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COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS.

RECORDS

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"PRELIMINARY REPORT ON MEASUREMENTS OF ICE THICKNESS ON THE ANTARCTIC ICE CAP BY SEISMIC AND GRAVIMETRIC METHODS".

by

M. J. GOODSPEED.

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ABSTRACT

The report describes work carried out during an ice thickness survey by seismic and gravimetric methods made in the summer of 1957-58 in MacRobertson Land, Antarctica.

Methods used during the survey are described and the equipment used is listed in detail.

Results have not yet been analysed fully but preliminary profiles are given. The accuracy limits applying to these profiles are given and future extensions of the calculations are discussed.

1. INTRODUCTION

Antarctica and Greenland are characterised by the existence of permanent and continuous ice cover over the greater part of their area and by an extremely inhospitable climate. Small permanent settlements have been developed at a few placesaround the Greenland coast but the only settlements on Antarctica have been established for scientific reasons and most will only be manned for the duration of the International Geophysical Year. Nevertheless the study of these areas, and in particular the study of the extent, thickness and physical properties of the ice cover, is of great scientific interest for the following reasons :-

(a) During the Pleistocene period the greater part of Northern Europe and North America was covered by similar ice caps, and in earlier geological times other large areas passed through periods of glaciation. The interpretation of the effects of the glacial periods on these regions involves assumptions which can only be checked on present-day ice caps, so that it is necessary to obtain all available information on the size, thickness and physical properties of these ice caps.

(b) The polar ice caps undoubtedly influence the weather in other parts of the world, for example, cyclonic disturbances originating close to the Antarctic coast frequently bring spells of cold and windy weather along the South Coast of Australia. Information on the polar ice caps is useful in furthering the understanding of these effects.

(c) As an extension of the meteorological application, changes in the total mass of ice retained in the polar ice caps, or in its distribution, would certainly be related to long term changes in the climates of these and other areas. For example, there is strong evidence of a rise in mean temperatures in Northern Europe and America within the last 50 years, associated with the recession of glaciers in Austria, Switzerland, Norway, Alaska etc. The relationship is not a simple one and all available information on rates of recession, flow rates, rates of accumulation etc. is needed. If relations can be established in a particular area between, on the one hand, the thickness, surface topography and nature of the underlying rock surface, and, on the other hand, the speed and direction of flow of the ice, then flow rates and directions over wide areas could be deduced from studies of surface topography with spot checks of ice depth at selected points. This would help extend present knowledge of the "mass economy" of the ice caps, that is, whether the amount of ice held in them is tending to increase or decrease. The possibility that seismic methods can give information from which the temperature, density and crystal orientation within the ice layer can be deduced must also be investigated.

(d) Any information obtainable on the geography and geology of the rock underneath the ice caps is of interest for its own sake. Early experiments on glaciers in the Austrian Alps (Brockhamp and Mothes, 1930) showed that the seismic method of geophysical prospecting could be used to measure ice thickness and it was subsequently used in Greenland (Brockhamp, Sorge & Wolcken, 1933) and on shelf ice in Antarctica

(Poulter, 1947). After the Second World War, improved means of transport on plateau ice, particularly in the use of the "weasel", a light, tracked vehicle developed for amphibious landings during the Pacific campaigns, led to the first extensive exploration of the Greenland and Antarctic ice caps with seismic equipment.

Expeditions Polaires Francaises carried out a very extensive series of traverses in Greenland between 1949 and 1952 (Joset and Holtzscherer, 1953, 1954) during which several coast-to-coast profiles were measured; and the Norwegian-British-Swedish Expedition based at Maudheim, Antarctica ran a seismic traverse of 385 miles (Robin, 1953) when for the first time ice thicknesses were measured on the inland ice plateau of Antarctica.

Measurement of the thickness and other properties of the Antarctic plateau-ice received a fresh impetus from the decision to direct particular attention to the Antarctic during the International Geophysical Year, 1957-58. Seismic ice thickness surveys have been and are being carried out by American, Russian, British, French and Australian parties, and the gravity meter is being used to give additional detail between seismic stations.

This report describes operations carried out by an Australian party based on Mawson, Antarctica during the summer of 1957-58. The author, a geophysicist with the Bureau of Mineral Resources, Geology and Geophysics, was attached to the Australian National Antarctic Research Expeditions (A.N.A.R.E.) for the purpose of carrying out the ice thickness survey. He had the active assistance and co-operation of the members of the 1957-58 party at Mawson. The traversing party consisting of six men was under the leadership of the Officer-in-Charge, Mawson, Mr. Keith Mather. The seismic equipment, gravity meter and microbarometers were provided by the Bureau of Mineral Resources; the seismic cab and shot-hole drill, together with all transport facilities and necessary supplies were provided by Australian National Antarctic Research Expeditions.

2. SEISMIC AND GRAVIMETRIC METHODS APPLIED TO ICE THICKNESS MEASUREMENT.

The seismic and gravimetric methods have been described fully by several authors (e.g. Nettleton, 1940) in relation to their application to prospecting for minerals etc. The principles may be summarised thus :-

1. SEISMIC METHODS

(a) Reflection method

Seismic energy is generated artificially near the surface, usually by detonating an explosive charge. The time taken for the energy to return to the surface after reflection at structural interfaces is measured. To deduce the depth of each reflecting interface it is necessary to know the velocity of propagation at all depths down to the interface.

This can be found in most cases by the refraction method.

(b) Refraction method

Seismic detectors ("geophones") are laid in a line at some distance from the shot point and record the arrival of energy returning to the surface after refraction by higher velocity layers beneath the surface. The relation between velocity and depth can be deduced from these measurements.

(c) Soundings in bore-holes

Small charges are detonated at a series of depths in a bore hole and the arrival of seismic energy at the surface is timed.

2. GRAVIMETRIC METHODS

Local anomalies in the gravitational field are measured and interpreted in terms of the depth shape and magnitude of subsurface density differences required to produce them.

In applying these methods to the measurement of ice thickness on the polar plateau, the following special circumstances arise :-

(1) The solid ice is generally overlain by a "low-velocity" layer representing the transition from recently deposited snow to ice which has been compacted by the pressure of overlying layers. The difficulty in getting energy into the medium is similar to that arising from the "weathered layer" in geophysical prospecting, but is more acute than usual because the velocity difference between the surface and deep layers is very great, accentuating the "defocussing" effect on rays originating near the surface, and because the snow, being of low density and relatively close to its melting point, absorbs a portion of the energy available, through melting close to the charge. It is also difficult to arrange the efficient tamping of the charge because of the amount of heat necessary to melt sufficient water.

A number of methods have been used to overcome these difficulties, such as the use of a pattern of charges suspended a few feet above the surface (Poulter, 1947). This method concentrates the energy into a vertically travelling beam to minimise "defocussing" effects. Another method involves drilling a hole so that the charge can be detonated at a depth where the seismic velocity is closer to its limiting value (as is usually done in geophysical prospecting). The latter method was used by the Australian party because the need for drilling holes arose also in connection with measurements of ice temperature and density; and because its use was expected to give results with much less preliminary experimentation than the air-shooting technique.

(2) Operation of seismic recording equipment at low temperatures has been reported as producing many electrical and mechanical troubles, such as electrolytic condensers losing capacity, optical systems cracking, etc. As might be expected, even more difficulties arise if the equipment is subjected to frequent temperature changes over wide ranges. For these reasons, the seismic equipment used during the traverse described here was transported and operated in a substantial, thermally insulated cab which was fitted with thermostatically-controlled electrical heaters. Photographic processing tanks were fitted in the cab, together with radio equipment for use during refraction shooting. Rubber insulation was necessary on the seismic cables because the plastic insulation frequently used in geophysical prospecting becomes brittle at the temperatures encountered.

(3) Attenuation and scattering of seismic energy is much reduced on the ice-cap; this is in general an advantage in that charges can be reduced in size and seismic events can generally be recognised on the record with little difficulty. However, unwanted seismic energy such as the noise of wind passing over the vehicles, is picked up by the geophones equally well. This necessitated some departure from the normal methods of laying out geophones; it was necessary to offset these from the hole around which the vehicles were located. The geophone arrays used are illustrated on Plate 4.

(4) In using the gravimeter it was decided that, because of the slowness of the transport available, it would be impracticable to use the normal "leapfrog" method (in which the instrument is returned to the previous station for a drift reading after each new station is read). Thus it was necessary to rely on readings of drift rate made at each camp site, and these rates may not coincide with the drift occurring while moving. However, errors arising in this way are not cumulative, and, in relation to anomalies produced by the ice/rock density contrast (41 ft/milligal assuming ice density 0.90 gm/cc., rock density 2.8 gm/cc) drift effects are small, Thus errors due to drift variations in using gravimeter readings to interpolate for ice thickness between the seismic stations where its thickness is measured relatively accurately are likely to be small.

