SURFACE ELEVATIONS ON THE LARSEN ICE SHELF

By R. G. B. Renner

Abstract. Ice-thickness profiles across the central part of the Larsen Ice Shelf were obtained from several flight traverses using a radio echo-sounding technique. These profiles, together with depth–density relationships derived from other Antarctic ice shelves, were used to calculate surface elevations on the Larsen Ice Shelf so that ground geophysical surveys in this area could be controlled more accurately.

During the Antarctic summer of 1966–67 several experimental traverses were flown over the Antarctic Peninsula by a British Antarctic Survey light aircraft carrying radio echo-sounding equipment capable of recording ice-thickness profiles (Swithinbank, 1968). The equipment and techniques, developed by the Scott Polar Research Institute, have been described elsewhere (Evans, 1963, 1967; Evans and Robin, 1966). The equipment was operated by Dr. C. W. M. Swithinbank and D. L. Petrie, both of the Scott Polar Research Institute. That part of the radio echo-sounding survey which concerns the present work covered the Larsen Ice Shelf on the east coast of the Antarctic Peninsula between lat. 66° and 68°50′S.

The main interest in the ice-thickness measurements arose from the need for surface elevations of the Larsen Ice Shelf so that ground geophysical surveys, employing gravity and magnetic methods, could be controlled more accurately. In addition, it would provide limiting factors to any geophysical interpretation involving ice depths and sub-surface topographical variations.

Previous to the application of this new technique of radio echo-sounding, glaciological work on the Larsen Ice Shelf had been restricted to a few subjective surface-elevation estimates (Mason, 1950; Fleet, 1965; Kennett, 1965) because of the many difficulties involved in such field determinations. These estimates had neither the control nor were there a sufficient number to be of real significance for geophysical purposes. Kennett (1966) used gravity anomalies from the geophysical traverses to determine ice-shelf thicknesses, assuming grounded ice models and supplementing this, where field evidence suggested a floating ice shelf, with depth estimates using the relationship suggested by Thiel and Ostenso (1961).

With the radio echo-sounder in full operation over the Larsen Ice Shelf, continuous profiles were recorded showing the upper and lower boundaries of the ice shelf. Conversion of the profile values to ice-shelf thicknesses (in metres) was by a simple scaling factor. Where the quality of the profile records permitted, ice thicknesses were calculated at regular intervals, but in some areas interference was observed on the profiles and this was possibly due to side reflections from adjacent rock exposures, sub-surface discontinuities or to very irregular surface relief on the ice shelf itself. In such instances only the more definite reflections were used, the others being ignored. To the total ice-thickness values obtained, a further 9 m. was added to allow for the surface high-velocity layer (personal communication from Dr. G. de Q. Robin), and the results are shown in Fig. 1. The ice thicknesses are estimated to have an accuracy of ±20 m. During the flights additional visual observations and fixes were recorded for navigational purposes, and these were also plotted on the base maps. (All flight records are kept at the Scott Polar Research Institute.)

Calculation of Surface Elevation from Total Ice Thickness

All of the records for the Larsen Ice Shelf indicate that the ice is floating, and therefore the relationship between surface elevation (h) and total ice thickness (H) can be represented by

$$H = \frac{\rho_w h}{\rho_w - \rho_i}, \tag{1}$$

where ρ_w is the density of sea-water and ρ_i is the density of ice below the compaction zone.

The boundary between grounded ice and floating ice appears to follow closely the coastal outline shown on the base maps of the area (personal communication from Dr. C. W. M. Swithinbank).

Below a depth of about 100 m., depth–density profiles in general tend to show that ice densities approach their maximum level, hence equation (1) is applicable. However, from 0 to 100 m. there is an increase in density with depth and some allowance should be made for this in the calculation of surface elevations. Robin (1958) has given a figure of +16 m. which should be added to the estimated thicknesses of Antarctic ice shelves to compensate for the low-density surface layers. It was because of the variable surface density that two methods of estimating the surface elevation were used on the Larsen Ice Shelf. Direct methods could not be used as no density values were available, so density data were sought from other Antarctic ice-shelf investigations.

