THE DEVON ISLAND EXPEDITION

In 1959 the Arctic Institute of North America undertook an integrated program of long term research on Devon Island in the Queen Elizabeth Islands of arctic Canada. The co-ordinated studies were designed to help understand the interrelationships between the glacier-ice of Devon Island, the ocean in Jones Sound, and the encompassing atmosphere. They are being carried out over a 3-year period under the leadership of Spencer Apollonio. The main effort is concentrated on attempts to evaluate such factors as physical, chemical, and biological variations in the arctic waters of Jones Sound caused by discharging glaciers; evaporation and transfer of moisture between the ocean waters and the ice-cap and glaciers; and the overall influences of solar radiation energy on the mass balance of the ice-cap, the biological production in the sea, and the growth and decay of sea-ice. Some supplementary studies in archaeology and geology are included in the expedition's work because of the marked deficiency of knowledge in those subjects for Devon Island.

In the late summer of 1960 a main base was established on the north shore of Devon Island near Cape Skogn by an advance party of eight men taken in with their materials by the Canada Department of Transport icebreaker "d'Iberville". During a 3-week period buildings were erected and routes inland and to the ice-cap explored and marked, while an archaeological reconnaissance of the Cape Sparbo area was made by a small party under Mr. Gordon Lowther of McGill University. Everything was installed for a beginning of the 3-year program in April 1961.

During the months of April to September 1961 21 men worked on extensive programs in geophysics, glaciology, marine biology and oceanography, meteorology, and surveying. Intensive work was also completed in archaeology and geology. The following personnel took part:

archaeology:	G. R. Lowther	McGill University
	M. Tamplin	University of Toronto
geology:	J. W. Cowie	Bristol University
	A. Ormiston	Harvard University
geophysics:	K. Vögtli	Generaldirektion, Post-Telegraph-Telephon (Switzerland)
	J. P. Greenhouse	University of British Columbia
	W. P. Molson, Jr.	McGill University
glaciology:	S. R. Ekman	University of Stockholm
	R. M. Koerner	University of Birmingham
	G. E. Stewart	McGill University
marine biology,	S. Apollonio	Arctic Institute of North America
oceanography:	B. Beck	Arctic Institute of North America
meteorology:	L. Dahlgren	University of Uppsala
	B. Holmgren	University of Uppsala
	J. W. Fellows	Arctic Institute of North America
	A. Gill	Arctic Institute of North America
	C. W. Nicol	Arctic Institute of North America
surveying:	R. Wyness	Royal Engineers (United Kingdom)
	P. Cress	University of Toronto
mechanic:	T. R. Welch	Arctic Institute of North America
pilot:	R. Carswell	Arctic Institute of North America

In addition to support from Arctic Institute general funds, the Devon Island Expedition has received major support in funds or equipment from the Defence Research Board of Canada, the Geophysical Research Directorate of the U.S.A.F., the Hudson's Bay Company, Massey-Ferguson Ltd., the Meteorological Branch of the Department of Transport (Canada), the Mount Everest Foundation, the National Research Council of Canada, the National Science Foundation (U.S.A.), the Office of Naval Research (U.S.A.), the Quartermaster Corps of the United States Army, the Royal Society, the Signal Corps of the United States Army, the United States Steel Foundation, and the United States Weather Bureau. In addition a large number of private individuals and companies gave significant help by contributing funds, services, or equipment.

The general summary that follows and the preliminary reports are all subject to revision after study of the data obtained.

Report of the field leader, April-September 1961

The main geophysical, glaciological, and surveying work was done on a glacier that forms an outlet for the Devon Island ice-cap and enters Jones Sound at about 83°10'W. For easy reference it has been tentatively named the "Harald Sverdrup Glacier". The glacier itself is about 10 miles long and 2 miles wide, flowing from south to north between valley walls that rise almost 1,300 feet above its surface. It has a prominent medial moraine, and about 5 miles from the coast a small outlet glacier flows back to the south where it almost joins a second and much smaller outlet glacier. An ice-cap station was maintained at approximately 75°28'N. and 83°W. at which meteorological reccords and glaciological studies were made. Travel on the glacier and ice-cap was by WEASEL, although a light aircraft (a Piper PA18 Super Cub) was operated on skis and low-pressure tires throughout the summer in support of many of the operations. The plane, flown by its owner, Ross Carswell, put in over 200 hours of flying without incident in spite of numerous landings on difficult and unprepared areas, including the glacier, the ice-cap, and open terrain after the snow had gone.

In the geophysics program numerous depth and volume determinations were made on the glacier and ice-cap, using an electrical resistance measurement method described in more detail separately. The maximum depth recorded on the glacier was 600 metres and the ice-cap meteorological station was found to be on ice 750 metres thick. Resistance properties of snow, firn, and ice were determined and two distinct resistance characteristics were observed in the ice. Some attempts have been made to relate these differences to the origin and history of the ice. Samples were collected in order to make a spectographic determination of the ionic composition of the ice in an attempt to relate that to its electrical properties. In August two visiting engineers from the U. S. Army attempted depth measurements on the glacier by a new method using radio altimetry, and the results obtained agreed generally with results obtained by the electrical resistance method. The glaciology program was initiated and carried out by S. Ekman and R. M. Koerner during May, June, and July, when Ekman was called home because of serious illness in his family. The program was then continued during August and September by Koerner and Stewart, following instructions left by Ekman. Over 50 pits were cut on the "Sverdrup Glacier" and ice-cap to allow determinations of snow-depth, density, temperature, and hardness; vertical distribution of snow, firn, and ice-crystal structures; internal temperature variations to depths of 12 metres; accumulation and ablation. There was an attempt to determine the runoff of melt-water into the sea, using water-level, current, and weir measurements. The glacier lost almost 2 meters of ice during 1961 and the firn line on the ice-cap reached its greatest height at about 1,700 metres.