(5) Owing to the length of the traverse envisaged, levelling by surveyors staff and theodolite was out of the question. It was necessary to rely on barometric methods completely. To reduce errors arising from horizontal pressure variations (Brombacher, 1944), pressure and temperature of the air were measured simultaneously at the end of five mile sections along the traverse. Altitude differences obtained thus were then progressively added to obtain the altitude of each station.

Since the ice is chemically homogeneous, unlike rocks which may change their constitution under the surface in an unknown way, it is possible to make measurements on the physical properties of ice samples in the laboratory and to anticipate that the results obtained will be reproduced in the field relatively precisely. Many such laboratory measurements have been carried out. For example, Bentley et al (1957) quote Robin (unpublished communication, 1956) as giving the following relation between the temperature (lower than -10°C) and the velocity of the longitudinal wave in ice :-

$$v_T = v_{-20} - 2.3 (T + 20)$$

where v_T and v_{-20} are the velocities in m/sec at T°C and -20°C respectively. Extremely precise measurements would be needed to deduce temperature from velocity using this relation.

Similarly, relations have been found in the laboratory between velocity and density and, in monocrystalline samples, between velocity and direction relative to the crystal axes. In the later case, differences of up to 15% have been reported. It has been suggested that, when ice flows, a tendency may exist for the individual crystals of which it consists to "line up" along the direction of flow and in this case measurements of velocity would enable flow direction to be deduced. These questions are discussed by Bentley et al (1957).

3. DESCRIPTION OF EQUIPMENT

A technical description of the equipment used is now given.

1. ICE DRILL

This drill was supplied by Australian National Antarctic Research Expeditions for use in glaciological studies including the drilling of shot holes for seismic work. A photograph is shown in Plate 3.

Manufacturers	- "Goldfields Diamond Drilling Company Pty. Ltd"., Victoria, Australia.
Vertical movement	- hydraullically powered in both directions by two pistons. Vertical travel 5 feet.
Rotational movement	- reversible hydraulic motor mounted on a platform which rises and falls as controlled by the vertical pistons.
Drill pipe	- 4 foot lengths fitted with auger flights for clearing cuttings, outside diameter 3½ inches.
Cutting heads	- A variety of types were supplied for testing, those used successfully were three-wing drag bits cutting a hole ¼" wider than the diameter across the clearing flights.
Power	- Hydraulic system driven by a 10 HP 2 cylinder Deutz diesel engine fitted with electric pre-heating and starter motor.

Capacity of drill - 200 feet.

2. SEISMIC EQUIPMENT.

This equipment was supplied by the Bureau of Mineral Resources, Geology and Geophysics.

(a) Amplifiers and Control System

Manufacturers	-	"Texas Instruments Incorporated" (formerly "Houston Technical Laboratories) Houston, Texas, U.S.A.
Manufacturers' designation	-	Model 7000-B Seismic Amplifier System.
Number of channels	-	twelve
Logarithmic Level Indicator	-	the signal from channel 6 is rectified and displayed on a logarithmic scale.
Frequency ranges of amplifiers	-	5 cs. to 500 cs.
Automatic Gain Control	-	Linear amplification, or A.G.C. at one of three speeds, can be applied.
Filters	-	a wide range of cut-off frequencies and cut-off slopes can be inserted. (see Plate 7).

(b) Oscillograph camera

Manufacturers	-	"Clevite Corporation Texas Division" (formerly "Technical Instruments Company") Houston, Texas, U.S.A.
Manufacturer's designation	-	Model 521 system oscillograph camera.
Number of traces	-	twenty five.
Disposition of channels	-	Traces 1-12 outputs of channels 1-12 recorded unmixed. Traces 13-24 outputs of channels 1-12 with 25% unilateral mix, direction selected from amplifier control system. Trace 25 - Time break and, after suppression trip, either "bleeper" signal from tuning fork or L.L.I. output, selected by switch on camera. "Uphole" break is recorded on Trace 24 with suppression on.
Width of photographic paper	-	15 cm.

(c) Shot Boxes

These are used to fire the electric detonators which detonate the charge, and supply simultaneously a pulse to mark the instant of detonation on the record.

They were supplied by the Bureau of Mineral Resources, Geology and Geophysics.

1. Technical Instruments Company 90 volt blaster, condenser-battery system.

2. South-western Industrial Electronics 2000volt blaster, condenser-generator system.

(d) Geophones

Manufacturers	-	"Clevite Corporation" (formerly "Technical Instruments Company") Houston, Texas, U.S.A.
Number & designations	-	Sixteen standard 20 cs. geophones Model 241/L, fifty standard 6 cs. geophones, Model 310.

(e) Seismic cables

Manufacturers	-	Vector Manufacturing Company, Houston, Texas, U.S.A.
Description	-	(13 conductor pairs Rubber covered, silicone filled, double ended cables with 13 moulded take-outs at 115 ft. intervals, total length 1500 feet.
Number	-	3

(f) Explosives

These were selected for stability at low temperatures.

1. Nobel's "704" blasting cartridges in 4 oz. charges.

2. RDX/TNT in 1 lb. charges with C.E. primer attached.

4. Nobel's No.8 submarine electric detonators with 360 inch leads.

3. SEISMIC CAB

This cab was supplied by Australian National Antarctic Research Expeditions for housing and transporting the seismic equipment. A photograph is shown on Plate 3.

Manufacturers	-	"Texas Instruments Incorporated" (formerly "Houston Technical Laboratories") Houston, Texas, U.S.A.
External Dimensions	-	6 ft. 6 ins. long 4 ft. 10 ins. wide 5 ft. 6 ins. high
Construction	-	All external walls are constructed of double-layer heavy plywood with an air gap loosely filled with insulating material. The outside is sheathed with polished aluminium sheeting.
Internal partitioning		The cab is divided internally into (a) a compartment for housing the seismic equipment, developing tanks

Internal partitioning (Cont[d].)	-	and radio transceiver. (b) an electrical compartment containing power supplies and general wiring. (c) a compartment for housing the lead-acid batteries for powering the equipment.
Heating	-	The equipment and battery compartments are fitted with electrical strip heaters whichcan be controlled by a thermostat. The developing tanks are provided with a separate immersion heater system.
Mounting	-	The cab is mounted in a steel cradle frame which is sprung-mounted on a sledge. The D.C. generator set is mounted on the same sledge.

4. D.C. GENERATOR SET

This generator was supplied by Australian National Antarctic Research Expeditions for heating and charging batteries in the seismic cab and general use by the field party.

Manufacturers	-	Mitchell and Co. Ltd., Vic Australia.
Engine	-	Lister single-cylinder deisel, 3 HP.
Description	-	32 volts,1.5 KW. D.C. generator.

5. BAROMETERS

These were supplied by Bureau of Mineral Resources, Geology and Geophysics.

Manufacturers	Askania-werke A.G., Berlin, Friedenau.
Designation	Microbarometer Gb5.
Type	Evacuated helical spring tube
Number	three

6. GRAVITY METER

Manufacturers	"Texas Instruments Incorporated" (formerly "Houston Technical Laboratories") Houston, Texas, U.S.A.
Designation	Worden Geodetic Model Ser. No. 169.

7. TRANSPORT

Transport was provided by Australian National Antarctic Research Expeditions.

Tractors	Caterpillar Diesel D-4
Number	Two-One fitted with bulldozer blade, one with Hyster winch at rear.

These tractors were used to tow all equipment and supplies in two separate trains.

Scout vehicle	"Weasel" (light tracked vehicle with Studebaker petrol motor).
Number	one

Comments on the suitability of the equipment.

Ice Drill.

The drill itself proved entirely suitable for the purpose of drilling holes on the plateau. However, the engine which powered it was extremely difficult to start at low temperatures and it is suggested that a petrol motor of equivalent power output would be more suitable or, as an alternative, the provision of a power take-off from one of the tractors.

The core-barrel supplied for taking cores at depths for density and crystallographic studies could not be used for this purpose due to persistent jamming. Further investigations will be necessary if it is desired to continue with this work.

Seismic Equipment.

This equipment functioned satisfactorily throughout the survey. The only fault which developed, phase distortion in some filter units, is not believed to be attributable to the particular conditions of use encountered.

Shot Boxes.

Of these, the larger S.I.E. unit was used in preference to the other, because of the ease of operation with gloved hands.

Geophones.

The 20 cs. geophones, Model 241/L, were used throughout and no failures were encountered.

Seismic Cables.

The cables were entirely satisfactory but the reels on which they were mounted were too broad, making it impracticable for one man to wind the cables in. This led to some waste of time.

Explosives.

These were entirely satisfactory.

Seismic Cab.

The ventilation system was modified to eliminate blockage by condensation. No other difficulties were encountered in the operation of the cab.

D.C. Generator Set.

This unit operated almost continuously for over three months with no maintenance other than periodic oil-changes. It was found necessary to mask off the cooling vents near the commutator brushes, which would otherwise become packed with snow in heavy drift conditions.

Barometers.

The reading scales on these instruments were found to stick at low temperatures. They have since been replaced by other units of the same model, re-lubricated with thinner oil.

Gravity Meter.