In the first method, the relationship of surface elevation to total thickness was plotted (Fig. 2), using data from other ice shelves. From these a mean curve was calculated (Fig. 6, curve 2).

In the second method, a more specific estimate of thickness for the Larsen Ice Shelf was derived, and this incorporated the use of variable densities in the surface layers. For an ice

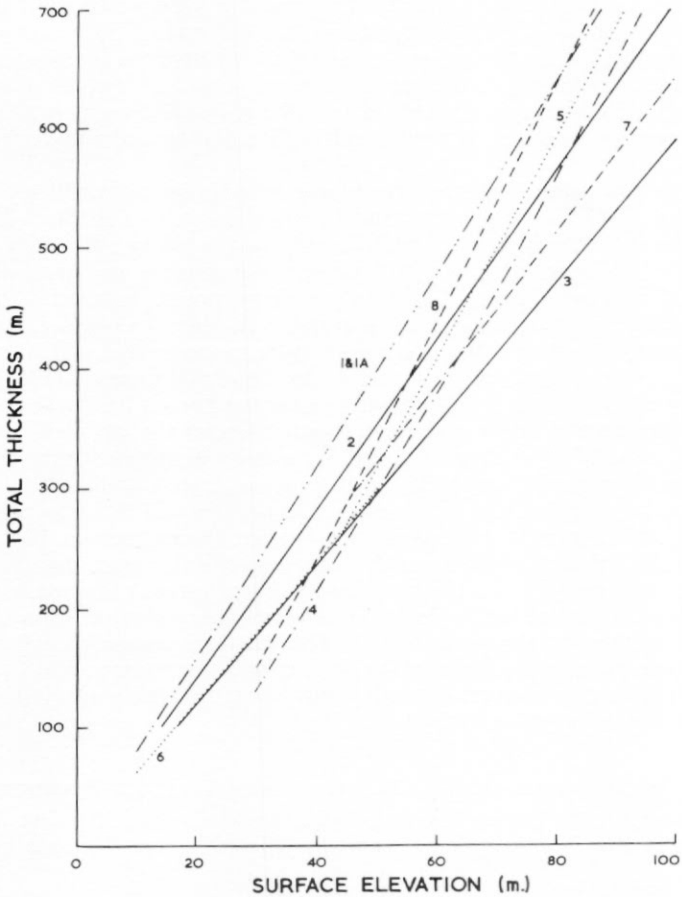

Fig. 2. Estimates of the relationship between surface elevation and total thickness for a floating ice shelf. 1. General case (Bentley, 1964); 1A. Skelton Inlet, $\rho = 0{\cdot}9$ g./cm.^{3}, values extrapolated (Crary, 1966); 2. Amery Ice Shelf, $\rho = 0{\cdot}88$ g./cm.^{3} (Budd, 1966); 3. Amery Ice Shelf, $\rho = 0{\cdot}85$ g./cm.^{3} (Budd, 1966); 4. Ross Ice Shelf (Thiel and Ostenso, 1961); 5. Ross Ice Shelf (Crary and others, 1962); 6. "Little America" station, $\rho = 0{\cdot}87$ g./cm.^{3} (Crary, 1961); 7. Skelton Inlet (Crary, 1966); 8. Maudheim Ice Shelf (Robin, 1958).

