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AIRBORNE RADIO ECHO SOUNDING OF GLACIERS IN THE ANTARCTIC PENINSULA

By

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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ABSTRACT

A TWIN OTTER aircraft of the British Antarctic Survey was equipped with a Scott Polar Research Institute Mark 4 radio echo sounder during the Antarctic summer 1969–70. Flights totalling about 10,000 km. were made from Adelaide station and Fossil Bluff. The Larsen Ice Shelf was found to be 200 m. thick at the ice front, increasing to more than 500 m. in Cabinet Inlet and Mobiloil Inlet. On the Wordie Ice Shelf east of long. 67°50′W., thicknesses were between about 150 m. at the ice front and 400 m. in the north-east at the foot of Hariot Glacier. Probable brine infiltration prevented widespread depth measurement in Wilkins Sound. In George VI Sound, in spite of extensive surface melt pools, soundings indicated a thickness of almost 500 m. near lat. 73°S., long. 70°W. On the Antarctic Peninsula plateau, thicknesses up to 1,630 m. were recorded. In the Weddell Sea a giant iceberg which is thought to have come from the Amery Ice Shelf was sounded. Tracks were plotted from flight-recorder data with a general purpose digital computer which also did the collation with the radio echo 35 mm. film record. The data obtained are presented together with data collected during the 1966–67 season by C. W. M. Swithinbank and D. L. Petrie.

CONTENTS

I. INTRODUCTION

RADIO echo sounding is the technique by which the thickness of ice can be measured by the reflection of a transmitted electromagnetic wave. A summary of radio echo sounding of glaciers was given by Evans (1967). Radio echo sounding from surface vehicles based on Halley Bay was described by Bailey and Evans (1968). More recent work by the British Antarctic Survey was reported in the *Polar Record* (Anonymous, 1968) and by Evans and Smith (1970). Swithinbank (1968) has described earlier airborne sounding in the Antarctic Peninsula.

The 1969–70 season was the first in which a Scott Polar Research Institute Mark 4 radio echo sounder was used. The Mark 4 version is a 35 MHz pulsed radar system similar to the Mark 2 which was used by Swithinbank and Petrie in 1967 and described by Evans and Smith (1969). The instrument measures ice thickness with a resolution of 10 m. and a minimum measurable thickness of about 20 m. The maximum measurable thickness depends on several factors including the temperature of the ice and the nature of the surface and bottom. The system performance of the Mark 4 is greater than that of the Mark 2, having an increased transmitter power and an improved receiver recovery characteristic. These factors increase the maximum and decrease the minimum measurable thickness. In addition, the Mark 4 can automatically annotate the 35 mm. film record with date, time, receiver gain and display parameters.

II. INSTALLATION

THE equipment can be operated either from an aircraft or from a surface vehicle. There was no successful sounding from the surface during the 1969–70 summer because of adverse travelling conditions in George VI Sound where it was hoped to conduct a local survey. The equipment was installed in a DHC-6 Twin Otter aircraft (No. 152) at Adelaide station during December 1969. The equipment console occupied the space of one passenger seat on the right of the cabin (Plate Ia). On the left of the cabin there was an auxiliary fuel tank used to increase the range of the aircraft. The console consisted of the radio echo sounder together with the recording and monitoring oscilloscopes and beneath the console the SFIM flight recorder which was used to record flight parameters for track plotting. The aerial system was modelled on that described by Evans and Smith (1969). It consisted of a folded wire dipole 6 m. long, centred on an impedance-matching unit fixed to the belly of the aircraft. The impedance-matching unit contained a network which allowed the aerial to be fed from a 50 ohm coaxial cable, and also a terminating resistor to load the centre of the dipole. Nylon cord joined the ends of the dipole to the tips of two 1 m. steel aerial masts, which were supplied by DeHavilland Aircraft of Canada, and which extended down from the wing tips (Plate Ib). There was no discernible drop in aircraft performance with this arrangement and the system was mechanically reliable. The 3 dB beam width of the aerial was 20° in the rolling plane. Directivity in the pitching plane was not measured. The gain of the aerial measured by reflection from a calm sea surface was about −10 dB. This rather low figure may be explained by the proximity of the skis and air frame. A conducting surface contains an antiphase image which opposes radiation from an aerial which is less than a quarter wave-length away; consequently, more power is dissipated in the terminating resistor at the expense of the radiated wave. Breakages occurred when this type of aerial was used on a Lockheed Super Constellation in 1967 as reported in the *Polar Record* (Anonymous, 1968), but there were no problems with the slower Twin Otter aircraft. Electrical power for the equipment (28 V, 4 A DC) was obtained from the aircraft's 28 V DC electrical system. The pitot and static air-pressure signals for the SFIM flight recorder were obtained from the standard aircraft pitot tube by means of tee-pieces supplied by DeHavilland. The air temperature was measured by means of a sensing element fitted by DeHavilland in the belly of the aircraft. Directional information was provided by a gyro-stabilized magnetic compass giving a synchro-output signal. The output was converted to a signal suitable for the flight recorder by means of an SE Laboratories synchro-DC converter. The terrain clearance height of the aircraft was obtained from the radio echo record. An intercom system was installed to allow all three crew members (pilot, glaciologist/navigator and radio echo operator) to converse freely.

III. OPERATION AND NAVIGATION

FLIGHT lines were planned in advance, but the absence of weather data for places away from occupied stations usually necessitated in-flight revision. The flight duration was generally limited by factors such as the uncertainty of terminal weather or of communications rather than by the endurance of the aircraft.

Depending upon loading and altitude, maximum endurance was about 5 hr. Most flights lasted between 2 and 4 hr., representing a maximum range of about 900 km.

It was usual to fly at 1,000 m. above the terrain, this altitude being a good compromise between loss of surface echo when the aircraft was low and loss of bottom echo due to confusion with echoes from distant oblique surface features when the aircraft was high. The surface echo was lost if the transient signals caused by the transmitted pulse had not decayed to a sufficiently low level by the time that the surface echo returned. The critical level depended upon the receiver gain in use. When bottom echoes were strong, the receiver gain would be reduced to make it insensitive to the transient signals. This allowed the surface to be resolved if the aircraft was flying at 500 m. terrain clearance. In general, the lower terrain clearance was only required when the surface was rough or badly crevassed and oblique echoes from the surface obscured the bottom echo. When conditions were favourable, as they were over smooth ice shelves, it was possible to fly at 2,500 m. in the interests of fuel economy.

One of the duties of the glaciologist/navigator was to note, whenever possible, the position of the aircraft on a map, using visual recognition of features close to the track of the aircraft. At the same time, a mark was made on the flight-recorder trace to allow correlation with flight parameters and the radio echo record. Maps published by the Directorate of Overseas Surveys at scales of 1 : 200,000 and 1 : 500,000 were used. The accuracy of the available sheets was very variable and in unsurveyed areas positions may be in error by up to 15 km. The flight-recorder data were first converted into air speed and compass heading. The fixes together with the flight-recorder data and the radio echo record were then converted to punched paper tape and used to compute the track of the aircraft. The vector obtained was used to increment the aircraft's position from each fix to the instant of the next fix. The difference between the "dead-reckoning" position and the new fix position was subtracted from the computed track proportionally with time since the last fix. In this way the computed track passed through each fix position but was controlled in detail by the flight-recorder data. The track obtained was therefore correct only in relation to the available mapping. The misclosure of the dead-reckoning track was due to a combination of wind drift and errors in measurement of the flight parameters. The absolute distance depended on the time between fixes, but expressed as a rate of drift the misclosure was typically 5 m. sec.$^{-1}$. The magnitude of the error in the corrected track depended upon the frequency of fixes, which in turn depended upon the abundance of mapped surface features. In areas such as the centre of the Antarctic Peninsula plateau and the centre of the Larsen Ice Shelf which lack mapped surface features, the computed track may be in error by more than 10 km. In well-mapped areas such as George VI Sound, the computed track may be expected to be within 1 km. of the actual track as it would appear on the available mapping. The photographic records produced by the radio echo sounder (35 mm. film) and the flight recorder (60 mm. paper) were processed at Adelaide station.

IV. RESULTS

FLIGHTS were made from both Adelaide station and Fossil Bluff. They extended over all accessible areas between lat. 66° and 74°S. and between long. 60° and 75°W. Fig. 1 shows flights made during the work reported here together with those on which bottom echoes were obtained during the 1966–67 season. It can be seen that tracks included the Larsen Ice Shelf, a large iceberg in the Weddell Sea, the Wordie Ice Shelf (where some detail is omitted in Fig. 1), Wilkins Sound, George VI Sound, the Fuchs Ice Piedmont, the mainland plateau region, and the ice-covered Biscoe Islands.

On Fig. 1 an ice rise is mapped to the east of Kenyon Peninsula in lat. 68°30′S., long. 61°W. This is an ice-covered island which was sounded and appears similar to Hearst Island to the south. Wilkins (1929, p. 374) reported seeing an ice-covered island somewhere in this area during one of his early flights, but he was uncertain of his position at the time. Ronne (1948, p. 366) flew over the area in good visibility in order to check Wilkins' observation but he failed to see it and must have flown to the south. He suggested that Wilkins was deceived by a low cloud formation on the ice shelf but the radio echo profile of the ice rise in Plate IIa shows that Wilkins was correct.

Two giant icebergs in the Weddell Sea have been visible on ESSA satellite photographs since October 1967 when they were just off the coast in long. 7°W. Swithinbank (1969) traced their progress to long. 40°W. and suggested their origin in the tongue of the Amery Ice Shelf which calved in December 1963 from a position in long. 73°E. and was sighted at intervals up to spring 1966, when it divided into two roughly equal parts while in long. 45°E. By January 1970, the larger of the two icebergs was on the west

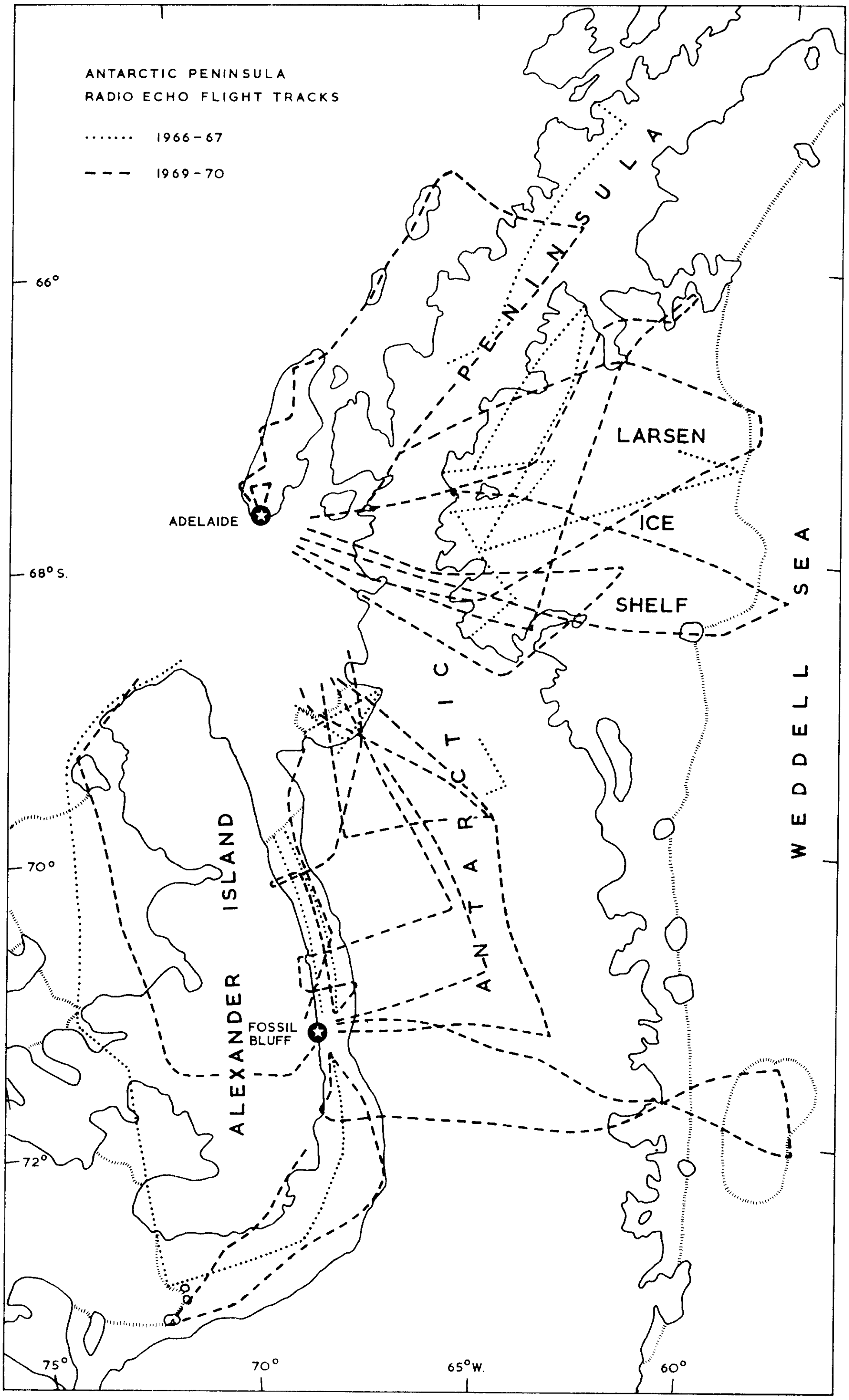

FIGURE 1
Flight tracks of the 1969–70 radio echo sounding work together with parts of the 1966–67 tracks where bottom echoes were obtained.