The gravity meter functioned well throughout the survey. Drift rates as measured on returning to previously occupied stations were reasonable, for example, the total drift between leaving and returning to Mawson was only 2.2 milligals.

Transport.

The main trouble here was that the transport provided by the tractors was extremely slow (maximum of 6 m.p.h., only attained when running down hill on the return journey). However, vehicles capable of towing the loads required for this type of operation at a higher speed would undoubtedly be very expensive. Weight could be cut down by eliminating the drill and using other seismic techniques such as air-shooting, and the recording equipment could be removed from the cab and operated at ambient temperature, fitted, for example, in a weasel. If air dropping were relied on to keep up supplies then much more rapid operations could be carried out using weasels only. However, maintenance time on the equipment would probably increase substantially and operations would be restricted to within aircraft range of base.

It was the experience of the author that for operations, such as the survey reported here, of a regional character proceeding beyond the operational range of available aircraft, the benefits of having well protected equipment and ample supplies and spares outweigh the disadvantage of relatively slow movement. However, if more detailed work closer to base is envisaged, then the use of lighter transport along the lines suggested above, is recommended.

OBJECTIVES AND SELECTION OF ROUTE.

The stated objectives of this survey, made on the basis of two years work, were :-

(a) To measure ice thickness over as wide an area as possible, extending as far to the south as possible, with the aim of contributing the maximum information towards a comprehensive picture of the ice burden on the Antarctic continent.

(b) To study the configuration of the underlying land surface along traverses within 100 miles of Mawson and along a main traverse generally to the South from Mawson in as great detail as is consistent with the other objectives.

(c) To study variations in seismic velocity with depth by refraction and/or reflection methods and endeavour to relate such variations to ice temperatures etc.

(d) To study velocity variations near the surface of the ice by small scale refraction methods and endeavour to relate such variations to ice temperature and compaction etc.

(e) To study velocity variations with azimuth by refraction methods, in order to investigate whether there is any relation to the direction of flow caused by crystal orientation.

(f) To supplement the seismic information by gravity measurements both at seismic stations and two or three stations in between.

Of these, (a), (b) and (e) were important in the selection of a route to be followed; the other objectives could be pursued along any traverse finally decided upon.

It was intended to carry out traverses including velocity/azimuth studies in the vicinity of Mawson during the field time remaining after the equipment had arrived at Mawson early in 1957, and had been prepared for the field. However, the arrival of the Expedition's vessel "Kista Dan" at Mawson was delayed by about a month due to impenetrable pack ice near Mawson, and it was not possible to have the equipment ready for field work before the onset of winter. This meant that, in order to take full advantage of the following field season (November 1957 to February 1958), it was advisable to postpone the work close to Mawson until the second year, and concentrate on traversing the maximum distance inland.

A well established route existed running from Mawson to the Prince Charles Mountains (Plate 2). This route was pioneered by Dovers (1954) and extended by Bechervaise (1955) and Bewsher (1956).. However, the route was not suitable for the seismic traverse for the following reasons :-

(1) It was known to be a very difficult route due to local crevassing, even for the light weasel. The much heavier D-4 tractors could not be expected to penetrate far along it in safety.

(2) It was felt the a route which kept away from mountain ranges would give results more typical of the continent as a whole.

The area due South from Mawson had been subjected to only cursory aerial examination but was believed to be free of mountain ranges for at least 400 miles inland. A radar altimeter run in this area had indicated that a surface elevation of around 10,000 feet was reached within 200 miles in this direction. This appeared to hold promise for a traverse running due South, which would be ideal from the point of view of inland penetration.

Further reconnaissance flights in R.A.A.F. (Antarctic Flight) aircraft showed no serious obstacles to a southerly traverse until about 400 miles from the coast, where mountain outcrops together with belts of heavy crevassing, were seen. These ranges did not appear to extend more than a few miles to the west of the proposed traverse, and it seemed likely that they could be skirted by a minor westerly deviation. A southerly traverse along meridian 62° East was then decided on, and particular attention was given to picking a route through the Masson, David and Casey Ranges (referred to collectively as the "Framnes Mountains"), which lie about ten miles south of Mawson and have belts of heavy crevassing associated with them.

A brief sortie of four days was made in late September to test the seismic equipment and assess the capabilities of the tractors and other equipment. The party set out on the main traverse on 9th November, 1957. Personnel were :-

K.B. Mather	-	Officer in Charge, Mawson.
R.L. Willing	-	Medical Officer.
M. Mellor	-	Glaciologist and Navigator.
M.J. Goodspeed	-	Seismic and Gravity.
N. Collins	-	Engineer.
B. Shaw	-	Radio Officer.

The first twentyfive miles involved several changes of direction to clear the Framnes Mountains and outlying peaks. Over this stretch the surface was almost entirely "blue ice", from which all loose and uncompacted snow had been ablated. This so-called "ablation zone" is characteristic of the immediate coastal fringe of the plateau ice, and represents an area where total annual surface accumulation (from precipitation and wind transport) is less than total annual ablation (sublimation, melting and wind scouring). The high ablation almost certainly arises from :-

(a) higher summer temperatures due to low altitude and proximity to the sea,

(b) steep slopes downwards to the North,

presenting a surface more nearly normal to incident solar radiation, thus increasing absorption of radiant energy and increasing sublimation rates. This high ablation rate exposes at the surface snow which is very compact, having been subjected to the pressure of overlying layers during its slow progress to the coast. The Framnes Mountain ranges run almost due North-South, thus channeling the ice as it flows northwards between them. This was the area envisaged for the velocity/azimuth studies which had to be postponed. Only one station was shot on the blue ice and results were unsatisfactory, probably due to high surface wave noise, but only a short time was spent there because the area was unrepresentative of the plateau ice cap.

As soon as the party had cleared the Framnes Mountains the character of the surface was seen to change to the much softer névé, which was found over the remainder of the route. This appears to be composed of particles of wind blown snow, with very small particle size, which have been compacted in varying degrees by wind and radiation. As the snow becomes overlain by successive layers of wind deposition, pressure increases the compaction until at sufficient depth almost pure ice results. Under the strong winds which, being largely katabatic in origin, are comparatively constant in direction, the surface is cut into small sharp-edged formations called "sastrugi" (from the Russian) which are normally less than one foot high but were found to reach to more than four feet in height in some places. Other larger formations of more rounded profile, called "dunes", were also encountered, particularly beyond 100 miles inland.

The party proceeded over these surfaces without serious difficulty, but with numerous delays due to weather, until on 4th January, 1958, at a point 335 miles due South from the coast, the ranges previously sighted from the air were seen ahead. Between leaving the Framnes Mountains and sighting these inland ranges, no other rock outcrops were seen from the traverse. Surface slopes were gentle with the exception of steep undulations, with cracked and crevassed surfaces, at the following distances from the coast :-

(1) 67 to 80 miles.

(2) 94 to 120 miles.

(3) 160 to 185 miles.

The first belt runs almost continuously for at least twenty miles to the East and West of the point where the traverse crossed it, but no rock outcrops were visible from the air along it.

The second belt occurs at the same distance inland as Depot Peak (6100 feet) which lies 62 miles East of the traverse. The altitude at this point of the traverse is about 6,500 feet.

The third belt occurs at about the same distance inland as the Northernmost peaks of the Prince Charles Mountains, which lie 50 miles East of the traverse. These peaks are around 7,200 feet high and plateau elevation at the corresponding part of the traverse is about 8,200 feet.

Altitudes along the traverse progressively increased to just over 8,600 feet at a point 200 miles inland, and then commenced to fall gently along the remainder of the Southerly traverse.

After the inland ranges had been sighted, the surface was found to become increasingly more difficult due to cracking and crevassing until, a further 15 miles South, it became necessary to start deviating West to clear these ranges. Course was altered to South West and a further 40 miles was run. At this point crevassed ice domes were visible all round, and scouting by the weasel showed that further progress was impossible due to treacherous surfaces in all directions except along the approach route. It was now necessary in any case to commence the return journey to ensure time being available for refraction work on the way. A further short traverse of 8 miles was run roughly South Easterly from the mid-point of the deviation route (see Plate 2) before returning to the due South traverse.

The party returned along the same route as was used on the outward journey, and arrived at Mawson on 16th February, 1958.

MEASUREMENTS MADE DURING SURVEY.

Altitude measurements were made progressively by simultaneous readings of atmospheric pressure and temperature at the tractor trains and at the weasel a known distance, generally five miles, ahead. The barometers used were compared together frequently.

The gravity meter was read at each of the stations for which an altitude was measured, and readings for zero drift were made when stationary.

Measurements of ice thickness by reflection methods were made at the points shown on Plate 2. The intention was to make these measurements at 20 miles intervals in general, reducing the interval in regions of particular interest such as the belts of undulations previously described. Short refraction spreads for shallow velocity information were shot at most stations and at two locations (Plate 2) spreads continuing for several miles from the shot point were shot for deeper velocity information. Shots were also made using:-

(1) a pattern of nine shallow holes in which small charges were detonated simultaneously,

(2) a pattern of seven charges suspended four feet above the surface on stakes and detonated simultaneously,

(3) geophones laid horizontally in an attempt to record shear wave reflections.