In the fields of marine biology and

oceanography tidal observations were made during a complete lunar cycle. The development of algae as indicated by chlorophyll concentrations in sea-ice was measured, and the chemical properties of the ice were examined. Routine measurements of photosynthesis in the coastal waters were made using three different methods; salinity, and the concentration of chlorophyll, phosphates, and silicates were determined, and zooplankton and phytoplankton investigated. Temperature and light penetration mesaurements were also recorded. Rather high chlorophyll concentrations and moderate photosynthesis rates were observed, and there is some evidence of limitation of nutrients.

Comparable observations in meteorology were made at the base camp near sea-level and at an altitude of 1,500 metres at the ice-cap station They included standard synoptic observations and measurements of total and net short and long wave solar radiation. Work at the ice-cap station also included a program of micrometeorological observations of wind and temperature. Snow-depth and density observations were also made whenever possible. A third station, on the "Sverdrup Glacier," provided continuous records of humidity and temperature in a Stevenson screen.

The glaciologists were supported in the field by two surveyors who studied the horizontal and vertical motions of the Sverdrup Glacier using standard surveying techniques to record motion of 29 stakes arranged in five profiles. The base-line for this survey was measured with tellurometer equipment by the Topographical Survey of Canada. The glacier was found to move about twice as far in August as in July, and the maximum total movement observed between June and the end of August was 9 metres.

The archaeological sites at Cape Sparbo, which had been discovered in 1960, were excavated during the season by G. R. Lowther for the National Museum of Canada, assisted by M. Tamplin. Over 350 artifacts were recovered and pre-Dorset, Dorset and Thule material was found. The site includes houses, tent rings, meat caches, and several other structures. Preliminary surveys were made on two other previously unreported sites located from the air and on the ground in the vicinity of Cape Hardy and Cape Sparbo. Excavations were also made at a number of sites near the main base, and 200 artifacts were recovered from pre-Dorset and Thule remains. The material excavated covers about 3,500 years of almost continuous occupation. Geological interpretations of the sites were provided by Cowie and Ormiston, with controlled local surveys and levelling being done by Wyness and Cress. Carswell located several new sites from the air between Cape Hardy and Belcher Point, at Rigby Inlet, and at Eskimo Inlet.

Fossil collecting and mapping were carried out in the area, including lower palaeozoic sediments at Cape Skogn, Dundas Harbour, Crocker Bay, Burnett Inlet, Maxwell Bay, Sverdrup Inlet, and Eskimo Inlet. The lithography and stratigraphy of the north and south coasts were related to earlier work at Dundas Harbour and to the work of the Geological Survey of Canada on the western end of the island during "Operation Franklin". The results permit correlation of the geology of Devon Island with that of Cornwallis Island and areas farther to the west. Devonian fossils were collected in Prince Alfred Bay and Arthur Fiord.

Five men will be continuing the meteorological and oceanographic programs during the winter of 1961-62. Investigations will be made into the mode of formation and the physical, chemical and biological properties of sea-ice. Work will be resumed on all phases of the expedition in the summer of 1962, except for geology and archaeology, but in meteorology more attention will be paid to solar radiation observations and micrometeorological processes near the surface, using wiresonde balloons and mast instruments. New instruments for this purpose, and for measuring light transmission through sea-ice will be prepared during the winter.

SPENCER APOLLONIO

Geology

During the summer of 1961 an attempt was made to trace the geological succession on eastern Devon Island upwards from the metamorphic basement rocks through any Precambrian sediments into the Cambrian and Ordovician. All fossil collections made were accurately located in measured stratigraphical order and came from rocks *in situ*. In addition a detailed map of the central part of Devon Island was begun and will be completed from aerial photographs at a scale of 1:250,000. Complete coverage at a large scale was not achieved because of restriction in the use of the expedition aircraft. When the fossil faunas have been identified in Bristol consideration will be given to the matter of faunal provinces and palaeoecology.

The areas visited in Devon Island all lay between 82°W. and 89°W. and the specific sites were located at:—

(1) The coast near Cape Skogn
(2) The large lake inland from Cape Newman Smith
(3) The western side of Dundas Harbour
(4) A valley at the northeastern end of Croker Bay
(5) The head of Burnett Inlet
(6) A valley running northeast from Fellfoot Point (to the east of Maxwell Bay)
(7) The big valley running south from Sverdrup Inlet

The Precambrian metamorphic basement complex was examined whenever time permitted. The foliation, strike, and dip were recorded; and the basic dykes sampled and faults traced. A petrological sample was taken from within each measured section in the sedimentary cover. No Precambrian sedimentary rocks were recognized.

The Cambrian rocks were measured and described in areas 1, 2, 3, 4, 5, and 7. It was found possible to use lithology to correlate formations throughout the area, and the formational names set up by Kurtz *et al.* for the Dundas Harbour area (1952) can be used over the whole of central Devon Island. Fossil horizons containing new faunas were found in the Lower and Middle Cambrian but no Upper Cambrian fossils were identified. Lower and Middle Ordovician rocks were measured and described in areas 3, 5, and 6, and faunas were collected at a number of horizons. Some of these fossils may be new.

