PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

International Studies of Ice Sheet and Bedrock

G. De Q. Robin, D. J. Drewry and D. T. Meldrum

Phil. Trans. R. Soc. Lond. B 1977 **279**, 185-196
doi: 10.1098/rstb.1977.0081

Phil. Trans. R. Soc. Lond. B. **279**, 185–196 (1977) [185]
Printed in Great Britain

International studies of ice sheet and bedrock

By G. de Q. Robin, D. J. Drewry and D. T. Meldrum
Scott Polar Research Institute, Cambridge

[Plates 1 and 2]

The main Antarctic ice sheet is so vast that large-scale international programmes are necessary for an adequate study of its dynamics, thermodynamics and past history. Radio echo sounding methods are providing reconnaissance mapping of the ice sheet on a continental scale. The soundings also yield significant information on the internal deformation of the ice sheet, on the flow of ice shelves and the nature of the bottom surface of the ice. This information is being used to amplify and extrapolate detailed results from other groups who are studying the mass balance, ice movement, and past history by deep drilling; it is also of value in isolating critical sites for future studies. Reconnaissance mapping has now shown the presence of sub-ice lakes larger than those reported in 1973. Studies of radio wave reflexions from internal layers which are believed to be former depositional surfaces, have shown that the conformity between these layers and the bedrock relief decreases as ice movement increases. Statistical analyses of bedrock relief and radio wave reflexion parameters are being used to delimit major geological provinces beneath the ice and investigate the structural and lithological transition between the Transantarctic Mountains and East Antarctica. Such studies have recently indicated the presence and structure of two large intra-cratonic sedimentary basins in eastern Antarctica.

Introduction

It is perhaps a paradox that under the excellent umbrella for international cooperation provided by the Antarctic Treaty, national pride in scientific accomplishment in Antarctica still plays an important part in the process of raising funds for Antarctic programmes. The intrinsic merits of these programmes, the growing complexity and relevance to other disciplines of the problems they study, and the vast scale of the Antarctic Continent are three factors which underlie what is probably a unique combination in the world today of group initiative, national patronage and international coordination in scientific research.

Work in Antarctica is still mostly carried out by national groups, their programmes being coordinated by the Scientific Committee on Antarctic Research (S.C.A.R.) and by the unions and committees of the International Council of Scientific Unions (I.C.S.U.). We want however to direct attention to a new type of cooperation which is increasing in studies of the ice sheet and bedrock, under programmes such as that of the International Antarctic Glaciological Project. In these programmes, smaller groups, usually from three or more nations, direct scientific and logistic resources to tackling problems that need a more widely-based approach than is possible under a national programme. In most cases this means organizing research on a regional rather than an Antarctic-wide basis, as for the G.A.P. (Glaciology of the Antarctic Peninsula) project.

In other cases, participation in programmes by a group who have a particular expertise enables them to apply their technique to a wide range of problems. The work of Dansgaard and colleagues on isotopic analysis of ice cores from many locations in Greenland and Antarctica is a case in point. Radio echo sounding of ice sheets from long range aircraft over Greenland and Antarctica provides another example of making the best use of expertise in several countries to help a range of studies in polar glaciology.

The development of radio echo sounding techniques need not be reviewed in this paper (see Robin 1972, 1975*a*; Bogorodskiy 1968; Evans & Smith 1969). Now that the basic principles have been established by various groups, the need is for systematic exploitation of the method, while further advances are likely to come from developments of more sophisticated equipment and techniques. Both the Scott Polar Research Institute (S.P.R.I.) in England and the Electromagnetic Laboratory of the Technical University of Denmark (T.U.D.) have cooperated for some years with the Division (formerly Office) of Polar Programs (D.P.P.) of the National Science Foundation of the U.S.A. in long-range flying programmes over Antarctica and Greenland. It was therefore logical for the D.P.P. to propose that, since the same aircraft was being operated over both areas, the S.P.R.I. and T.U.D. should standardize their methods and use the same equipment. This has proved advantageous, since it has meant that the considerable expertise in electronic and antenna design at the T.U.D. was directed towards development of new equipment in 1974 to replace the older S.P.R.I. mark IV system that had been in use since

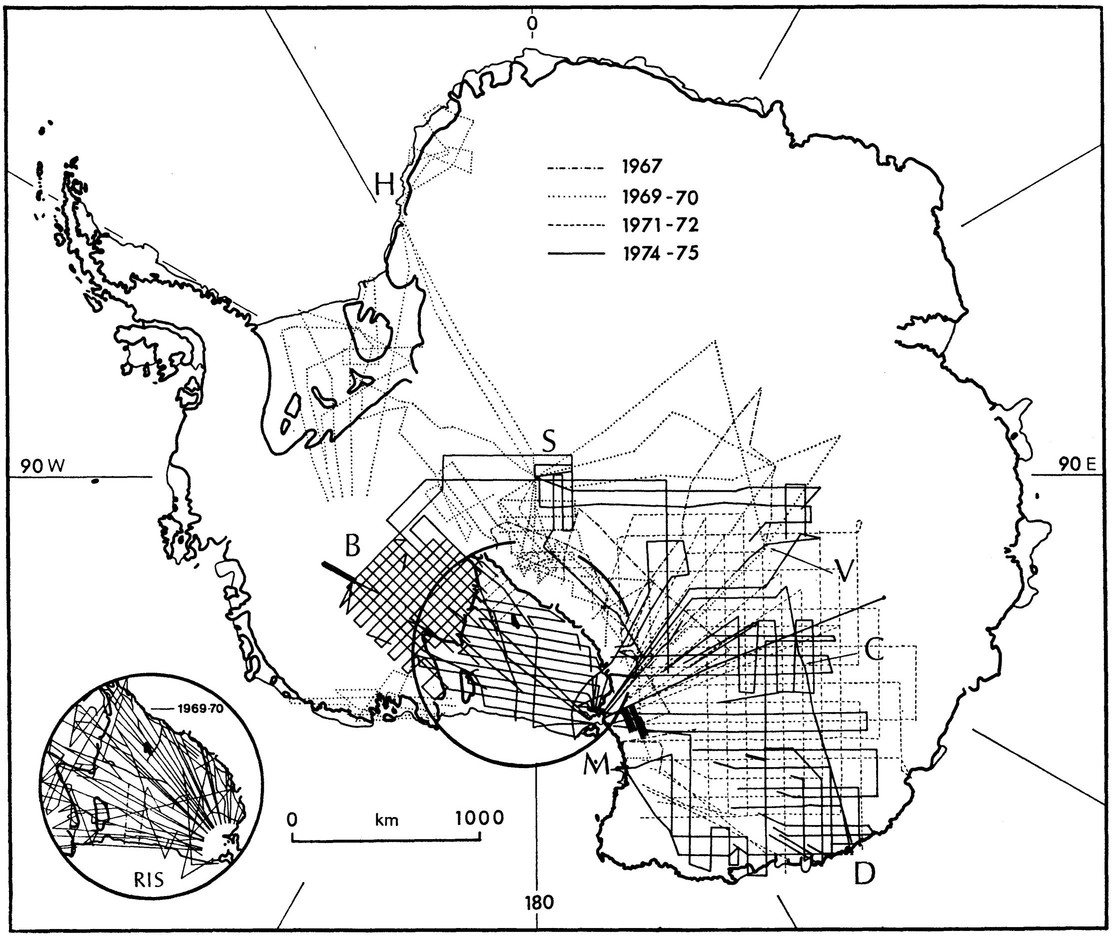


FIGURE 1. Radio echo sounding flightlines in Antarctica undertaken during N.S.F.–S.P.R.I. operations in 1967, 1969–70, 1971–2, and N.S.F.–S.P.R.I.–T.U.D. operation 1974–5. The inset shows 1967, and 1969–70 flightlines over the Ross Ice Shelf. Antarctic Stations: B, Byrd Station; C, Dome 'C'; D, Dumont D'Urville; H, Halley Bay; M, McMurdo; S, South Pole.

1969. The S.P.R.I. group has been able to work on new methods of automatic data reduction, and other aspects of radio echo sounding. These include the study and detailed recording of bottom roughness and echo strengths, problems of radio propagation in polar ice, dynamics and thermodynamics of large ice masses and geophysical investigations of subglacial geology. Access to radio echo records by scientists in the U.S.A. interested in similar topics has also been profitable and is expected to increase further.

Mapping

One prime need in the study of Antarctic Earth sciences is the provision of adequate maps of both the ice surface and the bedrock surface beneath the ice. Figure 1 shows the useful flight lines covered by the N.S.F.–S.P.R.I. programme in 1967, 1969, 1971 and 1974 seasons, the last being carried out in cooperation with the T.U.D. One major advance has been the provision by the D.P.P. of inertial navigation systems in the aircraft since 1971, which has made it possible to fly a systematic network of flightlines over featureless areas. Mapping of about 2×10^6 km^2 of East Antarctica, provided in S.P.R.I. map series A, no. 3 (Drewry 1975*a*) has met a primary need for development of the International Antarctic Glaciological Project. The thickness map of the Ross Ice Shelf (Robin 1975*b*) has also helped to direct planning of the multidisciplinary Ross Ice Shelf Project. A map of Byrd Land at present being prepared by K. E. Rose in the S.P.R.I. is expected to provide accurate data on which the West Antarctic Ice Sheet Project can be planned. Further maps of other areas will be provided as more data is collected.

