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Glaciological Research in the Antarctic Peninsula

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Glaciological research in the Antarctic Peninsula

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[Plates 1 and 2]

The Antarctic Peninsula is a good place for studies that take advantage of its wide range of latitude. Other worthwhile investigations are those that set in context the glacier/climate relationships and provide a framework of basic glaciological data. In order to speed reconnaissance mapping a series of seven 1:250000 map sheets was published which used satellite imagery as the only source for planimetric detail. In preparation for intermediate depth ice core drilling for glaciological and palaeoclimatic investigations a wide-ranging programme of radio echo sounding has been pursued since 1963; flight tracks now total 80000 km. Experimental results are presented for an area at the base of the peninsula between latitudes 73° S and 80° S. Track plotting was controlled by relating observed subglacial topographic features with the surface expression of the same features revealed in a Landsat image mosaic. Thus navigation was not subject to the cumulative position errors generally encountered on long flights far from fixed points (nunataks). Redefinition of the earlier speculative boundary of the inland ice sheet added 38000 km^2 to the land area of Antarctica while reducing the area of Ronne Ice Shelf by 11 %. An unmapped nunatak was found 187 km from the nearest known outcrop. Three major inlets contained the thickest floating ice ever measured. Floating ice 1860 m thick was identified at a point only 17 km from the Ellsworth Mountains; thus within 60 km of the highest mountain in Antarctica (5140 m) there is a trench reaching 1600 m below sea level. Subglacially, there is potentially a channel well below sea level that connects the Bellingshausen Sea with the Weddell Sea. A radio echo sounder was adapted to measure the surface velocity of glaciers by reference to the spatial fading pattern of the bottom echo. Checks on Fleming Glacier with optical survey instruments showed that the true rate of movement was 44 % faster than indicated by the fading pattern. It was concluded that the sounder had measured surface velocity with reference to a reflecting horizon which itself was deforming or sliding over the glacier bed. Experiments on ice shelves have been used to extend the flow law of ice to stresses lower than can be studied in the laboratory. At least down to the lowest stress considered (0.04 MN m^{-2}) the results supported a power law with a stress exponent of 3 as found in the laboratory for higher stresses. Ultra-clean sampling techniques were developed for detecting extremely low levels of impurities in snow (3×10^{-14}g g^{-1}). Thus DDT concentrations were found to be 40–100 times smaller than earlier reported for snow from central Antarctica. An extensive reconnaissance programme of 10 m ice core drilling has been pursued with the object of studying relationships between oxygen isotope fractionation and ice and air temperatures. The ice, water, and energy balances of two representative local glaciers have been studied as a contribution to the International Hydrological Decade.

1. Introduction

Systematic glaciological research came late to the Antarctic Peninsula largely because it involved travel in conditions that were difficult even by Antarctic standards. During the last few years ski-equipped aircraft have brought dramatic changes in the scope and relevance of research by providing access to areas in which studies of general rather than simply local significance could be pursued. However 30 years of pioneering studies conducted in the vicinity of occupied wintering stations have laid a firm foundation on which to build. Robin & Adie (1964) summarized the conclusions which could be drawn from these studies and considered the new dimensions then opening with the development of ice core drilling techniques. The practical constraints were discussed in detail at an international conference in 1973 which led to an agreed research strategy for the area (Swithinbank 1974).

Although there have been as many research stations in the Antarctic Peninsula area as there have been in the whole of the rest of the continent, the region remains comparatively unexplored in glaciological terms. The reasons are not so much human or even political as they are environmental. Much of the terrain consists of precipitous mountain glaciers plunging from alpine peaks or plateaux into an ice-choked sea, of calving ice cliffs and hanging glaciers, of steep ice piedmonts furrowed by crevasses, of rugged massifs fringed by icefalls, and an archipelago of ice-capped islands. Many of the existing stations of necessity cling to narrow footholds of uneven rock between encroaching glaciers and the cold sea. Hundreds of kilometres of coastline have been searched in unrewarding efforts to find safe havens for ships near smooth rock on which buildings can be erected. Access by sea to satisfactory station sites, of which there are few, nowhere coincides with satisfactory access by air. There is but one airstrip in the whole vast area that is marginally suitable for wheeled aircraft; another was destroyed by a volcanic eruption in 1967. While away from the coast there are many areas of smooth snow suitable for ski-equipped aircraft, nearly all of them are unusable as operating bases because of the impracticability of bringing in fuel by surface transport.

Bad weather is all too prevalent. The peninsula serves as a climatic barrier for a series of cyclonic systems moving eastwards from the Bellingshausen Sea. Persistent low cloud, fog, heavy snowfalls, and even rain in summer are accompanied by shifting and turbulent winds. The mountainous terrain gives rise to sudden katabatic winds, sometimes of extreme violence. Aviation is inhibited by the changeability of the weather and by the frequency of poor visibility and whiteout. The weather generally makes visual flying impossible on one side of the peninsula when it is possible on the other, so that a very short flight from the west coast, for example, to the Larsen Ice Shelf may take weeks to accomplish. Blizzards sweep bare the ice sheet in some places and in others deeply bury anything left on the surface. For understandable reasons there have been examples over the years of the unsuccessful application to the peninsula area of methods which have proved successful elsewhere in Antarctica. All these circumstances call for specialized and in many respects different techniques to be applied both in research planning and in field logistics.

However the Antarctic Peninsula is in a uniquely favourable position for certain special studies that can take advantage of its wide range of latitude. Other worthwhile investigations are those necessary to set in context the glacier/climate relationships and, in addition, to provide a minimum exploratory framework of basic glaciological data.

2. Mapping from satellites

'We have not yet completed the first main task to be tackled on any glacier, that of mapping its existing limits and studying its general form' (Robin & Adie 1964). Although significant progress has been made, the same could be said today. One of the sadder chapters of Antarctic history will record that mapping, instead of anticipating a predictable need, has instead lagged very far behind. The need is urgent for 1:250000 scale reconnaissance maps to position the results of 30 years of geological, geophysical and glaciological investigation; to give a planimetric base for aeronautical and hydrographic charts; to provide a bench-mark against which to measure future changes in the position of glacier margins; and to yield the first-ever small-scale maps almost free from plottable errors (Swithinbank & Lane 1975).

Strange as it may seem, the far side of the Moon is now much better mapped than parts of our own planet. Indeed position errors of more than 100 km were found in 1975 on the most up-to-date maps published at any scale of one part of the Antarctic Peninsula. Over much of the area we still lack maps even to minimum standards for air navigation, let alone for any scientific purpose. Unfortunately, the cost of conventional mapping under polar conditions is so high that it is unreasonable to suppose that it will proceed much faster in future than it has done in the past. For this reason the launching of the United States satellite Landsat-1 was a most significant event for the future of Antarctic small-scale mapping. Millions of square kilometres of the continent have now been covered by high resolution scanning radiometer imagery. Because of the clarity of the polar atmosphere, satellite pictures of the Antarctic contain a wealth of detail not generally seen in pictures from lower latitudes. Image quality is so good that single frames can be enlarged to a scale of 1:250000 without significant loss of definition. For unmapped or poorly mapped countries Landsat represents nothing less than a revolutionary advance in the ease of reconnaissance planimetric and photomapping.

More than 80% of the sector north of latitude 81° S between longitudes 20° W and 80° W is now covered by good quality cloud-free multi-spectral scanner imagery. Geologists, geophysicists, and glaciologists routinely take into the field satellite pictures at a scale of 1:250000 in place of maps. This is partly because there are large areas for which no satisfactory maps are available, but even where there are maps, the pictures are often preferred because they contain detail that would not be reproduced on conventional maps. With routine employment of satellite pictures, the British Antarctic Survey (B.A.S.) was faced with the problem of combining scanning radiometer imagery with a reliable graticule in order to locate features on the ground. By good fortune the first Antarctic imagery included some critical areas for which no satisfactory maps existed and where we had an immediate need for reconnaissance mapping at a scale of 1:250000. B.A.S. therefore requested the Directorate of Overseas Surveys to prepare and publish seven sheets, each sheet to be in two editions: one a direct half-tone reproduction of the band 7 (0.8 to 1.1 μm) scanner imagery, with the addition of graticule lines, symbols, spot heights and feature names. The other edition was an interpretative line drawing traced from the imagery, also having graticule, spot heights, feature names and symbolization representing ice-free areas and melt ponds. Both editions had a standard map border and legend and gave details of imagery and planimetric control. They were published in 1974, probably the first regular series of maps in any part of the world for which planimetric detail was taken entirely from satellite imagery.

Since publishing the maps there have been two full Antarctic field seasons in which to use them. They were very well received by field investigators and not least by aircraft pilots and navigators. While it can be conceded that the enthusiastic reception of a map that includes areas never before mapped at any scale may not be interpreted as a fair measure of the quality of the product, the maps have been routinely used to serve all the purposes of normal topographical maps. The photomaps (BAS 250P Series) were greatly preferred for field use because they showed many features that could not satisfactorily be reproduced on the line maps

(BAS 250PA Series). Among these features are escarpments, ice slopes, glacier flow lines, crevassed areas, and wind-blown snow-free areas of the ice sheet. All these are of significance to the surface traveller for selecting his route of travel and to the aviator for navigation in areas where there are no nunataks. They are particularly valuable for the precision air navigation required in geophysical survey flying.

In spite of the absence of contours, form lines, or hachuring, the photomaps do contain a great deal of relief information and are much more useful in this respect than the line maps. The low sun angle at which the imagery was obtained (24°–29°) gave a wide range of grey-scales that clearly represented slopes varying from steep escarpments in shadow to ice surface gradients of less than 1°. While there is no doubt that contour maps will eventually be needed in Antarctica as they are in other parts of the world, 90% of today's users ask only for maps which place features in their correct relative positions. Since the United States National Aeronautics and Space Administration, which operates the Landsat system, has not asked users of their satellite products to bear any part of the heavy costs involved, the economic advantages of satellite mapping over conventional mapping are overwhelming. Accepting that at this stage of the development of Antarctica, 90% of map users are concerned with planimetric positions rather than with contours, the situation can be summarized by stating that satellite maps yield perhaps 90% of the value of conventional maps at around 2% of their production cost.

The line maps will come into their own for the publication of special maps, because little can be overprinted on the half-tone photomaps without rendering them unreadable. The principal use will be for geological mapping, leading in stages to the preparation of coloured maps for publication at various scales. Another use will be for ice-depth charts analogous to nautical charts in which ice soundings will be indicated both digitally and by isopleths. Finally, aeromagnetic surveys will use them for track plots and for magnetic anomaly isopleths.

For ground control we have used and will continue to use Doppler satellite position-fixing. In a joint operation with the United States Geological Survey during the first few weeks of 1976, 26 positions over a vast area between latitudes 64° S and 80° S were each determined to an accuracy of a few metres.

The greatest potential value of Landsat scanning is in time series studies of a great variety of features. For example major calving events on Antarctic ice shelves can now be monitored as they occur. It has been established that icebergs totalling 858 ± 30 km^2 in area calved from Wordie Ice Shelf sometime during 1972 or 1973 (personal communication from A. Colvill).

3. Ice drilling

Polar ice sheets contain chronologically stored, essentially unaltered, and datable samples of the atmosphere and of atmospheric precipitation extending back from the present day over a period of several thousand years. They give access to the only uncontaminated samples of terrestrial material circulating in the atmosphere and to the most easily interpreted record of the amount of extra-terrestrial material falling on the earth. Few events in the history of polar research have excited so much interest and yielded so many significant new findings as the deep ice coring completed at Camp Century in Greenland and at Byrd Station in Antarctica (Dansgaard, Johnsen, Clausen & Gundestrup 1973). Valuable as these cores are in studies of climatic change, atmospheric circulation, industrial pollution, and surface level fluctuations on large ice sheets, their interpretation has been beset by uncertainties due to local factors. It is now evident that nothing short of a series of holes in different parts of the ice sheets will convincingly isolate the record of past general climatic changes from the record of local changes in ice surface level. The Antarctic Peninsula could form part of a chain of ice coring sites that would reliably connect the Byrd Station record with that of other continents. However, much careful reconnaissance and experiment must precede final site selection, and each stage of the internationally agreed programme was designed so that we may be reasonably certain of the scientific merit of the next stage before investing in it.

Antarctica is the coldest, the most isolated, and the highest of all the continents. Symmetrically placed with respect to the Earth's rotation, it is surrounded by a relatively simple pattern of circumpolar westerlies linking the circulation of lower latitudes with the polar heat sink. The peninsula is the only land mass that cuts across this subantarctic zone and it bridges all but 1000 km of the gap between Antarctica and South America. It separates the maritime climate of the Bellingshausen Sea from the continental climate to the east. The Weddell Sea contains the most persistent areas of pack ice in the Southern Hemisphere and serves as the principal source of cold bottom water that penetrates far even into the Northern Hemisphere (Reid & Lynn 1971). Sea-ice inhibits the normal ocean-air heat exchange and causes significant changes in the mean albedo of the earth (Flohn 1973). Secular and seasonal variations in the extent of sea-ice are thus believed to have a profound effect on atmospheric circulation (Fletcher 1969).

