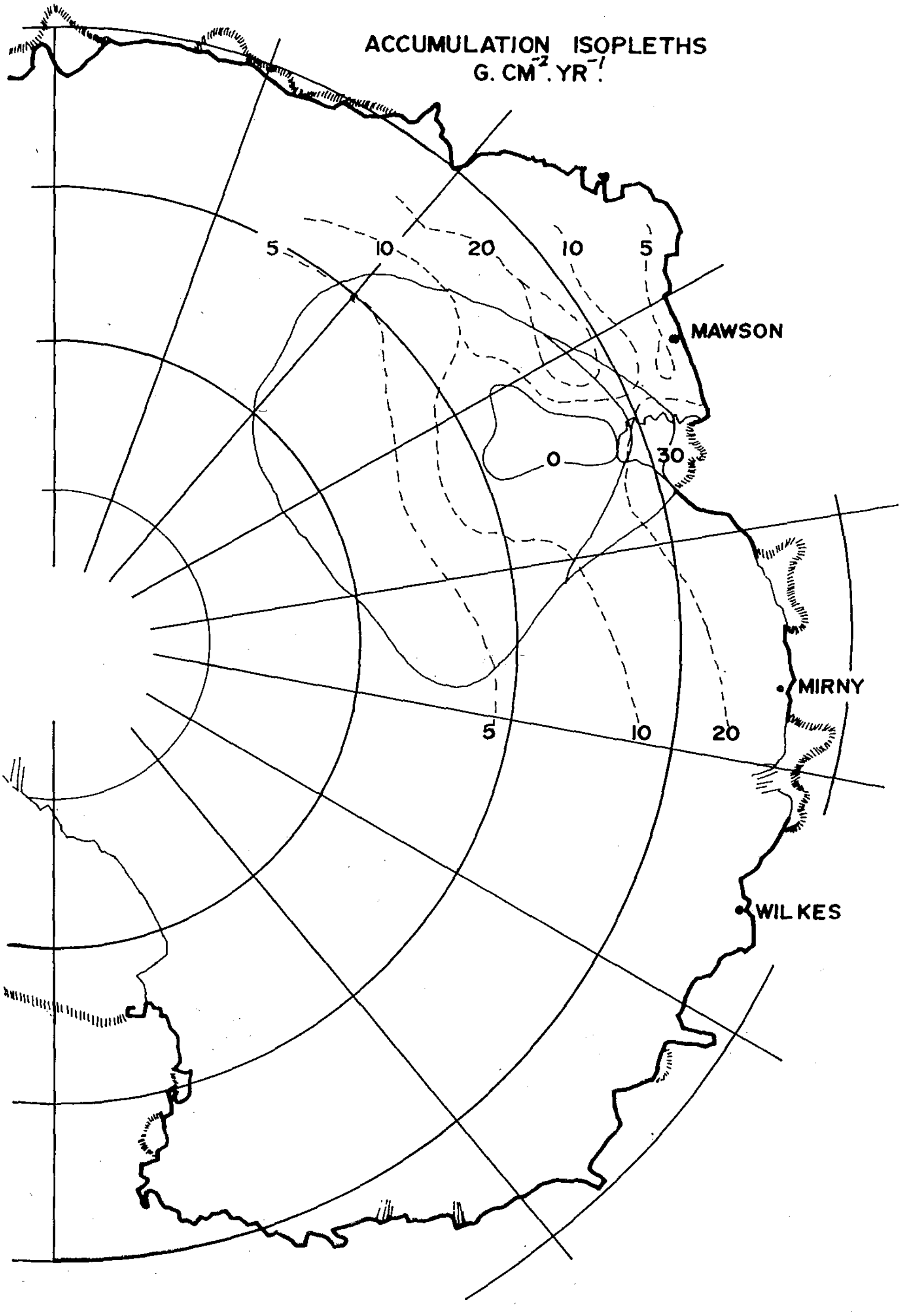

Fig. 13. Accumulation contours over the Amery Ice Shelf Lambert Glacier drainage basin used in the calculation of the mass budget of the region

The region of the Lambert Glacier itself is represented as zero. This is because a blue ice surface prevails over a large part of the region in summer and extensive melting has been observed.

Figures 14 and 15 illustrate the formation of melt streams in summer. Further inland the Lambert Glacier is highly crevassed, as may be seen in Fig. 16. The crevasses may accumulate snow and melt water but this does not imply a gain, but rather a redistribution of mass.