Radio echo techniques

Certain aspects of radio echo sounding are similar to marine echo sounding, especially difficulties arising from use of a broad beam of energy. While Harrison (1970) has developed deconvolution techniques to produce a more accurate surface profile from the proliferation of hyperbolae and cusps that one records over rough terrain, the T.U.D. group have designed an antenna and radio echo system operating at 300 MHz. This equipment has a much narrower beam width, which eliminates most of the troublesome hyperbolae that are inherent in the 60 MHz pulse system. Figure 2, plate 1, shows simultaneous records by the two systems obtained through the ice sheet a short distance inland of the McMurdo Sound ice-free area. While the clarity of the 300 MHz system is obvious, it can be seen that this system at present lacks the depth of penetration of the 60 MHz equipment. Although this is partly due to increased absorption of radio waves by ice at the higher frequency, the problem may be overcome by increasing the power used in the 300 MHz equipment. The advantages of the 300 MHz system for rough terrain beneath ice of limited depth is obvious. The technique was most valuable in survey by closely spaced flightlines of the bedrock relief under the ice sheet inland from McMurdo Sound. Earth scientists from the U.S., Japan and New Zealand studying this area under the Dry Valley Drilling Project (D.V.D.P.) need to understand the control exercised by bottom relief on past and present advances of glaciers into these valleys. The possibility that ground water emerging in the valleys originates from the bottom of the ice sheet may also be solved by radio echo sounding, either by direct observation of sub-ice lakes or water pockets or by calculations of thermal régime of the ice sheet using depth measurements combined with other glaciological data.

Echo strengths and reflexion coefficients

Radio echo returns from bedrock beneath the ice show rapid fluctuations in intensity as one moves over the surface. The theory of this rapid fading, based on earlier work on radar returns by Beckmann & Spizzichino (1963) has been further discussed by Harrison (1972), Berry (1973), and Oswald (1975). Detailed field measurements made on Devon Island in 1973 by Oswald (1975) have shown which aspects of the theory are satisfactory, and also showed that different rock types beneath the ice have different reflexion coefficients that can be measured if sufficient calibrated data is available. The most direct quantitative system is to photograph calibrated A-scope records of the received pulse (figure 3*b*, plate 1). Due to rapid fluctuations in echo strength, one needs an A-scope photograph every 1 or 2 m of path, as was shown in the Devon Island studies. For airborne work, a rapid ciné camera record taking 54 frames a second has been used in Antarctica, but owing to the large amount of film and data involved, such rapid runs were taken routinely only every 16 min or on operator demand in special situations. Automatic data-processing methods are being developed to handle over one million A-scope records we now hold.

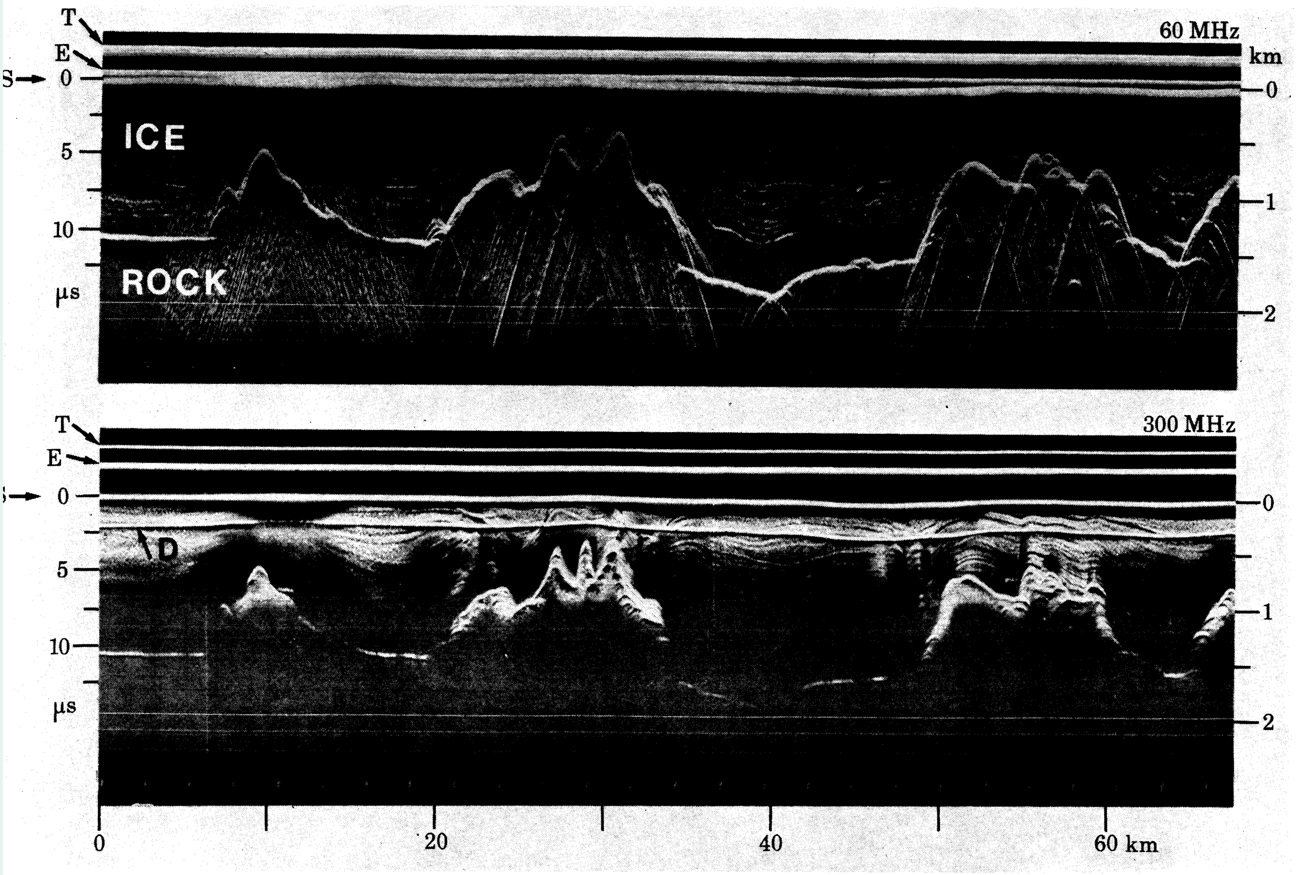
A technique of continuous echo strength measurement (e.s.m.) recording developed at the S.P.R.I. by C. S. Neal (1976) was used in the 1974–5 antarctic season to collect this type of data for analysis. This is done by applying the receiver output to the Y plates of an oscilloscope while running film continuously through an oscilloscope camera (figure 3*c*). This shows an output of echo strength against distance, obtained during the survey of the bottom roughness of the Ross Ice Shelf in 1974–5 (figure 1, main map, parallel flightlines). Figure 3 shows that over part of the track, the echo strength is practically constant, as for specular reflexion, then on other sections it drops in echo strength and undergoes rapid fading. This may be due to the opening of crevasses and penetration of seawater into the base of the ice shelf, or to some genuine roughness of the bottom surface. Although the greatest part of the Ross Ice Shelf shows a 'rough' bottom, there are large areas such as those near the ice front where reflexions indicate a smooth lower surface. Such information will be useful when selecting borehole sites on the ice shelf for the Ross Ice Shelf Program. Similar contrasts were observed during soundings of the Filchner and Ronne Ice Shelves in 1969–70, although in this case it was the ice of about 1000 m in depth that showed the smooth bottom surface, in contrast to the strong fading on the thinner parts of the Ronne Ice Shelf.

Description of plate 1

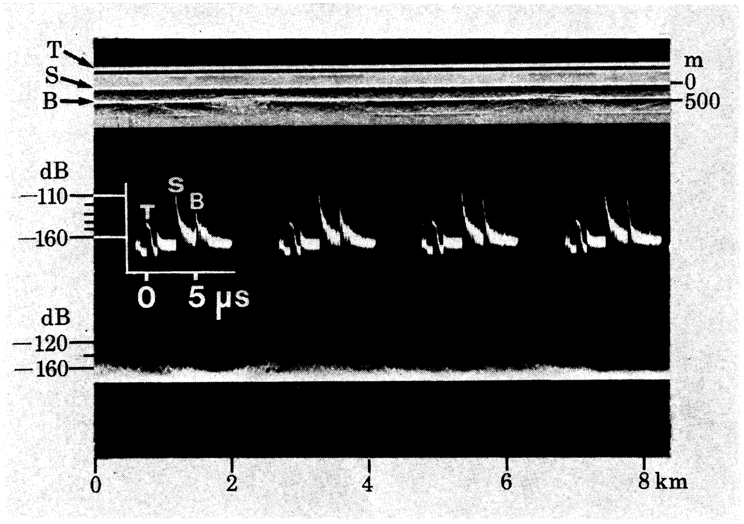
Figure 2. Simultaneous radio echo records inland of the McMurdo ice-free area. The upper print shows a record from the 60 MHz system; the lower one from 300 MHz system. Echo delay times (in μs) for one-way travel time are given on the left. Ice depth in kilometres is on the right. T, transmitter pulse; E, end of receiver suppression; S, ice surface return; D, multiple reflexion from ice surface.