The objectives set for the season were achieved but work remains to be done in order to understand 1) the metamorphic basement complex and the associated dykes, 2) the stratigraphy and palaentology of the Upper Ordovician and Silurian rocks in the western part of the island. These strata and their equivalents were studied during "Operation Franklin" of the Geological Survey of Canada, and also in considerable detail by R. Thorsteinsson on Cornwallis Island. Continuous air support would be required to improve on that work. 3) Although the structures in central Devon Island are very simple and would not repay study for academic purposes, the structures in and near Grinnell Peninsula are of interest, but again work in that area would require the use of an aircraft on a continuous close support basis.

J. W. Cowie

Measurement of electrical resistivity of ice

Measurements of the specific resistance of the ice of the Devon Island ice-cap (approx. 75°30′N. 83°W.) and of an outlet glacier discharging into Jones Sound gave values of 50,000 to 100,000 ohm-metres and they were about ten times higher for the underlying bedrock. This large difference makes it possible to measure accurately the thickness of the ice-cap or of the glaciers by an electrical method.

The method consists of sending a d.c. current through the ice by means of two widely spaced electrodes and observing the resulting electrical field. If the electrodes are separated by a distance equal to about twice the thickness of the ice a large proportion of the current will flow through the underlying rock. The large difference between the resistivities of the two media results in a distortion of the field that can be measured easily and from the amount of distortion the thickness of the ice can be calculated.

With an amount of equipment that can be carried in three packs, thicknesses exceeding 500 metres could be measured, and on a glacier 30 km. long and 2.5 km. wide 33 points were investigated in 1 month. Most of this time was spent on the often difficult travelling to the points of measurement, whereas the measuring itself required only 3 hours at each point.

The geo-electrical measurements give information not only about the thickness and electrical properties of the ice-masses but also about the conductivity of the bedrock. They indicate that the major part of the glacier is resting on compact rock, but in one small area the ice is underlain by thick sediments, which have a much lower resistivity than the ice-mass itself.

Several small areas of the glacier were of special interest because they had higher resistivities of the order of 1 megohm-metre. This kind of ice has a small conductivity comparable to that of the ice-masses of the Alps and of the Athabaska Glacier in Alberta[1]. There is as yet no explanation for the large difference in resistance between some arctic ice and that known for glaciers in middle latitudes. Devon Island has both kinds of ice and provides an excellent opportunity for the study of this problem.

Resistivity measurements on the ice of a meltwater-fed lake gave the same low values as those generally found on the glacier. Similar results were obtained by measuring of crevasses that had been filled with melt-water and frozen. These observations eliminate explanations based on the effects of recrystallization or pressure. Analysis of different samples of melt-water will supply evidence as to whether differences in salt content are the main cause. Measurements of sea-ice near the coast gave values of only 40 ohm-metres and thus showed that ice of high salinity can indeed have a quite low resistivity. On the other hand ice resulting from recent falls of rain or snow had a very high resistivity. If it could be confirmed that freshly formed ice-masses always have high resistivity such findings would be of great interest to glaciologists, because resistance measurements would provide an easy method for distinguishing between accumulation and ablation zones. Moreover, full understanding of the factors influencing the conductivity of old and new ice could provide information about the climatic conditions prevailing at the time of formation of ancient ice-masses.

K. VOEGTLI

[1]Keller and Frischknecht. 1960. J. Res. 64D439.

Glaciology

During the summer of 1961 a program of glaciological studies was initiated by S. Ekman of the University of Stockholm, assisted by R. M. Koerner. When Ekman was forced to return to Sweden on July 5, Koerner carried on the work, assisted by G. Stewart. The work involved a study of accumulation and ablation on the Devon ice-cap and on a selected valley outlet glacier (the "Sverdrup Glacier"), with particular attention to runoff on the glacier.

Before the melting season began, the accumulation of the 1960-61 winter was examined at various altitudes by digging a number of snow pits, and it was found that the accumulation varied very little with altitude. Old firn was recognized above altitudes of about 1,700 metres. Cores up to 12 metres long were obtained on the ice-cap. Ablation stakes were set in holes drilled in the surface of the valley outlet glacier, and along a profile to the highest point on the ice-cap at approximately 3-kilometre intervals.

When ablation had begun, synoptic meteorological observations, snow temperatures, and temperatures at the ice surface were recorded every 2 hours, together with the amount of ablation at a campsite on the valley glacier. These recordings were discontinued when the ice-surface temperature reached 0°C. Runoff measurements were made in a melt-water stream on the valley glacier near the campsite at about 300 metres above sea-level using an Ott current meter, and a velocity revolution counter. The area of the catchment basin of the stream was ascertained by triangulation on the ground.

The period July 13 to 28 was spent in work on the ice-cap where pits were dug into the previous winter's snow, and the progress of melting above and below the firn-line was examined. A line of snow pits at intervals of 2 miles was taken over the ice-cap and down to below the firn-line on the southern side. Superimposed banded ice was found in every pit. Densities, temperatures, and stratigraphy were studied in every pit, and ice samples were examined in order to determine their crystallographic structure. Work on the "Sverdrup Glacier" was resumed between July 29 and August 20. The scope of runoff measurements was extended to estimate the runoff through all the streams on the glacier surface, relating them to the runoff of the stream at the campsite. The major part of the water was found to flow at the sides of the glacier where the streams actively erode the ice. The stream on the west side carries about four times as much water as all the other streams combined. Regular measurements were made of the runoff past a line at 300-metre altitude and on one occasion runoff through all streams was measured as close to the glacier snout as possible. All the main glacier surface streams end in *moulins* at least 400 metres from the snout.