At various stations early in the traverse different geophone arrays were tried for recording reflection information. The arrays used were:-

(1) 'R' spread: The geophones are laid in a line at equal intervals, with the shot-hole on the same line and one geophone-interval from the end.

(2) Offset 'R' spread: The same geometric arrangement as for the 'R' spread but with the shot-hole several times the inter-geophone distance from the nearest geophone.

(3) 'S' spread: The "split-spread" used most frequently in oil search surveys. Geophones were laid at equal intervals along a line with the shot-hole at the midpoint. The interval between geophones was normally 50 feet.

(4) 'X' spread: The geophones are laid at equal intervals in the form of a rectangular cross with the shot at the centre. 50 feet intervals were again used.

(5) 'L' spread: Effectively two 'R' spreads with six geophones only in each, laid at right angles and with the shot-hole at the vertex.

(6) Offset 'L' spread: The same geometric arrangement as the 'L' spread but with a gap between the shot-hole and the nearest geophone on each leg of several times the distance between geophones.

These different geophone arrays are shown diagramatically in Plate 4. It was soon decided that the 'Offset L' arrangement gave the best results in the windy conditions which normally prevailed, and this array was used almost exclusively from then on. The following were the reasons for selecting it:-

(a) Wind passing over the seismic cab and other vehicles produced noise which was transmitted through the ice to geophones within about 300 feet - this made it necessary to have all geophones as far as possible from the vehicles. It was inconvenient to have the seismic cab this far from the hole, thus the nearest geophones had to be offset from the hole by a considerable distance.

(b) Having the spread in two directions at right angles made it possible to record both components of the dip of the underlying rock with one shot.

(c) Due to the limited amount of seismic cable available there was no other way of obtaining both dip components while using offset spreads. For example, an 'X' spread with offset on each arm, which would have been preferable, could not be laid due to shortage of cable. This shortage was caused by the late delivery of an order for the special cable required.

To reduce wind noise, geophones were buried between 1 and 2 feet below the snow surface. On 'blue ice', when this would have been prohibitively time consuming, the geophones were recessed with the tops flush with the surface.

For shooting early during the traverse, filters were set fairly widely, bracketing the reflection frequency, close to 100cs, reported by earlier workers. It was found that record quality improved when the high-cut filters were set to cut off sharply at the closest setting above this frequency, but that no improvement resulted from a sharp cut-off at the low frequency end. The low-cut filters were consequently set to cut off around 60 cs, to retain as much reflection 'character' as possible. Precise settings were varied slightly from station to station. A selection of band-pass characteristics for the settings most widely used is shown in Plate 7.

Table 1 gives a list of all stations where seismic work was done, the distance from Mawson along the traverse, filter settings on the best record at each station, and the types of work done at each.

DISCUSSION OF RESULTS

The point to which computations have been carried to date is first described.

1. BAROMETRIC READINGS FOR ALTITUDE

All microbarometer dial readings have been reduced to pressure values, corrected for instrument temperature. These values have been adjusted so that they are consistent at the points of simultaneous adjacent readings, and altitude differences, deduced from pressure and temperature (Brombacher, 1954, p 278) have been calculated. The results are plotted on Plate 5.

2. SEISMIC RECORDS

Results have been graphed from the deep refraction shots, velocities have been measured. As a result, a velocity of 12,660 ft/sec. is obtained for the longitudinal wave in the solid ice. Approaching the surface this velocity starts to decrease at a depth of 550 feet, to a value of about 1820 ft/sec. in the top 9 feet. This velocity distribution has been assumed to apply for all reflection stations. The effects of the top low-velocity layers were allowed for by applying a correction of 24 ms. to all measured reflection times to make the travel times the same as they would have been had the velocity of 12,660 ft./sec. continued to the surface. The effect of initiating the shot in a shot-hole was allowed for by adding the uphole-time to the reflection time.

In timing the reflections recorded with offset spreads, corrections were applied to allow for the offset.

No dip calculations have yet been carried out. At several stations complex reflection events, suggestive of moraine-like material between the solid ice and the rock have been recorded. Only the earliest event on each record, believed to be the reflection from the bottom of the ice, has so far been computed. Results are shown on Plate 5.

3. GRAVIMETER READINGS

To date, no drift corrections have been applied to the readings. The net drift between leaving and returning to Mawson was 2.2 milligals, representing a rate of .022 milligals per day. Of course, drift rates varying greatly from this value occurred during the traverse, but even so, the effect of zero drift is small in relation to the large anomalies produced by changes in ice thickness.

Corrections have been applied to the gravimeter readings for all seismic stations to reduce the values to sea level at the latitude of Mawson. ("Free air correction", Nettleton, 1940, p.54). The resulting 'free air anomalies' will contain components due to

(i) regional effects (including rock density variation)

(ii) the ice-thickness effect being sought.

"Free air" gravity anomalies obtained at the seismic stations are plotted, together with ice thickness values obtained from the seismic results, on Plate 6. It will be seen that the general correspondence is good, but that even by shifting the origins of the curves relative to one another: as has been done, they cannot be made to fit together along the whole length of the traverse. A profile of Bouguer anomalies, derived by assuming expected values for the densities of the ice and underlying rock has been drawn. This profile, also shown on Plate 6, represents the gravity anomalies which would be measured at sea level, if the effects of ice and rock above sea level were removed and depressions of the rock below sea level were filled in. It will be seen that these Bouguer anomalies at first become progressively more negative as one proceeds south from the coast. This is the type of curve which has been reported as occurring near the edge of most continents and has been explained (e.g. Heiskanen, 1953) as being the result of isostatic compensation. The subsequent rise after about 200 miles may be the result of a thinning of the earth's crust in the region where the rock surface is close to or below sea level.

These profiles will be revised when :-

(1) zero drift behaviour of the gravimeter has been analysed,

(2) densities of rock samples from the area have been measured,

(3) the results of measurements tying the value of gravity at Mawson to that at a pendulum station at Mirny, the Russian Antarctic base, have been analysed.

It may then be possible to draw conclusions as to the completeness or otherwise of isostatic adjustment tothe burden of ice on this part of the continent.

Analysis for interpolation of ice thickness between the seismic stations will then proceed by considering the "free-air" anomalies recorded at the intermediate stations in relation to the Bouguer anomaly curve.

In discussing the results at the present stage of calculations the following points must be borne in mind.

(a) In computing altitudes, no account has yet been taken of horizontal pressure patterns which could affect the accuracy of the results. Studies of weather records will make some assessment of probable error from this cause possible and it may be possible to make reliable corrections on this basis. With the method which has been used it is felt that the present "raw" results are probably accurate to ± 100 feet at the measured points.

(b) A constant correction has been applied to all seismic reflection times measured. The refraction data obtained at each station will enable more exact corrections to be made for each shot.

(c) The events picked and computed so far are the shallowest recognised on each record. In some cases these represent the solid rock surface, overlain by moraine-like material (Joset and Holtzscherer, 1954).

(d) The refraction measurements for velocity at depth were made in one direction only. If horizontal stratification exists deep in the ice, with possible differences between horizontal and vertical velocities, this could lead to errors in the depth assessments. However, it is felt that substantial depth errors from this cause are unlikely because -

(i) the limiting velocity, 12,660 ft/sec. is in good agreement with that reported by other authors for comparable altitudes and temperatures,

(ii) it is most likely that compaction to high density would remove stratification sufficiently to make the difference between horizontal and vertical velocities negligible.

The depths shown are probably accurate to ± 5%.

Considering the preliminary profile (plate 5) the following points are most noticeable.

The ice surface slopes, which are steep near the coast, gradually diminish until at 200 miles a maximum of 8650 feet is reached, followed by a gentle decline. There is no coastal ice shelf floating on sea water at Mawson as found by Robin at Maudheim. The profile from the coast to 174 miles inland resembles the "Mountain Ice Sheet" region of Robin's profile with rugged rock topography and one deep fjord-like ravine at 88 miles. This is just south of the first belt of undulations crossed. Along the traverse these undulations are expressed by a depression of the general surface contours, lying some 13 miles North of where the rock ravine was found, but to either side of the traverse heavily crevassed ice domes, suggesting marked rises of the rock surface, were seen. It is most likely that this East-West line of ice domes and depressions is an expression of an extremely rugged subglacial belt containing deep valleys and high peaks rising steeply from them.

On the profile there is no explanation for the second belt of undulations crossed on the surface at 109 miles. The rock profile here is rising steadily if irregularly and no ravines were detected. Again ice domes with crevasses were seen on either side of the traverse here, although they were much less pronounced than the first belt and no marked depressions were seen. The surface irregularities are probably the expression of a belt of irregular rock relief running East West and appearing through the ice surface at Depot Peak.

The exact depth of the high peak shown at 174 miles is based on a poor quality reflection. However, the gravity profile also indicates very shallow ice here and the proximity of crevassed domes in the area suggests that the height shown is not unreasonable. The surface here sloped steeply to the North down to a minor depression. The ice surface was extremely compacted, approaching the character of "blue ice", and was covered with irregular cracks. This region almost certainly represents a Westerly extension of the Prince Charles Mountains which outcrop 50 miles to the East.