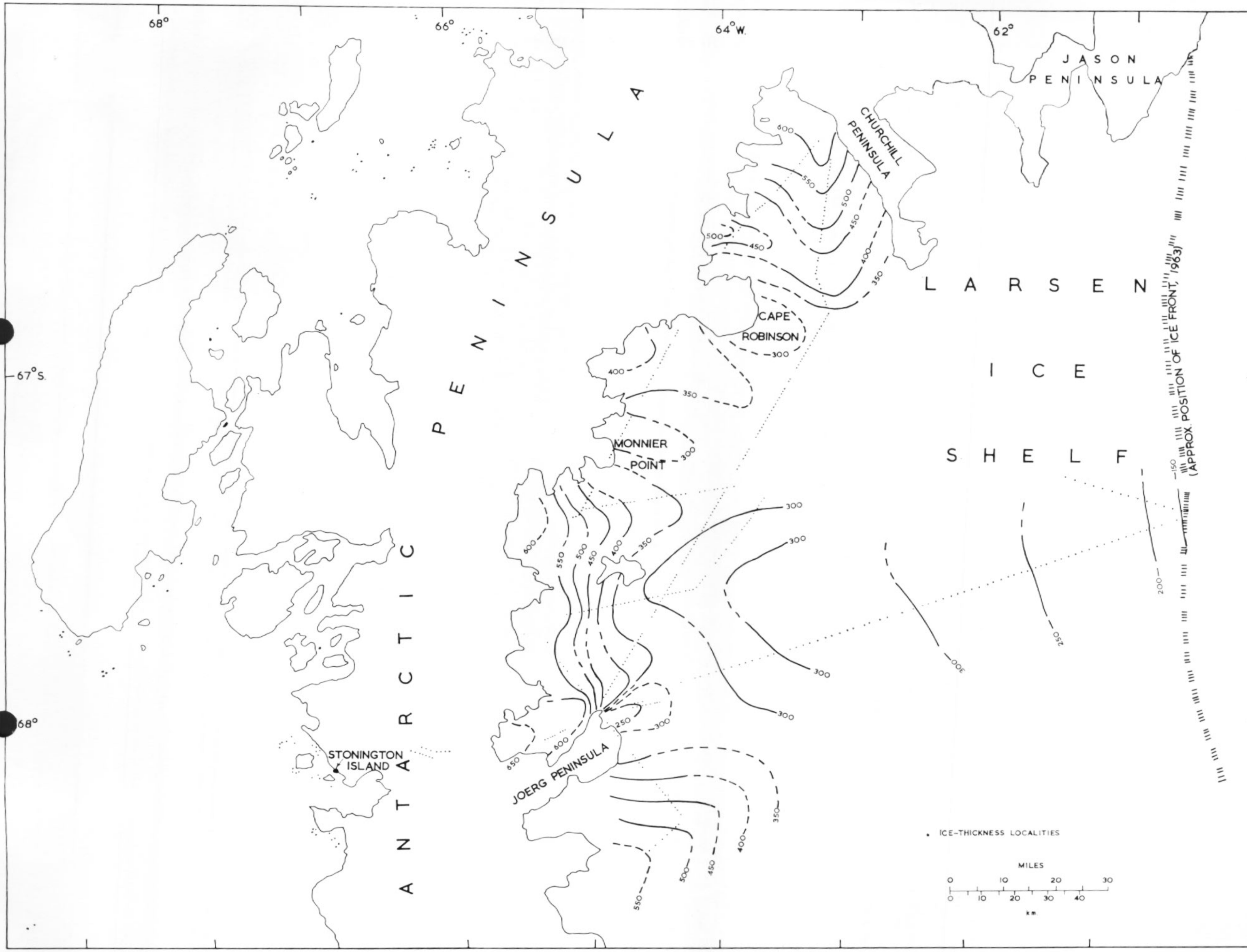

Fig. 1. Total-thickness contour map of the Larsen Ice Shelf (January–February 1967), showing the station positions. The contours are at 50 m. intervals.

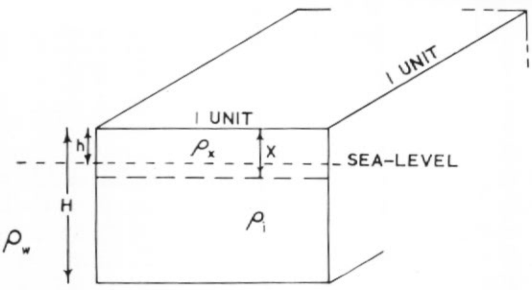

Fig. 3. An ice body in hydrostatic equilibrium, exhibiting variable surface density. H, total thickness; h, height above sea-level; X, depth of variable density; ρ_w, density of sea-water; ρ_i, density of ice below the compaction zone; ρ_x, mean density of ice above the compaction zone.