Work was resumed on the ice-cap on August 21 and continued there to the end of the summer field season on September 6. The snow-pit studies were repeated between the ice-cap station and the ice-cap summit. These revealed a profile of new firn lying on ice below the firn-line, indicating that the melting season on the ice-cap had been unusually short. Five-metre ice-cores were made at 60-metre altitude intervals from a point 60 metres above the firn-line to the ice-cap station at 1,400 metres. The cores will be examined for stratigraphy, density, gas bubble concentration, and crystallography by Koerner at the base camp during the winter. General observations were made of factors indicating recession at the edge of the glacier, they suggest that terminal recession of the various small ice-cap outlet glaciers is very small, but that vertical wastage is taking place.

The program for the summer of 1962 will be arranged after the study of the 1961 results, but it will definitely include a more detailed investigation of runoff using more accurate methods, since the methods used and the results obtained during the past season were not completely satisfactory. During the winter Koerner will obtain 10-metre cores at the ice-cap station, and 5-metre cores at 60 metre altitude intervals between the ice-cap edge and the ice-cap station, examining all the cores for crystallography and stratigraphy. Similar studies will be made of lake-ice and sea-ice in order to help the biological program. All glaciological studies will be extended during 1962 to include the smaller separate ice-caps and some areas of dead ice.

R. M. Koerner

Observations of glacial movements

Observations of the movement of an outlet glacier of the Devon Island ice-cap were made during the summer of 1961 to help arrive at an estimate of the amount of ice entering Jones Sound each year. The particular glacier selected (tentatively named "Sverdrup Glacier") is one of the two largest outlets west of Belcher Point and into Jones Sound proper. It flows 10 miles from south to north from the point at which it leaves the ice-cap, has an average width of 2 miles, and is 1.25 miles wide where it enters Jones Sound. It has two major tributaries less than 1 mile wide, and two other relatively insignificant tributaries. The ice slopes steeply at the edge of the glacier, with the perimeter rising vertically for 40 feet in most places. A melt-water stream 40 feet wide flows along the western edge of the glacier during the melting period.

The surface movement of the glacier was found by determining the position of stakes set into the ice relative to signals placed on the rock of the cliffs overlooking the glacier valley. The actual positions were found by resection, using a Wild T1A theodolite, which reads directly to 20 seconds, with angles being given to the nearest 5 seconds by the surveyor. Six signals were erected at distances of 2 miles apart in such a way that at least three were visible from any one stake. The signals consisted of 1-inch-diameter aluminum poles, 6 feet in length, placed vertically over a paint mark or rock and held in position by a rock cairn. A tin can was placed on each signal as a reference point for vertical angle observations. Twenty-nine stakes were placed in the glacier along five profiles, at locations previously selected from aerial photographs. The profiles were approximately 0.75 mile apart. The stakes were aluminum poles, 13 feet long and 1 inch in diameter inserted into drill holes in the ice approximately 10 feet deep. Profiles one, two, and three were linked by the placing of two stakes between each profile. One profile of seven stakes was measured three times (at the outset and after 30 and 60 days respectively) but the remaining stakes were fixed twice only. The vertical positions of profiles one and two were fixed twice by levelling from a rock mark on a cliff side. The greatest closing error on any stake was .15 feet (4.5 centimetres). A third round of levels was taken but not related to the rock mark

A minimum of five rounds was taken at each signal point. The greatest difference between the reduced angles for the triangulation was 28 seconds, and averaged 17 seconds. The difference from the mean angle is approximately one-half that figure. Observations improved during the season when the instrument and signals became familiar. The triangulation was adjusted by a braced quadrilateral and braced triangles, the greatest adjustment to any one angle being 6 seconds. There was sufficient light to observe at any time of the day or night from June 1 until the end of July, but the temperature dropped to the freezing point by 1800 hrs. every day.

On July 18 the Topographical Survey of Canada measured a base-line using tellurometer equipment. The direct reading was 5,285.1 feet (1610.90 metres). The ends of the base-line were named N and S, and it was joined to the previous triangulation by a braced quadrilateral; the greatest adjustment to any angle was 3 seconds. Reciprocal vertical angles were taken at N and S, which determined the height of S above N as 118.22 metres and 118 metres, the mean difference being 118.11 metres. Because the journey between a signal and a stake took an average time of 5 hours, and because it was difficult to get on or off the glacier at its perimeter, stake positions were fixed by resection. The first round of observations on all stakes was begun and completed on July 2. The second series on profile one only was begun and completed on July 7. Final observations on all stakes were begun on August 2 and completed on August 15. At each stake four rounds of horizontal angles, vertical angles to two signals were taken, extra rounds being taken when necessary to replace poor ones. The greatest difference between the mean and any single result was 15 seconds and averaged 6 seconds for the first observation on each stake.

There was still some snow left on June 8, and there was very little melting so that little difficulty was experienced in keeping the theodolite level during observations. When the melting rate increased the tripod was set up on thin flat rocks about 6 inches across, which were placed in holes cut 2 or 3 inches down into the ice, with ice chippings piled up about the foot of the legs. In this way the theodolite was kept level during rounds. There were only 4 days when the melting was sufficiently rapid to prevent work. Because of the ablation some of the aluminum poles had to be cut so that the theodolite could be set up over the stake.