South of this point the profile assumes a similar appearance to that found by Robin beyond the 475 kilometre point on his traverse. The rock surface is close to sea level, with comparatively slight relief. The depression below sea level at 316 miles is of interest; reflection quality here was very good and there is little doubt that this depression exists. Beyond this point the rock commences to rise again, presumably continuing up to the peak (Mount Menzies) which lies along the line of the traverse. This peak was measured at 11,200 feet by aircraft altimeter.

It is clear that the decline in altitude of the ice surface between the 200 mile point and tne range of mountains and nunataks of which Mt. Menzies is the most prominent peak is due to a damming of North-flowing ice by these ranges, together with a flow of ice eastwards into the Lambert Glacier-Amery Ice Shelf system predominantly along the Fisher Glacier. The high ranges at the 174 mile point are also damming Northerly flow considerably, leading to the highest surface point being found just South of them.

The nine-charge shallow pattern was tried at Shot point 9, where poor reflection quality was obtained with a single deep hole. No improvement resulted.

The air shots were tried at Shot Point 20, where good quality reflections were obtained by the normal method. No reflection could be detected from the air shots.

Little success was achieved in the attempt to record shear wave reflections by laying normal geophones on their sides. Most of these appeared to stick in this position. However, shear-wave refraction events, together with ground roll (Rayleigh wave) were recorded on several records shot for longitudinal wave reflections. These will be analysed for velocity and elastic modulus information.

Near-surface velocities from small scale refraction shots will be compared with temperatures recorded in the shot-holes by Mellor and densities obtained in pits at several locations.

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TABLE 1.

Shot Point No.	Distance along traverse	Reflection shooting.	Filter setting of best record.	Refraction Shooting.	Reflection Quality.
1	10	Offset "R": Offset = 500ft. Interval: 50 ft: Shot depth 24ft: Charge: 1 lb.	L48 - L160	Shallow: Offset "R"	Poor.
2	Experimental shot hole near Mawson				
3	25	"R" Interval 50 ft: Shot depth: 98 ft. Charge: 4 oz. - 1 lb. Horizontal geophone shooting. "X" Interval 50 ft. Shot depth: 48 ft. Charge 4 oz.	K70 - K120	Offset "R" interval: 50ft: total: 3,350 ft. Uphole sheeting Shallow "R" Interval 20 ft.	Good
4	45	"R", Interval 70 ft. Shot depth: 85 ft. Charge: 4 oz. - 2lb.	L60 - KK 120	"R" Interval: 70 ft.	Good
5	70	"S": Interval 70 ft. (E-W) "S": Interval 100 ft. (N-S) Shot depth: 90-ft. Charge: 1 lb. - 3lb.	L70 - KK120	"R" Interval 100 ft: Shallow "R", interval 20ft:	Good

TABLE 1 (Contd.) Page 2.

Shot Point No.	Distance along traverse miles.	Reflection shooting.	Filter setting of best record.	Refraction shooting.	Reflection quality
6	78	"L" Interval 100ft. Shot depth: 86ft. Charge: 1 lb. 5 lb.	L70 - KK120	"R", interval 100 ft.	Good
7	88	"Offset L", Offset 600ft. Interval: 100ft. Shot depth: 90ft. Charge: 1 lb. -5 lb.	L60- KK120	Shallow "R". interval 20ft.	Good
8	109	"Offset L": Offset 600ft. Interval: 100 ft: Shot depth:91ft. Charge: 1 lb - 5 lb.	L60-KK120	"R": interval 100ft. Shallow "R", interval 20ft.	Fair
9	129	"Offset L": Offset 600 ft. Interval: 100ft: Shot depth: 90ft. Charge: 1 lb - 5 lb. Pattern of 9 shallow holes Depth 2 ft: Charge 9x 4 oz.	L60-KK120	-	Poor
10	134	"Offset L": Offset 480 ft. Interval: 80ft: Shot depth 89ft. Charge: 1 lb.- 3lb. Uphole shooting	K60-KK120	"R": interval 80 ft. Shallow "R": interval 20ft.	Fair

TABLE 1 (Contd)

Shot Point No.	Distance along traverse lines	Reflection shooting	Filter setting of best Record	Refraction shooting	Reflection Quality
11	154	"Offset L" Offset: 600ft. Interval 100 ft. Shot depth: 95 ft. Charge: 1 lb - 5 lb.	K70-KK120	"R": interval 100 ft. Shallow "R": interval 20 ft.	fair
12	174	"Offset L": Offset :600ft. Interval 100 ft. Shot depth:87 ft. Charge: 4 oz.	KK90-KK215	"R", interval 100 ft. Shallow "R": interval 20ft.	Poor
13	195	"Offset L": Offset: 600ft. Interval 100 ft. Shot depth: 125 ft. Charge: 1 lb - 5 lb.	KK70-KK120	"R", interval 220 ft. Total: 12,320 ft. Shallow "R": interval 20 ft.	Fair
14	216	"Offset L": Offset 600ft. Interval 100 ft. Shot depth 86 ft. Charge: 4 oz.	K70-KK120	"R": interval 100 ft. Shallow "R": interval 20 ft.	Good

TA LE 1 (Contd)

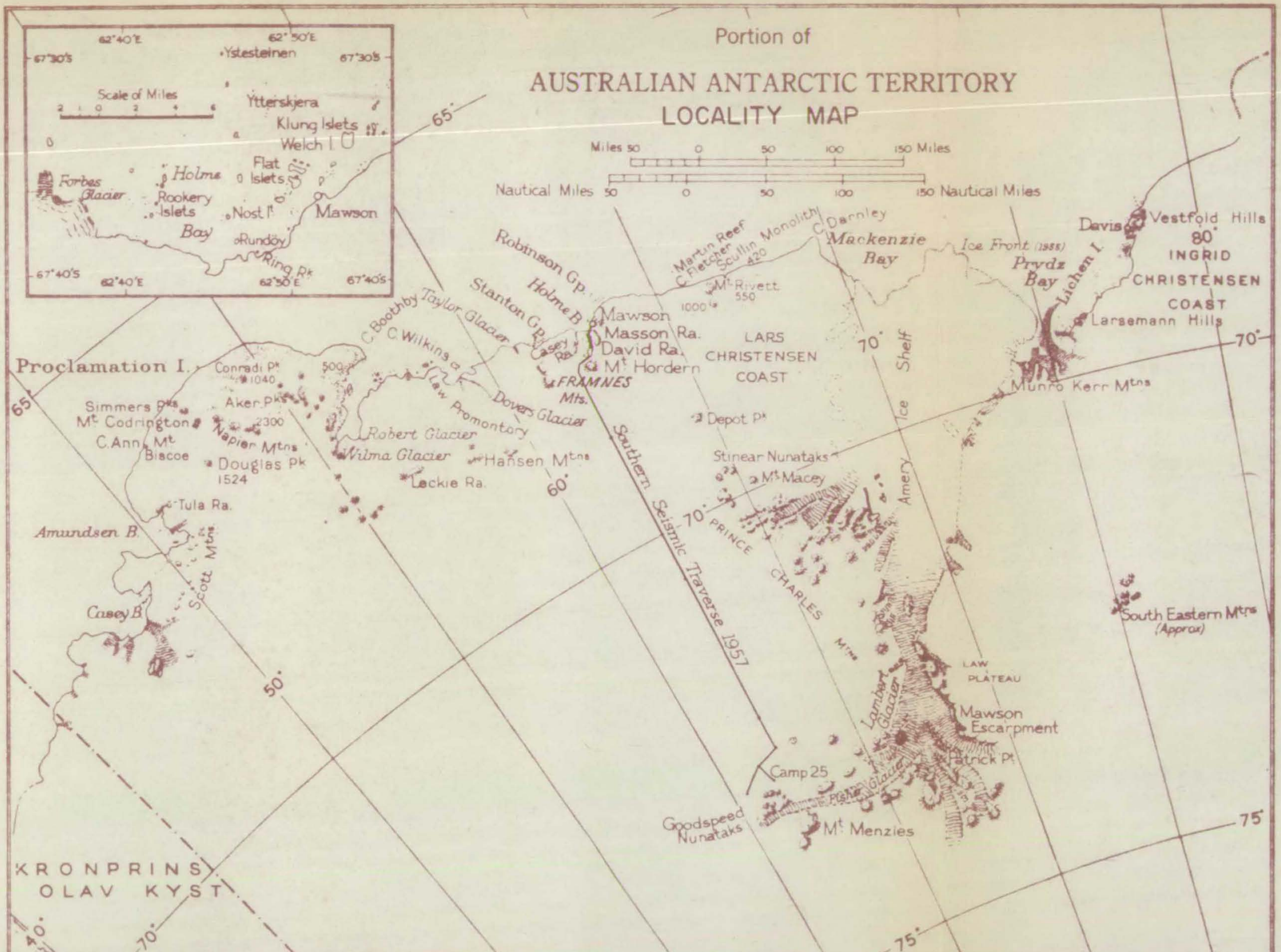
Shot Point No.	Distance along traverse lines	Reflection shooting	Filter setting of best record	Refraction shooting	Reflection Quality
15	258	"Offset L": Offset 600 ft. Interval: 100 ft. Shot depth: 125 ft. Charge: 1 lb.	K70-KK120	"R": interval 100 ft. Shallow "R": interval 20 ft.	Good
16	273	"S", Interval 100 ft. Shot depth: 30 ft. Charge: 10 lbs. (Experimental)	KK70-KK120	"R": interval 100 ft.	Good
17	301	"Offset L": Offset 600 ft. Interval 100 ft. Shot depth : 95 ft. Charge: 1 lb.	K70-KK120	"R": interval 100 ft. Shallow "R": interval 20 ft.	Good
18	333	"Offset L": Offset 480 ft. Interval: 80 ft. Shot depth: 90 ft. Charge: 1 lb.	K70-KK120	"R": interval 80 ft. Shallow "R", interval 20 ft.	Good