Shifts with time in the relative importance of maritime versus continental climate at sites on the Antarctic Peninsula should reflect changes in one of the major driving forces of climate. A series of ice cores taken from a range of latitude between the South Shetland Islands in the north and Palmer Land in the south should bear stratigraphically datable traces of even small shifts in the positions of climatic belts. Such drilling need not be costly: cores of up to a few hundred metres in length can be obtained from dry holes at a small fraction of the cost of deep drilling. From the cores it may be possible to obtain for each site an unbroken historical record of mean annual temperature, snow accumulation (precipitation), and microparticle content extending over several hundreds and possibly thousands of years. The analysis of these data may do much to resolve the elevation-change versus climatic-change ambiguity that has limited the reliability of climatic records obtained from single-core studies (Dansgaard *et al.* 1973, pp. 37–38). It should also throw light on cause-and-effect relationships in climate, since dated events in Antarctica can be correlated with climatic fluctuations recorded elsewhere over the last few hundred years.

4. Radio echo sounding

Three developments of the past ten years have revolutionized studies of the Antarctic ice sheet – ice core drilling, high resolution satellite imagery, and radio echo sounding. Ice thickness measurements provide background data essential to proper drill site selection and to almost any kind of glaciological activity, while satellite pictures provide data for maps without which it would be impossible to study spatial relationships in ice thickness and other data.

About 99% of the area of Antarctica lies hidden beneath the ice sheet. Radio echo sounding, using a pulsed radar at a frequency to which ice is transparent, can be used to study sub-surface glacier dynamics, bedrock morphology, and the physical characteristics of the ice/rock interface. In the United Kingdom, the British Antarctic Survey (B.A.S.) and the Scott Polar Research Institute (S.P.R.I.) have been closely involved for more than a decade in the rapid development of radio echo sounding from an early experiment at Halley Bay to a now widely-practised technique for the study of glaciers. Using a S.P.R.I. radio echo sounder, B.A.S. was first to record glacier thickness from a moving vehicle (Walford 1964; Bailey & Evans 1968) and also first to operate an airborne system in the Antarctic (Swithinbank 1968). B.A.S. glaciologists have since been involved in a total of 480 h of radio echo flight time and B.A.S. aircraft

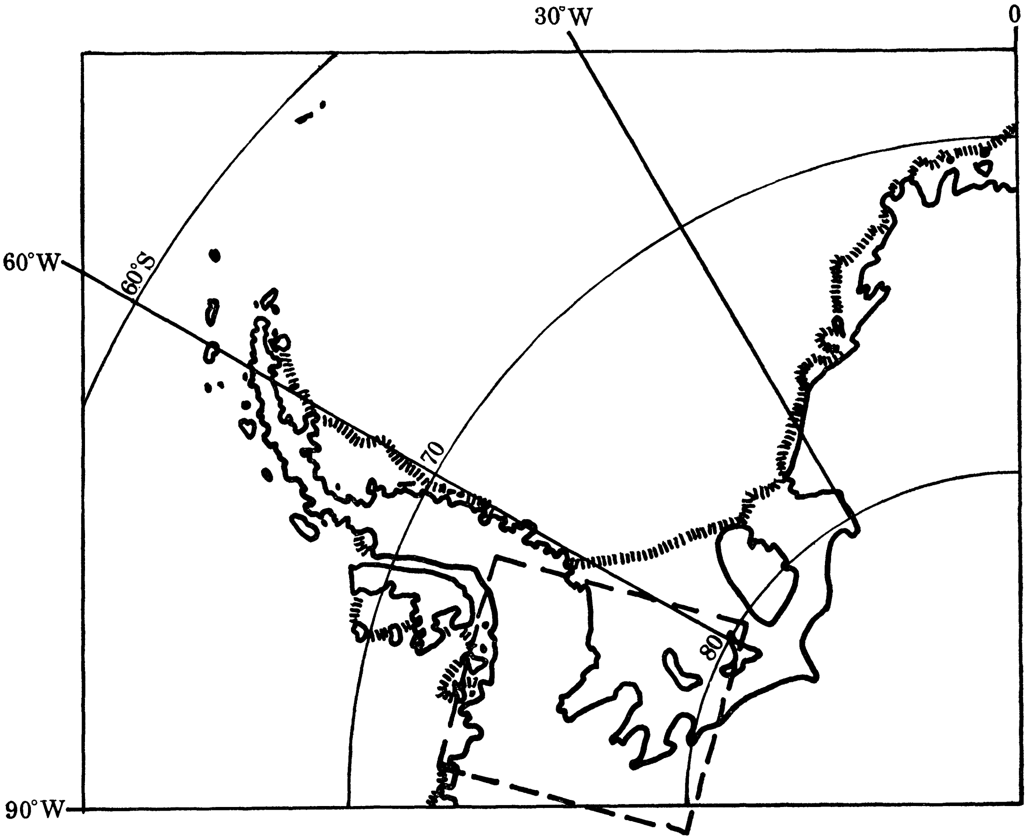


Figure 1. The Antarctic Peninsula. Inset shows area covered by figures 2–6.

have flown ice sounding profiles over tracks totalling 80000 km. Results have included published maps giving the first information on ice sheet thicknesses in the Antarctic Peninsula area (Smith 1972*a*) and extensive data on subglacial morphology that is of wide interest to the Earth sciences. New techniques have been developed for the production of contour maps from data taken along flight lines (Smith 1971) and for automatic plotting of airborne geophysical data (Smith 1972*b*). Melt water on George VI Ice Shelf prompted a theoretical study of the absorption and scattering of radio waves by water and ice lenses (Smith & Evans 1972). B.A.S. was jointly involved with S.P.R.I. and the U.S. National Science Foundation in the first major survey of the main continental ice sheet using long-range aircraft of the U.S. Navy (Robin, Swithinbank & Smith 1969). Unexpectedly, lakes were discovered beneath the ice sheet, one under 4200 m of ice; a whole series has since been found (Oswald & Robin 1973). A symptom of the changing character of Antarctic field work is that whereas in 1958 two days of hard labour by a seismic crew produced seven spot soundings (Crary 1966), in 1967 our radio echo aircraft took 3 min to make a continuous depth profile over the same ground (Swithinbank 1969).

In recent years a modified S.P.R.I. Mark 4 radio echo sounder has been used in a DHC-6 Twin Otter aircraft to study the ice sheet from the South Shetland Islands in latitude 62° S to the Ellsworth Mountains in latitude 80° S. As an example of the rapidity with which major discoveries can still be made in Antarctica, figures 1–9 summarize the results obtained in January 1975 by one small aircraft in just three days of flying based on the remote American Siple Station. Our flight tracks (figure 2) radiated from the station towards Ronne Ice Shelf, but although we were using the latest published maps to navigate the aircraft, it was found impossible to reconcile the true extent of the ice shelf with any of the maps. This being perhaps the last extensive unexplored area on Earth, it is not surprising that our redefinition of the earlier speculative boundary of the inland ice sheet (figure 3) has added 38000 km² to the land area of

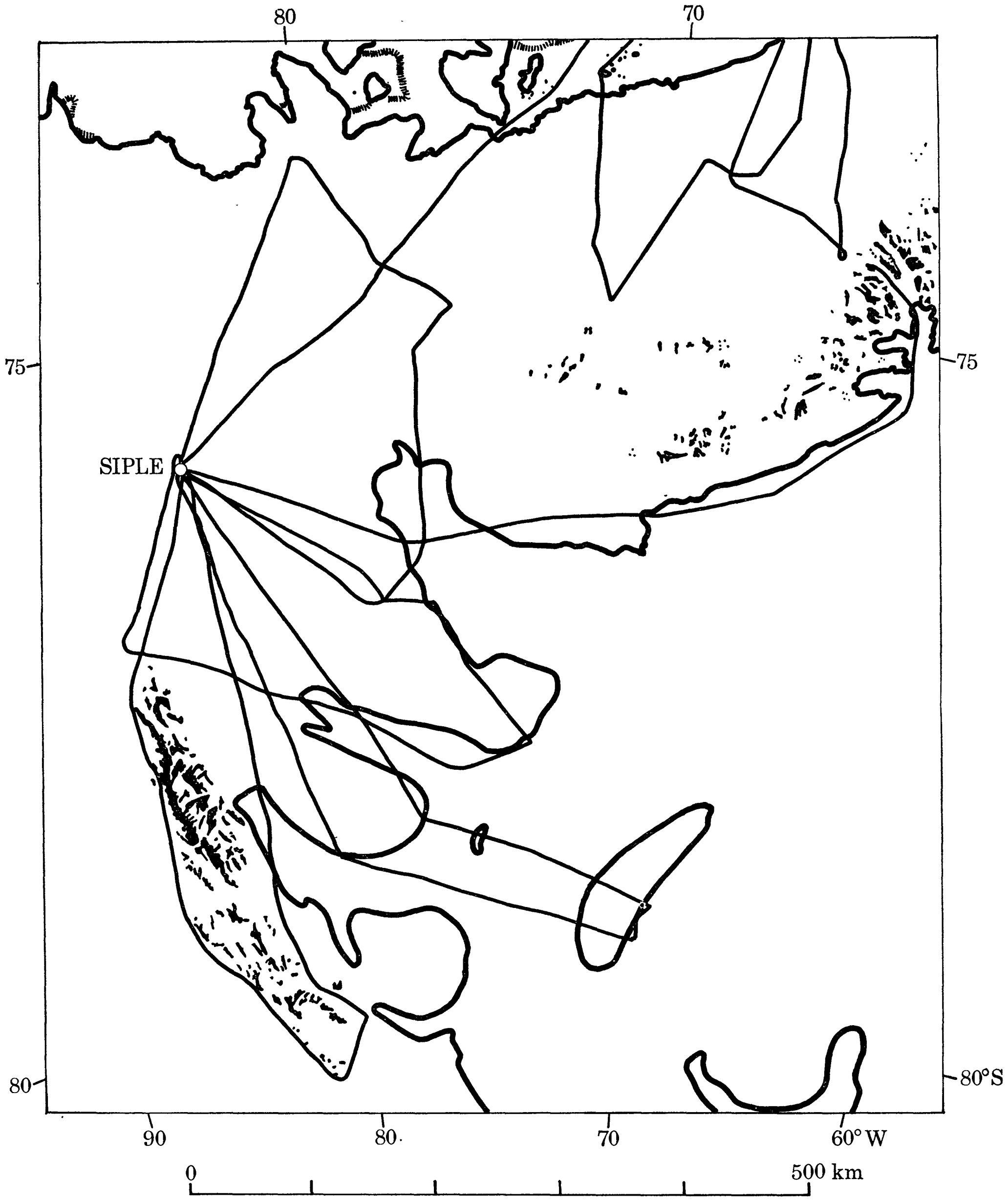


Figure 2. B.A.S. radio echo sounding flight tracks between latitudes 73° S and 80° S.