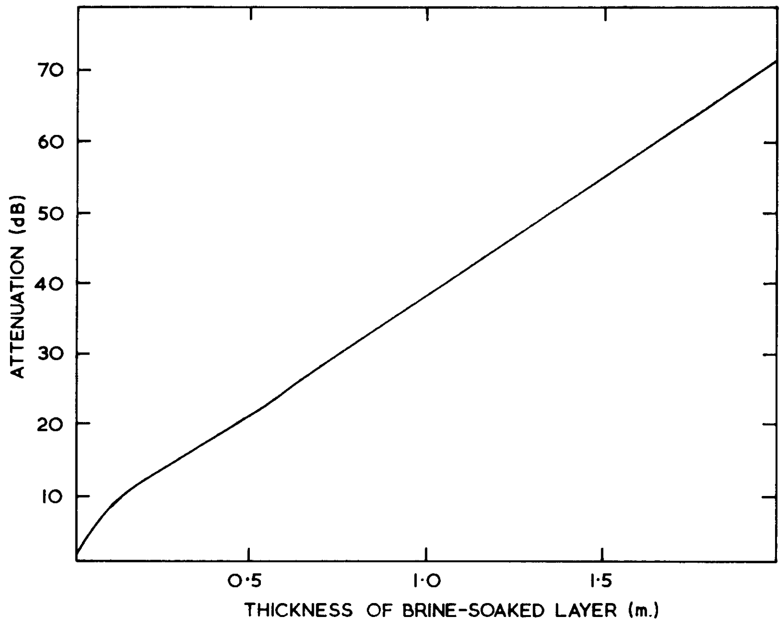

FIGURE 2

The attenuation of a 35 MHz wave passing through a brine-soaked layer in firn snow of density 0·8 g. cm.$^{-3}$ as a function of the layer thickness. Note that in radio echo sounding the pulse will traverse the layer twice and the net attenuation will be twice the value indicated. A conductivity of 3 ohm^{-1} m.$^{-1}$ has been assumed for the brine.

side of the Weddell Sea in lat. 72°S., long. 59°W., and was radio echo sounded during a flight from Fossil Bluff. Ice thicknesses were between 200 and 250 m. which agree with estimates of the thickness of the Amery Ice Shelf (personal communication from W. Budd, 10 March 1970). More interesting is the attenuation of the bottom echo, which was between 6 and 10 dB per 100 m. path in ice. This is too high for pure ice but agrees with Budd's measurement of 7·5 dB per 100 m. made on the Amery Ice Shelf. There is no evidence on the radio echo of a brine layer close to sea-level which could explain the high attenuation, but it might be explained by the origin of the Amery Ice Shelf itself. It is fed by the fast-moving Lambert Glacier which is very disturbed where it enters the ice shelf. It is possible that brine is able to well up in rifts in such a way as to soak the bulk of the ice, which then consolidates to form a smooth ice shelf while retaining its brine contamination. The rates of movement and snow accumulation

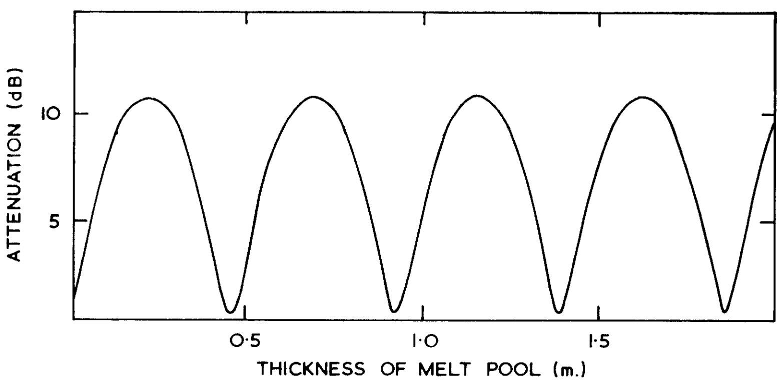

FIGURE 3

The attenuation of a 35 MHz wave passing through a layer of melt water on the surface of solid ice as a function of the layer thickness. The conductivity of the melt water has been assumed to be 2×10^{-4} ohm^{-1} m.$^{-1}$, although the shape of the graph does not vary rapidly with the conductivity of the melt water below 10^{-2} ohm^{-1} m^{-1}.

over the Amery Ice Shelf as reported by Budd (1966) are such that ice which originated in Lambert Glacier might be expected to represent a substantial proportion of the ice-shelf thickness at the ice front. This could explain the high attenuation observed in the ice shelf, and the same attenuation found in the iceberg lends support to the theory of its origin.

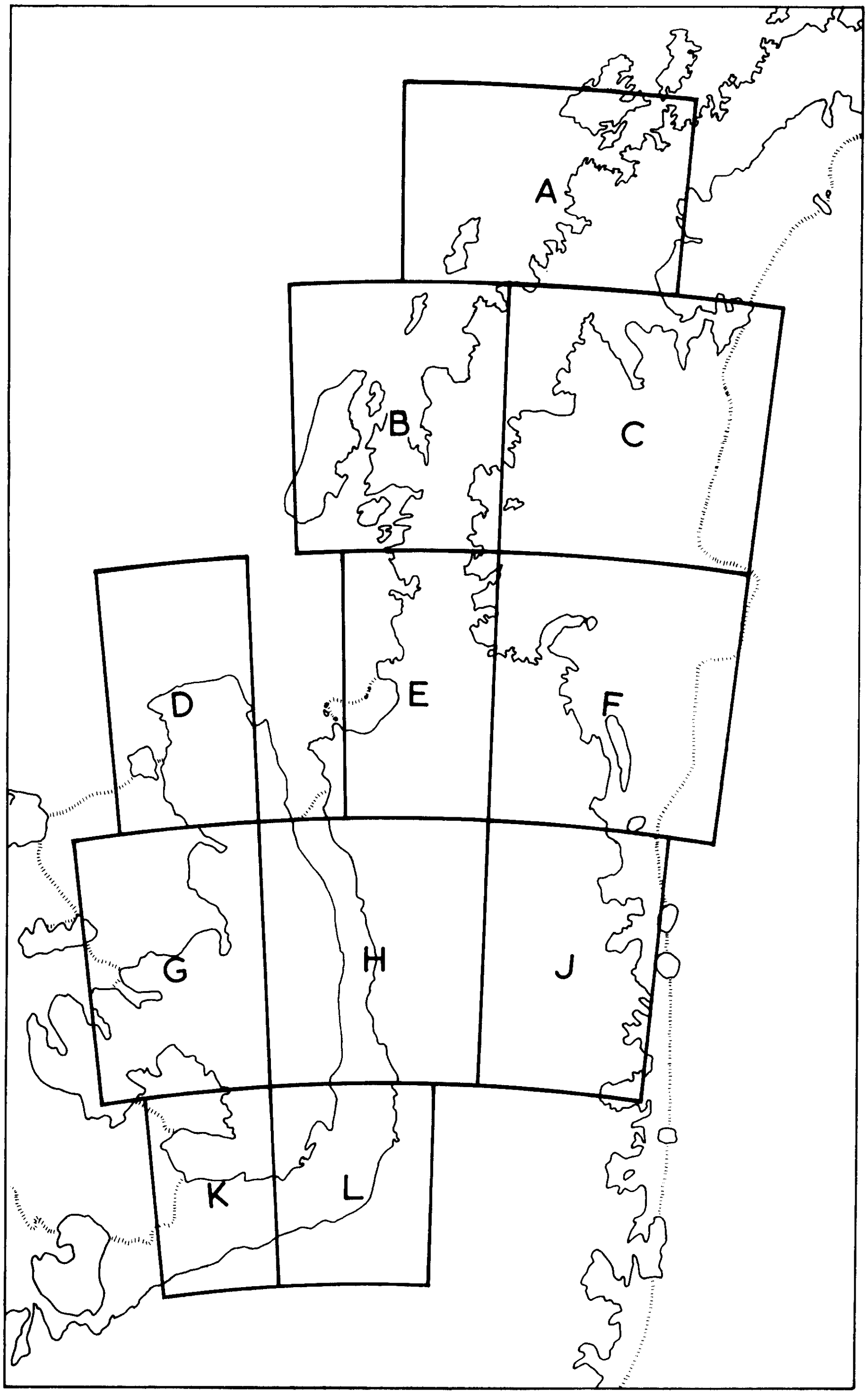

FIGURE 4

An index of charts A to L. These charts show ice thicknesses in metres obtained by Swithinbank in 1966–67 and by the author in 1969–70. Some details are omitted from charts E and H on the Wordie Ice Shelf and in George VI Sound. These areas appear at a larger scale on charts M and N, respectively.

Soundings were most successful on ice shelves. On the Larsen Ice Shelf, soundings were almost continuous except for a few scattered areas where echoes were not obtained. These areas were invariably in the vicinity of rifts in the ice shelf and usually coincided with a reflecting layer at about sea-level (Plate IIb). This situation predominated south of lat. 68°30′S. Swithinbank (1968) suggested that brine infiltration at sea-level is the reason for the absence of a bottom echo and the presence of an echo at sea-level in these areas. Fig. 2 shows the attenuation to a transmitted wave at 35 MHz due to a layer of brine-soaked snow in otherwise dry snow having a density of 0·8 g. cm.$^{-3}$. It may be seen that for a layer 2 m. thick the attenuation would be 73 dB. Both the forward and the reflected pulse suffer this attenuation and a total attenuation of 146 dB would invariably reduce the echo strength to below the receiver noise level. Such brine layers have been observed in the Ross Ice Shelf near Scott Base by Stuart and Bull (1963), in the Lazarev Ice Shelf by Dubrovin (1962) and in the Brunt Ice Shelf (personal communication from R. H. Thomas).

The surface of the Wordie Ice Shelf was very disturbed. Severe crevassing often prevented successful sounding because oblique echoes from the surface obscured the bottom echo, but some measurements were possible and thicknesses from 150 m. to more than 400 m. were in good agreement with those found by C. W. M. Swithinbank and D. L. Petrie, who studied this ice shelf in more detail. No normal bottom echoes were obtained on the Wordie Ice Shelf west of long. 67°50′W. either by the author or by Swithinbank. It appears that this meridian divides the crevassed eastern part from the rifted western part. The distinction between rifts and crevasses is that rifts extend to the bottom of an ice shelf and allow brine to well up and infiltrate the ice at sea-level, thus preventing sounding to the bottom.