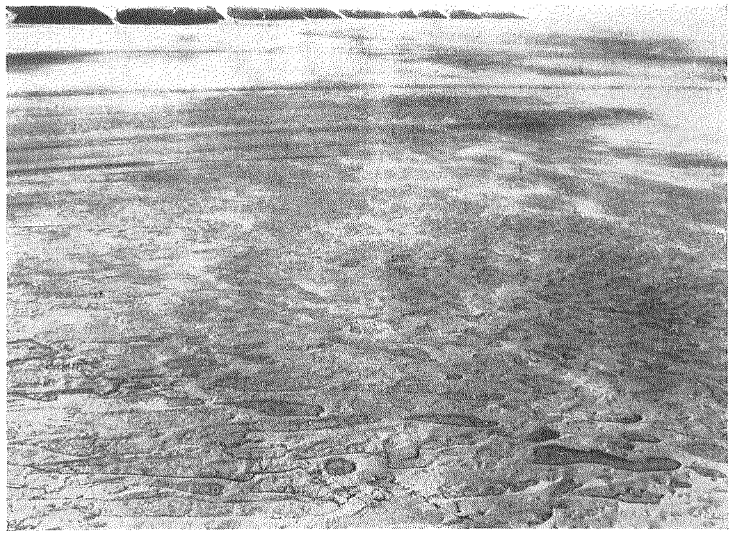

Fig. 14. Evidence of surface melt water on the Lambert Glacier near Mt. Stinear, approximately lat. 72°S (A.N.A.R.E. photograph)

Fig. 15. Looking across the Lambert Glacier to the Mawson Escarpment shows the glacier surface covered in melt lakes in late summer (A.N.A.R.E. photograph)