Antarctica while reducing the area of Ronne Ice Shelf by 11%. More surprisingly, while flying in an area which, according to the maps, was on the ice shelf and 187 km from the nearest rock outcrop, we came upon a nunatak. Recognizing the geological significance of exposed rock occurring in an unknown area midway between the southernmost nunataks of the Antarctandes and the contrasting Ellsworth Mountains province, we landed to take specimens. These have since been radiometrically dated at twice the age of the oldest rocks found in the Antarctic Peninsula (personal communication from P. D. Clarkson & M. Brook). Evidently the nunatak represents an up-faulted slice of the metamorphic basement underlying the

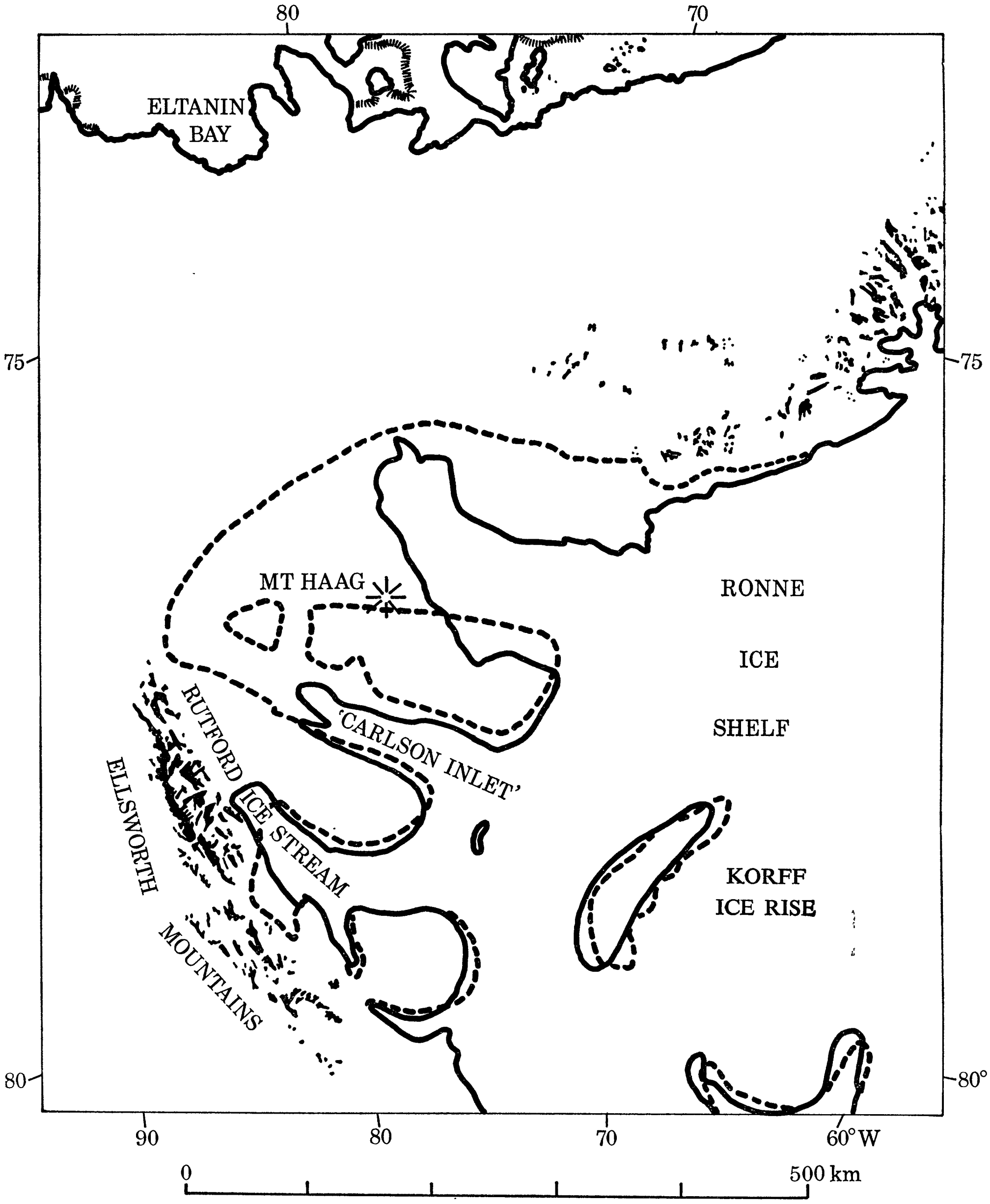


FIGURE 3. Old (pecked) and new (full-drawn) coastlines. Old coastline from *World* 1:5000000, *Sheet* 13, *Antarctica* (New York, American Geographical Society 1970). New coastline from radio echo sounding extended by topographic interpretation of an unpublished 1:1000000 scale Landsat scanning radiometer image mosaic supplied by United States Geological Survey.

Ellsworth Mountains. This means that we have halved the 400 km range of uncertainty in the position of the boundary between two of Antarctica's major orogenic provinces. On returning home we found that the nunatak had been seen before and was named Mount Haag (Ronne 1948, p. 375), but its reported position being 65 km in error, it had been omitted from later maps. Its height, we noted, had been overestimated by 2300 m.

Surface elevations (figure 4) were determined by continuous recording of the pressure altitude of the aircraft in relation to terrain clearance measured by radar. Calibration of the pressure altitude was controlled by the height of Siple Station determined by Doppler satellite (personal

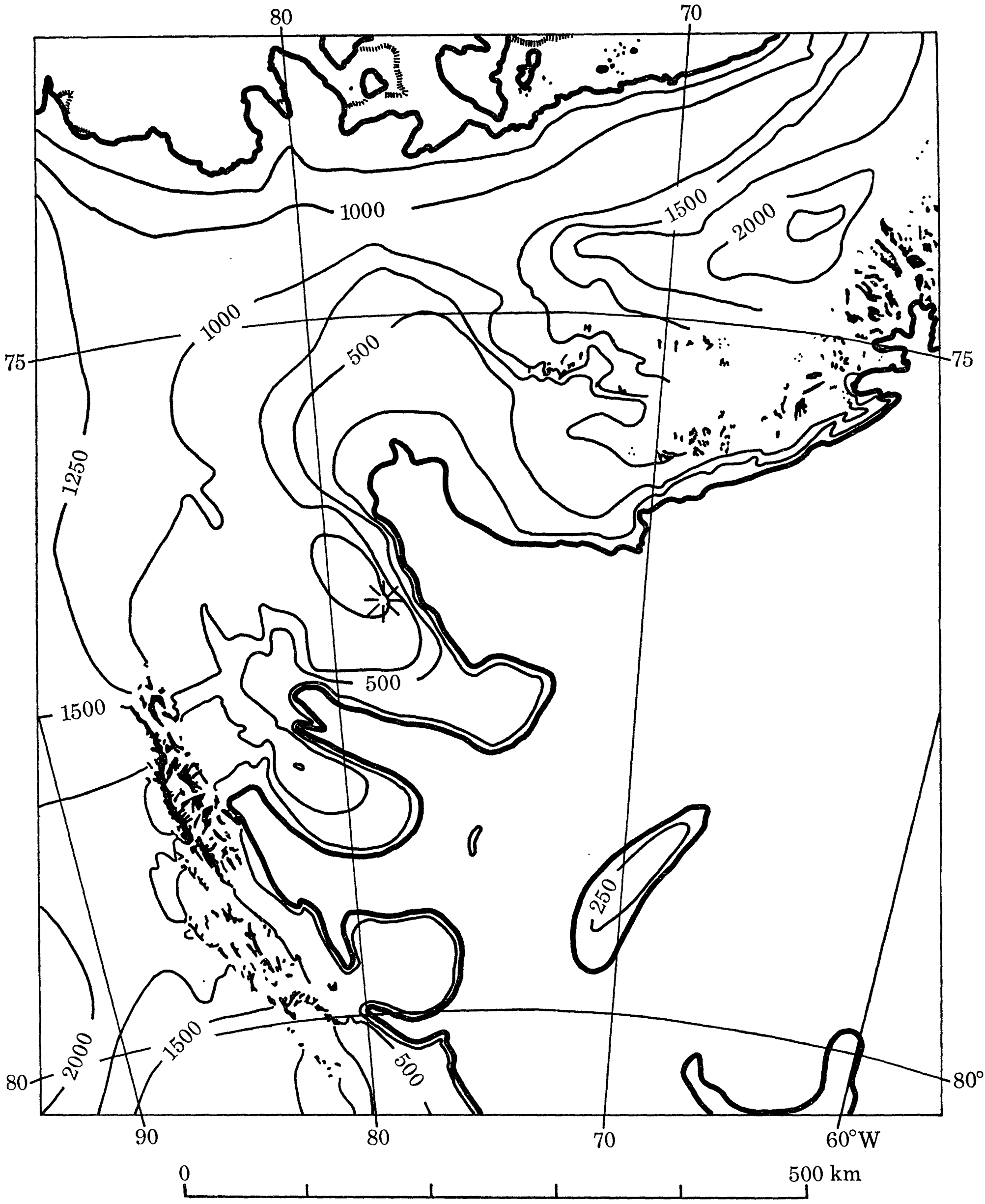


FIGURE 4. Surface elevation (m) from radio echo altimetry extended by data from Bentley & Ostenso (1961), Behrendt (1962, 1964), Bentley & Chang (1971), and *World* 1:5000000, *Sheet 13, Antarctica* (New York, American Geographical Society 1970).

communication from W. R. MacDonald) and by spot checks on the ratio between surface elevation and ice thickness over freely floating areas of the ice shelf. The major findings compared with earlier maps of the area (Behrendt 1970, p. 489) is that there are three ice streams flowing southeastwards into long fjord-like inlets. The northernmost drains ice from a large area extending from the western boundary of the map to longitude 74° W. The middle ice stream has a relatively small drainage basin and is correspondingly less active; the name 'Carlson Inlet' has been proposed by the U.S. Board on Geographic Names. The southernmost, known as Rutford Ice Stream, is narrower (26 km) but probably fast-flowing, since it drains a large

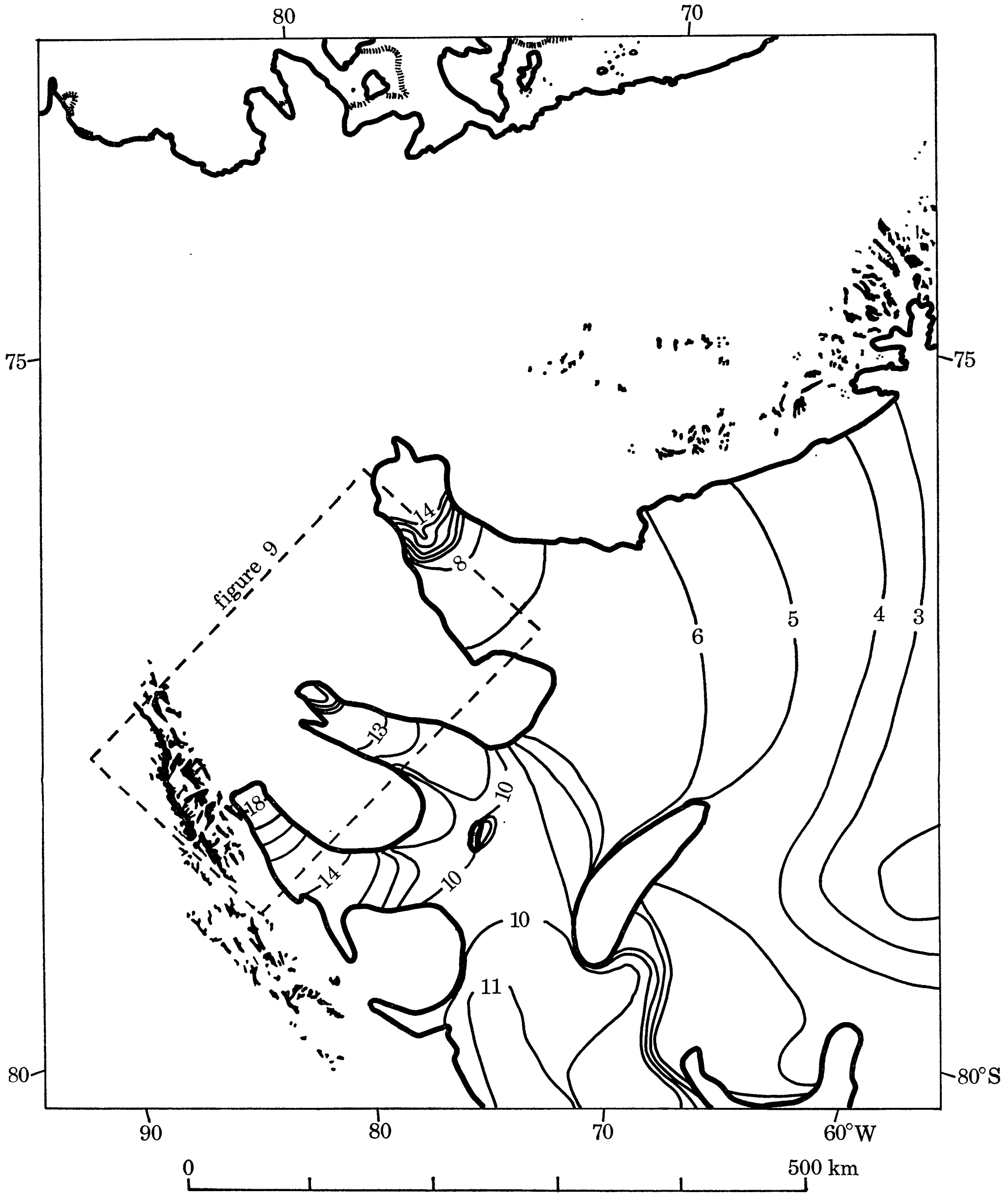


FIGURE 5. Ice shelf thickness (× 100 m) from radio echo sounding extended by data from Behrendt (1962), *World* 1:5000000, *Sheet* 13, *Antarctica* (New York, American Geographical Society 1970), and Scott Polar Research Institute (unpublished). Inset shows area covered by figure 9.

tract of the ice sheet to the west that is dammed up by and diverted round the northern end of the Ellsworth Mountains.