In Wilkins Sound, bottom echoes were obtained in relatively few places. Elsewhere, a reflecting layer at sea-level appeared and no bottom echo was received. The apparent thickness changed so abruptly from about 200 m. to about 50 m. without any detectable change in surface elevation that, if the ice is in hydrostatic equilibrium, the thickness change cannot be real and once again it must be supposed that brine has infiltrated at sea-level.

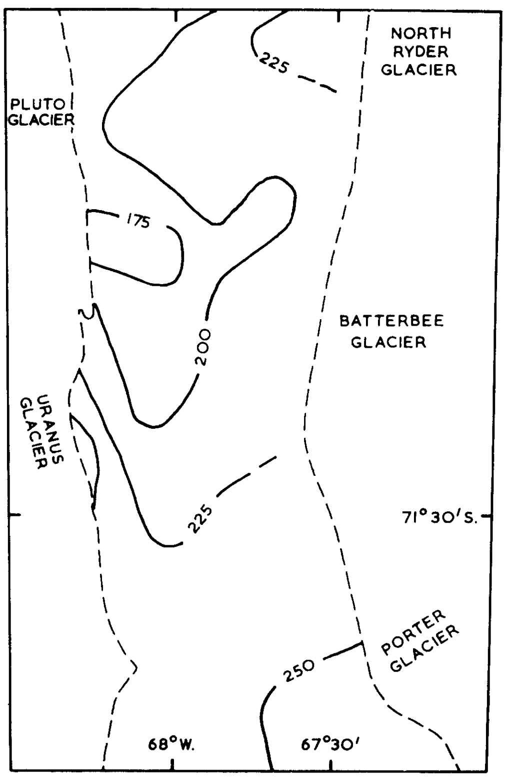

FIGURE 5

Contours of ice thickness in the Fossil Bluff area of George VI Sound. The contour interval is 25 m. and the contours are derived from the appropriate chart. The validity may be deduced from the density of points on the chart.

In spite of extensive surface melt-water pools on George VI Sound, no difficulty was encountered in measuring thicknesses over the whole ice shelf up to a maximum of almost 500 m. near lat. 73°S., long. 70°W. Attenuation of the radio echo pulse by a melt pool depends critically on the depth of the pool (Fig. 3). The melt pools freeze each winter and except in a few places they are only about 0·5 m. deep (personal communication from A. C. Wager). It may be seen from Fig. 3 that the attenuation due to this thickness of melt water is typically 7 dB in each direction. An additional attenuation of about 14 dB due to water would not normally prevent detection of the bottom echo on a floating ice shelf. Measurements of the received echo strength indicated an attenuation of 3·8 dB per 100 m. in lat. 70°15′S., long. 68°30′W. and 2·9 dB per 100 m. in lat. 73°S., long. 70°W. These measurements are characteristic of an average ice temperature of about −5° C in the north and −10° C in the south (Robin and others, 1969, p. 476).

The relatively high mean annual temperature of the Fuchs Ice Piedmont on Adelaide Island explains the difficulty in measuring ice thickness there. The only reliable measurements obtained were within a few kilometres of the southern end of the island in the vicinity of Adelaide station. Here, measurements up to 250 m. indicated that the bedrock inland from the station was close to sea-level for at least 5 km. The echo strengths obtained indicated an attenuation of 4·8 dB per 100 m. path in ice, corresponding to an average ice temperature of about −2° C. The mean annual air temperature at this point is about −6° C.

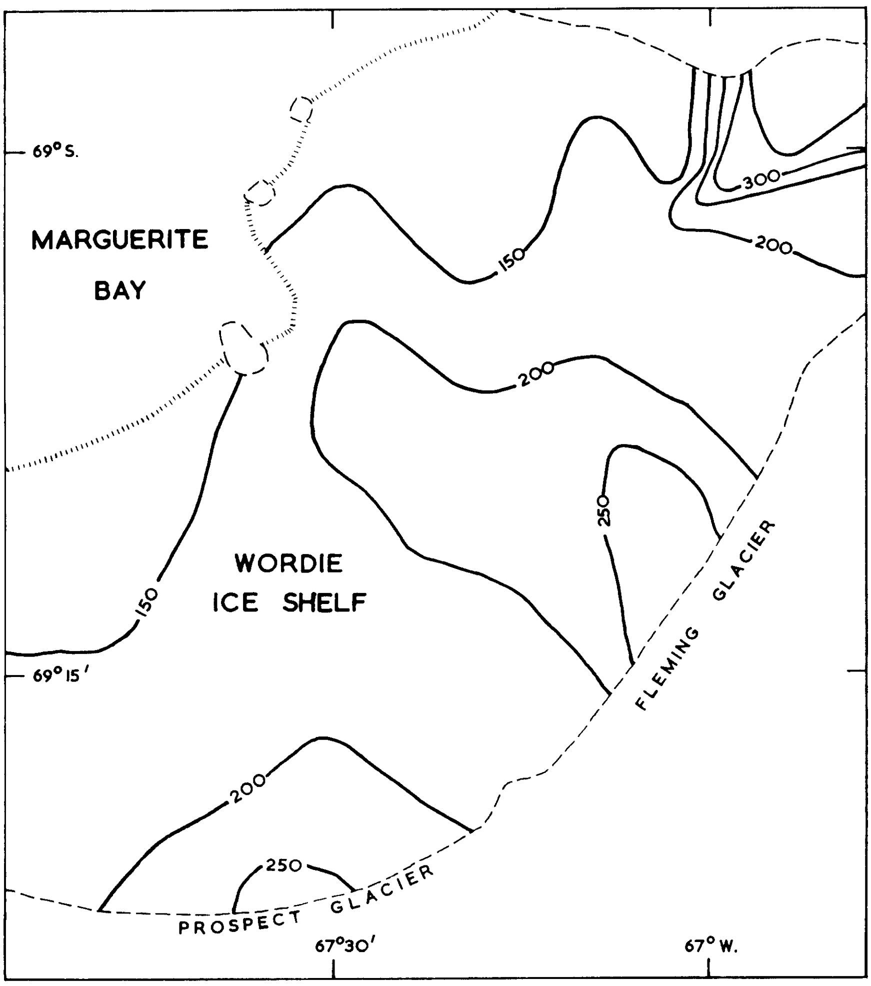

FIGURE 6

Contours of ice thickness on the Wordie Ice Shelf. The contour interval is 50 m. The effects on ice thickness of Fleming Glacier and Prospect Glacier may be clearly seen. The thickening in the north-east corner is due to Hariot Glacier. (Note also the comments regarding Plate IIb.)

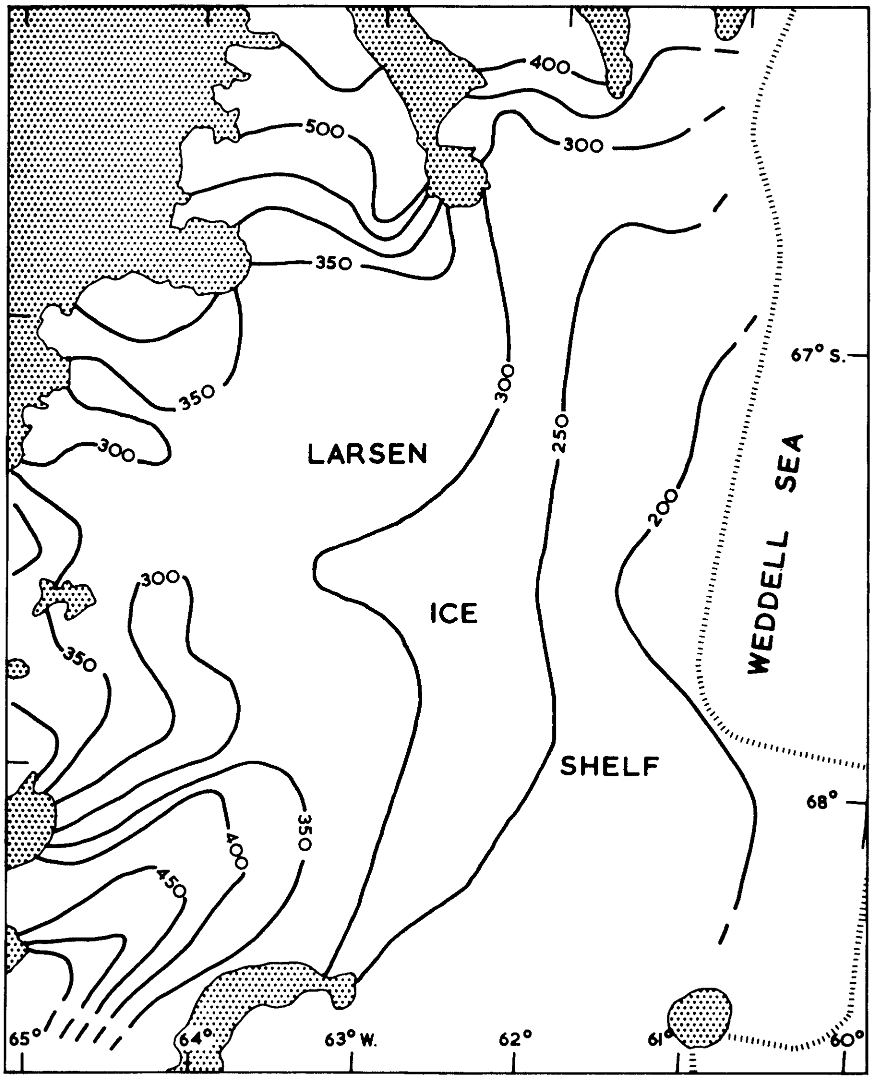

FIGURE 7

Contours of ice thickness on the Larsen Ice Shelf. The contour interval is 50 m. A number of glaciers can be seen to have a pronounced effect on the ice thickness. Perhaps the most conspicuous is the thick area in the south-west where the ice from Mercator Ice Piedmont enters the ice shelf. It may be that this large stream is responsible for the bulge in the Larsen ice front in lat. 68°S. being constrained in the south by the ice rise in lat. 68°30′S.

The 10 m. temperature is likely to be higher than the mean annual temperature because of some surface melting and the bottom of the ice is probably at the melting point.

The Biscoe Islands can be expected to have similar properties to the Fuchs Ice Piedmont, and a similar difficulty was experienced in receiving bottom echoes. Nevertheless, thicknesses up to 270 m. were recorded on the largest member of the group, Renaud Island.

Linton (1964) suggested that the subglacial topography of the Antarctic Peninsula plateau is essentially the pre-glacial surface having "smooth aspect and modest relief" uplifted to about 1,200 m. a.s.l. Radio echo measurements indicate that his figure of 1,200 m. a.s.l. is typical for the bedrock beneath the plateau. However, there appears to be somewhat more relief than Linton expected (Plate III). Either the residual relief of the peneplain from which the plateau was derived was greater than the 300–500 m. which Linton suggested or subsequent erosion has had more effect on the plateau region than he supposed. The greatest reliable ice thickness measured was 1,630 m. in lat. 70°S., long. 67°W.

The data are presented as 14 ice-thickness charts which are indexed in Fig. 4. Ice thicknesses obtained by Swithinbank and Petrie in 1966–67 and by the author in 1969–70 are marked in metres. A velocity of 169 m. μsec.$^{-1}$ for radio waves in ice has been used to calculate the ice thickness. Strictly, this only applies to solid ice and it is usual to add a correction for the higher velocity in the less dense upper layers. Swithinbank added 5 m. to the calculated thickness for the 1966–67 data except where solid ice was expected. The author has added 10 m. to the calculated thickness for all the 1969–70 data. The systematic difference between the two groups of data has been compared at all the common points and was found to be less than the equipment resolution. Each of the charts A to L covers 2° of latitude and up to 5° of longitude. Some soundings on charts E and H are omitted and included at a larger scale on charts M and N, respectively. In addition, contours of ice thickness have been deduced from these data for George VI Sound (Fig. 5), the Wordie Ice Shelf (Fig. 6) and Larsen Ice Shelf (Fig. 7). The reliability of these contours should be judged by reference to the density of data points for the appropriate chart.