TABLE 1 (Contd)

Shot Point No.	Distance along traverse lines	Reflection shooting	Filter setting of best record	Refraction shooting	Reflection Quality
19	343	"Offset L": Offset 480 ft. Interval: 80 ft. Shot depth: 100 ft. Charge: 4 oz.	K70-KK120	"R":Interval 80 ft. Shallow R: interval 20 ft.	Good
20	358	Horizontal geophone shooting "Offset L" Offset 4600 ft. Interval: 100 ft. Shot depth: 92 ft. Charge: 4 oz.	K70-KK120	"R": Interval 100 ft. Shallow "R": Interval 20 ft.	Good
21	378	Air pattern shooting "Offset L":Offset 480 ft. Interval: 80 ft. Shot depth: 80 ft. Charge: 1 lb.	K70-KK120	"R": interval 80 ft.	Good
2	399	"Offset L": Offset 600 ft. Interval: 100 ft. Shot depth: 90 ft. Charge: 1 lb.	K70-KK120	-	No reflection due to seismic interference.

TABLE 1 (Contd)

Shot Point No.	Distance along traverse lines	Reflection shooting	Filter setting of best record	Refraction shooting	Reflection Quality
23	386	"Offset L" Offset 600 ft. Interval: 100 ft. Shot depth: 90 ft. Charge 1 lb.	K70-KK120	"R" Interval 100 ft Shallow "R" interval 20ft.	Uncertain reflection
24	317	"Offset I", Offset 600 ft. Interval: 100 ft. Shot depth: 75 ft. Charge: 5 lb.	K70-KK120	-	Good
25	237	"Offset L": Offset 660ft. Interval: 110 ft. Shot depth: 85 ft. Charge: 1 lb. - 5 lb.	K70-KK120	"R" Interval 220 ft. Total: 21,890 ft. Shallow "R": Interval 20 ft.	Fair



Division of National Mapping, 1958

MISC/58/210

G158-15

PLATE 2

LEGEND

SP20 SEISMIC TRAVERSE 1957–58

•374 RADAR ALTIMETER SPOT HEIGHT (metres)

ROUTES FOLLOWED 1954-55-56

SCALE IN MILES

10 0 10 20 30 40 50 60

SEISMIC AND GRAVIMETRIC TRAVERSE

Geophysical Section Bureau of Mineral Resources Geology and Geophysics

G 158 – 20

(A) TRACTOR TRAINS ASSEMBLED, SHOWING SEISMIC CAB AND SHOT-HOLE DRILL

(B) SHOT-HOLE DRILL IN OPERATION

PHOTOGRAPHS BY ANARE

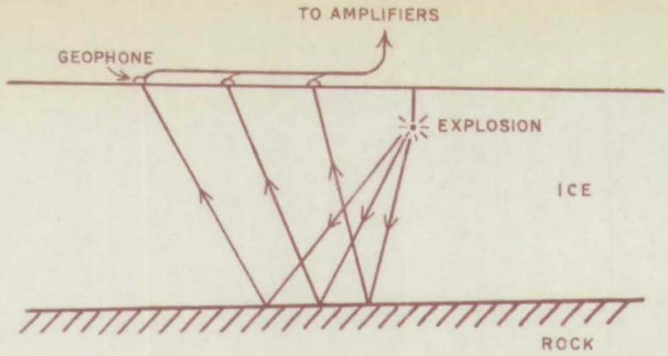


FIG A - REFLECTION METHOD

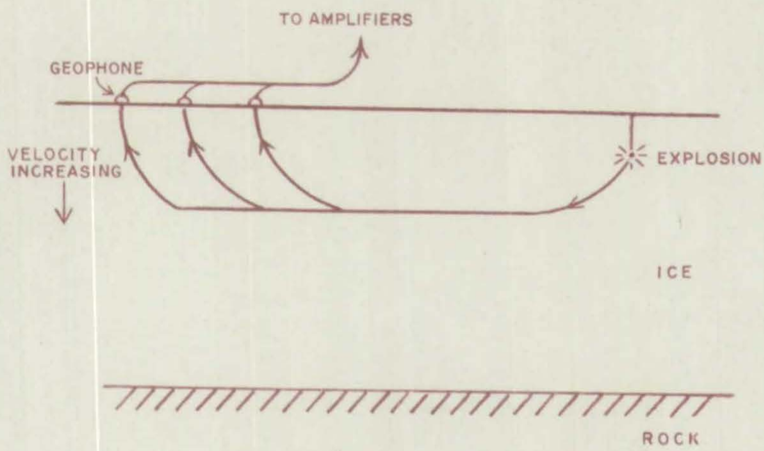
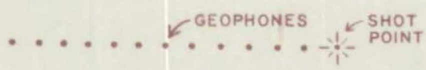
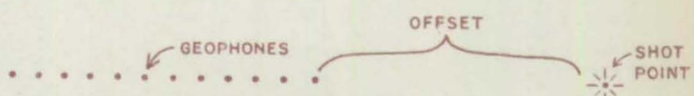