Ice shelf thicknesses (figure 5) include the thickest ice ever found floating on the sea. We measured 1860 m of floating ice on Rutford Ice Stream only 17 km from the eastern escarpment of the Ellsworth Mountains. This is nearly twice as thick as the thickest ice found on the Ross Ice Shelf (Robin 1975). Both the other ice streams contain exceptionally thick ice towards the head of their inlets. The rate of thinning as the ice moves seawards is evidently principally controlled by the boundary configuration of each inlet. Ice moving down the northern ice stream

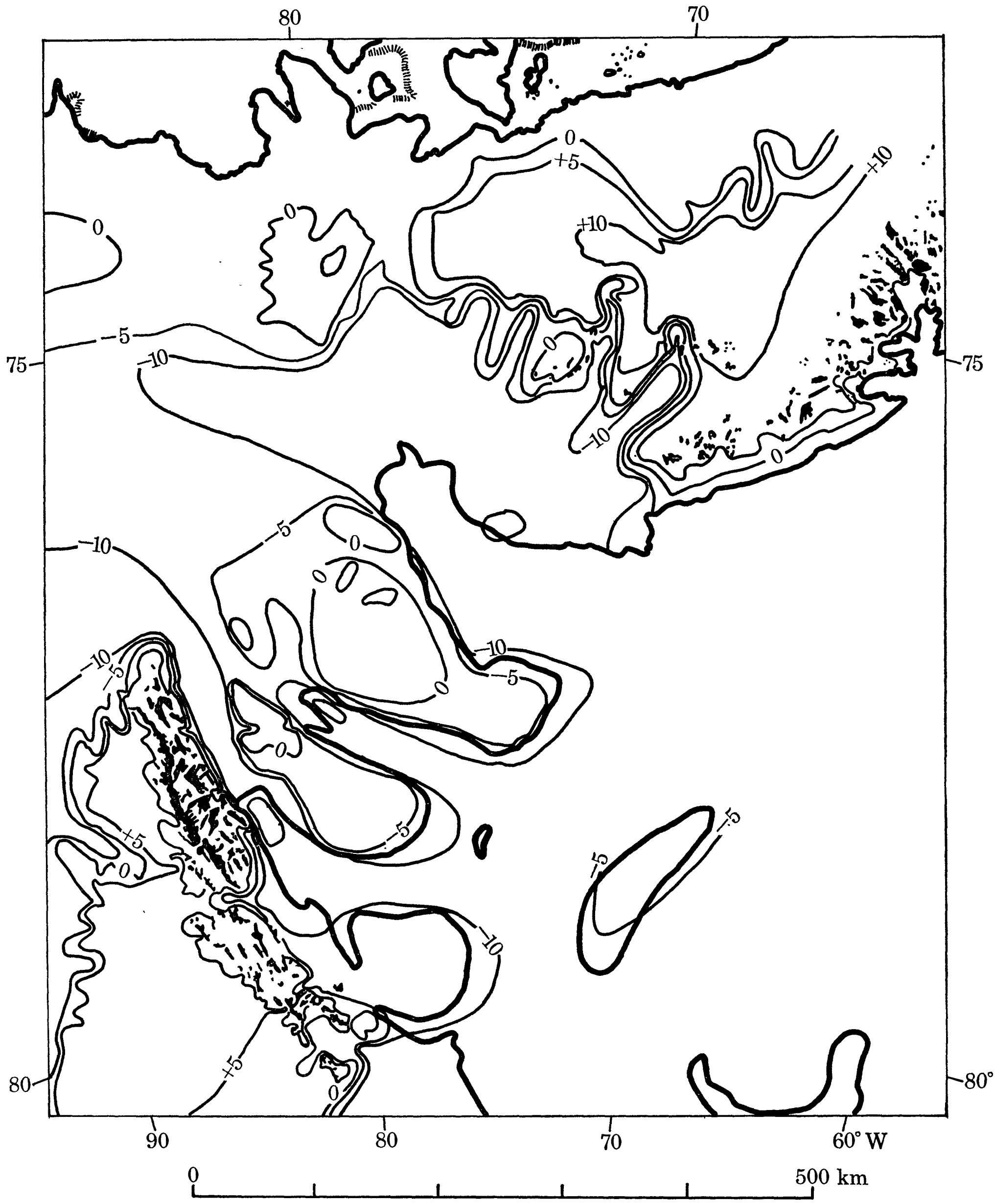


FIGURE 6. Bedrock elevation (m) from radio echo sounding extended by data from Bentley & Ostenso (1961), Behrendt (1962, 1964), Bentley & Chang (1971), and *World* 1:5000000, *Sheet* 13, *Antarctica* (New York, American Geographical Society 1970).

thins from 1400 m to 800 m over a distance of only 45 km where the sides of the inlet begin to diverge.

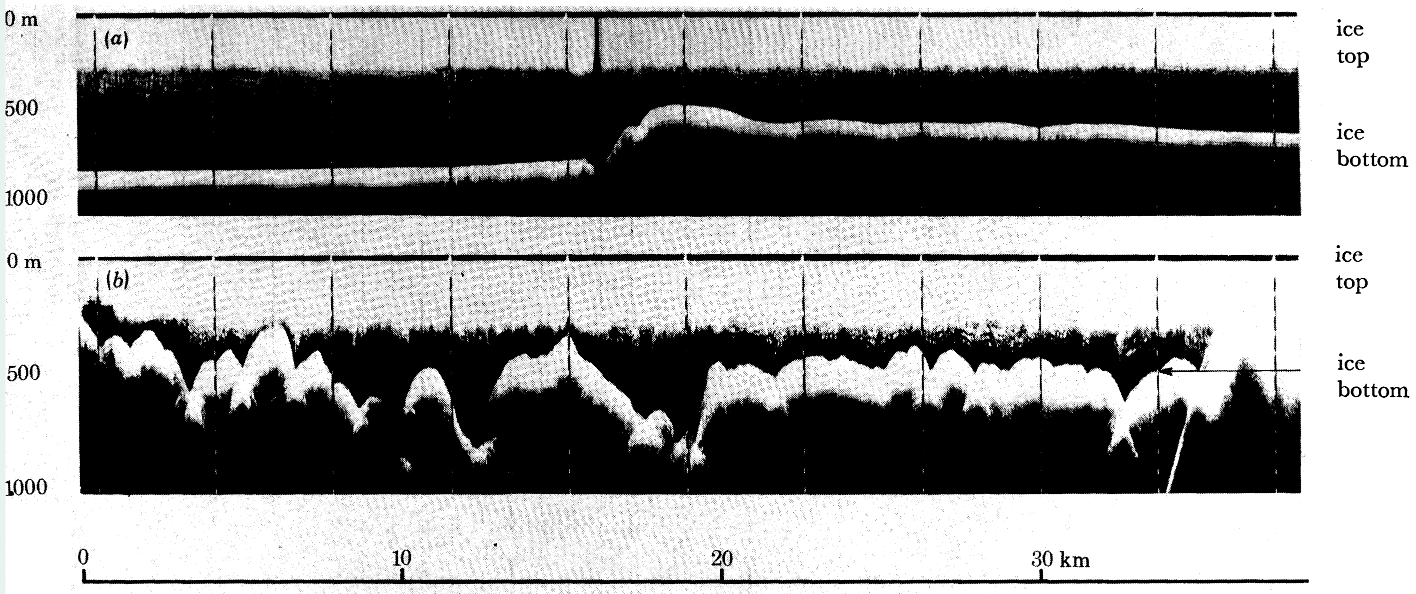
The principal feature of the bedrock elevation (figure 6) is that much of it is not only below sea level but substantially below the level of the Antarctic continental shelf. The subglacial Antarctic Peninsula is seen to be separated from the Ellsworth Mountains continental fragment by deep troughs now occupied by the major ice streams. There is little doubt that as Behrendt (1970, p. 491) inferred from seismic sounding and gravity observations, there is potentially a channel well below sea level that connects the Bellingshausen Sea with the Weddell Sea. The most remarkable feature can be inferred from our 1860 m ice shelf sounding on Rutford Ice Stream: within 60 km of the highest mountain in Antarctica (Vinson Massif, 5140 m) there must be a trench extending to at least 1600 m below sea level.

Figures 7 and 8, plate 1, show a variety of subglacial features recorded by the radio echo oscilloscope camera. A particularly unusual feature is the grounded area (figure 8*b*). Crevasse patterns on the surface indicated that the 1100 m thick ice shelf was forcing its way over an 11 km wide shoal that was found to rise to a depth of 500 m below sea level. The minimum ice thickness on top of the shoal was 600 m. Re-forming on the downstream side of the obstruction, the ice shelf was attenuated by 200 m to a thickness of 900 m.

The experience of all those who have used radio echo sounding from aircraft indicates that our ability to measure ice depth has outstripped our ability to know where we are measuring it. Although equipment is available to establish the position of an aircraft to a greater accuracy than is necessary, nobody has used it for radio echo sounding. Throughout the past decade radio echo sounding aircraft have been navigated by continuous monitoring of airspeed and compass headings and, in recent years, by coordinate readings from Doppler radar or inertial navigation systems. Partly because the instruments are so complex and expensive it is sometimes forgotten that all of them are dead-reckoning systems which are subject to cumulative errors proportional to the elapsed time since the aircraft's true position was last known. Although these errors can afterwards be distributed along the track on the assumption that they accumulated linearly with time, unacceptably large position errors have sometimes arisen (Smith 1972*b*).

We have found that satellite pictures can now serve in place of maps in unmapped areas. Even at great distances from any fixed point or nunatak the true position of the aircraft can be found by relating subglacial features revealed by the radio echo sounder with the surface expression of those features recorded by the spacecraft. Figure 9, plate 2, shows surface features seen from a spacecraft flying at a height of 930 km. Ice surface topography along the lower flight track reflects, in a subdued but unmistakeable form, a series of subglacial features also shown in figure 8*a*. Note (from left to right in each case) the coincidence of a surface escarpment with the start of the bottom echo, the outline of a surface depression with the shoulders of a 900 m deep subglacial valley, and two terraces preceding the sharp edge of Rutford Ice Stream where the bottom echo drops away. Similarly along the upper flight track in figure 9 and the bottom profile in figure 8*c* note (from left to right) the coincidence of a smooth surface with a smooth bottom, two surface depressions with two subglacial valleys, and a major surface escarpment where the bottom echo drops sharply away to the 1200 m deep northern ice stream.

The perfect fit between the radio echo trace and the plotted track is in neither of these cases a chance coincidence. Both tracks have been made to fit the satellite picture by a small but constant correction to the calculated ground speed together with a small and parallel adjustment