V. ACKNOWLEDGEMENTS

THE author wishes to thank the members of Adelaide station and Fossil Bluff for help with the field work, particularly A. C. Wager, who did most of the navigation, and also Dr. S. Evans and Dr. C. W. M. Swithinbank of the Scott Polar Research Institute for help in preparing for the field season and in preparing this paper. He is indebted to R. H. Thomas for providing a number of references.

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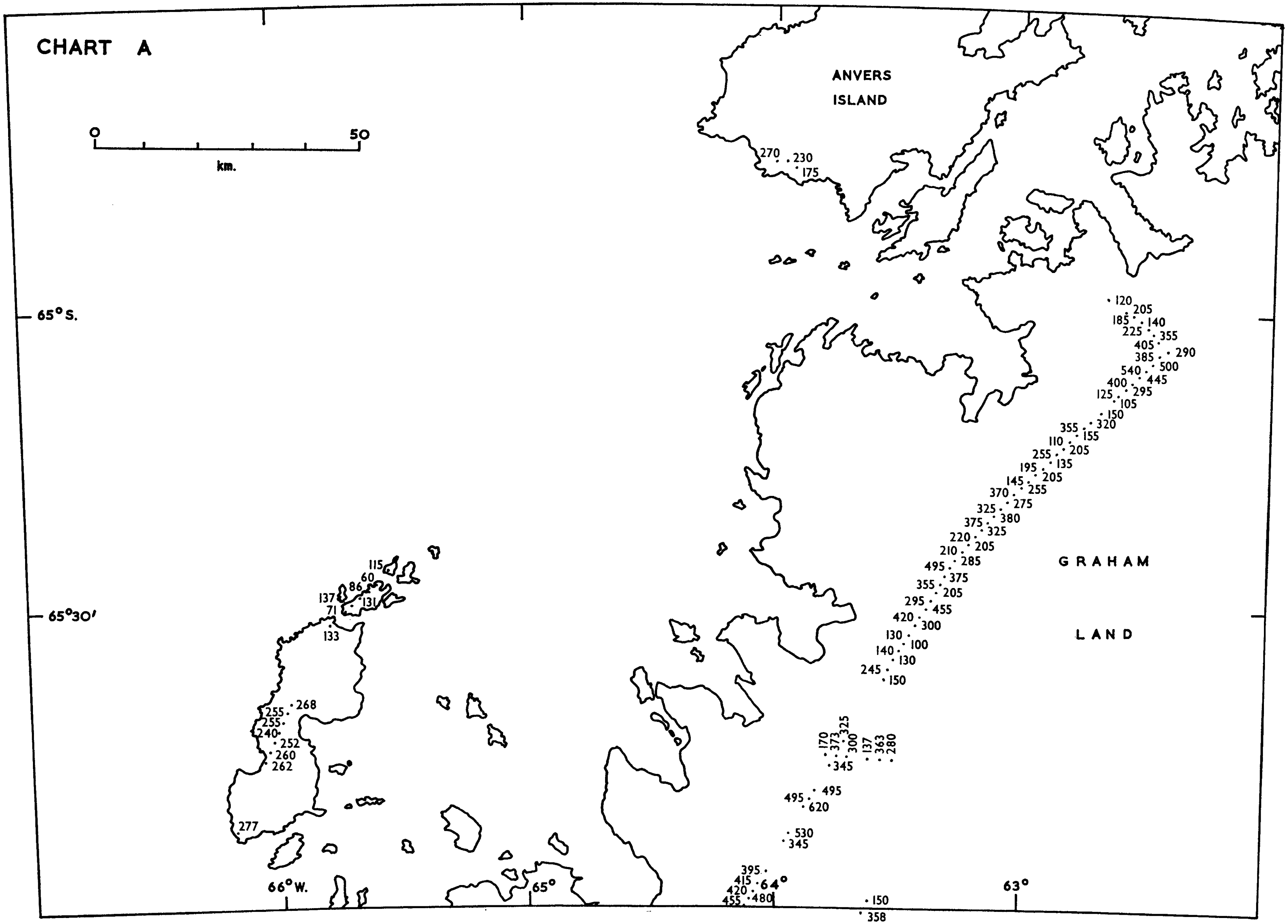
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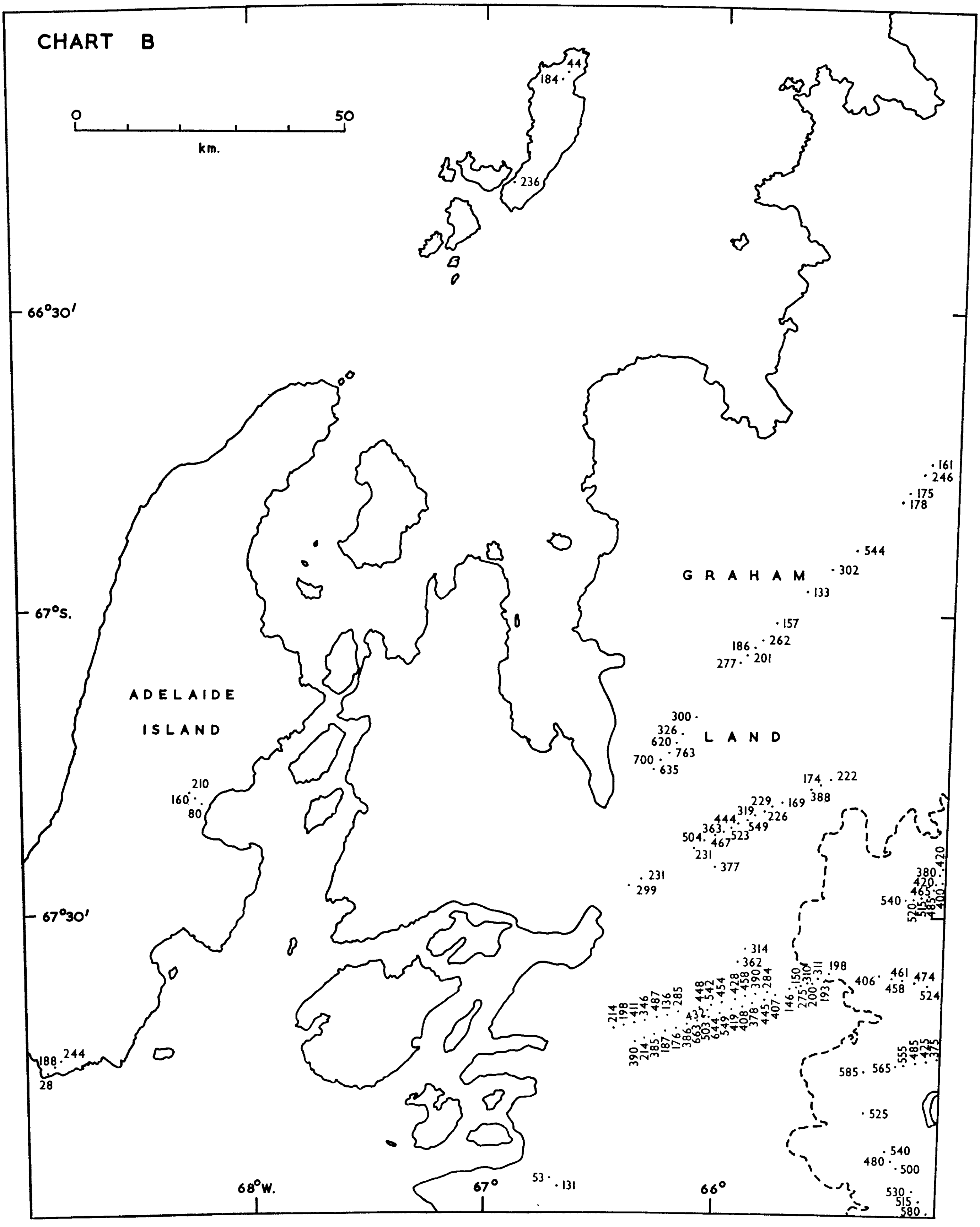