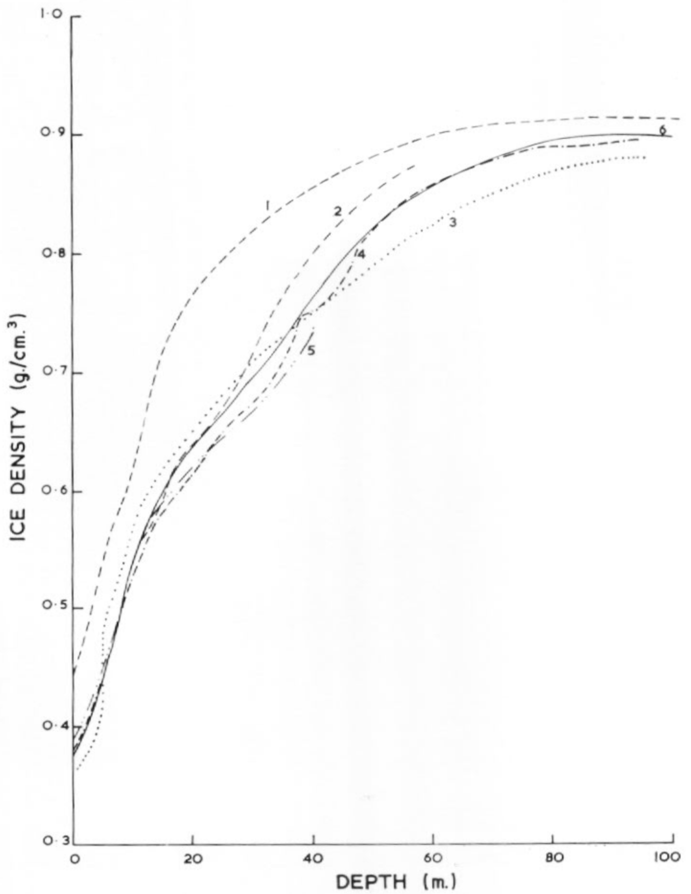

Fig. 4. Density changes of firn with depth.
1. Skelton Inlet, extrapolated (Crary, 1966); 2. Ross Ice Shelf, representative value (Crary and others, 1962); 3. Maudheim Ice Shelf (Schytt, 1958); 4. S.I.P.R.E. deep bore hole at "Little America" station (Crary, 1961); 5. "Little America" station (Crary, 1961); 6. Mean from results for the Ross Ice Shelf.

shelf in hydrostatic equilibrium, the change in surface elevation with total thickness, incorporating an allowance for near-surface low densities (Fig. 3), can be represented by

$$h = H\left(1 - \frac{\rho_i}{\rho_w}\right) - X\left(\frac{\rho_x - \rho_i}{\rho_w}\right), \tag{2}$$

where h is the surface elevation, H the total thickness, ρ_w the density of sea-water, ρ_i the density of ice, X the thickness with variable density, ρ_x the mean density for depth X.

Dr. Swithinbank (personal communication) has suggested that climatological factors affecting the Larsen Ice Shelf would give it a depth–density profile within the limits of those (Fig. 4) accorded to Skelton Inlet and the Ross Ice Shelf. A mean value (Fig. 4, curve 6) was taken for the Ross Ice Shelf, while curve 1 in Fig. 4 represented Skelton Inlet (Crary, 1966, extrapolation to 100 m.). An average density of 0·92 g./cm.³ has been given by Crary (1966) for depths below 80 m. in Skelton Inlet, but for depths below 100 m. on the Ross Ice Shelf a density of 0·9 g./cm.³ has been estimated. Curve 1 in Fig. 4 was used to calculate the mean density for 0–80 m. in Skelton Inlet, and curve 6 in Fig. 4 was used for 0–100 m. on the Ross Ice Shelf; density values of 0·82 and 0·76 g./cm.³, respectively, were obtained.