Figure 3. 60 MHz 'Z-scope', 60 MHz 'A-scope' and 60 MHz e.s.m. recordings over an 8 km portion of the Ross Ice Shelf. The upper record (*a*) shows a 60 MHz 'Z-scope' profile with the ice depth scale on right, T, S as in figure 2; B is bottom. The middle record (*b*) shows 'A-scope' frames taken every 20 s, with the left-hand frame calibrated for amplitude of signal against one-way travel time. Automatic time calibration scales are also visible on the right-hand frame. The lower record (*c*) shows continuous echo strength measurements (e.s.m.).

Figure 4. Radio echo record (1974–5) of sub-ice lake in the vicinity of Vostok station, using a differentiated output. This section corresponds to line XY on figure 5.



IGURE 2

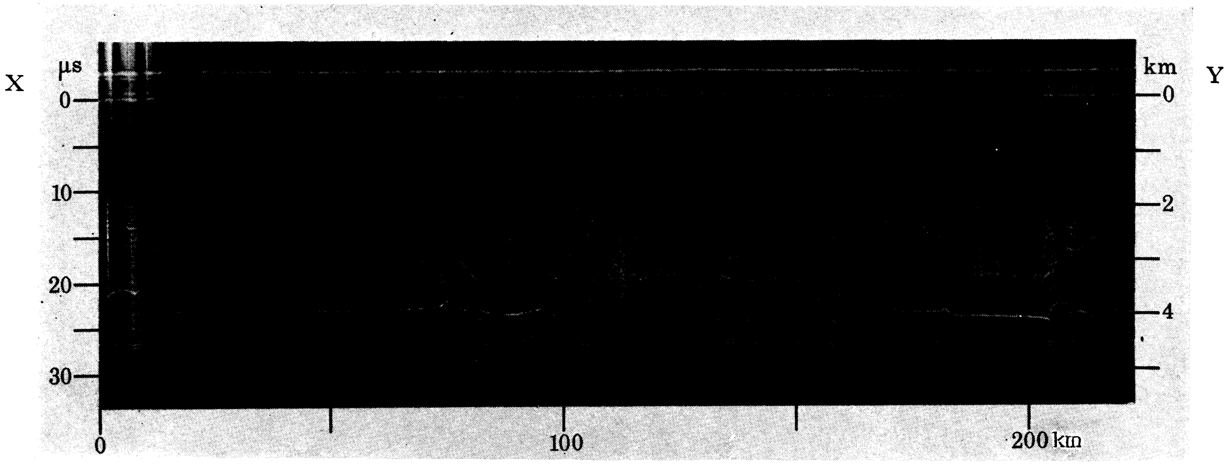


(*a*)

FIGURE 3 (*b*)

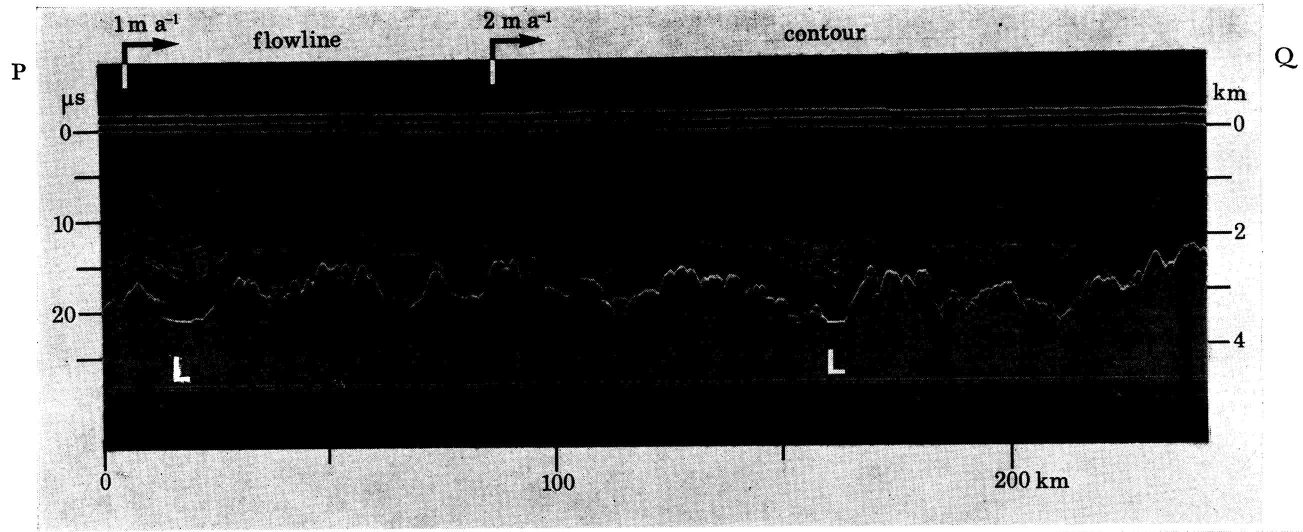
(*c*)

FIGURE 4



FIGURES 2–4. For description see opposite.

(*Facing p.* 188)



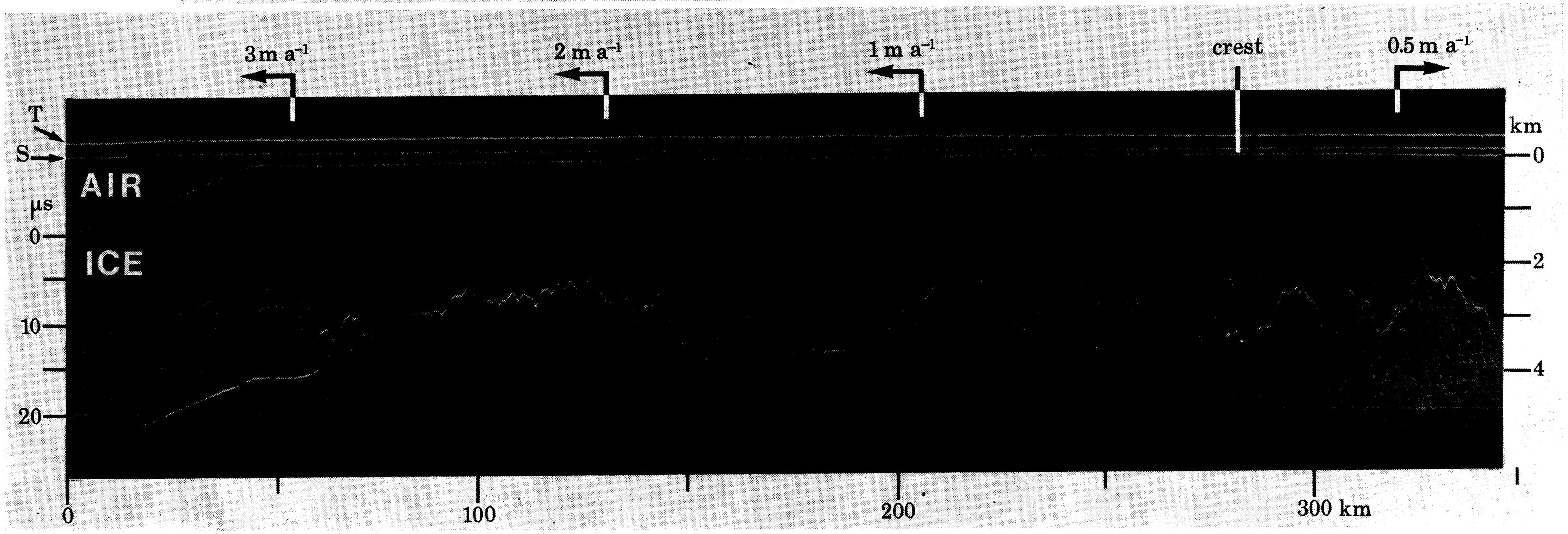


FIGURE 6. Radio echo profile showing bedrock, two small sub-ice lakes and internal layering near dome 'B' in central Antarctica. The section on the left lies along a flowline, that on the right shows the profile along a surface contour of the ice sheet. Profile location shown by line PQ on figure 5.

FIGURE 7. Radio echo profile across the crest of the ice sheet to the sub-ice lake shown in figures 4 and 5. The profile lies along a flowline and shows changes in deformation of layers as the ice movement increases away from the crest of dome 'B'. Profile location shown by line RS on figure 5.