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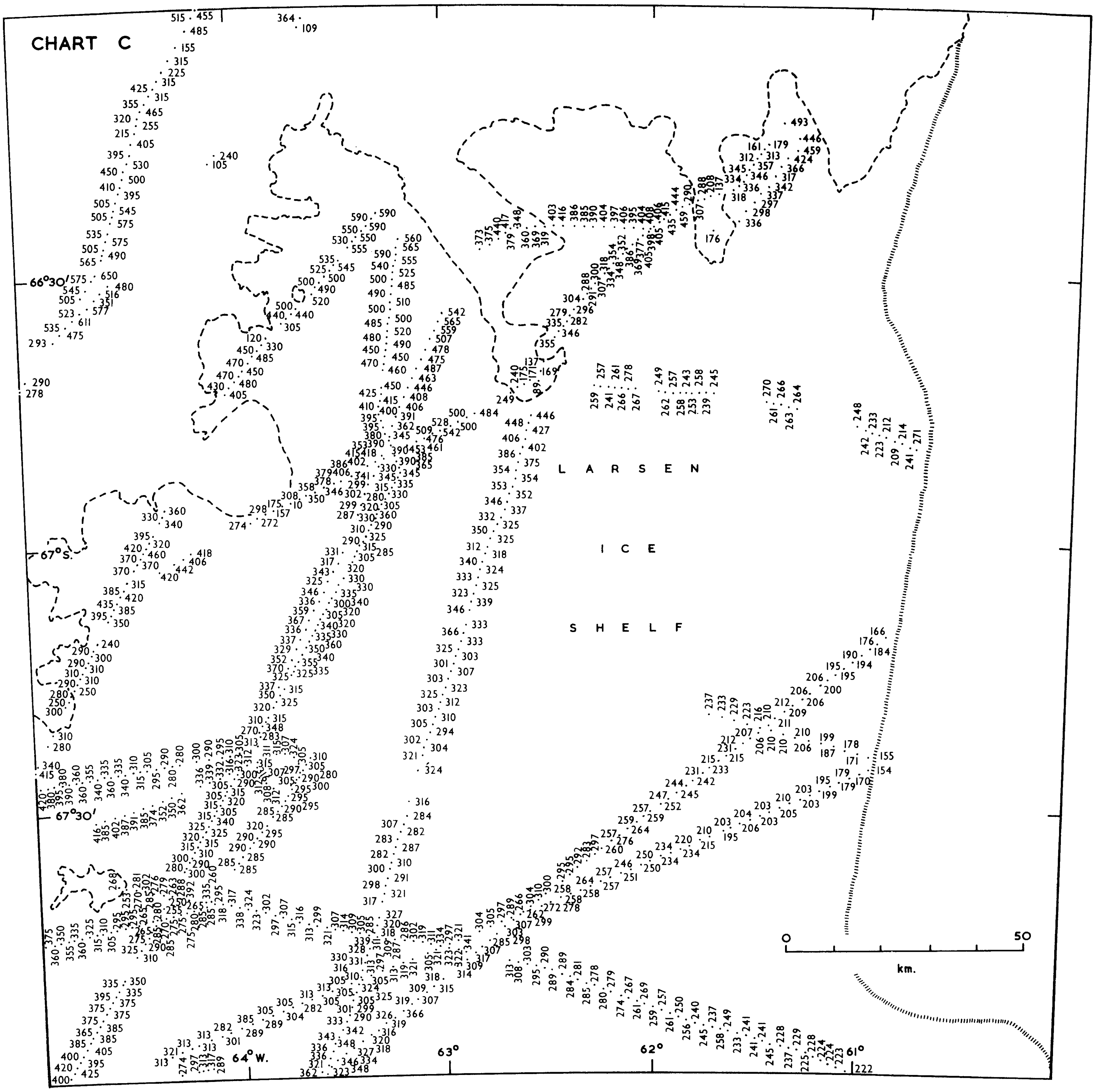
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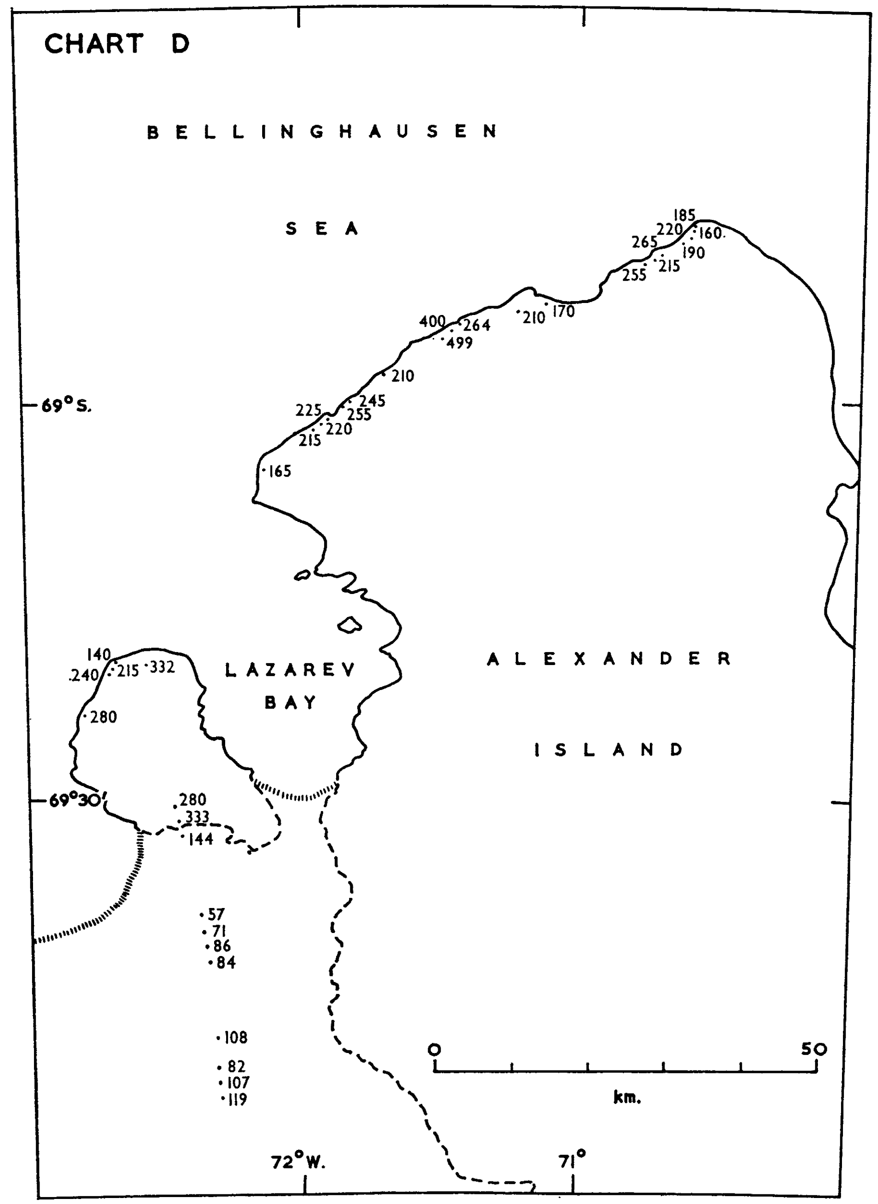
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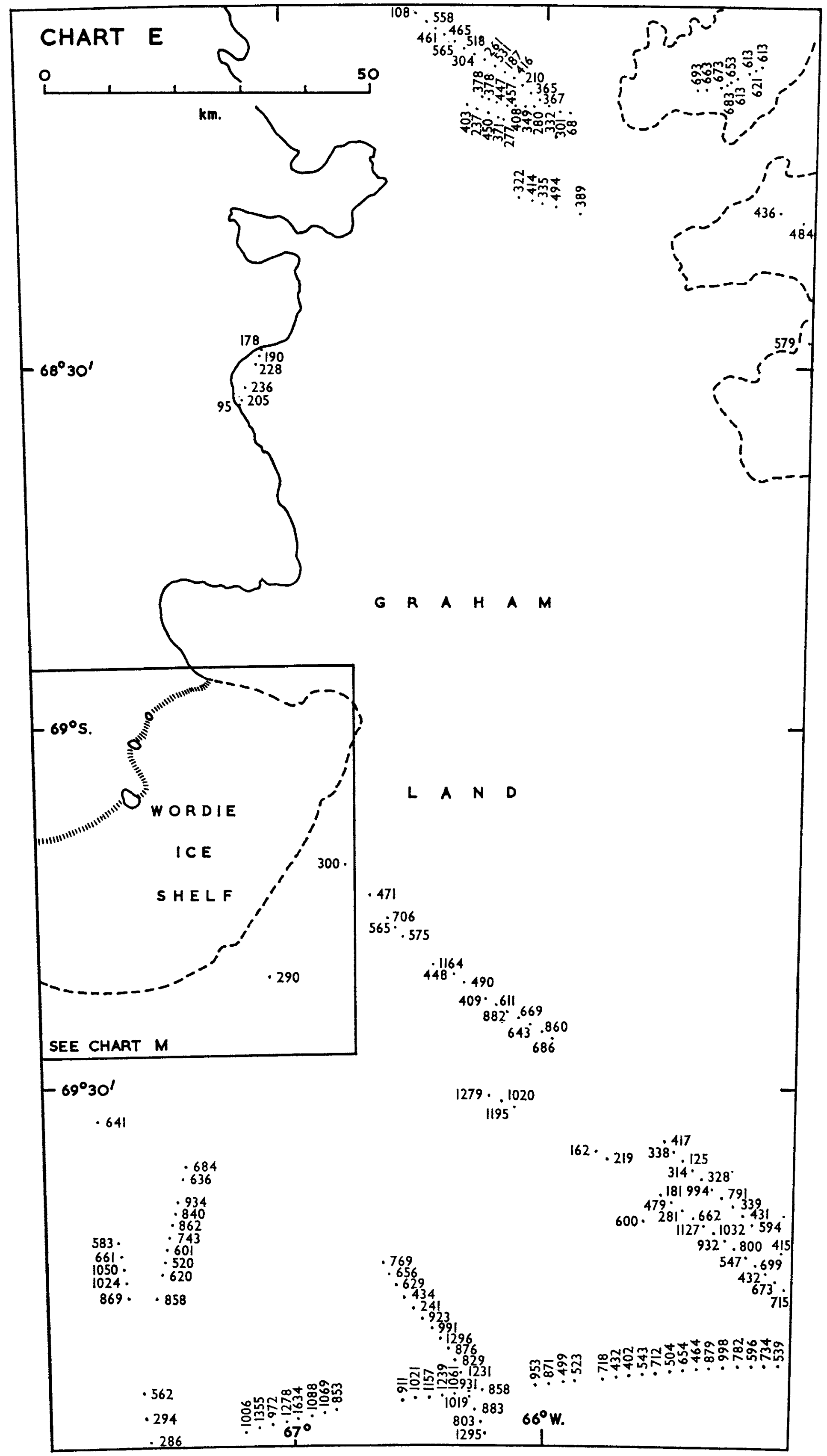
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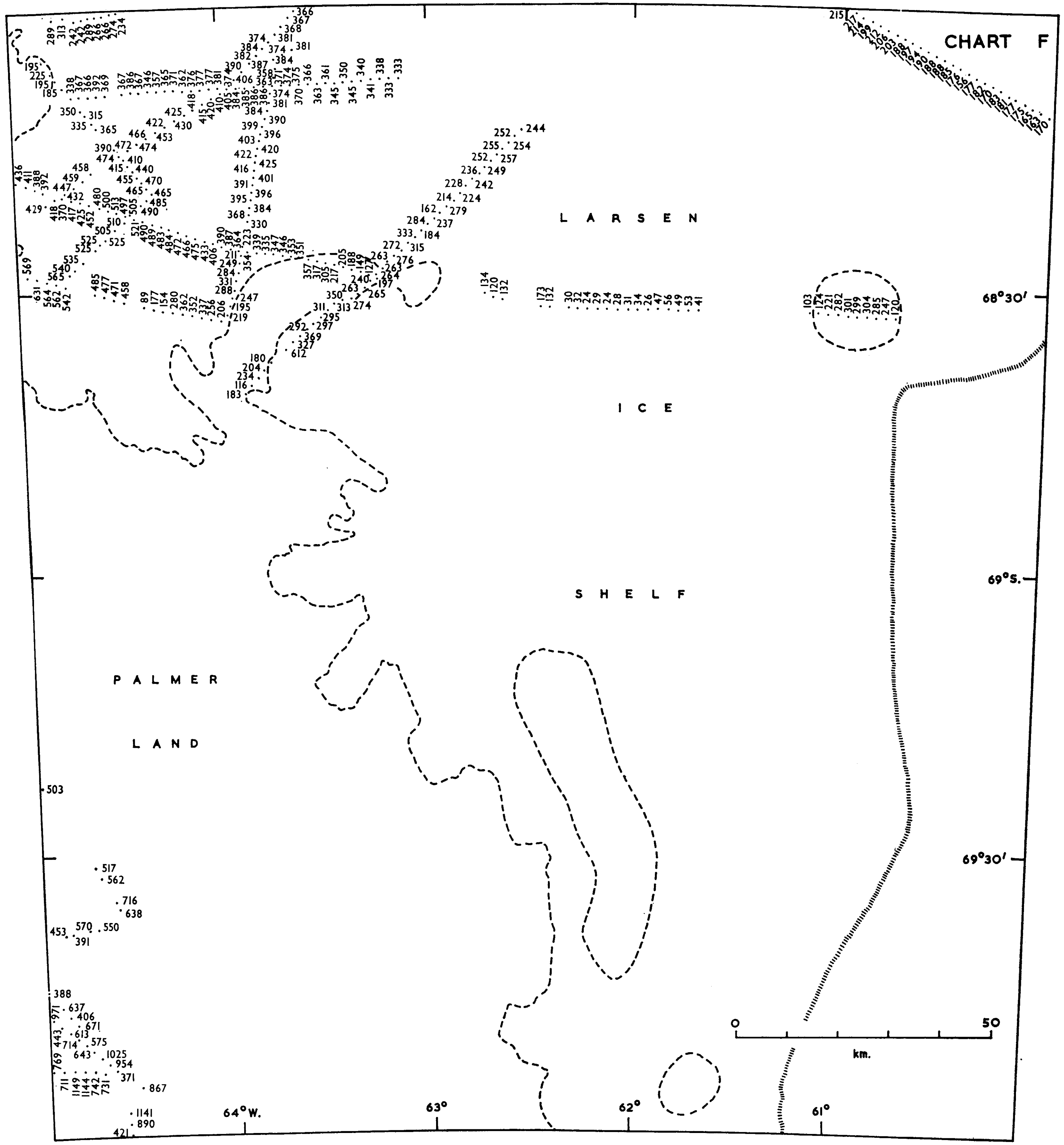
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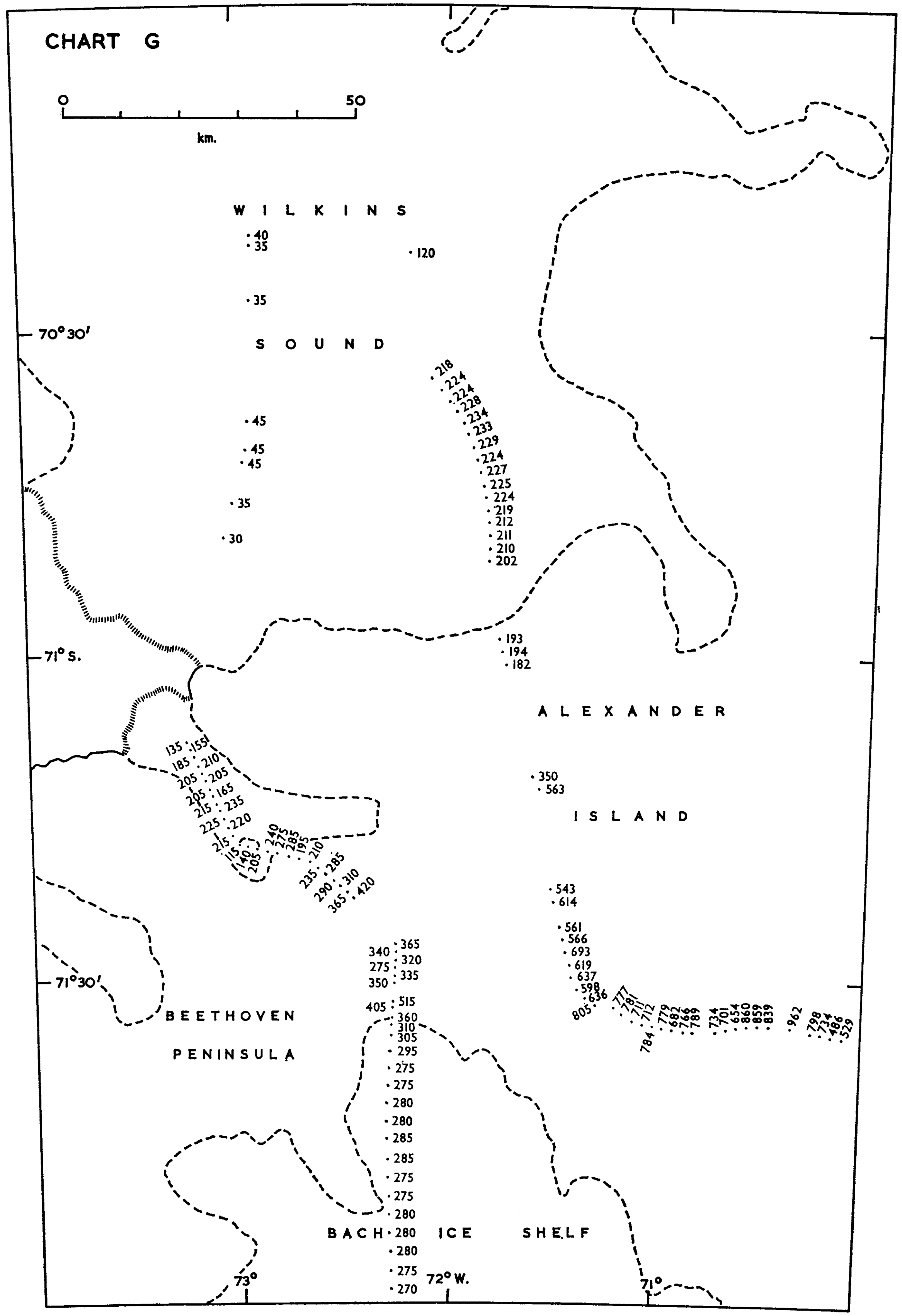
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BEETHOVEN PENINSULA
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72° W.
71°