The centre stake of profile one moved 3.49 metres in 35 days and 6.59 metres during the next 37. The remaining stakes in profile one confirmed the increased rate of movement during the second period. The vertical movement of the stake tops was small, being only about 25 cm. for the greatest rise, but the movement indicated that the ice rose slightly at the edges and sank very slightly in the centre.

The profile stakes and the signals were left in position. The stakes will be resurveyed in 1962 to determine the amount of movement during the winter. The stakes will then be re-established and the cycle of observations repeated using the same signal stations. We should like to acknowledge help given by Keith Arnold (Department of Mines and Technical Surveys) who gave advice in the preliminary planning, and to Paul Atkinson, of the Topographical Survey of Canada, who measured our base-line.

P. Cress
R. Wyness

Measurements of electrical resistivity of ice-formations

This is a preliminary report on the field work carried out by the geophysical party under Dr. Kurt Vögtli during the summer season of 1961. A description of the techniques has been added since, although they are well-known geophysical survey methods, prior to the last 2 or 3 years few attempts had been made to adapt them to use with ice. The recent development of a sensitive voltmeter with a very high input resistance to replace the more cumbersome potentiometer is the most notable innovation in the present work. The final statement of results will come from Dr. Vögtli, who initiated, supervised, and took part in the work.

The work had two main purposes. The first was to provide measurements of the thickness of glacier ice using geoelectric means. The second was to determine the resistivity of arctic land-ice. The latter problem has attracted attention in the last 2 years since it had been found that ice from the Greenland ice-cap has a resistivity of the order of 10^{-3} times that of continental European glaciers. The reasons for this difference are generally thought to be a matter of chemical composition and origin. However no further arctic field work had been done. The interest lies not so much in the actual resistivity, but rather in the possibility that variation in resistivity of the ice can be linked with variations in the physical properties of the ice and that an understanding of it can be used as a glaciological tool. At the present time there is no literature on the subject in English and only a small amount in German.

Method

The basis of the method is measurement of the difference in electrical potential (ΔV) between two points on the surface of a medium, caused by a current (I) passed through that medium. The potential field generated by a given current depends only on the resistivity of the medium (measured in ohm-metres). If the medium is composed of layers of different resistivities, then each of these layers exerts an influence according to its extent and its depth below the surface; in such a case measurement of ΔV and I would give an apparent value of the resistivity (ρ_{app}) that is a composite effect from all layers. Analysis of apparent resistivities can be used to determine the depth, extend, and individual resistivity of the various layers.

The potential field for any given situation can be calculated theoretically by solving Laplace's equation $\nabla^2 V = 0$ with the appropriate boundary conditions. In a homogeneous isotropic medium of resistivity ρ, bounded in one plane by a material of infinite resistivity (as, for example, the surface of the ground bounded by air), the solution of the Laplace equation gives the potential V at a point in the medium distant r from the source of current I placed on the interface as being $V = \frac{\rho I}{2 \pi r}$ (m.k.s. sytem). To illustrate, consider two electrodes connected to opposite terminals of a battery and inserted in the earth so that a current I flows between them. This is equivalent to having two current sources +I and −I separated by a distance d on the air-earth interface. Assuming for the moment that the rock is uniform to a considerable depth, then the potential anywhere is given by the sum of the potentials due to the two sources. Viewed in a vertical plane through the electrodes the situation is as shown in Fig. 1.

where a, b and d are as shown in the figure. In practice the electrode configuration of either Wenner or Schlumberger is used. These are shown in Fig. 2 together with the expressions for ΔV for each.

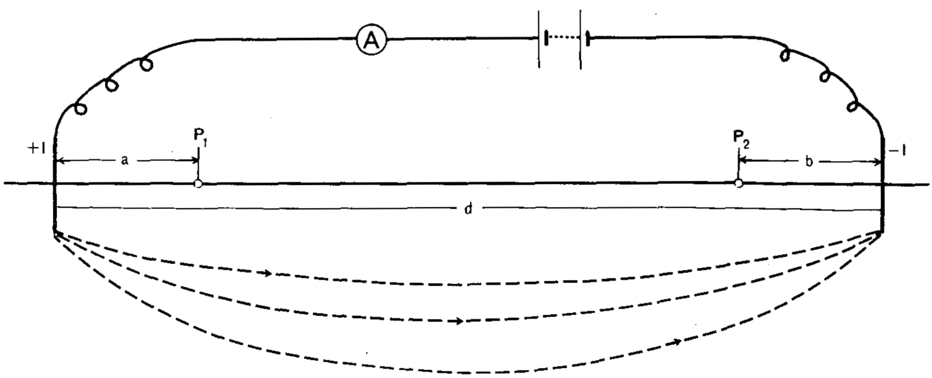


Fig. 1. General arrangement of electrodes.