SUB-GLACIAL REFLECTING SURFACES – LAKES

The presence of substantial areas of water deep under the inland antarctic ice was first suggested in 1968 to explain the occurrence of anomalously strong echoes at a depth of 4200 m near Sovetskaya (Robin, Swithinbank & Smith 1970). Subsequent work by Oswald on the results of the 1971–2 N.S.F.–S.P.R.I. Antarctic field season showed that smooth surfaces with high reflexion coefficients and a lateral extent of a few kilometres were not uncommon in East Antarctica (Oswald & Robin 1973). Further examples were found during the 1974–5 joint N.S.F.–S.P.R.I.–T.U.D. field season. A detailed study of the reflexion properties of 17 such sites led to their being termed lakes, a description which was corroborated by the observed tendency of the sites to be concentrated in rock basins in areas of low surface slope and low ice velocity (e.g. dome C), in general agreement with the requirements of hydrostatic equilibrium and low rates of debris deposition. Later density calculations based on the same season's data added further weight to the identification of the features as subglacial lakes (Oswald 1975).

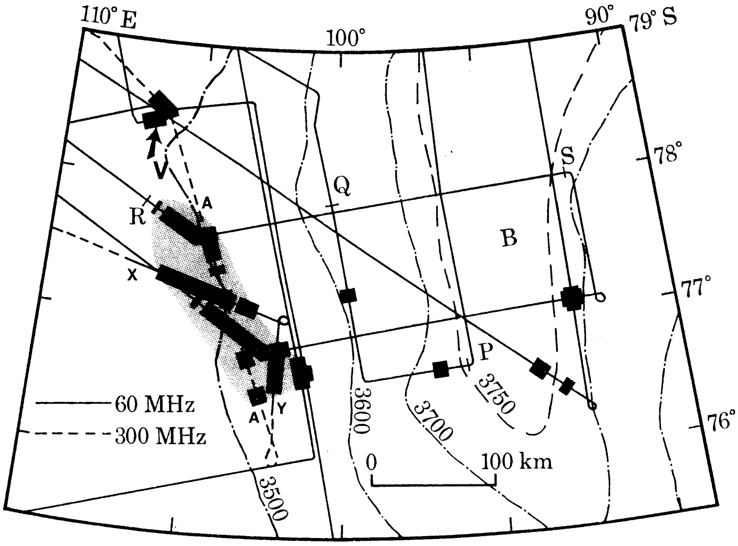


FIGURE 5. Sketch map of the location of sub-ice lakes detected by radio echo sounding in the dome 'B'–Vostok station (V) region. Flight tracks for 1971–2 and 1974–5 seasons are shown. Thickened portions of the lines locate sub-ice water bodies. The contours represent height in metres above sea level.

Whereas the lakes reported by Oswald are of the order of the ice thickness in lateral extent, a much larger one, centred about 150 km NNW of Vostok (figure 4, plate 1), was discovered during the 1974–5 season. In the course of an informal discussion of this feature, an exchange scientist at McMurdo Station, I. A. Zotikov from the U.S.S.R., drew attention to a report by Robinson (1960), senior aviation navigator with the Soviet Antarctic Expedition of 1959, on the existence of shallow snow surface depressions in the Vostok area. He wrote:

> 'Natural landmarks in the interior of the continent include, in addition to individual mountains and mountain ridges, oval depressions with gentle "shores" which are visible from an airplane over the plateau. The depth of these depressions usually does not exceed 20–30 m and their length, 10–12 km. These unusual depressions are sometimes called "lakes" by pilots. These "lakes" are clearly distinguishable from the air as spots against

> the white background of the plateau, especially when the angles of course of the sun are close to 180°.'

A subsequent flight over the large subglacial lake did in fact give visual confirmation of this, with the 'shores' showing as areas of whiter snow which corresponded well in some cases with the edges of the radio echo lake. We would suggest that these 'lakes' are visible because of the difference in appearance of a uniform flat surface (the 'lake') and a gently sloping one (the 'shore'). This could be due either to changes in albedo caused by differences in relative sun angle between the two surfaces, or less directly to changes of texture resulting from differing snow accumulation rates.

The extent of the subglacial lake cannot be unambiguously defined, since unfortunately one of the radio echo recording cameras jammed during part of this flight, but the impression formed at the time was that lake echoes were present over much more of the discontinuous section AA shown in figure 5. Careful inspection of 1971–2 records also revealed lake echoes on tracks close to this area. We believe that all these echoes originate from a practically continuous body of water, the long dimension of the lake being about 180 km with a typical width of 45 km. The ice thickness over the lake is about 3.95 km with the water surface situated at a fairly uniform depth about 500 m below sea level.

The removal of basal friction over such a large area must be expected to produce some effect on the upper surface of the ice sheet, and in our case of a substantially level basal surface, a level upper surface seems a plausible result. Our measurements are not sufficiently precise, but indicate a mean surface slope of less than 1 in 2000 compared with the regional value of about 1 in 700.

Numerous smaller lakes and wet areas of the type described by Oswald (1975) were also identified in the Vostok region, as shown in figure 5, together with one of intermediate size within a few kilometres of Vostok station (lake position approximately 78° 27′ S, 106° 45′ E). This appears to be at least 15 km long and ties in with previous observations of a depression in the internal layering at Vostok (Robin, Swithinbank & Smith 1970). The ice depth here is approximately 4.05 km with the water surface depressed about 650 m below sea level.

INTERNAL REFLEXIONS FROM LAYERING IN ICE SHEETS

Internal reflexions of radio waves from layers within the Greenland ice sheet were first reported in Bailey, Evans & Robin (1964), and they have since been observed over wide areas of the Greenland and Antarctic ice sheets. Gudmandsen (1975) has discussed results from Greenland in some detail, Harrison (1972) and Paren & Robin (1975) have also considered possible causes of these reflexions.

Robin, Evans & Bailey (1969) showed that a reflecting layer at depths from 350 to 450 m that was observed over a line for 40 km to the south of Camp Century, Greenland, formed the surface of the ice sheet about 1000 a B.P. New evidence that these internally reflecting layers represent former depositional surfaces (isochrons) has recently been provided by comparison of radio echo soundings along the Byrd Station Strain Network (Whillans 1976) with measurements of surface strain rate, ice movement and net accumulation (Whillans 1973). Using the latter measurements Whillans calculated the depth of the isochrons of 2500, 5500 and 30000 a B.P. on a simple vertical column model that does not involve the ice depth. He found that these isochrons matched certain internally reflecting surfaces quite closely. He has concluded that although the depth of ice in this region may have undergone small changes during the last 30000 years, no major changes of ice flow can have taken place along this line during this period.

Since the stability of the ice of Byrd Land has been suspect for some time (Johnsen, Dansgaard, Clausen & Langway 1972; Hughes 1973; Weertman 1975, 1976; Thomas 1976), this is a conclusion of importance both to glaciologists and those studying sea level changes. Robin (1977) has also pointed out the importance of the work to climatologists interpreting isotopic changes in the Byrd ice core. This comparison of isochrons calculated from strain measurements and the use of internal radio reflexions provides an admirable example of the value of bringing together techniques from different laboratories and different countries to throw light on a central glaciological problem.

Table 1. Proportional thickness variations between different layers on figure 7

position on distance scale/km	bedrock morphology	proportional thickness between horizons (1) surface to layer 1	(2) layer 1 to layer 2	(3) layer 2 to layer 3	(4) layer 3 to bedrock
55	lake	1.00	0.92	0.54	0.41
68	peak	1.00	0.85	0.59	0.40
77	valley	1.00	0.76	0.47	0.92
98	peak	1.00	0.76	0.59	0.36
113	rough level	1.00	0.73	0.53	0.66
128	peak	1.00	0.87	0.56	0.51
185	deepest valley	1.00	0.82	0.54	0.89
213	peak	1.00	0.76	0.50	0.33
258	peak	1.00	0.83	0.59	0.28
287	valley near crest	1.00	0.78	0.49	0.68
mean value		1.00	0.81	0.54	0.54

There is no alternative hypothesis that can explain the continuity of internally reflecting layers over hundreds of kilometres in Greenland and Antarctica. We can therefore discuss the flow and deformation of the Antarctic ice sheet, as seen in figures 6 and 7, plate 2, on this basis. Simple age-depth calculations (Dansgaard & Johnsen 1969) based on a long-term mean ice accumulation of 2.0 cm a^{-1} in central Antarctica indicate that the deepest layers seen on figures 6 and 7 are 200000 years old, as minimum.

Figure 6 shows two types of profile, the section on the left being along the flowline of ice, while the right-hand section follows a contour. Layering on the latter conforms much more closely to the underlying relief than along the flowline. The same effect is seen in figure 7, which follows a flowline across the crest of a ridge (dome B) where ice movement is assumed to be zero. Estimated ice velocities on figures 6 and 7 are based on steady-state calculations, which have been approximately confirmed by astronomical determinations that show Vostok station to be moving at about 3 m a^{-1} (Liebert & Leonhardt 1974). We see in figure 7 that conformity between internal layering and bedrock relief decreases as the ice velocity increases. This fits the concept of relatively rigid upper layers of ice sliding over less rigid lower layers which can deform more easily due to warmer ice temperatures.