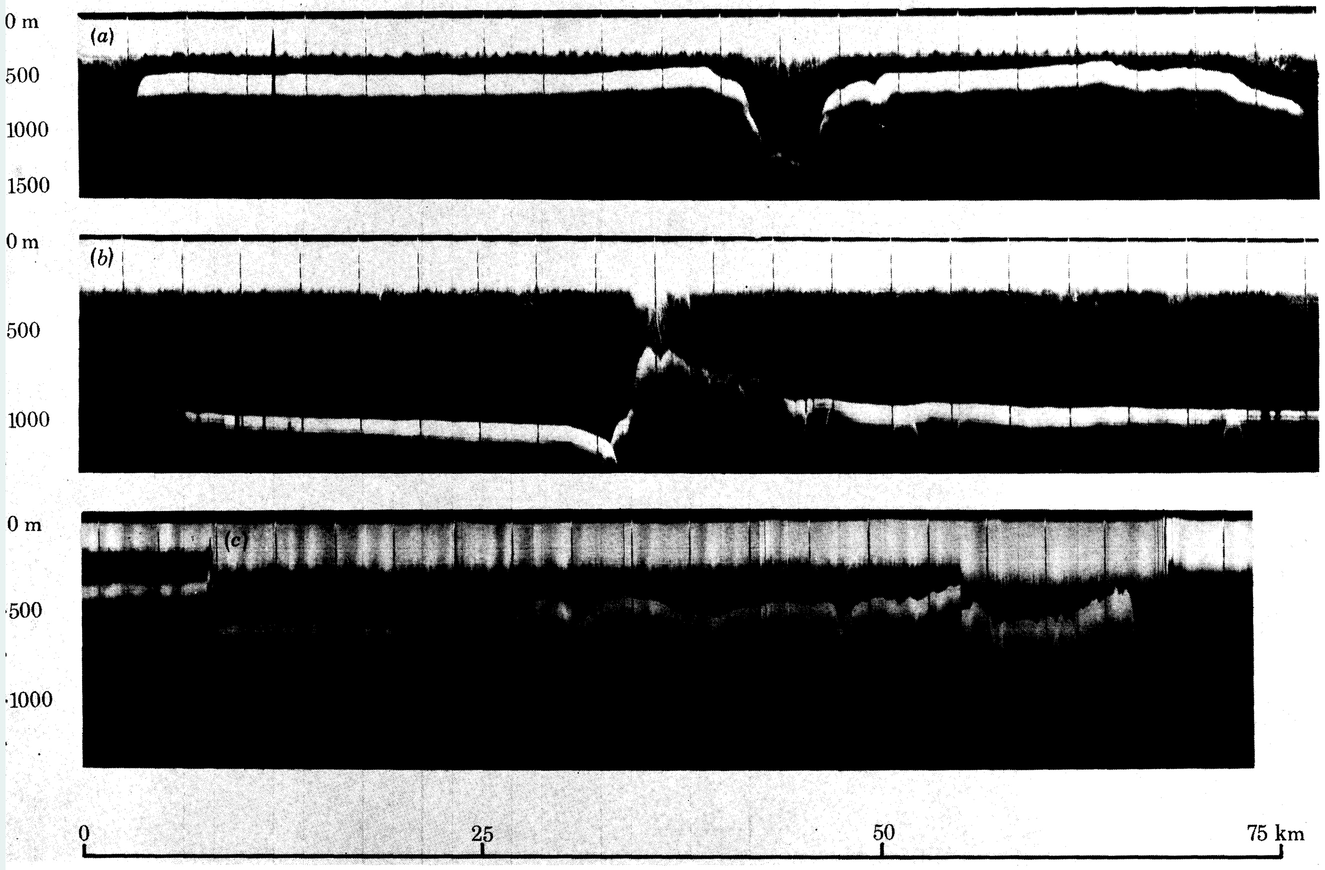
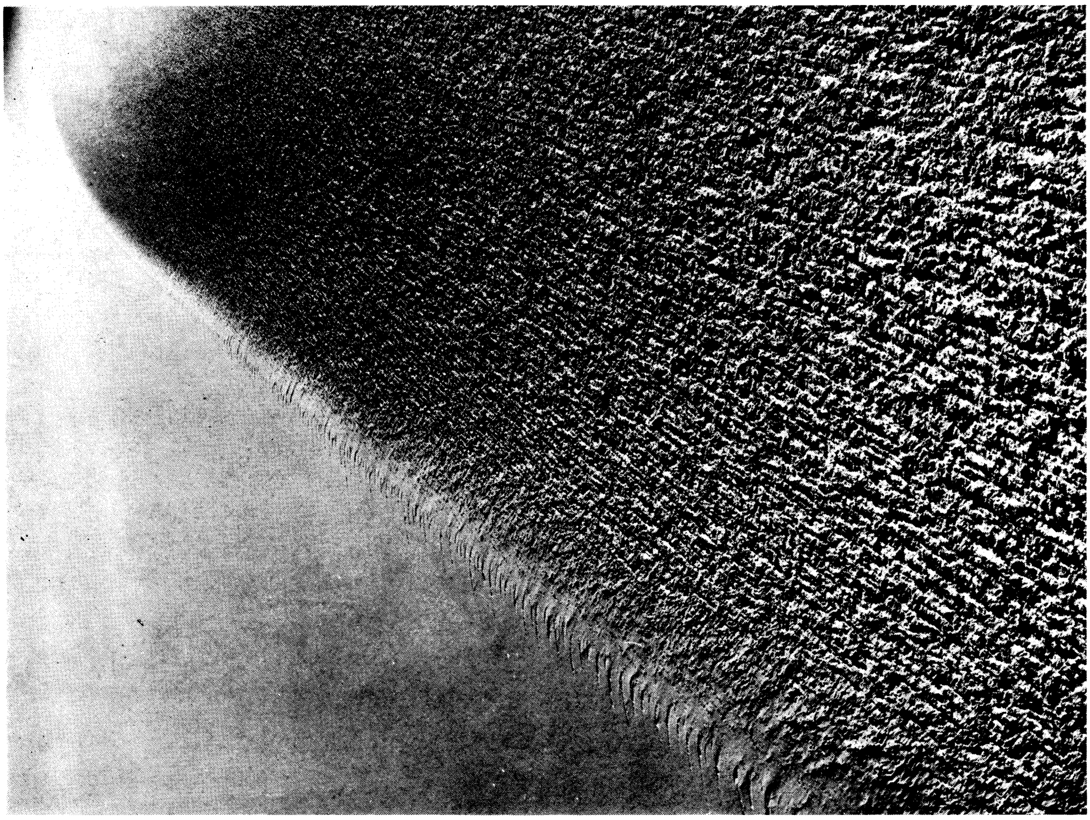


Figure 7 (above). Contrasting examples of subglacial relief: (*a*) Smooth seawater surface beneath 800 m of floating ice on Ronne Ice Shelf (left) and smooth rock surface beneath Korff Ice Rise (right); (*b*) subdued alpine relief north of Mount Haag. Mount Haag itself interrupts the bottom echo (far right).

Figure 8 (below). Subglacial features also identified in satellite pictures: (*a*) isolated valley in plateau (see lower flight track in figure 9); (*b*) 1100 m thick floating ice (left) dammed up behind locally grounded area in 78° 45′ S, 75° 40′ W giving rise to bottom crevasses (hyperbolic echoes) on thinner ice shelf (right); (*c*) ice sheet bordering northern ice stream (see upper flight track in figure 9). The jumps in the bottom echo represent oscilloscope scale changes made by the operator. The vertical scale bar (left) refers to the middle portion of the trace.



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FIGURES 9 AND 10. For description see opposite.

to the dead-reckoning track. Knowing the orientation of each feature and the exact time at which the aircraft crossed it, the flight tracks are uniquely constrained and therefore fixed in their proper relationship to the subglacial landscape that we are studying. The significance of this development is that the Antarctic ice sheet, until recently regarded as a vast and featureless expanse of snow where navigators necessarily relied on dead-reckoning, now takes on character and meaning. Far from being featureless, much of the ice sheet offers a wealth of surface detail that can be used to interpolate subglacial features between even a sparse network of radio echo flight lines.

Figure 9 shows that another characteristic of the area is the extremely well-defined boundaries of the ice streams. Flying over them, we generally found it possible to define the edges of the major ice streams to an accuracy of ± 100 m. There is no good oblique picture of an ice stream in this area but figure 10, plate 2, shows a similarly well-defined feature flowing into the Ross Ice Shelf. We believe that the sharp boundary represents either the line between wet-based ice (right) and ice frozen to its bed (left) or alternatively the line between floating ice (right) and grounded ice (left). The similarity between the surface of this ice stream and the characteristic surface of surging glaciers has drawn attention to the possible instability of the whole inland ice sheet of Lesser Antarctica (Hughes 1973). Surging of even one large drainage basin could cause a catastrophic rise in world sea level (Hughes 1975).

5. RADIO ECHO STUDIES OF GLACIER FLOW

With cold, deep, fast-flowing and readily accessible glaciers the Antarctic Peninsula has shown itself to be an admirable testing-ground for new techniques. A case in point was the discovery that not only the surface velocity of glaciers but also the rate at which the ice slides over its bed could in places be measured by studying the reflections of pulsed v.h.f. radio waves transmitted into the ice. Usually the glacier bed is rough, so that the echo from the bed becomes a distorted version of the transmitted pulse: it is lengthened and the amplitude and phase of the carrier wave vary within its length. The echoes also vary rapidly with horizontal displacement of the radio echo sounder, and this variation is known as the spatial fading pattern. Nye, Kyte & Threlfall (1972) regarded the fading pattern as a stable, finely-structured frame of reference fixed with respect to the glacier bed, and suggested that the horizontal movement of a glacier surface could be measured relative to this frame of reference. The advantage over conventional methods of measuring ice movement by optical surveys relative to fixed points on rock would be that it could be expected to be equally effective in the middle of an ice sheet where there are no fixed points for reference. If successful, the techniques would offer the prospect of providing ice

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DESCRIPTION OF PLATE 2

FIGURE 9. Portions of two flight tracks plotted on Landsat scanning radiometer image showing the northern ice stream (top), Mount Haag (circled), 'Carlson Inlet' (middle), and Rutford Ice Stream flowing from left to right along the foot of the Ellsworth Mountains. The radio echo record from the lower flight track is shown in figure 8*a* and that from the upper flight track in figure 8*c*. The highest mountain in Antarctica (Vinson Massif, 5140 m) can also be seen (bottom centre). Photo: U.S. National Aeronautics and Space Administration through U.S. Geological Survey.

FIGURE 10. The northern edge of an ice stream in 83° 50′ S, 150° W. The camera is facing northeast. Radio echo sounding gave ice depths of around 800 m both on and beside the ice stream. Photo: U.S. Navy.

velocity measurements quickly, with fairly simple equipment and without the need for expensive traverses. Walford (1972) tried the experiment on Fleming Glacier and was successful in measuring relative positions to an accuracy of one hundredth of a wavelength through ice 1100 m thick. At the frequency of 35 MHz then used by the sounder this represented ± 50 mm. The apparent rate of movement of a surface marker was determined to an accuracy of ± 8 % in only 3 days. As a check, conventional optical survey techniques were used to determine the velocity independently relative to nearby nunataks. Walford concluded that the discrepancy between radio echo and optical survey values (table 1) was not significant and that the radio echo method had satisfactorily determined the rate of ice movement. Doake (1975*a*) visited a nearby site 2 years later in an attempt to achieve greater precision in both radio echo and optical survey methods. He found a greater difference between results from the two methods (table 1) and concluded not only that it was significant but that the radio echo method was giving velocities relative to a reflecting layer near but not at the ice-rock boundary. The difference between the two values represented the motion of the reflecting layer relative to the glacier bed. Intrigued by the new possibility of measuring, in principle, the rate of basal sliding, Doake (1975*b*) returned to the site in December 1974 to further refine the experiment. New results (table 1) confirmed his earlier conclusions and led to observations being made at other sites. Higher up the glacier displacements determined by the radio echo method were the same, within limits of error, as those determined by optical survey. If here the reflecting surface was the true glacier bed and not a morainic layer embedded in the ice, it was to be expected that the radio echo velocity would be the same as the survey velocity.

TABLE 1. RATE OF MOVEMENT (m/a) OF FLEMING GLACIER MEASURED BY RADIO ECHO AND OPTICAL SURVEY METHODS

date	period day	radio echo	optical survey	reference
January 1972	3	139 ± 11	168 ± 18	Walford (1972)
January 1974	7	138 ± 5	201 ± 20	Doake (1975*a*)
December 1974	10	142 ± 11	201 ± 4	Doake (1975*b*)

While Doake has found that the radio echo method cannot in general be used alone to determine unambiguously the surface velocity of an ice sheet, when combined with an independent method it can determine something of greater value – the relative contributions to glacier flow of internal deformation and basal slip. True surface movement anywhere on polar ice sheets can now be measured by Doppler microwave measurements to satellites (*Antarctic Journal* 1974).

6. GLACIER PHYSICS

B.A.S. glaciological programmes have contributed to contemporary understanding of the physical properties of ice. By concentrating on the study of ice shelves, which are particularly well represented in the Antarctic Peninsula sector, fundamental advances have been made at relatively low cost compared with work on the inland ice sheet. Ice shelves are floating glaciers which creep under their own weight, the creep rates being dependent on the ice flow law at low stresses. It has been found possible to measure the horizontal components of strain rate, the ice thickness, surface elevation, and the density and temperature close to the upper surface (Thomas & Coslett 1970; Thomas 1971, 1973*a*, *b*, *c*; Coslett, Guyatt & Thomas 1975).

The significance of this work was reviewed in *Nature* (1971, p. 222). Laboratory studies of ice creep are often hindered by the length of time required for the experiment. This is particularly true at low stresses where a transient creep term dominates and the presence of a small steady-state creep may be masked. Investigators in a number of countries have studied the creep of polycrystalline ice in the laboratory, and the results have been applied, sometimes in extrapolated form, to explain glacier flow. In principle, flow measurements on an Alpine glacier should therefore be capable of telling something about ice creep over very long times, but this is usually not possible in practice because of the very complicated stress systems in a valley glacier. A floating ice shelf, however, is a much simpler system. It rests on a virtually frictionless bed and spreads under its own weight in a manner which is often uniform for distances large compared with its thickness. From laboratory work it had been suggested that the flow became more Newtonian as the stress decreased below 0.1 MN m^{-2}, meaning that the strain rate tended to be proportional to the stress rather than to some higher power of the stress. The ice shelf data, however, show no such tendency down to the lowest stress considered (0.04 MN m^{-2}), and seem to support a power law with a stress exponent of 3 as found in the laboratory for higher stresses. Taking into account the mean temperature of the ice shelves, it was possible to show reasonable agreement between the constants in the flow law derived from laboratory experiments and those derived from field data. Excellent agreement can be obtained if appropriate corrections are made for the fact that some ice shelves are not completely free to spread in all directions, but are confined at the sides to some extent. These results are of obvious interest when the laboratory flow law is being extrapolated in the theory of more complex glaciers, but they are also significant as an example of the validity of a power flow law in a solid down to very low strain rates.