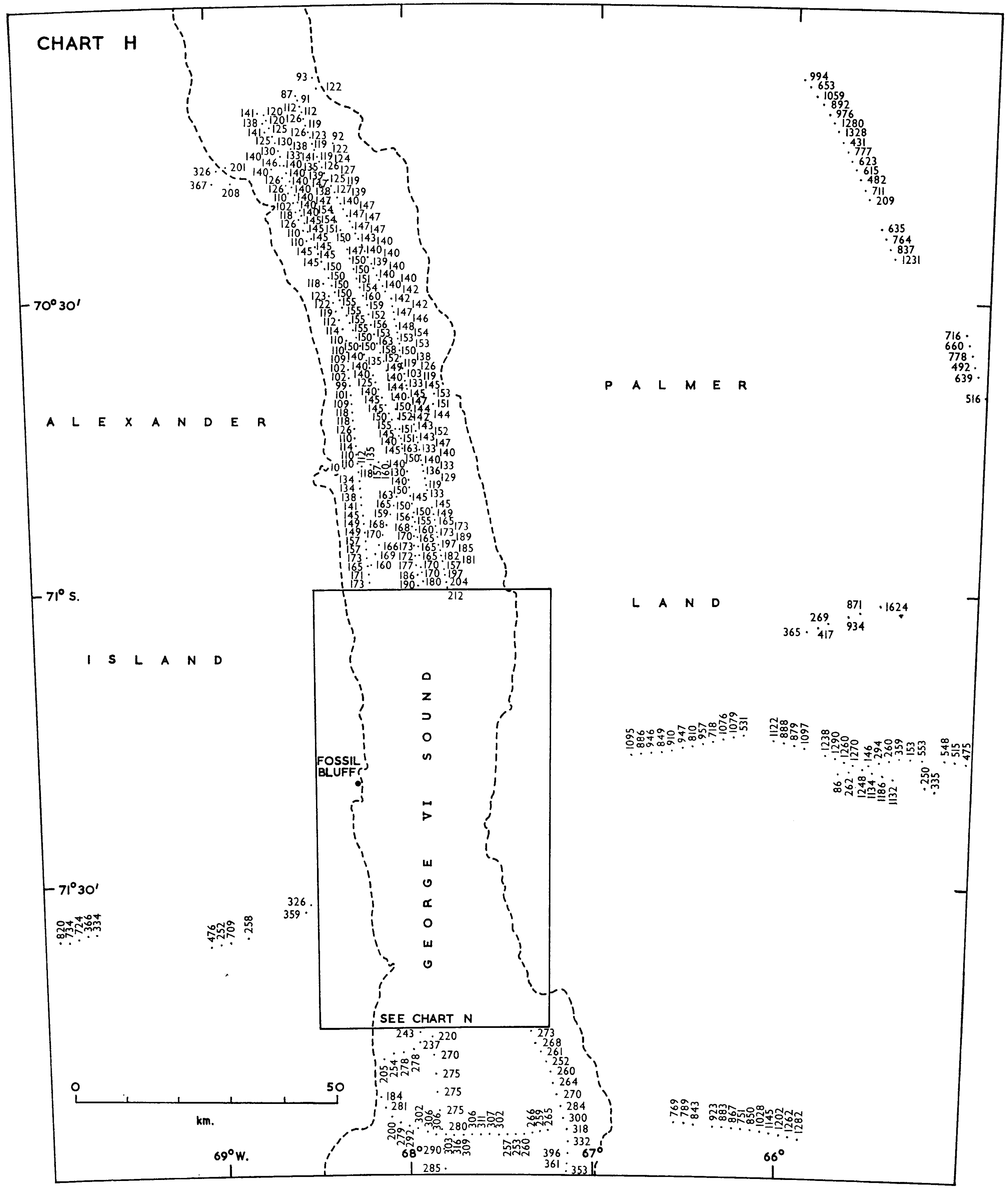


CHART H
ALEXANDER
ISLAND
PALMER
LAND
GEORGE VI SOUND
FOSSIL
BLUFF
SEE CHART N
70°30′
71° S.
71°30′
69°W.
68°
67°
66°
0
50
km.

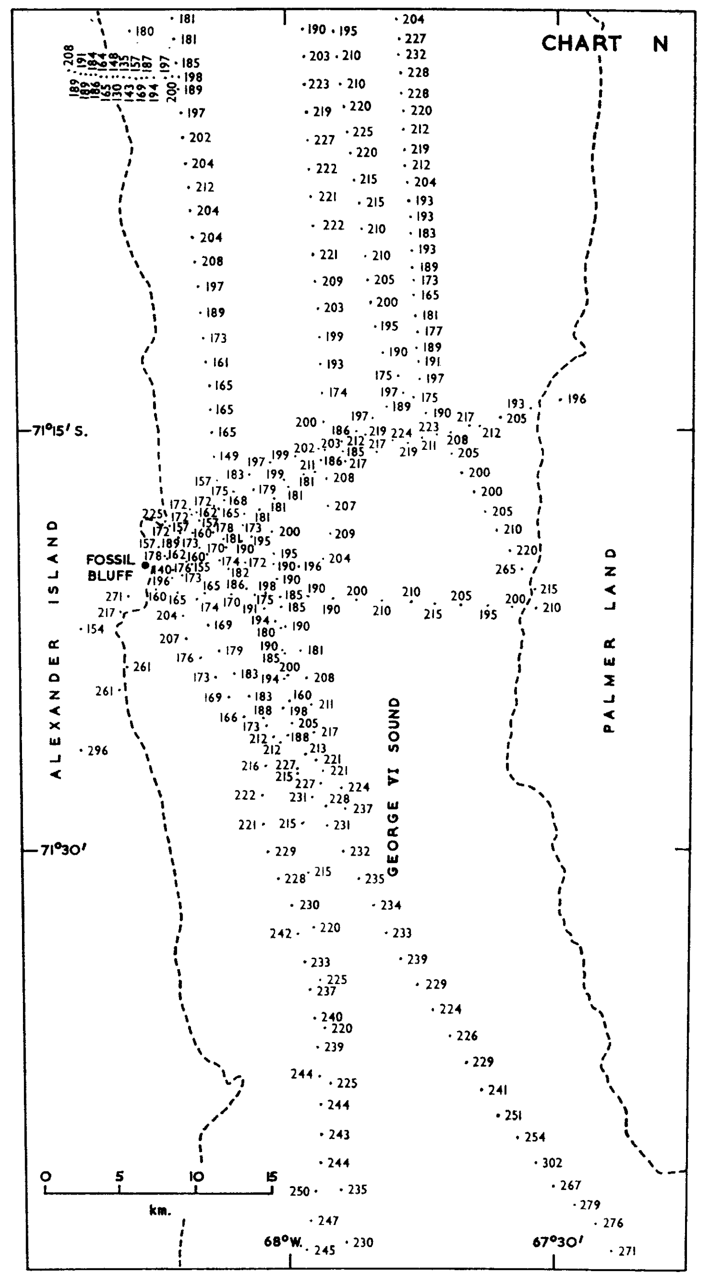


CHART N
71°15′ S.
71°30′
68°W.
67°30′
ALEXANDER ISLAND
PALMER LAND
GEORGE VI SOUND
FOSSIL BLUFF
0 5 10 15
km.

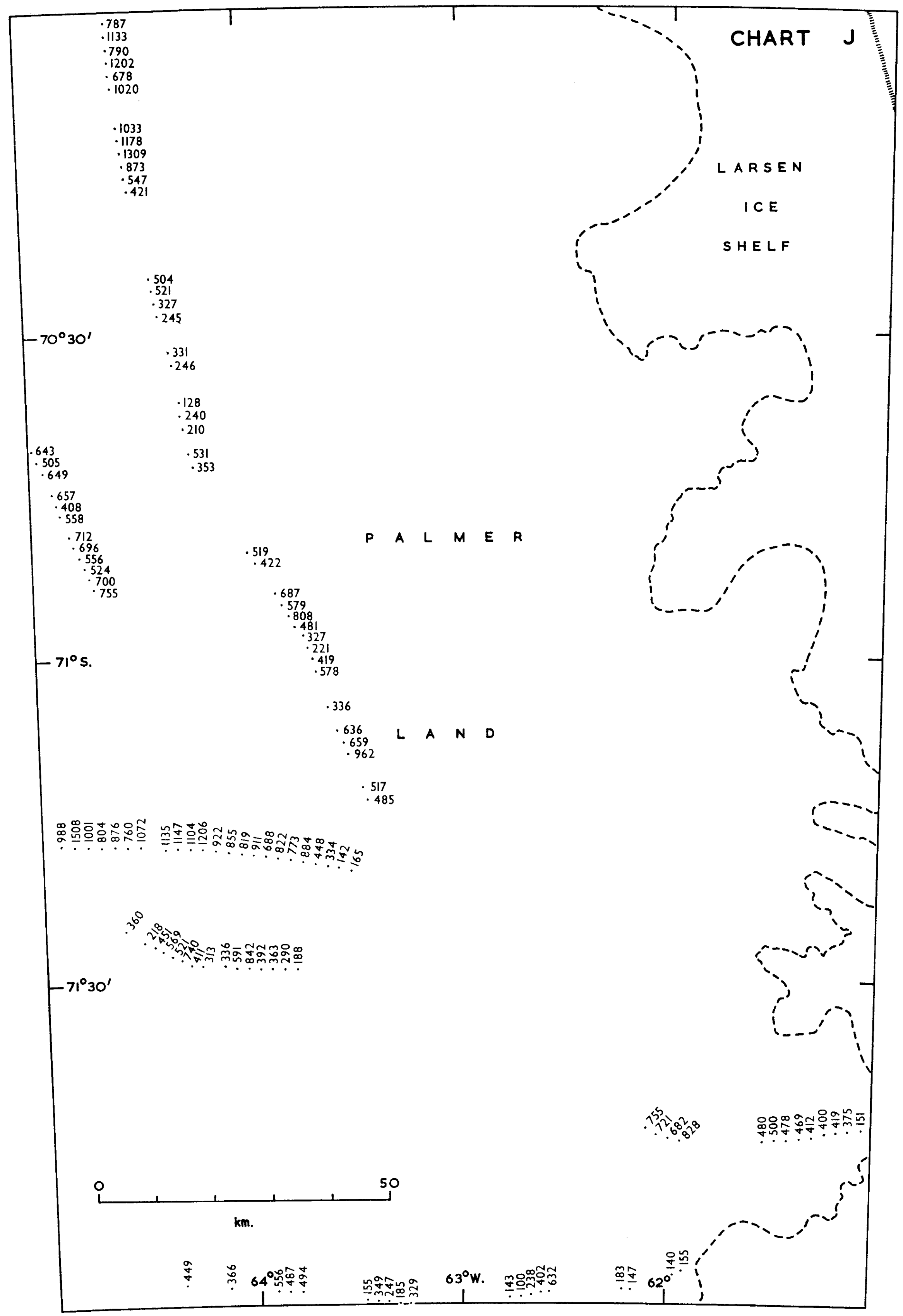


CHART J
LARSEN
ICE
SHELF
PALMER
LAND
70°30′
71° S.
71°30′
64°
63°W.
62°
0
50
km.