We have traced the position of three layers between 58 and 287 km on figure 7, the deepest layer (3) being of an estimated age around 180000 years, layer 2 around 113000 years and layer 1 around 52000 years. In table 1 we show the way in which the thickness between the various layers varies along this flowline by normalizing values to the thickness between the surface and layer 1 at each point. In spite of inaccuracies in following individual layers, we see that in 90% of the measurements, the height of the ice column between the internal layers varies in the same proportion as that between the surface and layer 1 to within ±10% of the mean value. This means that as a first approximation, use of a vertical column model involving uniform vertical strain, as used by Whillans above, is satisfactory.

Between layer 3 and bedrock however, the layer thickness varies by a factor approaching two around the mean value, as can readily be seen in figure 7. In this layer, shear stresses τ_{xy} will be dominant near bedrock, whereas in the upper layers longitudinal stresses, or more strictly the difference between horizontal (σ_x) and vertical stresses (σ_y) will cause most deformation. In the upper layers, which are colder and of much greater rigidity, the ice is seen to move as a slab which deforms uniformly throughout to match changes in ice thickness. This contrasts with the layer above bedrock where shear strain rates must vary considerably along the flowline. It is hoped that this type of information from radio echo sounding can be used to develop useful modifications of the theory of ice flow given in Budd (1970).

Although the system performance is sufficient to record internal reflexions to 3500 m over the lake around 58 km, internal reflexions fade out at 100 km at about 2500 m depth, 500 m above bedrock. Near the centre of outflow, from about 290 to 330 km, layering is seen to be closer to bedrock especially over peaks. In central Greenland where the ice is 3000 m thick and bedrock is relatively flat, Gudmandsen (1975) shows ‘traces of layers about 200 m above bedrock’.

The maximum depth at which layers can be detected depends on radio echo system performance, absorption of radio waves in ice, and on variations of layer thickness with depth. These factors have been discussed in papers already mentioned. In figure 7 we see that the separation between the deepest visible layer and bedrock increases as we move away from the centre of outflow and is a maximum over deep valleys. We must remember that figure 7 is a two-dimensional cross-section of a three-dimensional problem. In the lower levels ice may tend to flow around rather than over subglacial peaks, as may occur at 326 km. These considerations, along with the variability of shear strain rates in the lowest layers, lead to the suggestion that layering is not visible on the records at the lowest levels because it is no longer present, due to the variable deformation over a rough relief. This concept calls into question the validity of dating of ice cores close to bedrock since uniform deposition and strain is used in calculating dates at these levels. A similar point has been made in relation to the ice core from Camp Century in Robin (1977).

Where continuity of radio echo layering is clear, there is little doubt that age continuity down the core is satisfactory. Where there is no layering present and the system performance is adequate in relation to absorption, serious doubts about continuity arise. Radio echo surveys upstream of possible sites of future ice coring programmes are needed to select the sites with the least disturbance of stratigraphy. Such sites include the vicinity of dome C (74° 30′ S, 123° E), although ice depths of 3800 m may prove too great. The South Pole itself, and the ice domes between the Pole and the Transantarctic Mountains also warrant a careful radio echo survey for this purpose.

GEOLOGY–GEOPHYSICS

Since less than 5% of Antarctica is accessible to surface geological investigations, remote sensing techniques are used to provide information on terrain characteristics, bedrock composition and structural details. Radio echo sounding is one of several geophysical techniques used for the interdisciplinary and international scientific study of the continent beneath the ice. In 1971 S.C.A.R. drew attention to a number of current geological problems in Antarctica. Of these, the S.P.R.I. radio echo group has been involved particularly in determining the configuration of the sub-ice bedrock surface, investigation of crustal provinces within central East Antarctica and examination of the lithological and structural transition between the Transantarctic Mountains and East Antarctica.

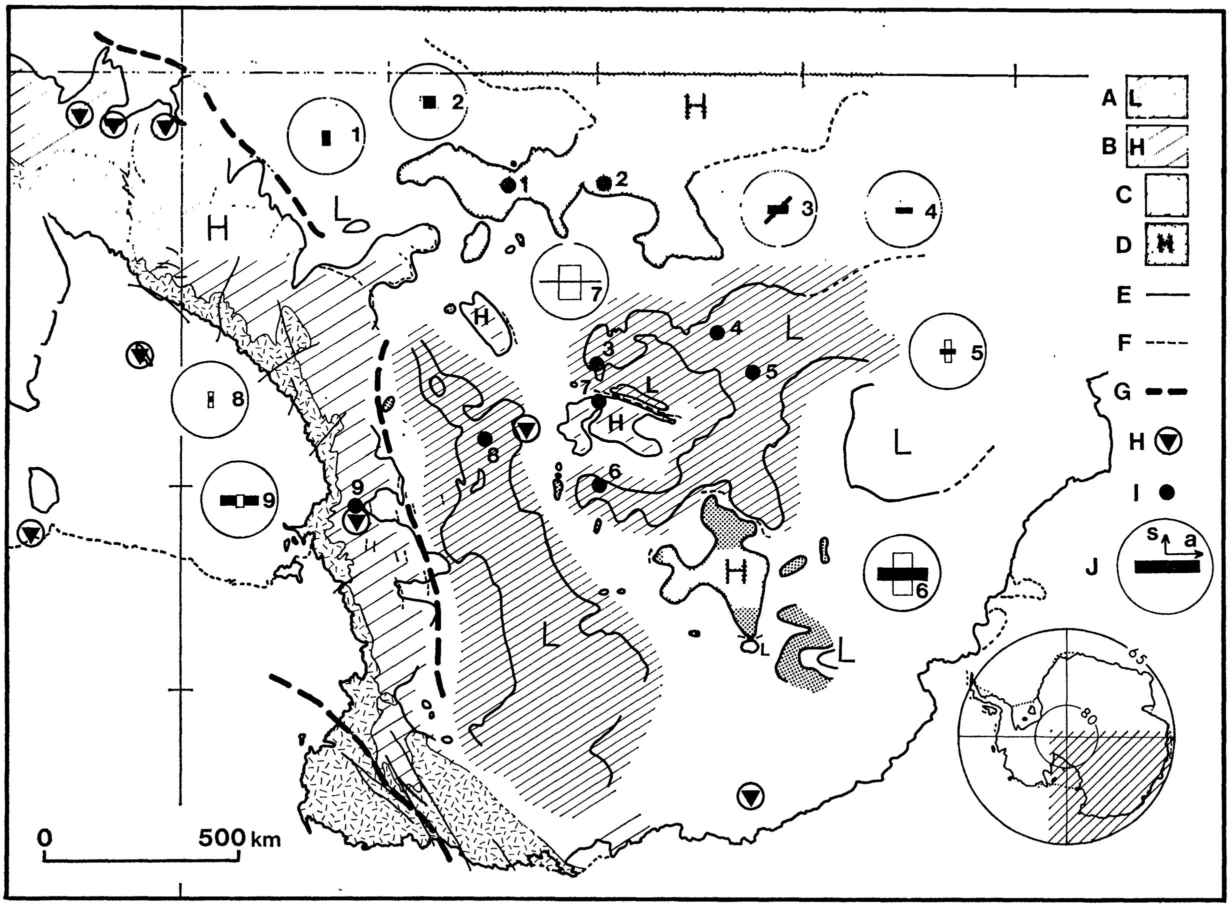


FIGURE 8. Geological elements of East Antarctica, principally from radio echo sounding. A, sedimentary basins (the included contour is −500 m a.s.l.; L, low); B, areas of Beacon Supergroup strata, exposed or inferred from radio echo sounding (the bounding contour is +250 m a.s.l.; H, high); C, exposures of granitic and metamorphic basement of the Transantarctic Mountains; D, undifferentiated highland (areas above +250 m a.s.l.; H, high); E, faults detected from surface investigations; F, faults inferred from radio echo soundings; G, inferred boundaries of orogens; H, location of significant seismic refraction profiles; I, location of terrain fabric studies (numbers correspond to fabric diagrams given under J); J, fabric diagrams at numbered localities (I). Autocorrelation distance (a) and standard deviation (s) of elevations were determined in two orthogonal directions (or more), open lines, grid north–south direction; solid lines, grid east–west direction. The length of lines corresponds to the autocorrelation distance (a = 20 km). The thickness corresponds to value of standard deviation (s = 300 m).

Bedrock configuration of Antarctica

Since 1967, 345000 km of airborne radio echo profiling has been accomplished, primarily in East Antarctica (sector 90° E–180°), while in 1974–5 over 0.5×10^6 km^2 of West Antarctica (Marie Byrd Land) were mapped systematically. Flights, organized on a grid network of scale either 50 or 100 km have revealed the major physiographic elements, and in 1974 a 1:5000000 map sheet for East Antarctica was produced (Drewry 1975*a*). A similar chart is in preparation for Marie Byrd Land.

Continuous radio echo profiling provides very detailed information of sub-ice bedrock relief. In areas adjacent to the Transantarctic Mountains such data have been used to extend geological patterns beneath the ice, especially those related to the distinctive, structurally controlled surfaces produced by the Beacon Supergroup Series (Drewry 1972*a*, *b*; Calkin 1974). Elsewhere many new features have been mapped: numerous large mountain blocks and a complex of basins in central East Antarctica which includes a marked trench or rift structure (figure 8). Other topographic features, ill-defined by seismic-gravity soundings, have been determined with new precision: the inland flank of the Transantarctic Mountains, the Gamburtsev Mountains and the Wilkes subglacial basin.