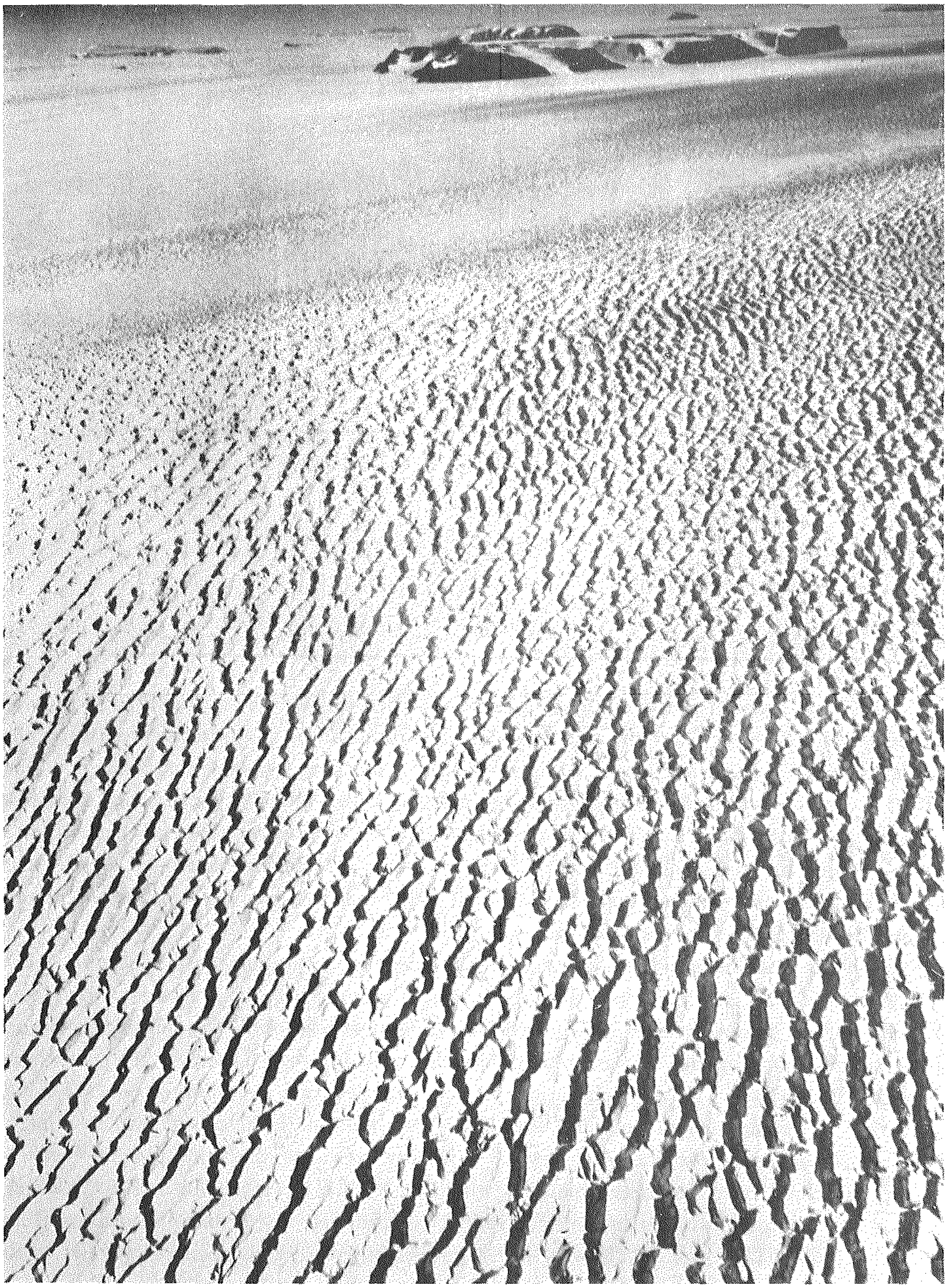

Fig. 16. Crevasse and flow line patterns in the Lambert Glacier, looking NW towards the Southern Prince Charles Mts. from lat. 72°30′S and a height of 3 000 m (A.N.A.R.E. photograph)

The estimates of the accumulation rate in the inland region have been obtained from similar values found for equivalent elevations and distance inland from Wilkes, Mirny and Mawson. The results of the 1964 U.S.S.R. traverse from Sovietskaya to Molodezhnaya should contribute to the knowledge of the outer boundary of this region.

We divide the whole Amery Ice Shelf Lambert Glacier drainage basin into three regions:

1) the area which flows only into the Lambert Glacier—and hence passes through the G 3 section (Lambert basin),
2) the area which flows into the Amery Ice Shelf from the sides (Amery sides),
3) the Amery Ice Shelf.

Table 2 lists for these three regions the area, average accumulation rate and total annual net gain.

Table 2.

Region	Area cm^2	Mean rate of accumulation $g \cdot cm^{-2} \cdot yr^{-1}$	Total gain $g \cdot yr^{-1}$
Lambert basin	12.4×10^{15}	5.1	62×10^{15}
Amery sides	0.90	15	14
Amery Ice Shelf	0.30	30	9
Total	$13.6 \pm 20\%$	$6.2 \pm 30\%$	$85 \pm 50\%$

The total gain to the whole region as obtained from Table 2 is $85 \times 10^{15}\, g \cdot yr^{-1}$ compared to $27 \times 10^{15}\, g \cdot yr^{-1}$ for the flow past the ice front. This suggests that the accumulation rate is a factor of about 3 times higher than that required for balance. This effect is even more pronounced for flow past G 3. Errors of 40% in the flux and 50% in the gain still show a significant positive budget. Giovinetto (1966) has calculated a mass budget for the drainage basin of the western side of the Ross Ice Shelf. His results suggest a prevailing accumulation rate twice that required for balance—although again the probable errors are also large.

Such an imbalance would imply that the ice cap is building up and for a more dynamic area such as the Amery Ice Shelf basin the imbalance may be more magnified. Giovinetto and Schwerdtfeger (1966) have shown that stratigraphic studies at the South Pole suggest an increase in accumulation rate from 5.4 to $7.5\, g \cdot cm^{-2}$ (20%) over the period 1760 to 1957. Larger fluctuations in accumulation rate over longer periods could give rise to fluctuations in outward flow but with a possible large phase shift in time.

IV. 3. *Changes in the ice shelf front.* Finally we note that the position of the Amery Ice Shelf front has been changing with time. This is illustrated in Fig. 17 which shows the plotted positions of the ice front as determined by various expeditions from 1936 to 1965. The profiles show a fairly uniform forward movement of the ice shelf together with a spreading outwards, orthogonal to the boundary. The mean forward motion from 1936 to 1963 was about $1.5\, km \cdot yr^{-1}$, which agrees very closely with the value obtained from astrofixes taken on the ice front in 1957 (U.S.S.R.) and 1963 (A.N.A.R.E.).