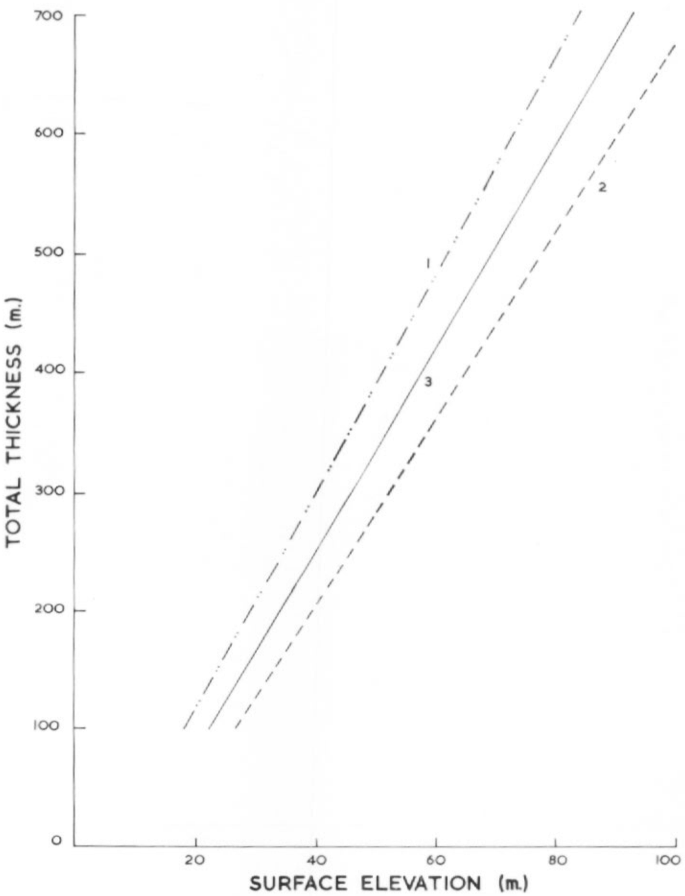

Fig. 5. Change in surface elevation with total thickness for a floating ice shelf.
1. Skelton Inlet; 0–80 m., $\rho = 0{\cdot}82$ g./cm.³; below 80 m., $\rho = 0{\cdot}92$ g./cm.³ (Crary, 1966); 2. Mean for Ross Ice Shelf; 0–100 m., $\rho = 0{\cdot}76$ g./cm.³; below 100 m., $\rho = 0{\cdot}90$ g./cm.³; 3. Mean of 1 and 2 above.

By substituting these values in equation (2), the variation in surface elevation with total thickness was calculated, and the results are shown in Fig. 5. The estimate for the Larsen Ice Shelf was assumed to be midway between these two parameters (Fig. 5, curve 3).

Curve 3 in Fig. 5 is reproduced as curve 1 in Fig. 6 so that a direct comparison can be made between the two methods used for the surface-elevation calculations on the Larsen Ice Shelf. Curve 1 in Fig. 6, which can be represented by

$$h = \frac{H}{8 \cdot 3} + 10, \tag{3}$$

was used to derive the surface elevations from which Fig. 7 was drawn. Equation (3) can be compared with the equation ($h = \frac{H}{10} + 16$) derived by Robin (1958) for the Maudheim Ice Shelf. Provided the assumptions made are correct, the elevations calculated are accurate to ± 3 m. Allowing for an error of $\pm 0 \cdot 015$ g./cm.^{3} in ice density for the Larsen Ice Shelf, which would place it at approximately the limiting density values suggested, i.e. those of Skelton Inlet or the Ross Ice Shelf, the error in the surface elevation would be ± 10 m. Fig. 8 shows sections drawn across the Larsen Ice Shelf to illustrate the thickening of the ice shelf within the inlets.