The bottom melting of ice shelves is the least known term in the mass balance of Antarctica, which in turn is the principal factor controlling world sea level. Recent studies on George VI Ice Shelf (Pearson & Rose, in press) have shown for the first time on any ice shelf that the bottom melting rate may initially be a function of the elapsed time since the ice started floating. Radio echo sounding has shown unexpected differences between Bach and Wilkins ice shelves which may indicate different origins. Other smaller ice shelves fringing the Antarctic Peninsula show marked differences in behaviour and properties. It is an ideal area for the study of conditions for the existence, growth, stability and decay of ice shelves, each ice shelf having its own subset of necessary conditions. Ocean temperature and salinity are also important in most ice shelf studies and represent the connecting link between the glaciology of ice shelves and processes affecting the rest of the world.

7. Glacier chemistry

The ice sheet provides a vast area for the deposition and preservation of atmospheric precipitation which is almost free from local sources of anthropogenic contamination. Chemical impurities trapped in the snow are stored chronologically, low temperatures ensuring minimal thermal breakdown, minimal diffusion and negligible microbiological degradation. Studies on the nature and distribution of these substances have two main objectives: to establish baseline levels of pollutants in the global atmospheric environment and their variation with time and to discover relationships between properties of the snow cover and climate.

Low latitude measurements of global background levels of pollutants are hampered by contamination problems at the very low concentrations found, by the proximity of local sources of emission, and by interference from other more dominant compounds (as in oceanic measurements). Studies in the interior of Antarctica largely overcome the last two problems. Moreover the year and season of deposition of a particular snow sample may be established by investigation of the stratigraphy of the snow section from which it was taken (Peel 1976*a*).

FIGURE 11. Glaciologists in surgical clothing take clean snow samples to study very low levels of impurities.

The organochlorine insecticide DDT, which was employed extensively in the Northern Hemisphere during the 1940s to 1960s and continues to be used in the Southern Hemisphere, has been detected in biota all over the world. Because the production rate and areas of usage have been well documented, because there is no natural source, and because for a long time it was believed that DDT might cause extensive damage to the biota as a result of bioconcentration, DDT and its metabolites have been searched for over a wide sector of the global environment. Many measurements have been made close to the area of dispersion and are therefore of limited significance for modelling the global scale dispersion mechanism. Efforts have recently been increased to determine global baseline levels in the various available reservoirs. Present models of the dynamics of DDT circulation can account for only a small fraction of the amounts of DDT and DDE which are known to have been released into the environment. Major unknowns include the extent to which the atmosphere and oceans act as reservoirs and the transfer rate of these residues from the atmosphere to the oceans where according to present ideas, they may be removed from circulation by transfer to the abyss. Such atmospheric and oceanic transport mechanisms may carry pollutants into the ecologically protected area of Antarctica and it is necessary to assess the extent to which this is occurring and the relative importance of alternative routes.

Representative snow samples from the previous 5–10 years accumulation were collected during December 1969 on a journey of 450 km inland from Halley Bay station (Peel 1975*a*). Sampling procedures were designed to reduce contamination to a minimum by repeatedly trimming large snow blocks before packing them for transport. The snow was returned to England in the frozen state, wrapped in pre-cleaned aluminium foil and sealed in steel containers. Elaborate procedures (figure 11) were developed to avoid accidental contamination of the samples (Peel, in press) and evidently as a result, DDT concentrations were found to be 40 to 100 times smaller than earlier reported by Peterle (1969) for snow from central Antarctica. When Peel's values are compared with mean values reported for animal species which remain closely associated with the antarctic continent throughout their life cycle we obtain enrichment factors (concentration in animal/concentration in environment) of approximately 90000. This figure is comparable with values observed in other parts of the world. The results suggest that those animal species which live in close proximity to the continent are in equilibrium with the surrounding air and natural water. The DDT that they contain is likely to have been of airborne origin and not brought into their environment by transport along the oceanic food chain. The results also indicate that previous estimates of the global airborne load of these substances which were used in the first model to describe global DDT dissipation are much too large. In particular, the transfer rate of DDT from the atmosphere to the oceans has been overestimated. There must be a major sink for DDT in another part of the environment (Peel 1975*b*). The next step must be to look more closely at the atmospheric input of pollutant material into the Antarctic regions by observing short-term variations with relation to known air mass movements. Only then will it be possible to make more than order of magnitude extrapolations to a wider area and a wider significance.

The key to the climatic record contained in ice cores is the oxygen isotope ratio, which can be related to the air temperature at the time the snow fell. Ice samples can be dated by counting from the surface the number of annual waves in the oxygen isotope ratio (the δ value). Long-term changes in the mean annual isotope ratio may reflect climatic variations (Dansgaard *et al.* 1973). The results are more easily interpreted if cores are drilled from an ice dome summit with a simple radial flow pattern, since there should have been no horizontal ice movement since the snow was deposited. Over most of the peninsula a 500 m core should date back at least a few hundred and perhaps even a thousand years. An extensive reconnaissance programme of shallow drilling was pursued by B.A.S. glaciologists throughout the period 1972–6 to select the most suitable sites for deeper drilling. An ideal site would have the longest record possible; at the same time the annual layers should not be so thin that the δ variations may be eliminated by diffusion. Core samples are also being used in a collaborative study with the University of Copenhagen on the isotopic fractionation process and its relationship with the air temperature in different environments. Other samples have been taken for particulate and dissolved salt analysis in a search for additional climate-linked parameters.

10 m cores were taken from sites ranging from latitudes 64° S to 74° S from Charcot Island on the Pacific coast to Gipps Ice Rise on the Atlantic coast. The temperature at the bottom of each hole was measured because this is close to the mean annual air temperature in any dry snow region (Loewe 1970). A system of marker stakes was left at most sites to enable snow accumulation and surface strain rates to be calculated after a second set of measurements had been made a year later. Each core was divided into a number of samples, the number depending on the core density and the assumed annual accumulation which had been estimated from

stratigraphic analysis in a snow pit. These samples were transported back to base in polythene bags, where they were melted, transferred to 30 ml polythene bottles and refrozen. The samples were kept frozen until they reached Cambridge, when they were repacked and sent to the Geophysical Isotope Laboratory at the University of Copenhagen for isotopic analysis. Separate samples were analysed for gross β radioactivity which identifies characteristic nuclear test debris horizons and may lend support to stable isotope interpretations.

The main conclusions to be drawn from the results are that profiles from sites on the east coast show marked seasonal oscillations of the δ values which are likely to be preserved down to 500 m. In areas with mean annual temperatures warmer than -15 °C summer melting obliterates the isotopic stratification. Profiles from the west side of the peninsula show complex δ value cycles, probably due to large values of snow accumulation there. The most promising areas for deep drilling appear to be on the east coast and at sites along the Antarctic Peninsula ice divide.

The measured 10 m temperatures have given the first comprehensive view of the wide range of climates to be found in the Antarctic Peninsula. P. J. Martin (personal communication) has analysed sixty 10 m ice temperatures measured in latitudes 64°–73° S, longitudes 64°–75° W. He finds that in general, mean annual air temperatures decrease by 1.8 °C for each degree of latitude southwards. The temperature variation with altitude is 0.77 °C/100 m, which is close to the adiabatic lapse rate and suggests that dry katabatic winds may be the controlling factor. When latitude and altitude are taken into account, east coast temperatures are about 10 °C colder than those on the west coast and in the central regions. The transition from the maritime climate of the west coast to the continental climate of the east coast in places occurs within a distance of only 70 km.

8. Local glacier studies

Three quarters of the Earth's total supply of fresh water is in the form of ice and snow and 90 % of this ice and snow is in the Antarctic. An understanding of the behaviour of glaciers and their climatic environment is therefore relevant to studies of the world's water resources. It has been a prime aim of the International Hydrological Decade to determine the heat, ice, and water balances (Unesco/I.A.S.H. 1970; Unesco/I.A.S.H. 1973) and temporal variations of glaciers. B.A.S. contributed to this programme over the years 1972–6 by maintaining two stations in contrasting environments. The northern station was on Hodges Glacier in South Georgia and the southern station was 1800 km further south on Spartan Glacier in Alexander Island. Both glaciers lay on a chain of stations that extended from Alaska in the north to Antarctica in the south. South Georgia, on the Scotia arc of islands that connects the Andes with the Antarctic Peninsula, was chosen to represent the subantarctic oceanic environment. These two representative glaciers were the only glaciers studied along 4000 km of the meridian from Patagonia to the South Pole.

The Hodges Glacier programme was planned and established in collaboration with the Institute of Hydrology. The Institute supplied half of the instrumentation, including two automatic weather stations, and also gave the services of an experienced hydrologist during two summer seasons. A small hut at the foot of the glacier was manned 75 % of the time in order to keep watch on recording instruments, make ice balance measurements, and maintain a flume and V-notch weir to monitor run-off. Six rain gauges and up to 65 snow stakes were maintained over the 4-year period. Data collected between November 1971 and April 1974 have now been analysed. While the ice balance in 1973 was marginally positive, in 1974 it was strongly negative. There was a good correlation between meteorological data obtained on the glacier and at the permanent base at King Edward Point, giving hope that in future it will be practicable to predict the behaviour of the glacier without a major observation programme in the catchment itself (personal communication from I. G. G. Hogg). On the basis of a trigonometric scheme set up in 1972 a fully contoured map of the basin has been completed at a scale of 1:2500 (unpublished map by R. J. C. Hayward).

Analysis of data from two summers showed satisfactory agreement between energy input and observed melt at the meteorological station. The flux of sensible heat was as important as the radiation contribution but the exchange of latent heat was insignificant. Work is in progress to evaluate the energy balance of the whole glacier. At nine sites the radiation input, measured horizontally at the meteorological station, was corrected for topographic screening, surface orientation, slope (which varied between 15° and 45°), and albedo. Together these factors accounted for a reduction in the possible radiation on an infinite horizontal plane ranging from 10% to 83%. The flux of sensible heat was assumed to vary little with position because of the small altitude range of the glacier and the turbulent nature of the wind in the area. Preliminary comparisons between observed and predicted melt at a site high up on the glacier have been encouraging. However the integrated melt observed at the flume was some 16% smaller than that determined by ice balance measurements. This discrepancy may be due to a leak in the catchment and to some uncertainty in the calibration of the flume. The derived relationship between meteorological parameters and glacier mass balance is to be tested by extrapolating back to the International Geophysical Year of 1957–8 by using synoptic data which have been continuously recorded since that time. A comparison can then be made between the predicted size of the glacier and the size actually recorded at the time (unpublished map by J. Smith, scale 1:6015, 1958).

Much further south, on Alexander Island, two small huts were flown into Spartan Glacier where a similar set of meteorological instruments was maintained by a two-man wintering party. This was undoubtedly the smallest wintering station in Antarctica and there was little separation between cramped living quarters and cramped working space. Problems were encountered in maintaining a constant power supply because there was too little wind for the wind generator storage battery system that had been expected to serve as the principal source of power. Spartan Glacier was selected to represent a polar environment, and the programme included a detailed investigation of heat exchange at the surface of the glacier and its relationship with mass balance (Jamieson & Wager, in press). A complex recording system was developed in order to obtain wind, temperature, and humidity profiles to relate to measured incoming and outgoing radiation. Radiometers were mounted horizontally above the sloping glacier surface according to standard practice, but this introduced errors in the determination of radiation components. Approximately half the outgoing short wave radiation was reflected specularly while the remainder was scattered diffusely. This introduced errors of up to 30% in the measured outgoing short wave radiation. It was not possible to calculate a correction because it would involve an uncertain proportion of specular reflexion, as well as the glacier slope, the elevation and azimuth of the Sun. The error could be eliminated in future by mounting the radiometers parallel to the glacier surface.