The rate of spreading has averaged about $1\%\, yr^{-1}$ compared to $0.6\%\, yr^{-1}$ longitudinal

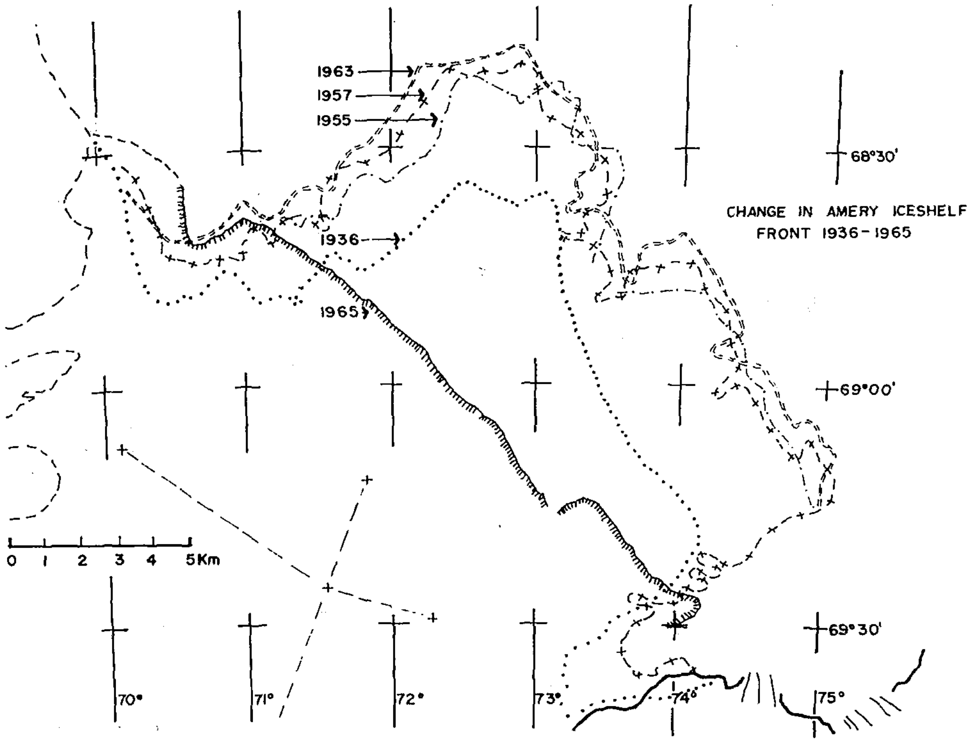

Fig. 17. The position of the Amery Ice Shelf front plotted by different expeditions:
1936 Lars Christensen Expedition
1955 A.N.A.R.E.
1957 Soviet Antarctic Expedition
1963 A.N.A.R.E.
1965 A.N.A.R.E.

The errors in positioning is estimated at ± 3 km, but in spite of this the general forward movement and spreading out is significant. A position on the front was astrofixed by the Soviet Expedition in 1957 and a repeat of this by A.N.A.R.E. in 1963 gave a velocity estimate of $1\,500 \pm 300\ \mathrm{m{\cdot}yr^{-1}}$. The large breakout of the ice shelf occurred later in 1963

expansion at G 1.

In 1963 a large part of the ice shelf ($160 \times 60 = 9\,600\ \mathrm{km^2}$) broke off and floated away to the west. This loss to the ice shelf represented about 40 years growth and 1/5 of the ice shelf area.

V. Conclusions and Future Program

Conclusions

1) The results at this stage provide a good estimate of the accumulation over the ice shelf but the ice thickness and velocities will have to be determined more precisely to enable a firm conclusion to be reached on the mass budget of the ice shelf. For the inland drainage basin, mass budget estimates are hampered by almost a complete lack of direct accumulation measurements.

2) In spite of the high errors in the results available at this stage, the present indications are that the Amery Ice Shelf itself is close to balance but the supply of ice may

be up to 20% lower than the loss at the front—with a consequent 6 cm (or 0.03%) yr^{-1} average thinning of the ice shelf.

3) On the other hand the supply to the Amery Ice Shelf Lambert Glacier drainage basin appears to be greater than the loss at the ice front by about a factor of 3. This would result in the ice cap increasing in average thickness over this region by about 4 cm (or 0.002%) yr^{-1}.

4) The ice shelf front has not been stationary over recent decades, but after moving steadily forward and spreading outwards for about 40 years lost about 1/5 of its area in a major breakout in 1963.

Future work. In the summer of 1967–68 it is planned to remeasure the strain grids at T 5, G 1 and G 2, and later at G 3 and T 4. Astrofixes are also to be repeated to give more accurate velocity results. An attempt will be made to measure the ice thickness by a modified 440 Mc radioaltimeter unit from a helicopter. The ice front is to be recharted at frequent intervals.

In 1968 it is planned to place a 4-man team on the ice shelf with light vehicles and caravans to carry out a one-year program of study. An elevation profile is to be established by optical levelling inland from the ice front. A tellurometer traverse aims at measuring strain down the centre and across two transverse profiles. It is proposed to core two holes into the ice shelf, using a C.R.R.E.L. thermal drill, one at G 1 and one at G 3, with the major aims of studying the stratigraphy, density profile, and the temperature distribution through the ice.

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