In West Antarctica, between the 120° W meridian and the Ross Ice Shelf, preliminary radio echo results indicate a sub-ice surface near to and in places above isostatically adjusted sea level – in strong contrast to bedrock east of Byrd station (K. E. Rose, personal communication 1976). In addition there is a deep trough running along the front of the Transantarctic Mountains in southern Byrd Land. The significance of this feature for interpretation of the structural juncture between East and West Antarctica is at present being investigated.

Sub-ice geological provinces

(*a*) *Techniques*

Information of a general nature on the geological composition of bedrock may be obtained from radio echo records by the use of various techniques. Large-scale maps of bedrock relief allow determination of macro-scale physiographic provinces and the qualitative isolation of a number of surface characteristics. Numerical parameterization of the fine structure of surface roughness can be undertaken on two-dimensional radio echo profiles by statistical analyses (e.g. autocorrelation, power spectral and curvature techniques) of the variation of relief within morpho-provinces (Drewry 1975*b*). Such studies allow acquisition of distinctive terrain roughness signatures and regional correlations to be determined which are associated with possible structural or other geological factors. Furthermore, information on lineation or structural ‘grain’ exhibited by terrain can be derived by considering surface properties computed in two or more different directions. Figure 8 incorporates such data and shows the strong contrast in surface fabric between typical basin areas (smooth and apparently isotropic) and mountainous zones (rough with strong surface anisotropy).

The strength of the returned radar signal is dependent on micro-scale surface roughness and the electrical properties of sub-ice materials. If changes in the coefficient of reflexion can be isolated from variations of absorption of radio waves in the ice mass, it should be practicable to depict major variations in geology. The analysis of such data is providing an interesting area of current research.

(*b*) *Geological interpretation*

Statistical studies using autocorrelation methods have indicated the presence of distinctive terrain provinces in East Antarctica (Drewry 1975*b*). Within both highland and lowland groups there exist sub-types, differences probably being related to geological factors such as variations in cratonization and block uplifts and differential stripping of spatially variable thicknesses of sediments. Associations in terrain roughness and surface characteristics are indicated between the Transantarctic Mountains (both ice-free and ice-covered portions) and smaller isolated highland massifs in East Antarctica, which appear to constitute block-faulted ranges possibly supporting a succession of Phanerozoic sediments and volcanics. A separate region (divided into two distinctive sub-zones) is represented by the Gamburtsev Mountains. One sector is rugged and typical of terrain developed in basement crystalline and/or intrusive bodies. The presence, however, of an integral but much smoother province argues for a geological history of some complexity involving periods of orogenesis and basement reactivation (Drewry 1975*b*).

Two major intra-cratonic basinal structures have been identified and studied in East Antarctica: the Wilkes Basin and a second for which the name 'Aurora Basin' is suggested (Drewry 1976), see figure 8. The former lies inland and sub-parallel to the Transantarctic Mountains, while the 'Aurora Basin' forms a branching system of sub-depressions trending northwest towards the Wilkes Land coast.

Use of reflexion coefficients and terrain roughness statistics indicate significant differences between basins and their surrounding regions (figure 8). Small-scale surface irregularities and slowly changing reflectivities are interpreted as suggesting the presence, within these depressions, of a smoothing cover of sediments. Residual anomalies from aeromagnetic profiling, when combined with the radar topographic data, exhibit low gradients over basins but steep, fluctuating characteristics over adjacent basement highs. Source-depth calculations from over-snow magnetic determinations across the Wilkes Basin indicate an average thickness for the sedimentary layer of ~ 3 km. This conclusion is corroborated by reinterpretation of gravity anomalies, which average ~ -110 mGal over the basin. Sediments are probably absent or extremely attenuated on the margins of the Wilkes Basin: seismic refraction shooting has detected the near-surface presence of granitic crust. Much less is known regarding the structure of the more complicated 'Aurora Basin'. The distribution and tectonic setting of these basins, however, is thought to be governed by intra-cratonic fracture patterns possibly related to ancient orogenic sutures. Any sediments must predate growth of the ice sheet and are older than Miocene.

Transantarctic Mountains–East Antarctic transition

The gross geological inferences outlined above indicate the nature of the transition into East Antarctica. The structural setting is complex involving passage from differentially tilted crustal fault-blocks of the Transantarctic Mountains, with either marked or negligible sub-ice discordance (i.e. inner flank fault-scarps) into the major meridional sedimentary depression of the Wilkes Basin (figure 8). The continuing epeirogenic uplift of the mountains along an axis somewhere close to the Ross Sea coast was initiated in Early Cenozoic times (Drewry 1975*c*) and has involved considerable erosion of Upper Jurassic and later strata. Consequently the Beacon Supergroup Series passes laterally into the Wilkes Basin where it may become overlain by Late Mesozoic and Palaeogene clastics – derived from the mountains themselves. The recurrence of 'Beacon-type' terrain in isolated massifs inland beyond the Wilkes Basin may argue for extensive sedimentation over central East Antarctica during Phanerozoic times.

Glacial geologic history

Radio echo sounding records from ice-covered portions of the Transantarctic Mountains have identified numerous inland trending valley networks. Morphometric properties of these valleys, determined from deconvoluted profiles, and comparisons with ice-free troughs in the exposed mountains, have enabled the glacial origin of these valleys to be determined (Drewry 1972*a*, *b*). The existence of such inland oriented subglacial troughs has implications for growth models of the East Antarctic ice sheet. Their presence is considered to demonstrate that the ice sheet developed initially from the expansion of valley glaciers within these mountains during the Early to Mid-Miocene (Drewry 1975*c*). It is hoped that investigations of a similar nature may result from current analysis of radio echo records in Marie Byrd Land where a series of ice streams draining into the Ross Ice Shelf may have eroded detectable bedrock channels.

References (Robin *et al.*)

Bailey, J. T., Evans, S. & Robin, G. de Q. 1964 *Nature, Lond.* **204**, 420–421.
Beckmann, P. & Spizzichino, A. 1963 *The scattering of electromagnetic waves from rough surfaces.* London: Pergamon Press.
Berry, M. V. 1973 *Phil. Trans. R. Soc. Lond.* A **273**, 611–654.
Bogorodskiy, V. V. 1968 *Fizicheskiye metody issledovaniya lëdnikov* [Physical methods of glacier study]. Leningrad. Gidrometeorologicheskoye Izdatel'stvo. 214 pp.
Budd, W. F. 1970 *J. Glaciol.* **9**, 29–48.
Calkin, P. E. 1974 *J. Glaciol.* **13**, 415–430.
Dansgaard, W. & Johnsen, S. J. 1969 *J. Glaciol.* **8**, 215–223.
Drewry, D. J. 1972*a* In *Antarctic geology and geophysics* (ed. R. J. Adie), pp. 693–704. Oslo: Universitetsforlaget.
Drewry, D. J. 1972*b* *Inst. Brit. Geog. Spec. Publ.* no. 4, 43–57.
Drewry, D. J. 1975*a* *Polar Record* **17**, 359–374.
Drewry, D. J. 1975*b* *Nature, Lond.* **256**, 194–195.
Drewry, D. J. 1975*c* *J. geol. Soc. Lond.* **131**, 255–273.
Drewry, D. J. (in press). *Tectonophysics* (Durham Geodynamics Meeting April 1976).
Evans, S. & Smith, B. M. E. 1969 *J. Sci. Instrum.* (2) **2**, 131–136.
Gudmandsen, P. 1975 *J. Glaciol.* **15**, 95–100.
Harrison, C. H. 1970 *Geophysics* **35**, 1099–1115.
Harrison, C. H. 1972 Unpublished Ph.D. thesis. University of Cambridge (Scott Polar Research Institute).
Hughes, T. 1973 *J. geophys. Res.* **78**, 7884–7910.
Johnsen, S. J., Dansgaard, W., Clausen, H. B. & Langway, Jun. C. C. 1972 *Nature, Lond.* **235**, 429–434.
Liebert, J. & Leonhardt, G. 1974 *Inform. Bull. Soviet Antarctic Exped.* no. 88, 68–70.
Neal, C. S. 1976 *J. Glaciol.* **17**, 527–530.
Oswald, G. K. A. 1975 *J. Glaciol.* **15**, 75–87.
Oswald, G. K. A. & Robin, G. de Q. 1973 *Nature, Lond.* **245**, 251–254.
Paren, J. G. & Robin, G. de Q. 1975 *J. Glaciol.* **14**, 251–258.
Robin, G. de Q. 1972 In *Antarctic geology and geophysics* (ed. R. J. Adie), pp. 675–682. Oslo: Universitetsforlaget.
Robin, G. de Q. 1975*a* *J. Glaciol.* **15**, 49–63.
Robin, G. de Q. 1975*b* *Nature, Lond.* **253**, 168–172.
Robin, G. de Q. 1977 *Phil. Trans. R. Soc. Lond.* B **280** (In the press). [Roy. Soc. Devensian Cold Stage meeting, April 1976.]
Robin, G. de Q., Evans, S. & Bailey, J. T. 1969 *Phil. Trans. R. Soc. Lond.* A **265**, 437–505.
Robin, G. de Q., Swithinbank, C. W. M. & Smith, B. M. E. 1970 *Int. Assoc. Sci. Hydrol. Publ.* **86**, 97–115.
Robinson, R. V. 1960 *Inform. Bull. Soviet Antarctic Exped.* no. 18, 28–29.
Thomas, R. H. 1976 *Nature, Lond.* **259**, 180–183.
Weertman, J. 1975 *Nature, Lond.* **253**, 159.
Weertman, J. 1976 *Nature, Lond.* **260**, 284–286.
Whillans, I. M. 1973 *Science, N.Y.* **182**, 476–479.
Whillans, I. M. 1976 *Nature, Lond.* **264**, 152–155.