The change in heat content of the upper 10 m of the snow was measured to ± 10%. Sensible heat exchange was assessed by analysing wind and air temperature profiles up to 5 m. Calculation

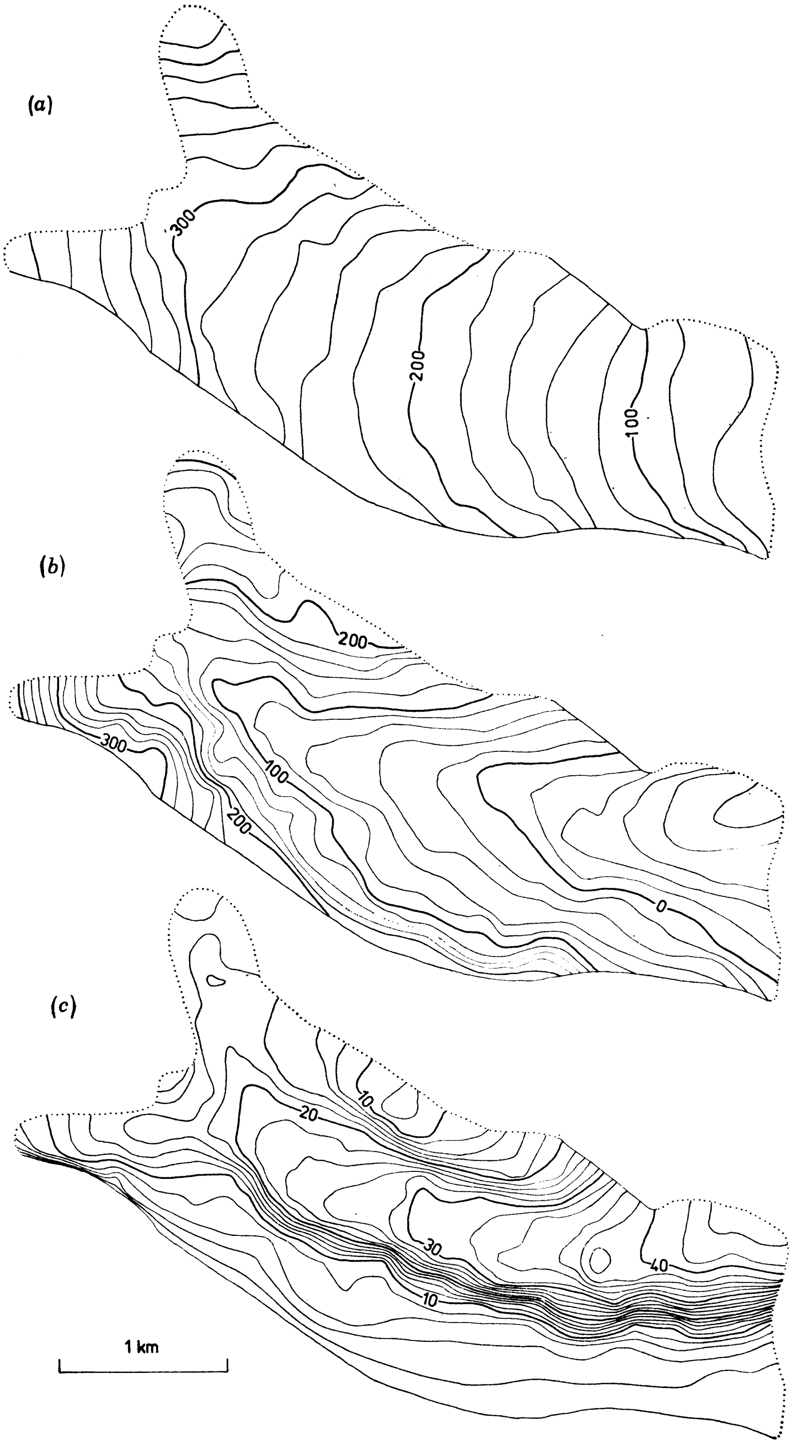

FIGURE 12. Spartan Glacier, Alexander Island. (*a*) Surface elevation (m); (*b*) Bedrock elevation (m); (*c*) Surface velocity (mm/day). The glacier boundary where dotted is indeterminate. Modified from Wager (in press) and Jamieson & Wager (in press).

was complicated because the wind profiles were often characterized by a thin downslope surface wind which produced a turning point in the wind profile. Since this situation has not been adequately treated in theoretical studies, simple logarithmic profiles were fitted to the profiles in order to estimate the sensible heat input. The overall analysis suggests that the mass balance of the glacier is largely determined by the sensible heat input, although the radiative contribution is more significant than it is in the subantarctic environment of South Georgia.

A map has been completed at a scale of 1:5000 together with a series of precise levelling profiles against which even small changes in the volume of ice should be detectable in the future. A stake system was surveyed to determine the rate of movement of the glacier (figure 12*c*) and ice temperatures were found to be -7.7 °C at 10 m depth, which must be close to the mean annual air temperature. To complete the comprehensive study of the glacier an ice-depth survey more detailed than anything yet attempted in any part of the world was undertaken during the winter of 1972 (Wager, in press). The radio echo sounder was mounted on a sledge together with heavy batteries and a $\frac{1}{2}$-wave folded dipole aerial with a 4 m wingspan. The instrument was dragged up, down, and across the glacier along tracks totalling 40 km. Measured ice depths varied from 70 m to 220 m, the smaller being the more difficult to determine because no echo can normally be distinguished during the first 0.8 μs following the transmitted pulse. However the actual ice/rock boundary at the sides of a valley glacier serves as a reliable zero ice depth, allowing subglacial cross profiles to be interpolated where the ice is too shallow for radio sounding (figure 12*b*).

One of the objects of these local glacier studies is to reach a point at which it will be possible to predict the state of health of a glacier from the prevailing meteorological conditions. However, at any given time one glacier may be retreating whilst a neighbouring glacier is advancing. It is therefore vital to assess regional glacier behaviour before general statements can be made. This has been carried out in South Georgia by examining early photographs and maps. Work has begun recently on establishing height profiles across a series of glaciers between fixed points away from the glacier margins; the same profiles should be remeasured later. Such measurements will lead to more reliable estimates of regional ice volume changes. It is planned to establish similar profiles at points widely distributed along the Antarctic Peninsula so that changes can be correlated with climatic trends observed at meteorological stations.

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Note added in proof (December 1976). Following the realization of the true size of Mount Haag (figures 3 and 7 and p. 169) it has since been renamed Haag Nunataks.

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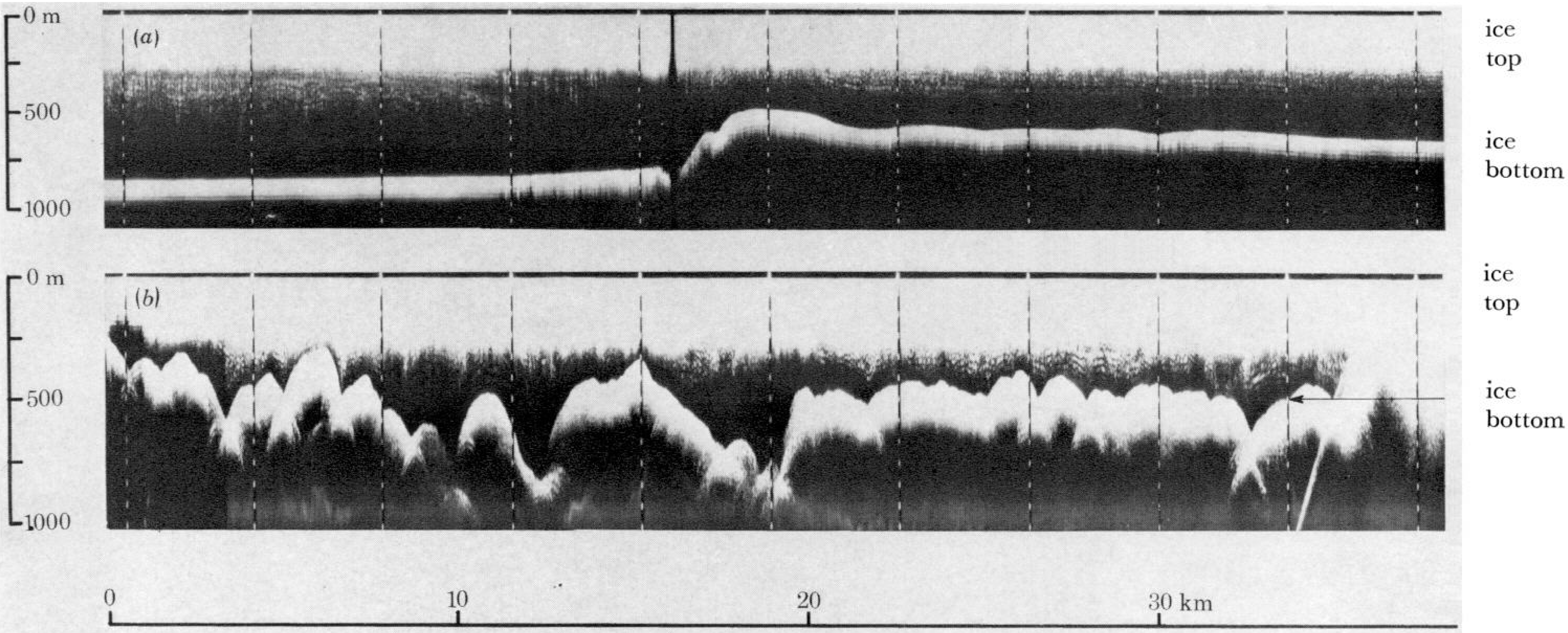