FIG B - REFRACTION METHOD

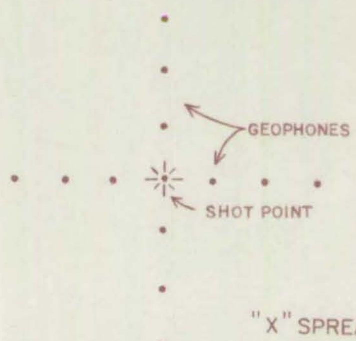


"R" SPREAD

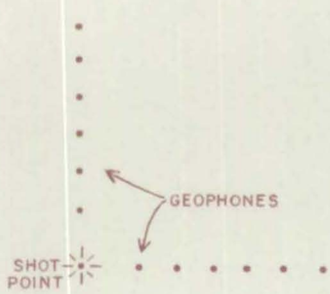


OFFSET "R" SPREAD

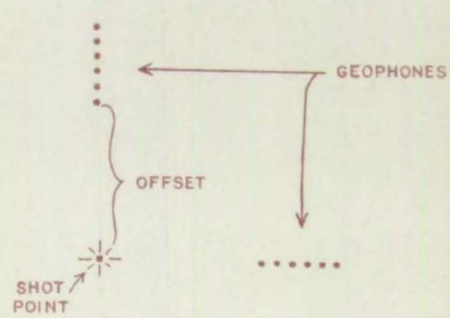
"S" SPREAD



"X" SPREAD

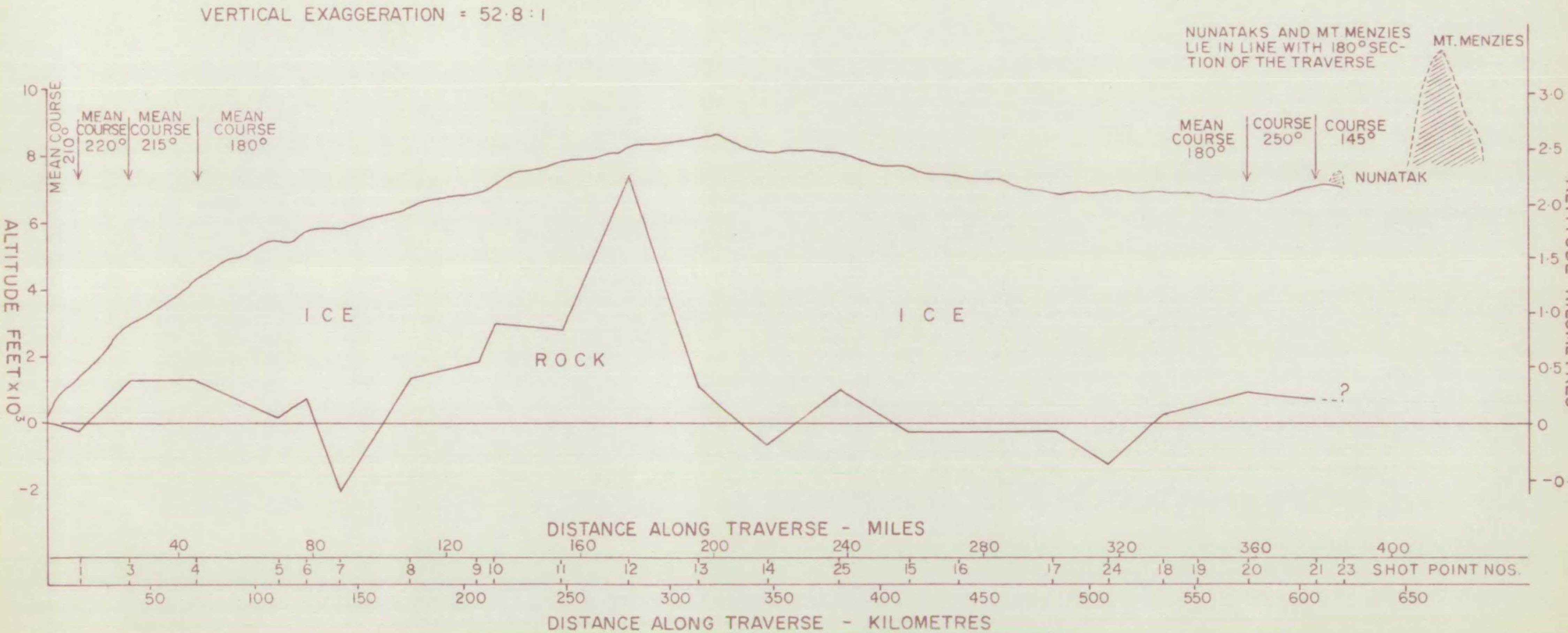


"L" SPREAD



OFFSET "L" SPREAD

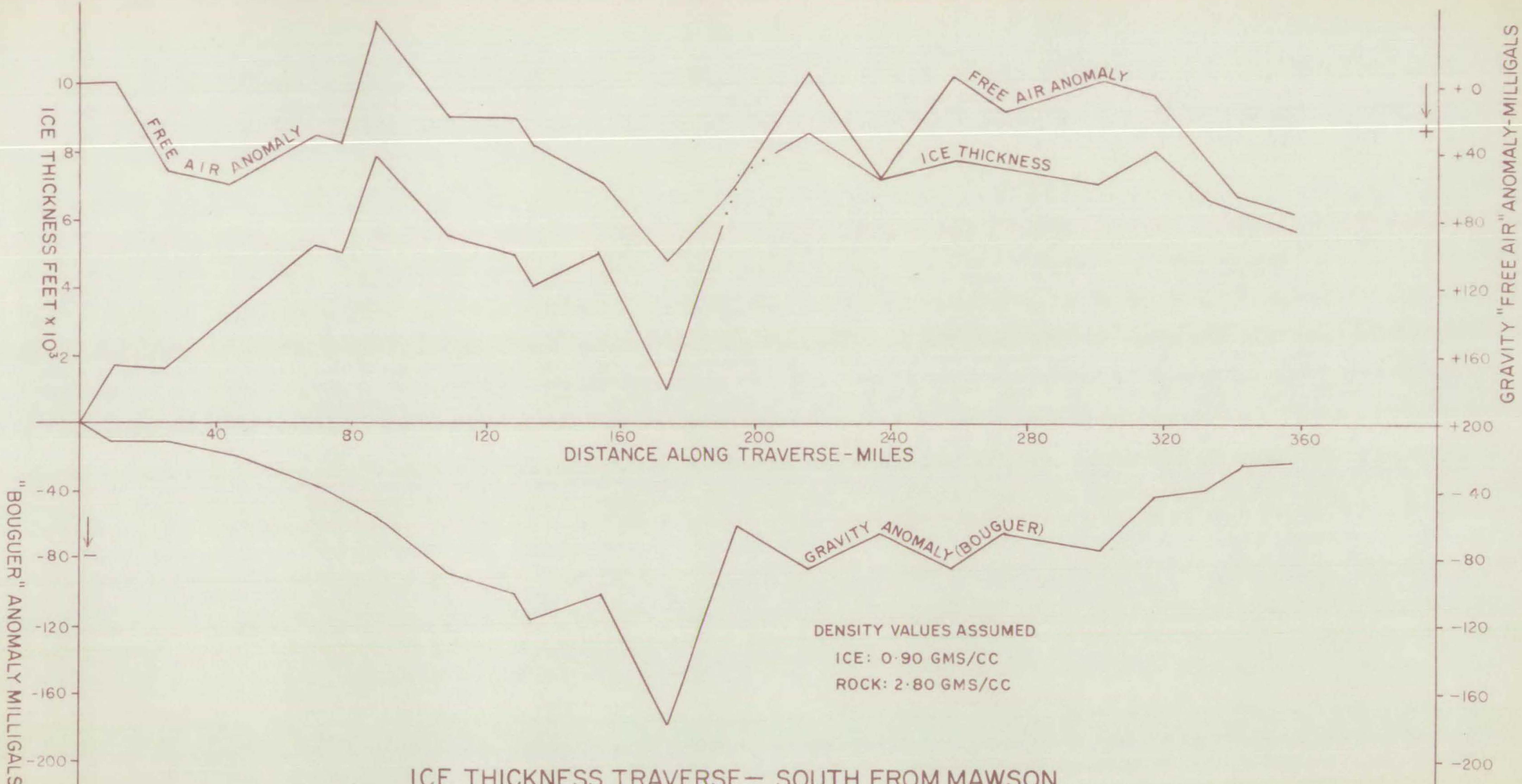
SEISMIC METHODS AND GEOPHONE ARRAYS



ICE THICKNESS TRAVERSE - SOUTH FROM MAWSON
PRELIMINARY PROFILE - ICE AND ROCK SURFACES

G158-16

PLATE 5

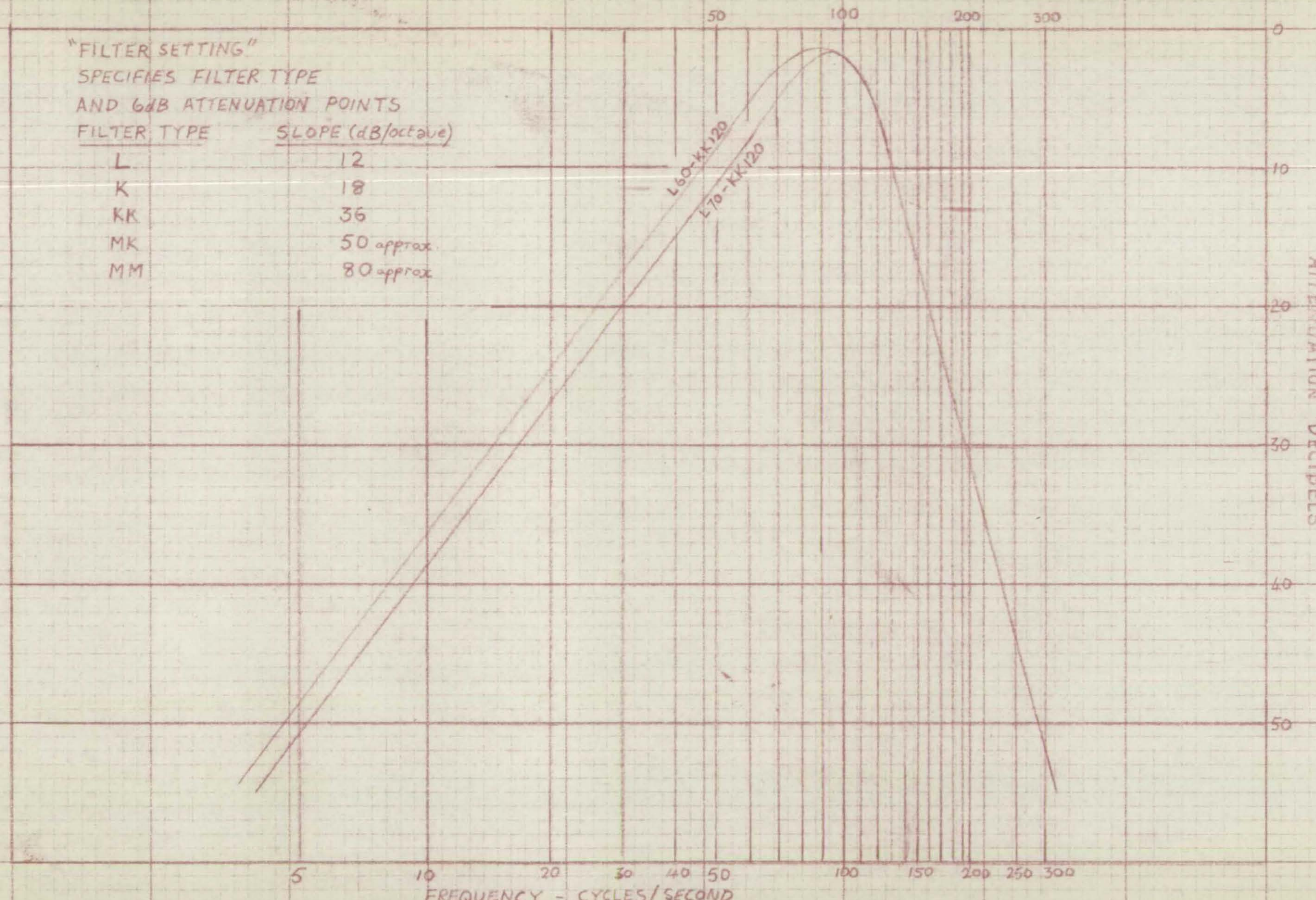