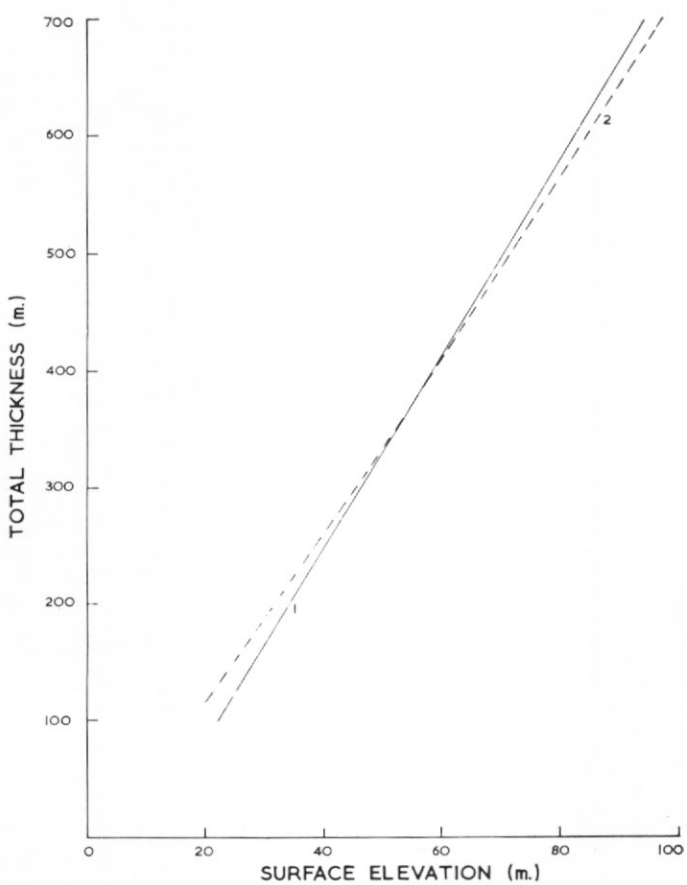

Fig. 6. Comparison of the methods used to estimate the surface elevation of the Larsen Ice Shelf. 1. Mean from Fig. 5; 2. Mean from Fig. 2.

TABLE I. COMPARISON OF SURFACE-ELEVATION ESTIMATES FOR THE LARSEN ICE SHELF

Locality	*Position*		*Surface elevations* (m. a.s.l.)				
	lat. S.	long. W.	Freeman (1963);* surveyed in 1946	Mason (1950); surveyed in 1947–48	Forster and Gibbs (1963);* surveyed in 1958–61	Kennett (1965); surveyed in 1963–64	This paper; from a survey by Swithinbank in 1967
Mobiloil Inlet	68°33′	65°21′			90		95
Mobiloil Inlet	68°32′	65°16′				82	90
Mobiloil Inlet	68°29·5′	65°03′				85	85
Solberg Inlet	68°16′	65°09′	122				65–70
Solberg Inlet	68°12·5′	64°53′	113				60
Trail Inlet	68°08′	65°42′	110				95–100
Three Slice Nunatak	68°01·5′	64°59′		110			75–80
Seligman Inlet	67°42′	65°17′				110	80
Mill Inlet	67°00′	64°30′		91–122			65–70
Adie Inlet	66°18′	62°45′				79	78
Adie Inlet	66°16′	62°42′				102	85
Adie Inlet	66°15′	62°36′				75	85
Adie Inlet	66°14′	62°39′				89	90