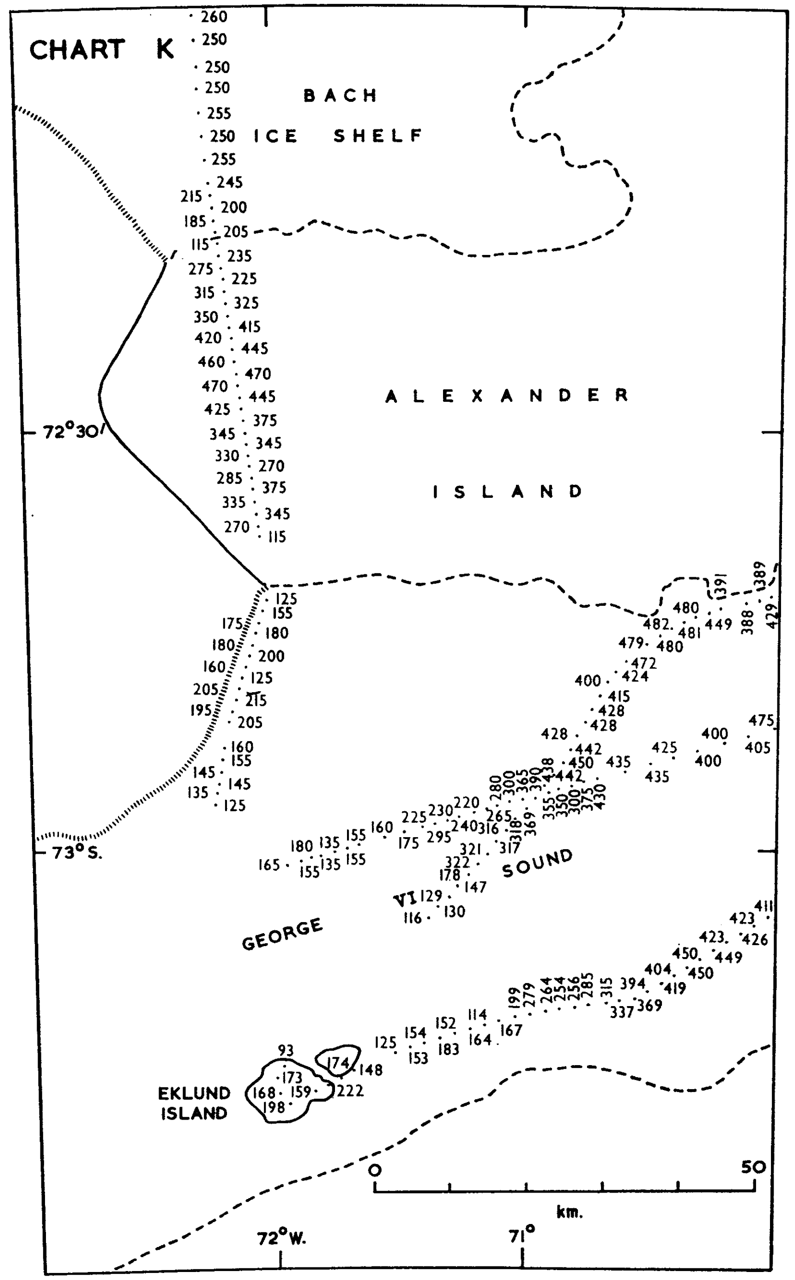


CHART K
BACH
ICE SHELF
ALEXANDER
ISLAND
GEORGE
VI
SOUND
EKLUND
ISLAND
72°30'
73°S.
72°W.
71°
0
50
km.

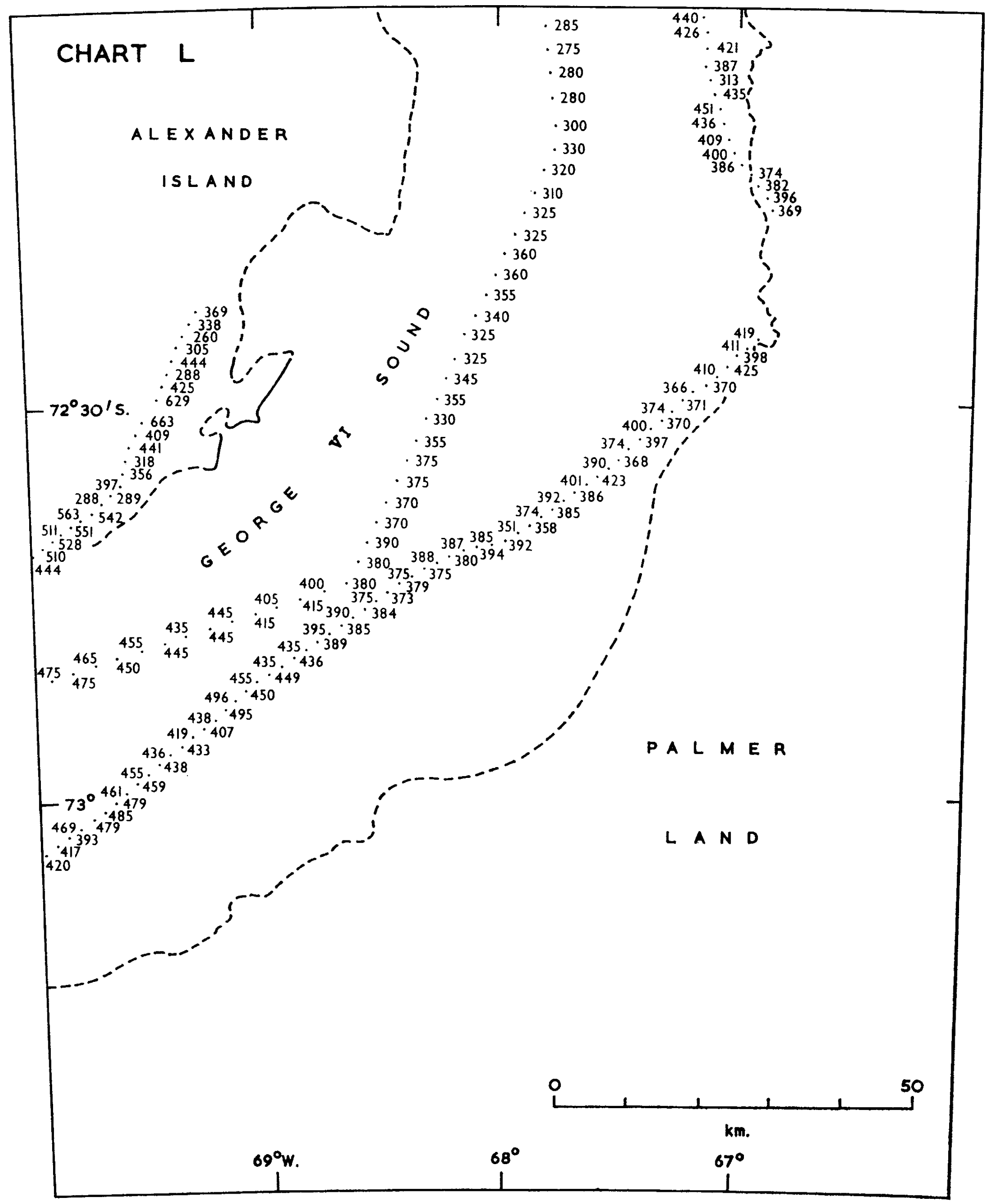


CHART L
ALEXANDER
ISLAND
GEORGE VI SOUND
PALMER
LAND
72°30'S.
73°
69°W.
68°
67°
0
50
km.

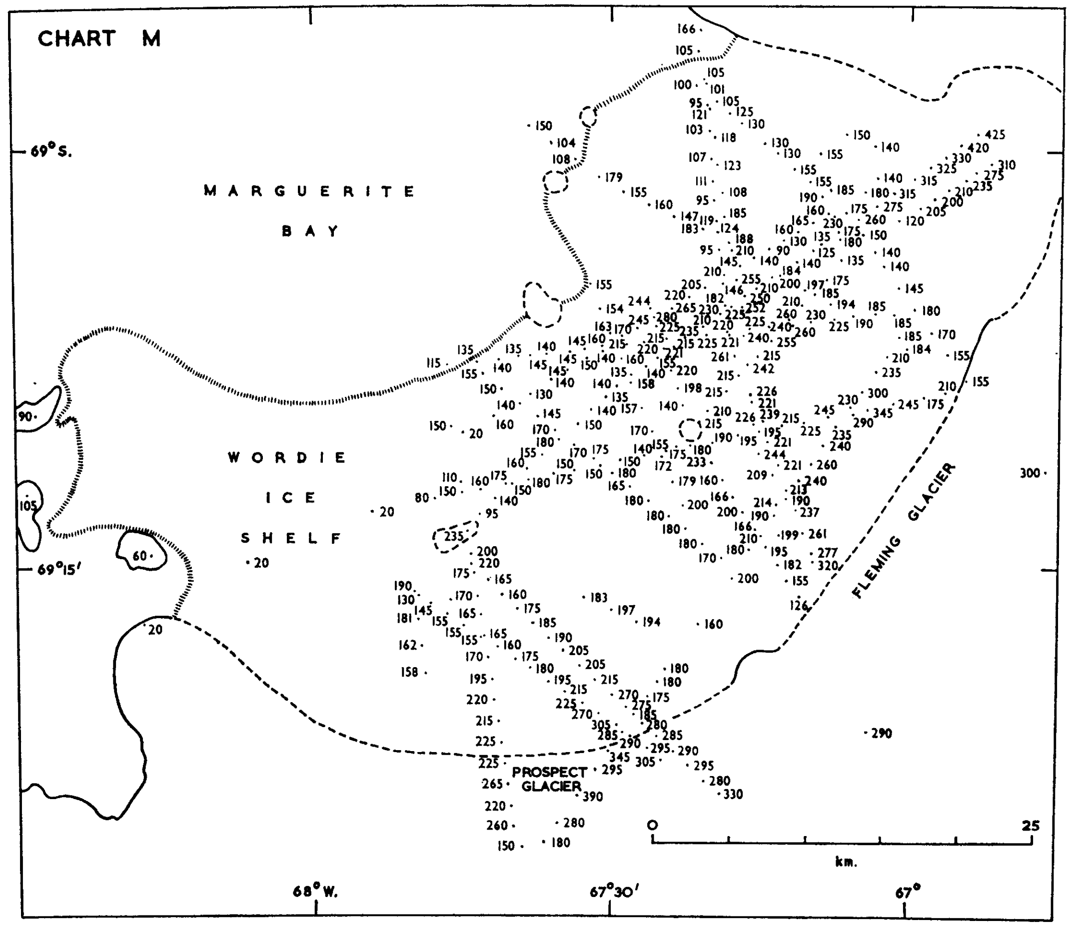
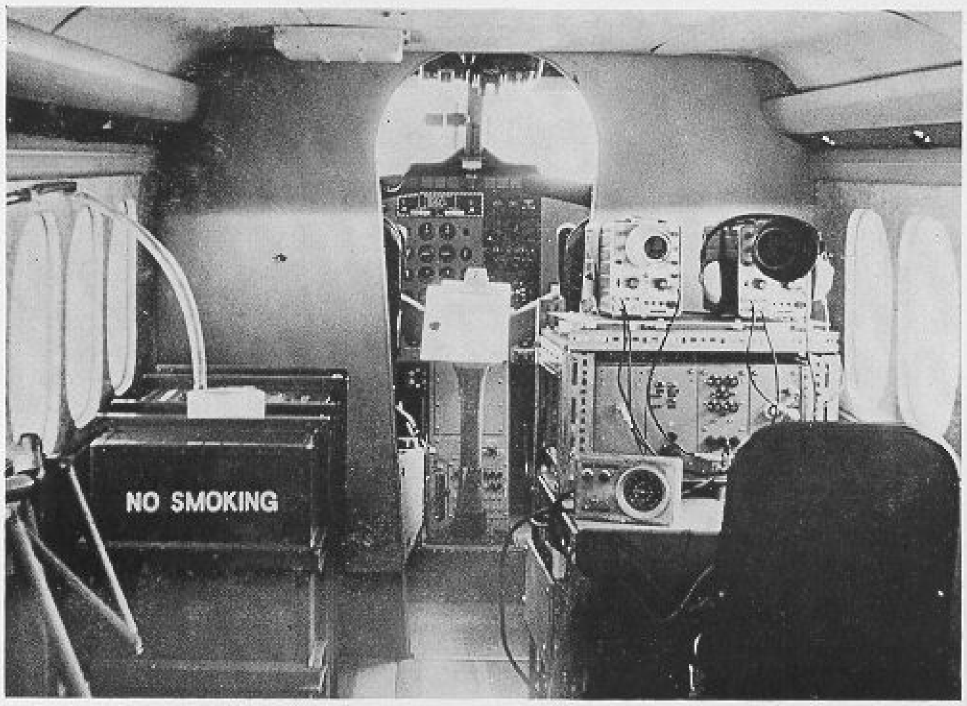