If a voltmeter is now connected between any two points P_1 and P_2 then the values of I and $VP_1 - VP_2 = \Delta V$ can be used with the above formula to find ρ:

$$\Delta V=\left[\left(\frac{\rho I}{2\pi a}-\frac{\rho I}{2\pi(d-a)}\right)-\left(\frac{\rho I}{2\pi(d-b)}-\frac{\rho I}{2\pi b}\right)\right]$$

It is important to realize that the depth to which the current will penetrate increases with the distance between the electrodes. This is not obvious but can be shown by plotting the lines of equipotential in each case. As a general rule, current I penetrates to a depth approximately equal to "a" in each

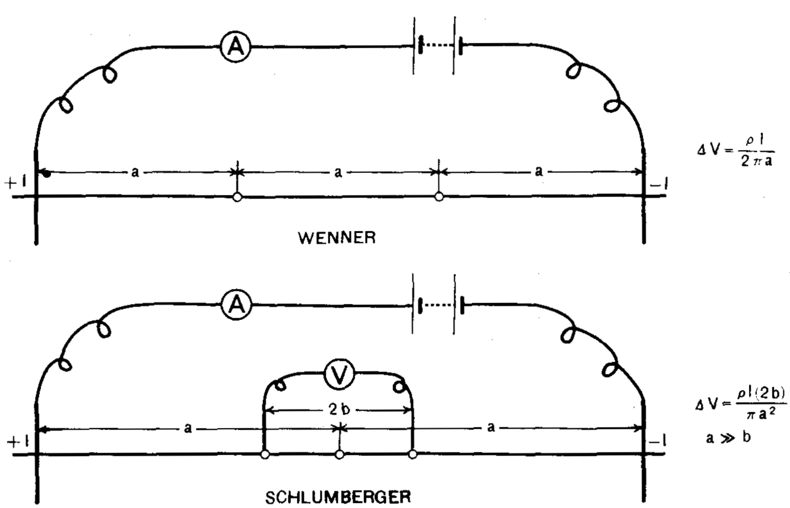


Fig. 2. Arrangement of electrodes after Wenner and Schlumberger.

method, and effects produced at that depth can be measured on the surface.

When instead of a homogeneous medium layers with different resistivities are encountered ρ must be replaced by ρ_{app} in the above equations. The current flow will be bent toward the layers of lower resistivity and away from the layers of higher resistivity. The potential field is thus distorted from that produced in the homogeneous medium and the value ΔV at the surface is altered (Fig. 3). A single measurement cannot tell the observer whether the observed resistivity is the true resistivity of a homogeneous medium or the apparent resistivity of a medium of several layers. However, by varying the distance "a" the current can be made to penetrate to different depths at which it will experience various deflections depending on the layers encountered. By plotting ρ_{app} against "a" a profile is obtained that can be compared with similar profiles calculated theoretically for particular situations. These theoretical curves have been found by solving Laplace's equation with appropriate boundary conditions for two or more layers with various combinations of resistivities and depths. If the plotted profile fits a theoretical curve, a picture of the resistivities and stratification below the surface is obtained.

Effect of layers on current flow

When applied to depth finding in ice, the problem is essentially one of separating two layers, ice and bedrock. The method of either Wenner or Schlumberger may be used but preferably both, since the theoretical curves for each are available and this gives two independent results. Once the ice and bedrock resistivities have been determined however, one method is sufficient, and Schlumberger's being faster is preferable.

In a party of three, one man reads the instruments while the other two move the electrodes. The distance must first be measured out on either side of the instrument set up, and the electrode positions marked with flags. Distances of "a" are chosen so as to give an even spacing on the logarithmic scale (i.e. an equal number of points in the ranges 1 to 10, 10 to 10^2, 10^2 to 10^3 metres). This is desirable since the theoretical curves are plotted on "log-log" paper. Starting from maximum separation the electrodes are moved toward the centre with a reading being taken in each position. Between readings the cable must be rewound on the reels as the length of line required decreases; this precaution eliminates wear on the cables and the inevitable "snagging" that occurs when they are dragged across the ice. Finally the flags are retrieved and the

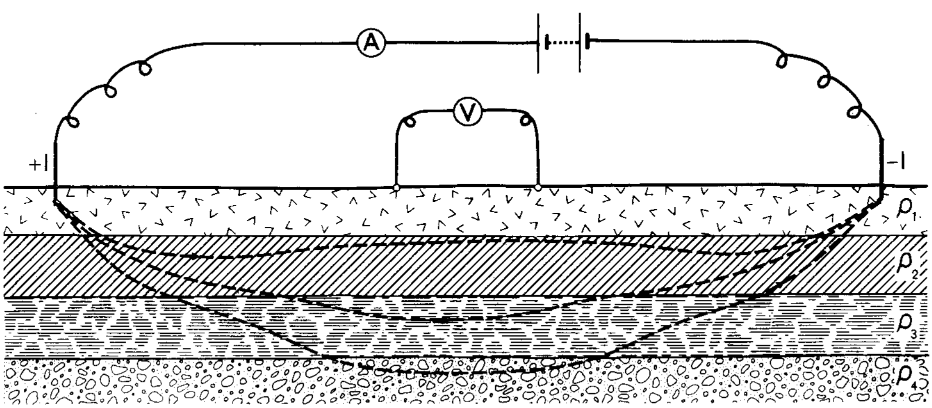


Fig. 3. Distortion of electrical field by layers of varying resistivity.

equipment is packed up. A profile with "a" up to 1000 metres can be completed in about 3 hours under good conditions. The data are plotted on "log-log" paper and compared with theoretical curves.

The instruments used were a Simpson Model 269 Microammeter and a Keithley "300" Electrometer. The latter is a vacuum-tube voltmeter with a very high input resistance (10^{14} ohms), necessary when dealing with small currents and high resistivities. The current electrodes were of iron, whereas the potential electrodes used consisted of a copper rod in a solution of $CuSO_4$ all encased in a china pot with a porous lower section. The solution is necessary since a spontaneous potential exists between the ice and the electrodes that must be the same and constant for both potential electrodes if the voltmeter is to read zero before current flows. With metals alone the difference is usually sufficient to throw the voltmeter off scale on the more sensitive ranges, making readings of ΔV impossible.