* Directorate of Overseas Surveys, 1963, D.O.S. 610, sheet W6864, 1 : 200,000

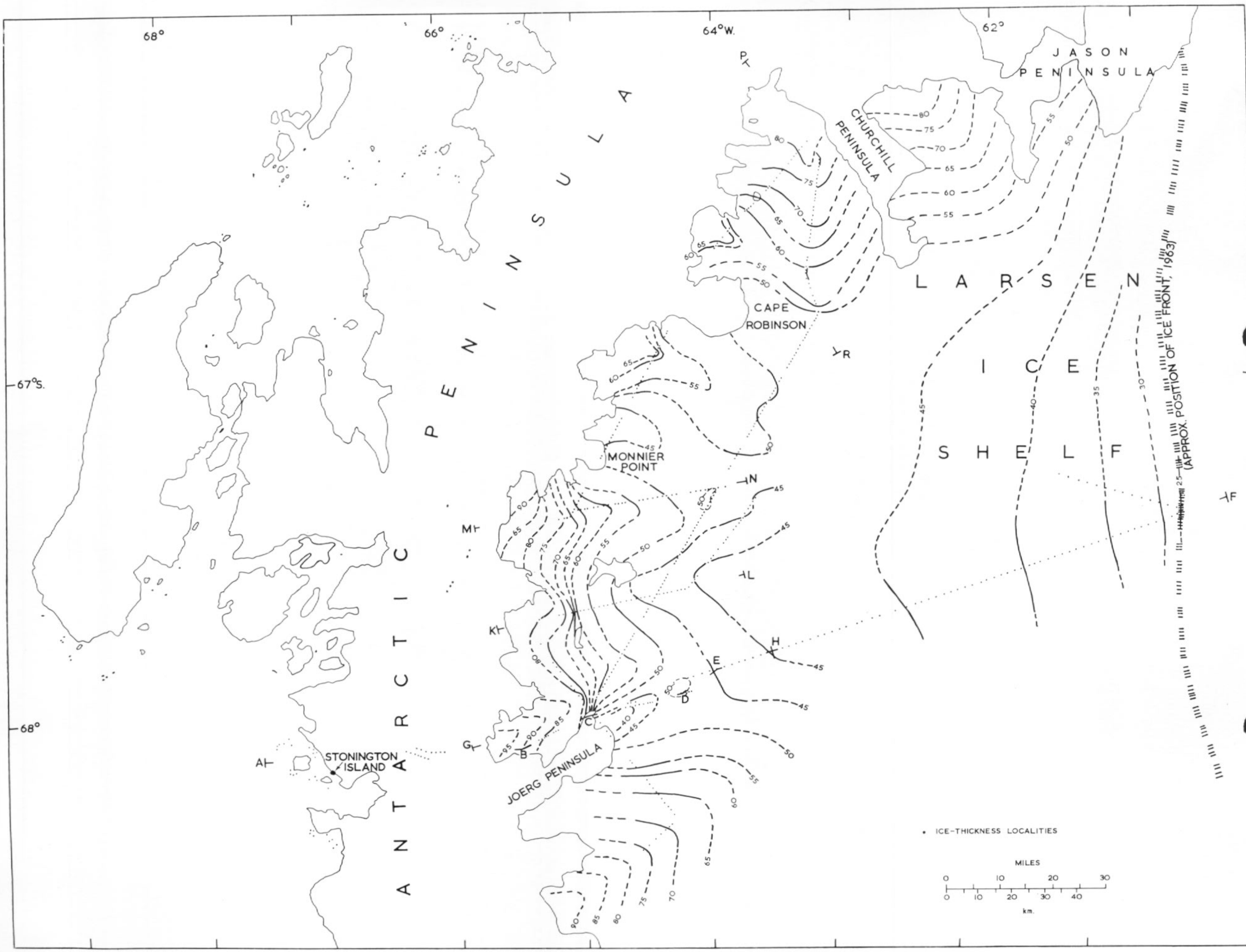

Fig. 7. Surface-elevation contour map of the Larsen Ice Shelf, showing the lines of section illustrated in Fig. 8. The contours are at 5 m. intervals.