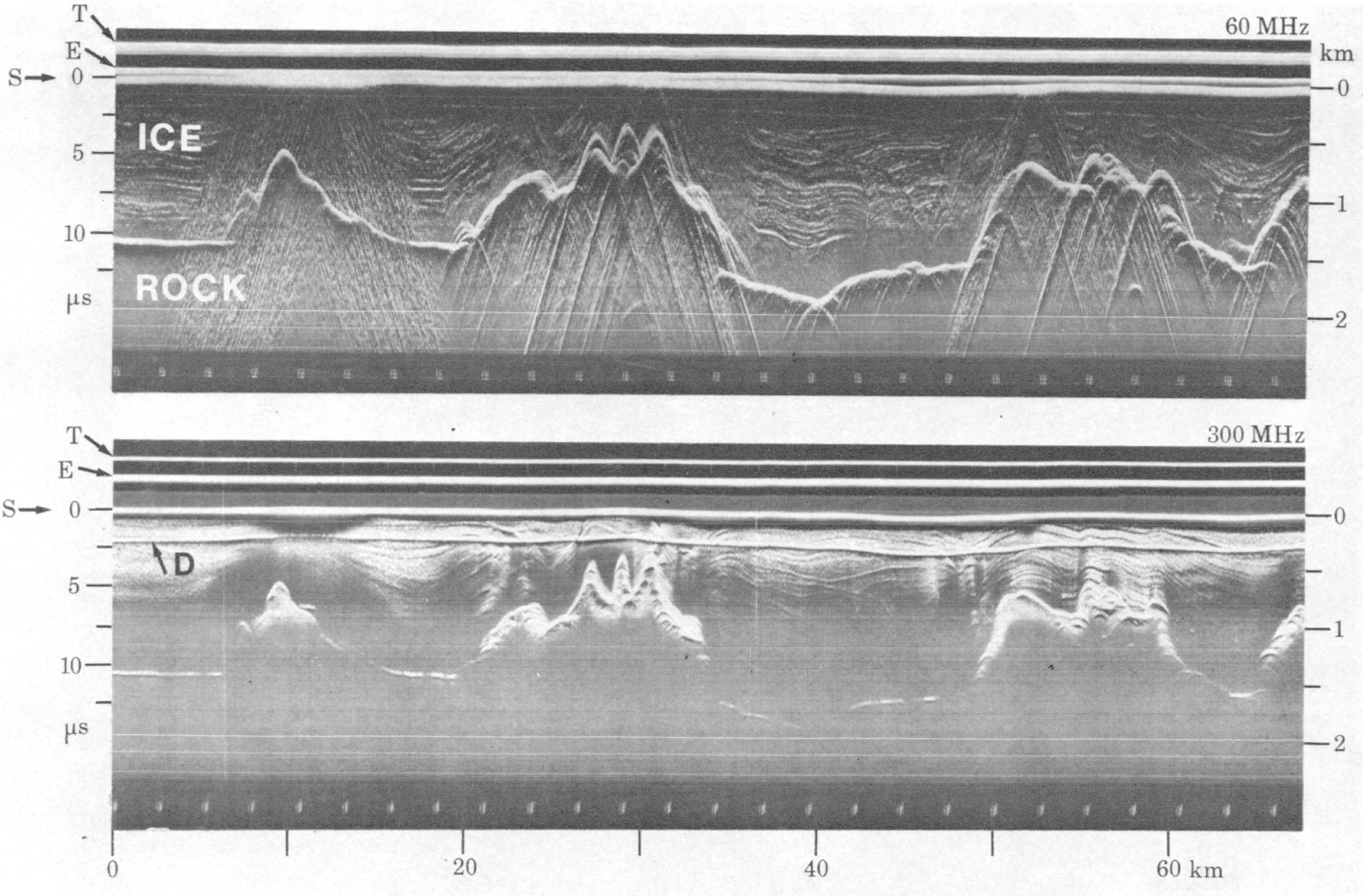


FIGURE 2

(a)

FIGURE 3 (b)

(c)