Other practical problems that arise can be summarized briefly as follows:

(a) Loss of current due to conduction by meltwater streams. This effect is minimized by appropriate positioning of the profile.

(b) The difficulty in getting a current to enter the ice. Current flow is governed more by contact resistance between electrode and ice than by the path resistance in ice. Cold dry snow makes a particularly bad contact. Salt or brine improves all contacts considerable and there should always be a supply of one or the other.

(c) The resistance of bedrock. A knowledge of the possible rock types to be found below the ice is essential, especially if there are sediments whose resistivity differs little from that of the ice.

(d) Crevasses, which affect measurements directly according to their size and position relative to the profile. Areas of heavy crevassing cannot be worked with this method.

(e) Insulation losses. Great care must be taken to ensure complete insulation of the instruments from the ice and from each other. Since cable reels are seldom well insulated they must be suspended off the ice during readings if they are not actually beside the electrodes.

(f) Telluric currents. Earth currents associated with ionospheric and magnetic storms can disrupt readings. If possible the profile should be made perpendicular to the direction of such currents.

The accuracy of a depth measurement is almost entirely determined by the "fit" obtained between experimental and theoretical curves. A single reading can have an accuracy of between 30 and 10 per cent depending on the "fit". Subsequent readings in the same area improve the knowledge of resistivity layers involved, and in general an overall accuracy within 15 per cent can be obtained.

Comparison with seismic methods of sounding can be summarized briefly. The seismic method is more accurate, more expensive, and the equipment necessary is more bulky. It is preferable for work on a thick ice-cap, being faster at great depths and yielding more information per shot. Geo-electric methods can probably be used under a greater variety of conditions than seismic methods and are probably just as fast to depths such as are found on a glacier.

Field work

The geophysical party and equipment arrived on Devon Island on June 7. Before going to the glacier on June 12, resistivity measurements were made on the ice of a lake and on sea-ice near the base camp. Water samples of both were taken.

The period from June 12 to July 9 was spent at the camp at the first fork of the glacier. During this time, 24 measurements were made, using the method of Schlumberger. It was possible to average only one sounding a day over a prolonged period because travel to and from the sounding points made it difficult to complete two a day regularly. The ice in this general area had a value of resistivity throughout its depth of around 60,000 ohm-metres. Bedrock resistivity was of the order of 400,000 ohm-metres, but at one point the ice was underlain by low-resistance silt indicative of an old lake bed. A typical curve on this section is shown in Fig. 4. On July 9 camp was moved to the upper fork. On July 12 operations were moved to the ice-cap station for a short time and three soundings were made. These established a depth of ice of the order of 750 metres, and showed the order of resistivity to be the same as that found in Greenland (~60,000 ohm-meters).

Three areas of anomalously high resistivity were found on this part of the glacier. The first (with 2 megohm-metres) was on ice lying in an embayment of the cliff and not moving with the glacier, the other two occurred on ridges running near the glacier centre, at soundings 34 and 27. These ridges have almost vertical banding parallel to their length. In both the effect occurred in the top few metres.

After Dr. Vögtli's departure a week was spent at base camp during which time resistance readings were taken in the bedrock under the base and on the dolomitic sediments overlooking the camp. The resistivity of the bedrock was not typical, possibly because of sea-water infiltration and high salt content. Its conductivity dropped off rapidly

Fig. 4 Sample profile from lower part of glacier.

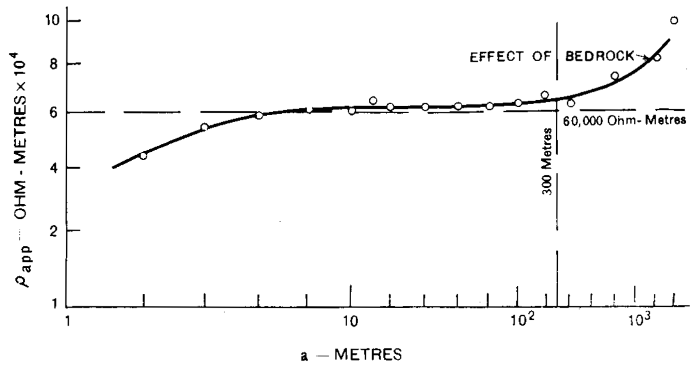
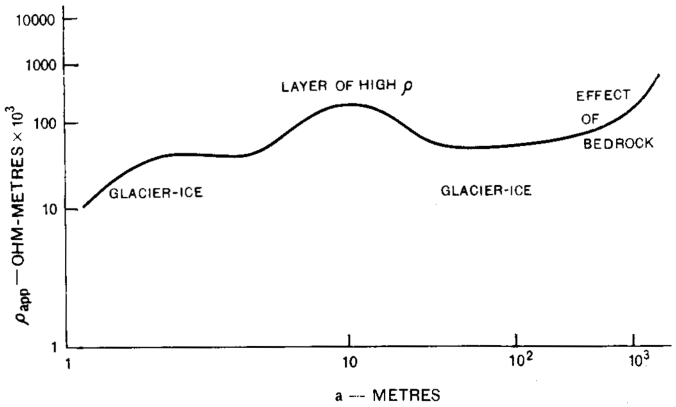


Fig. 5. Sample profile from upper part of glacier.



The period from July 19 to July 26, when Dr. Vögtli left the island, was spent at the upper-fork camp completing soundings 25 to 36. The glacier in this region has a characteristic layer of ice of higher resistivity (of the order of 100,000 ohm-metres) from 10 to 40 metres below the surface (Fig. 5).

with depth. The readings for the dolomite should prove useful since dolomitic rocks underlie the ice-cap in places and may underlie the glaciers also.