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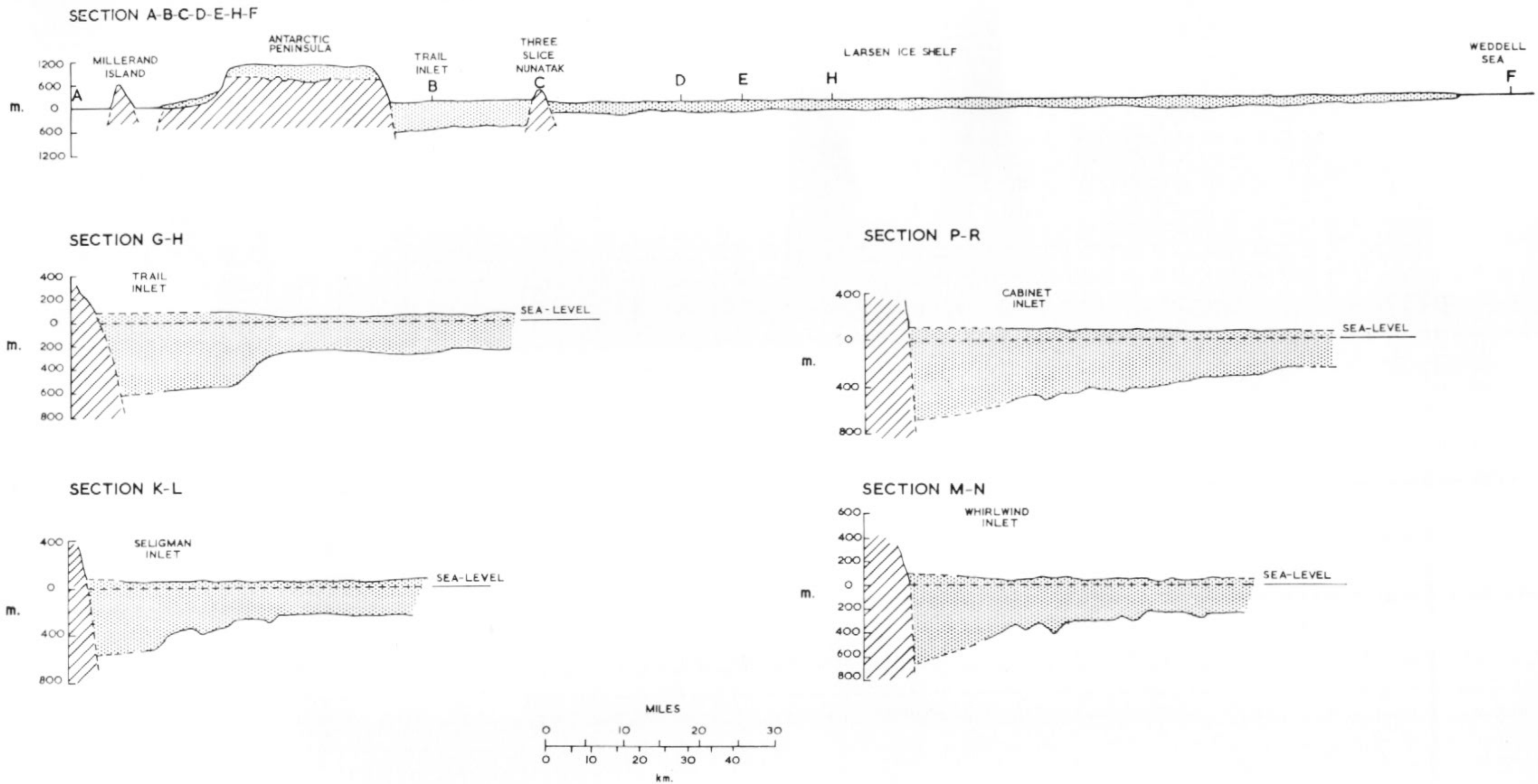

Fig. 8. Sections through the Larsen Ice Shelf along the lines shown in Fig. 7. Rock is hatched and ice is stippled.

Discussion of Results

Previous estimates of surface elevations on the Larsen Ice Shelf are given in Table I, where they are compared with values interpolated from the present work. The earlier estimates based on barometric traverses were subject to both regional and local atmospheric changes, accurate records of which are not available for the Larsen Ice Shelf. Kennett (1965) calculated that pressure variations accounted for a maximum error of ±20 m. in his elevation values. Superimposed upon the regional trend of surface-elevation contours (Fig. 7) are local irregularities in the form of surface undulations of the ice shelf. These features, which are particularly common in the Three Slice Nunatak area, may have amplitudes of the order of 30 m., but they have remained undetected by both the radio echo-sounding and barometric methods. Despite the inaccuracies involved, the values determined by Kennett (1965) at seven localities on the Larsen Ice Shelf by a barometric method show a mean deviation of only ±9 m. from the estimates derived by the radio echo-sounding method. However, the advantages of the latter method greatly outweigh those of the barometric traverses over such an area as the Larsen Ice Shelf, not only in greater overall accuracy but particularly in the speed of surveying the area.

Acknowledgements

The author wishes to thank Dr. C. W. M. Swithinbank of the Scott Polar Research Institute, Cambridge, for his co-operation in allowing access to unpublished radio echo-sounding data and in the presentation of the results. My thanks are also due to Dr. R. J. Adie for his advice on the preparation of the paper.

MS. received 1 March 1968

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