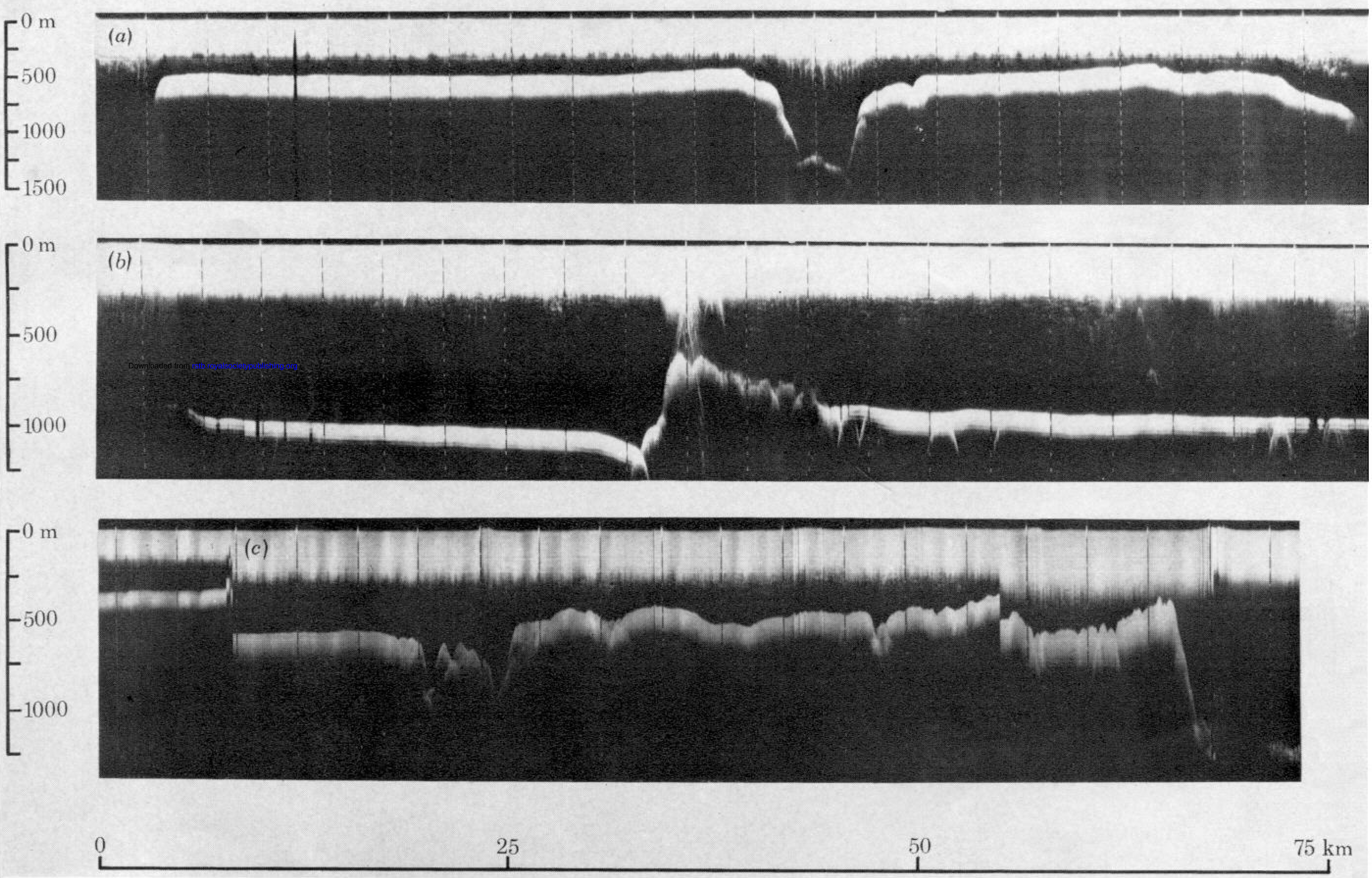
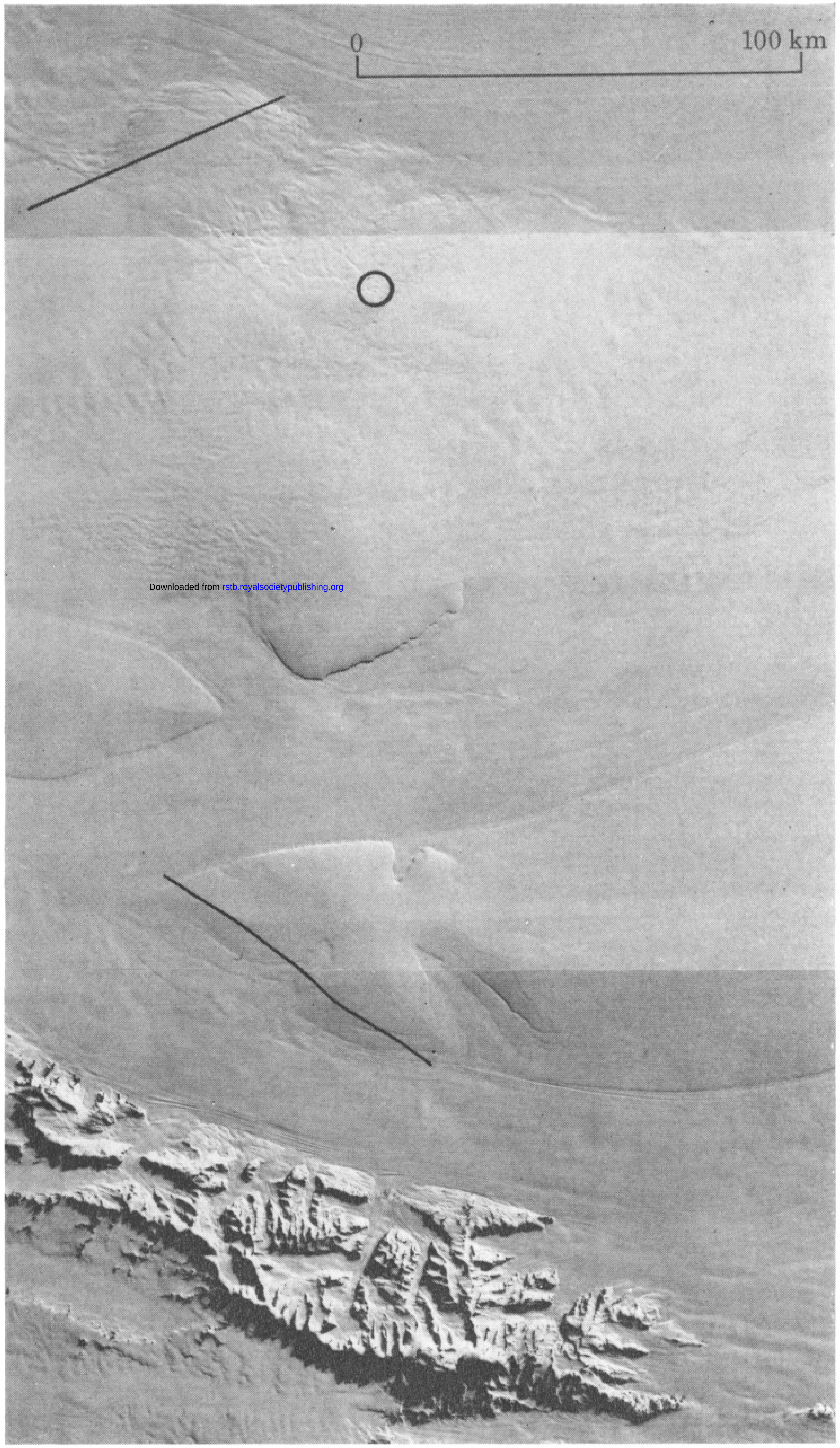
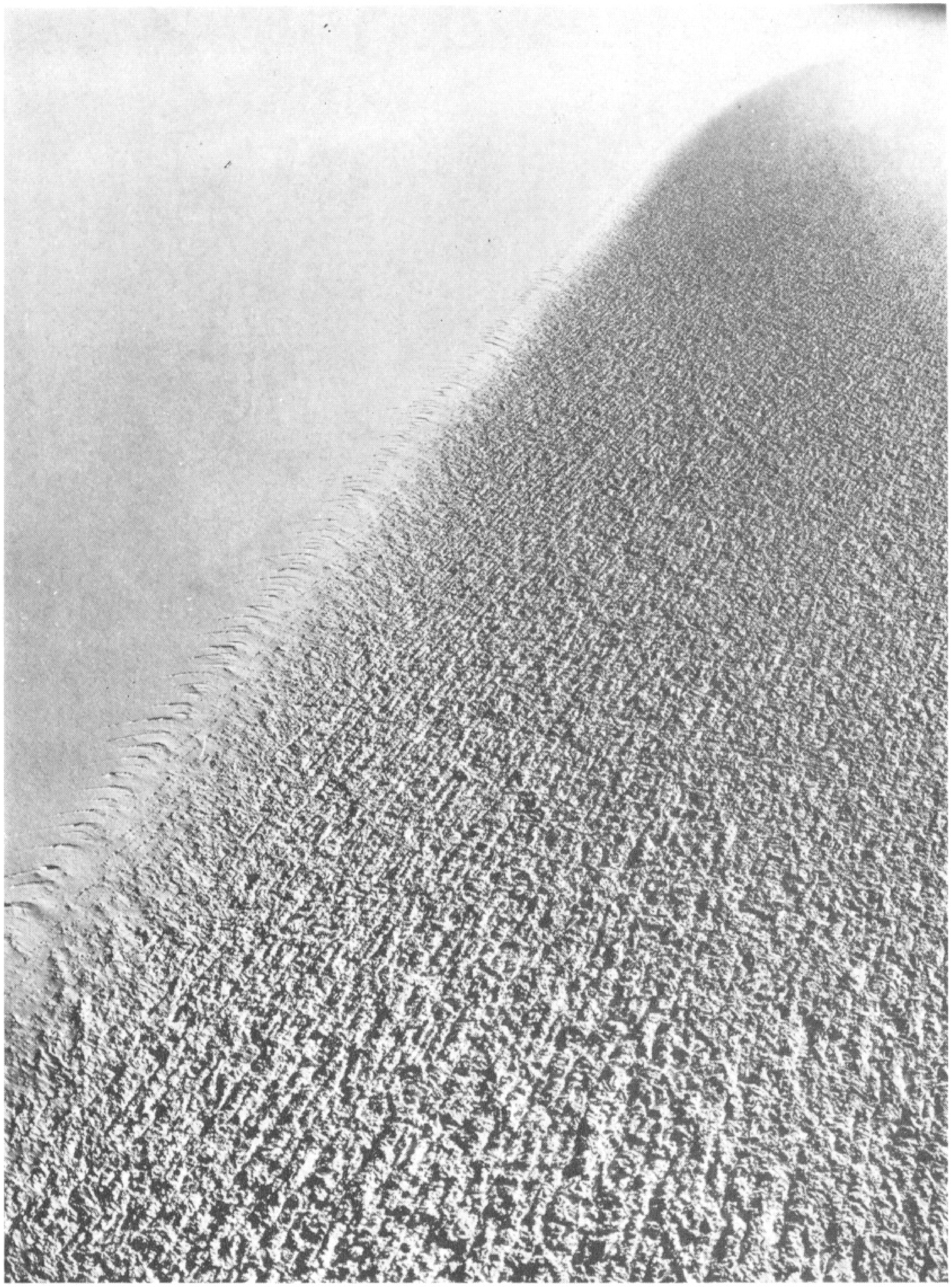


FIGURE 7 (above). Contrasting examples of subglacial relief: (*a*) Smooth seawater surface beneath 800 m of floating ice on Ronne Ice Shelf (left) and smooth rock surface beneath Korff Ice Rise (right); (*b*) subdued alpine relief north of Mount Haag. Mount Haag itself interrupts the bottom echo (far right).

FIGURE 8 (below). Subglacial features also identified in satellite pictures: (*a*) isolated valley in plateau (see lower flight track in figure 9); (*b*) 1100 m thick floating ice (left) dammed up behind locally grounded area in 78° 45′ S, 75° 40′ W giving rise to bottom crevasses (hyperbolic echoes) on thinner ice shelf (right); (*c*) ice sheet bordering northern ice stream (see upper flight track in figure 9). The jumps in the bottom echo represent oscilloscope scale changes made by the operator. The vertical scale bar (left) refers to the middle portion of the trace.





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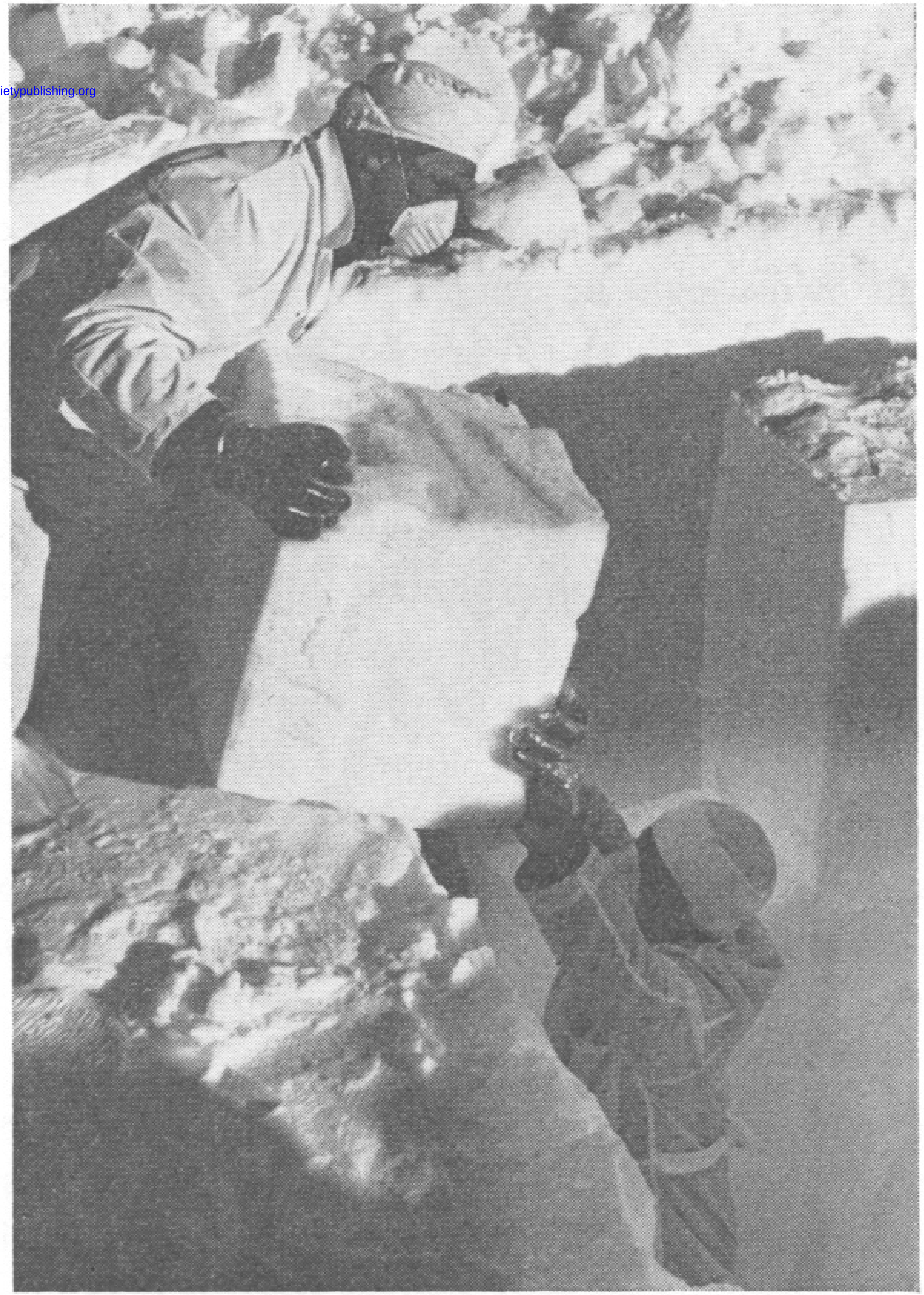
FIGURES 9 AND 10. For description see opposite.



IGURE 11. Glaciologists in surgical clothing take clean snow samples to study very low levels of impurities.