On August 6 a team of U.S. Army Engineers took ice-depth readings at six points on the glacier using converted radio altimeters. This method had been tested on ice-caps and had not been previously used on glaciers. Complete results have not yet been obtained but there were difficulties involved in the work, possibly because of the presence of water below the glacier surface.

The time from August 7 to August 23 was spent at the upper-fork camp. The depth-finding program having been completed, an opportunity was taken to investigate the regions of high resistivity discovered earlier. They were of interest for two reasons. Firstly, knowledge of the location and sources of high-resistivity ice could help understand its causes, and secondly, if such values are likely to arise in future depth-finding interpretations, it would be useful to be acquainted with the structures they are associated with and the area they will affect. Work was accordingly concentrated on the two ridges in which this effect was found and on the glaciers from which it was suspected the ice might derive.

A fairly detailed series of profiles along a half-mile stretch of one such ridge together with readings spread out along a four-mile stretch of the second, led to the following general observations:

(a) The high resistivity occurs in strips that run parallel to the axis of the ridges (and the glacier). The area of high resistivity lies within the top 10 metres of ice.

(b) The value of ρ in such a strip is not consistent along its length. If anything, the resistivity showed a tendency to increase down-glacier. An attempt to trace the strip containing sounding 27 back to a source or mother lode of some type was unsuccessful.

(c) These facts tend to point to a phenomenon generated in these ridges themselves, and the most obvious cause would be the existence of stress within the ice. This is backed up by two other observations; firstly, a plot of resistivity across one ridge showed remarkable coincidence with the crack pattern; and secondly, a core taken at the point of highest resistivity on this same ridge showed, according to the glaciologist, a bubble pattern clearly indicative of stress. A water sample from this core has been sent to Dr. Vögtli for analysis along with his other samples. However, not all ridges give a high value of ρ. No cores could be taken in other locations but this should certainly be done in future.

The tributary glacier examined in most detail was the "Piper Glacier". A profile across the width of its mouth did not reach bedrock, which was thus shown to be deeper than 700 ft. Moreover, the top 100 metres showed a resistivity averaging around 200,000 ohm-metres, dropping to the value of ordinary glacier ice below 200 metres. A series of readings taken along the centre line of the glacier to within 70 metres of the plateau at the top showed a great variation of resistivity ranging from 600,000 ohm-metres at one point to 60,000 ohm-metres at the same depth at others. No consistent pattern could be detected in the variation, using the limited number of points done. A water sample was taken from the area of highest resistivity; the core here did not show signs of stress as did the core from the ridge. Although this ridge crossed directly in front of the glacier mouth (and was in fact pushed up by the pressure of the tributary glacier building up on the main stream of ice), no path of high-resistivity ice could be found connecting areas of similar resistivity on the two features. Chemical analysis should yield evidence as to whether or not the two phenomena stem from the same cause.

Two other pieces of work were done for Dr. Vögtli. One was to confirm the high value of ρ in the embayment mentioned earlier. The second was to check the isotropy of the banded ice that shows up on either side of the moraine on the upper section of the glacier. This involved doing Wenner and Schlumberger profiles at right angles and comparing the values obtained.

The period from August 24 to August 28 was spent on the ice-cap. It was originally planned to do two long profiles at right angles with a view to obtaining the ice resistivities to a depth of 1500 metres in an accumulation zone. It was not expected that the bottom would be reached with the available amount of cable. On reaching the summit however, the $CuSO_4$ solution had frozen, cracking two of the potential electrodes; as a result copper electrodes had to be used. The instability of the metal electrodes on sensitive voltage ranges, coupled with insufficient current due to the layer of cold dry snow allowed reliable readings to be taken to a depth of 100 metres only. For this, snow had to be melted and a salt solution poured on the current electrodes at each point. The first 80 to 100 metres showed an average value of 200,000 ohm-metres. If this value is typical of the firn, it should be easy to distinguish the firn from the older glacier ice underneath. However, since the firn value should merge gradually into the glacier-ice value at depth, no clear-cut division or two-layer interpretation can be expected.

Plans for summer 1962

Most field time in 1962 will be spent in depth sounding of the glaciers. It is hoped that the ice-cap will be sounded by seismic methods since it would be much faster at the thickest parts, and a limited number of shots would provide an accuracy check for the geo-electrical work.

If possible 2 weeks will be spent at the ice-cap summit, and near the firn-line in mid-summer when conditions are more favourable. Firn can be distinguished from glacier-ice by seismic methods but if geo-electric methods are workable they would be quicker and much less expensive. It would be desirable in addition to co-ordinate resistivity measurements on the glacier with the crystallographic work that is being done. Being able to predict conditions below the surface by measurements on the surface would be a very valuable development of technique.

Another field of interest is the possibility of correlating the radiation penetration in the upper layers of the ice with the resistivity of the ice. It is pure speculation as to whether or not such a relationship exists, but during the course of measurements this summer certain variations were noted in the upper metre or two of ice, which were possibly due to excitation from solar radiation.

During the winter the instruments and power supply are to be built into a special lightweight and convenient unit as a specialized instrument for this type of work. This equipment will include all the refinements evolved during the 1961 season. There might be some benefit from carrying on a program of experiments with radio altimetry equipment and checking it against the geo-electric and seismic work during the one operation.

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