ICE THICKNESS TRAVERSE — SOUTH FROM MAWSON

PRELIMINARY PROFILE - ICE THICKNESS & GRAVITY ANOMALIES

G158-17

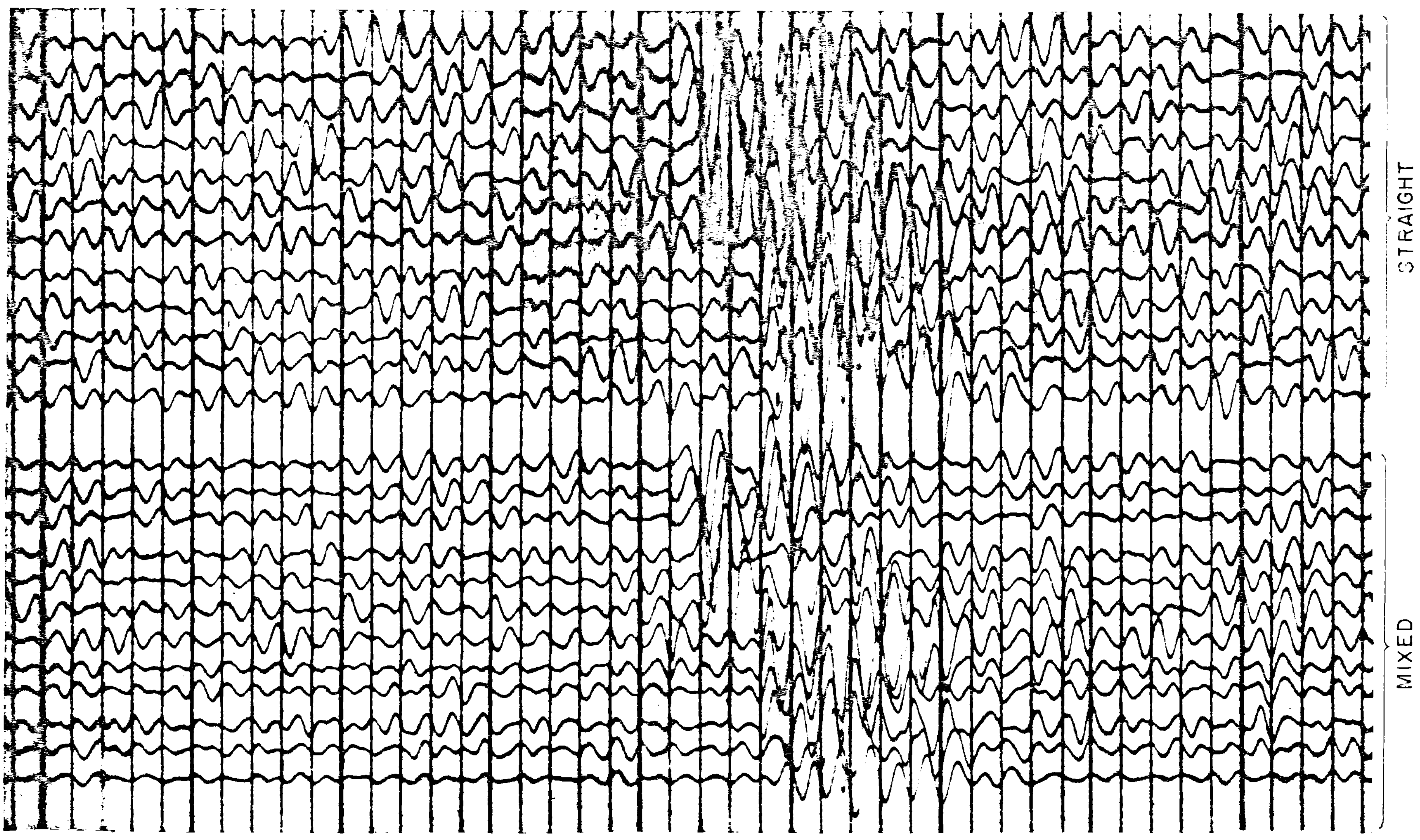
PLATE 6



SEISMIC FILTER CHARACTERISTICS

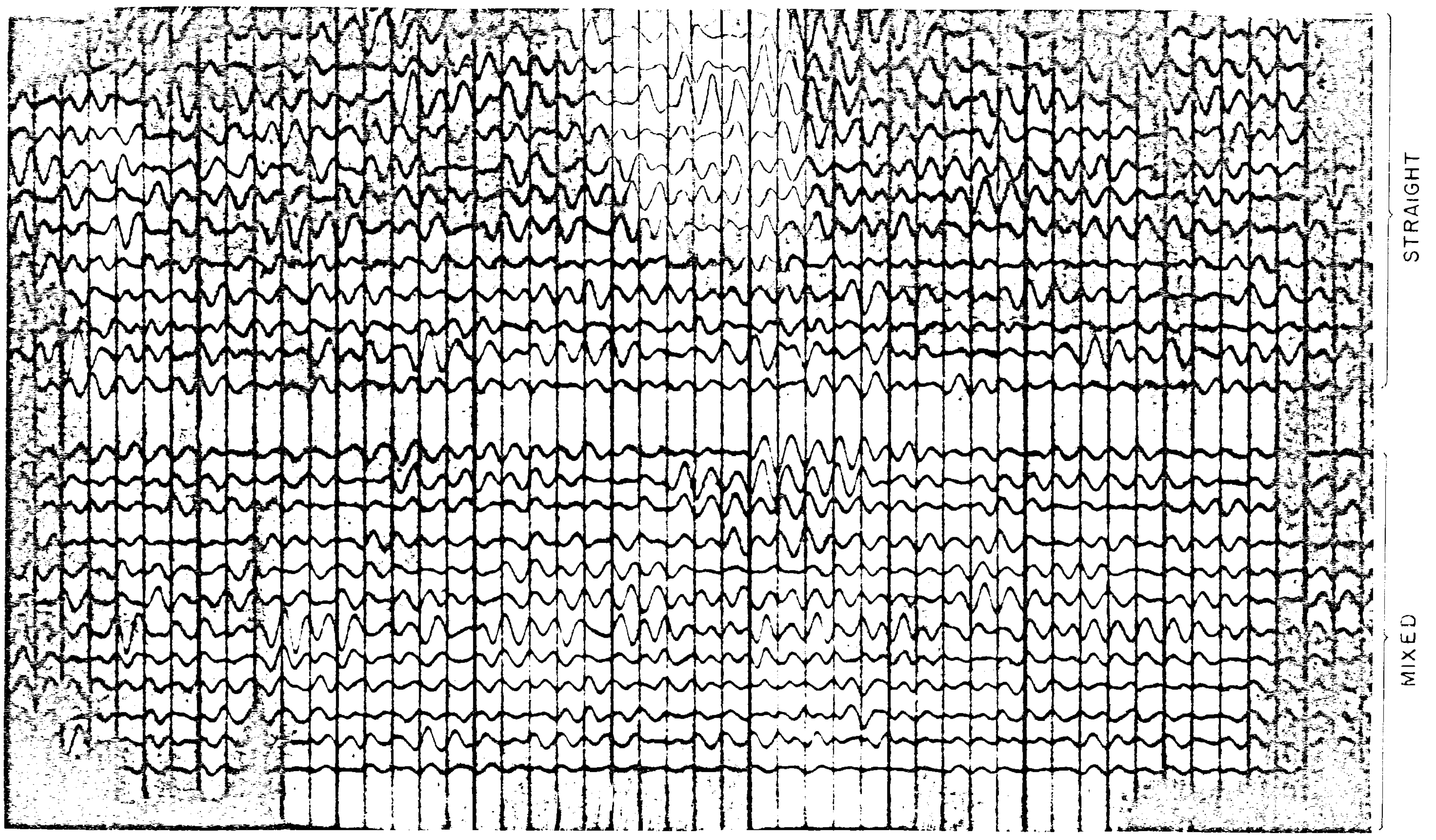
G 158-18

PLATE 7



a GOOD REFLECTION
"Offset L" spread 5 lb. TNT at 90 feet (2·3 kilogrammes at 27 metres)

b FAIR REFLECTION
"Offset L" spread 1 lb. TNT at 80 feet (450 grammes at 24 metres)



c POOR REFLECTION
"Offset L" spread 1 lb. TNT at 95 feet (450 grammes at 29 metres)

EXAMPLES OF REFLECTION QUALITY