CHART M
MARGUERITE
BAY
WORDIE
ICE
SHELF
FLEMING GLACIER
PROSPECT
GLACIER
69°S.
69°15′
68°W.
67°30′
67°
0
25
km.

PLATE I

a. The interior of the Twin Otter aircraft, looking towards the cockpit. On the right of the cabin is the radio echo console, on the left an auxiliary fuel tank.

b. The exterior of the Twin Otter aircraft, showing one of the 1 m. aerial support poles fitted beneath the outboard end of the wing. From the base of the pole part of the aerial may be seen leading to the impedance-matching unit beneath the fuselage.

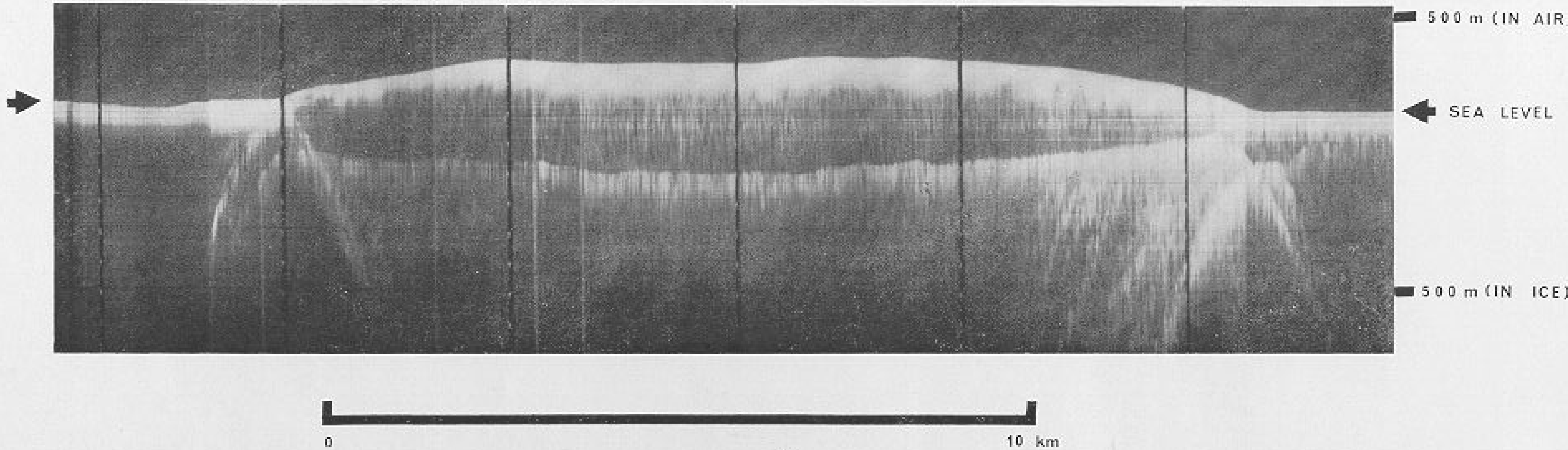


a

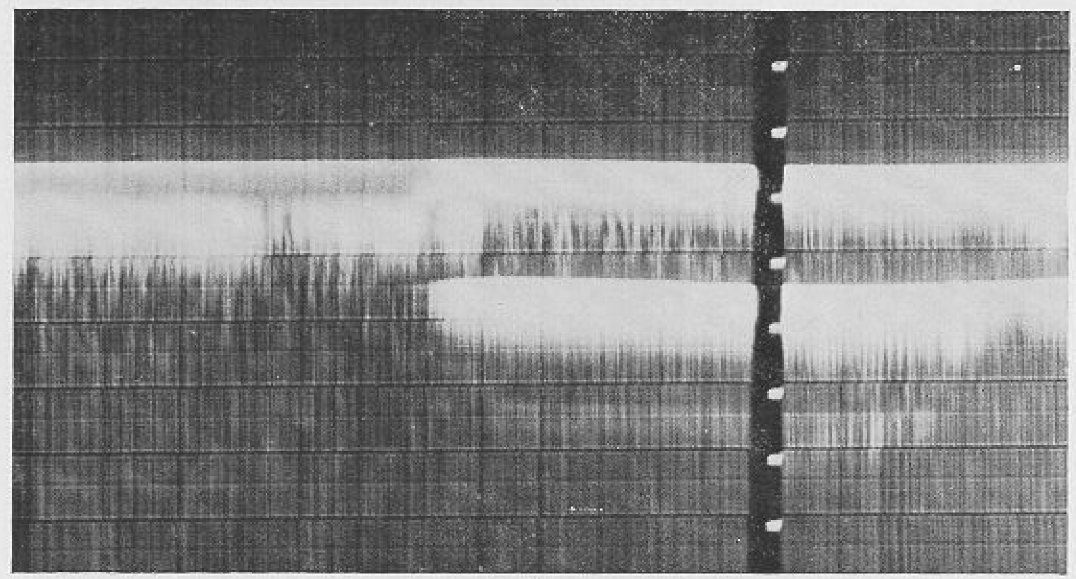
b

PLATE III

An example of a radio echo record obtained in lat. 70°S., long. 66°W. Bedrock elevations may be seen to vary from 400 to 1,300 m. a.s.l. The shape of the topography is not represented accurately because of the wide beam aerial, but the relief is clearly almost 1,000 m.



a



b

PLATE II

PLATE II

a. An east–west cross-sectional profile of the "January" ice rise (lat. 68°30′S., long. 61°W.). The surface elevation rises to about 270 m. a.s.l. and the maximum ice thickness is about 320 m.

b. A discontinuous bottom echo obtained on the Larsen Ice Shelf (lat. 68°S., long. 60°W.). On the right of the diagram the ice thickness is 150 m., and the bottom echo is strong enough for a double echo (reflected from the top of the ice down to a second reflection from the bottom) to be seen. On the left of the diagram a reflecting layer about 45 m. below the ice surface has appeared and the bottom echo has been extinguished. Since the surface is flat, it is supposed that brine has percolated horizontally through the porous upper layers from one of the nearby rifts which contain sea-water.

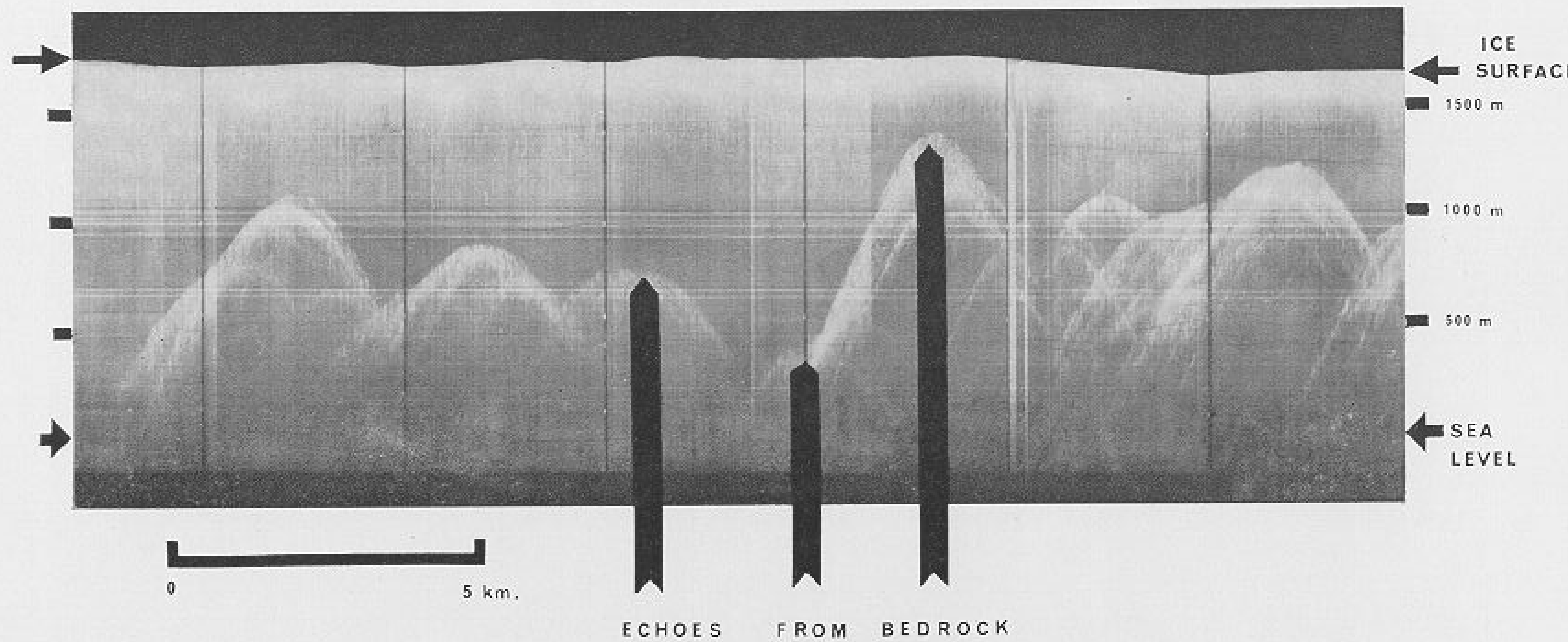

ICE SURFACE
1500 m
1000 m
500 m
SEA LEVEL
0
5 km.
ECHOES FROM BEDROCK

PLATE III