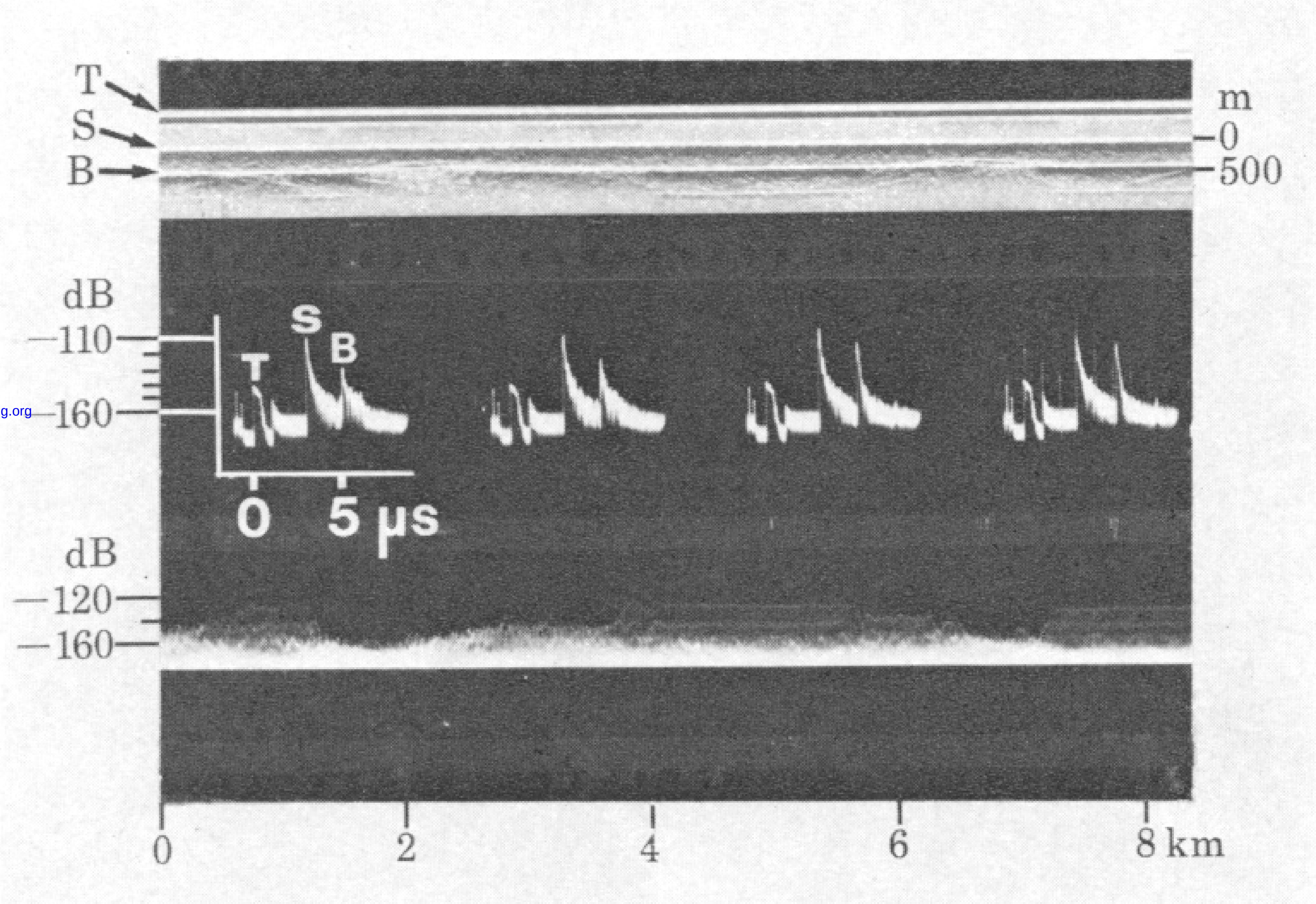
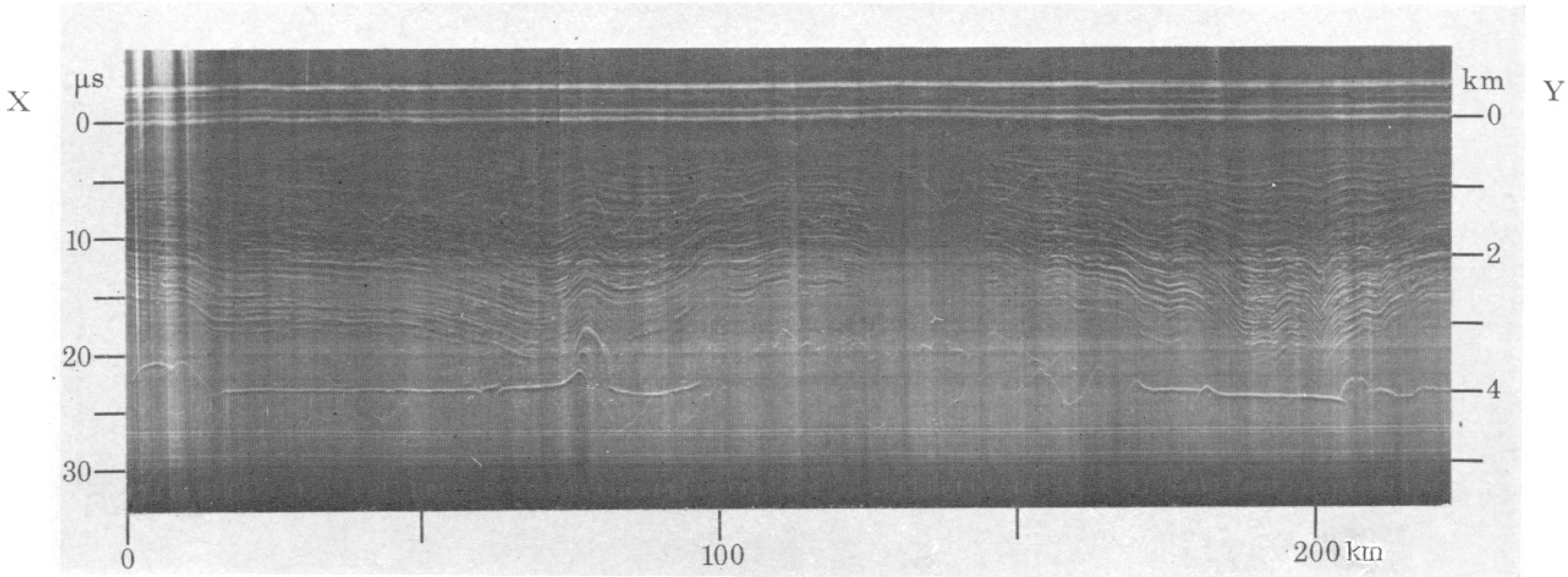
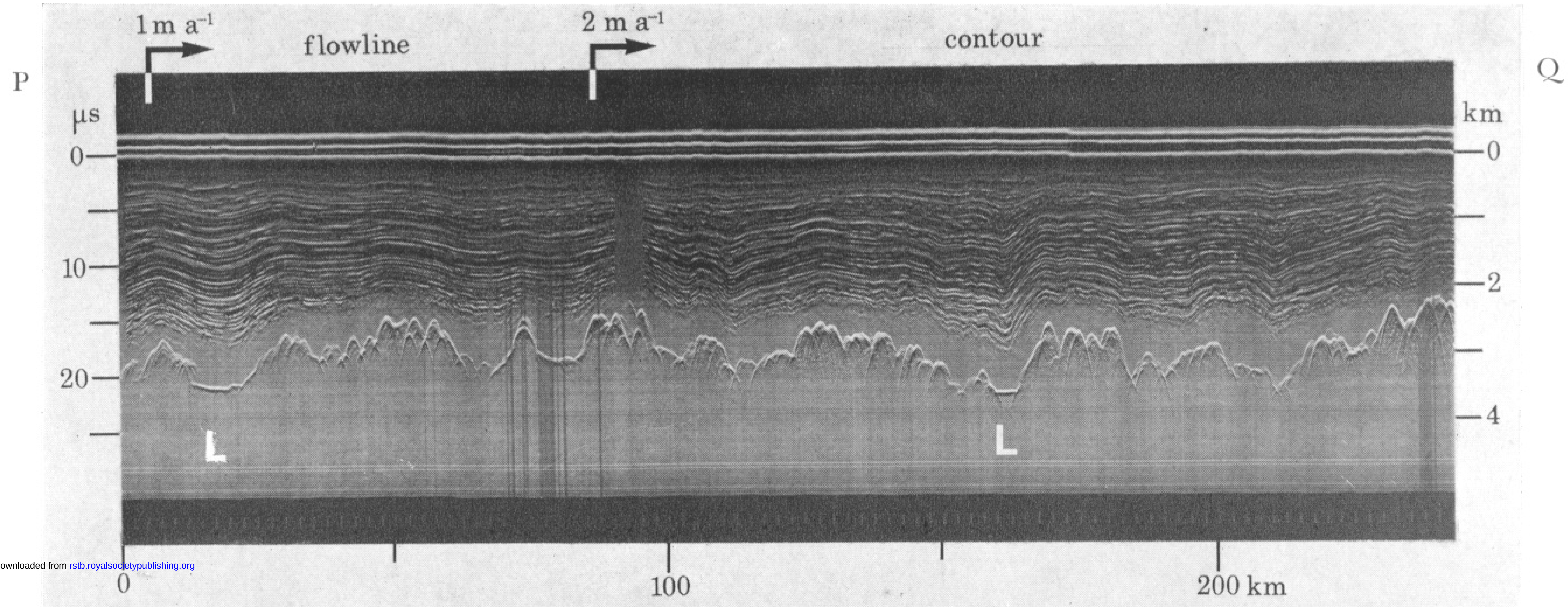


FIGURE 4



FIGURES 2–4. For description see opposite.



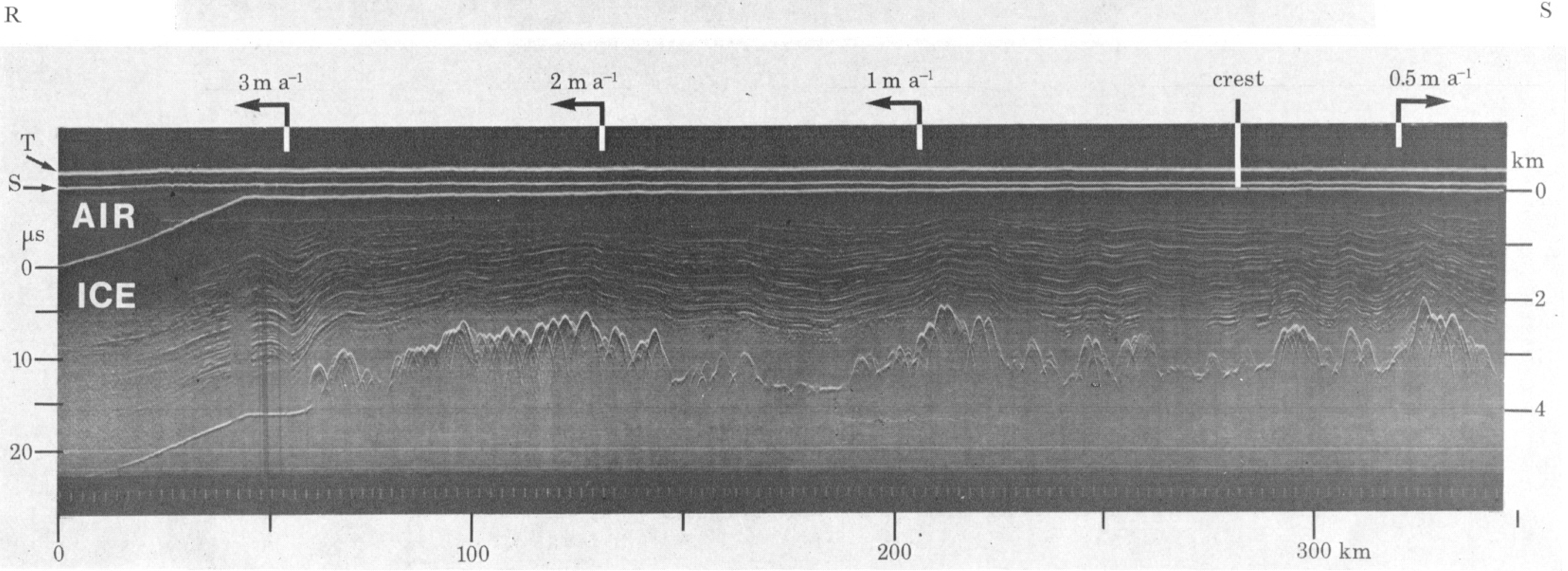


Figure 6. Radio echo profile showing bedrock, two small sub-ice lakes and internal layering near dome 'B' in central Antarctica. The section on the left lies along a flowline, that on the right shows the profile along a surface contour of the ice sheet. Profile location shown by line PQ on figure 5.

Figure 7. Radio echo profile across the crest of the ice sheet to the sub-ice lake shown in figures 4 and 5. The profile lies along a flowline and shows changes in deformation of layers as the ice movement increases away from the crest of dome 'B'. Profile location shown by line RS on figure 5.