Electromagnetic Sounding from Observations Taken During The First International Polar Year

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ABSTRACT

Measurements of magnetic field variations and natural earth currents, made by the German IPY I party at Kingua Fjord on Baffin Island, have been analyzed to obtain information on the electrical conductivity structure in the region. It is shown first, that these observations from 1882 form a remarkably consistent set, and secondly, that the station site displays the characteristics of a "normal continental station" located on crystalline rock. A similar treatment of magnetic measurements made at Fort Rae by the British IPY I party yielded inconclusive results, probably because of the station's proximity to the auroral zone.

ABRÉGÉ

L'équipe de chercheurs allemands IPY I a mesuré les variations du champ magnétique et les courants telluriques à Kingua Fjord dans l'île de Baffin. Les résultats de leurs recherches ont été analysés dans le but d'obtenir des informations sur la répartition de la conductivité électrique dans la région. On voit tout d'abord que ces observations faites en 1882 forment un tout d'une homogénéité remarquable; on découvre également que l'emplacement géographique de la station possède les caractéristiques d'une "station normale continentale" située sur une couche de roches cristallines. On a interprété de la même façon les données sur le champ magnétique obtenues à Fort Rae par l'équipe de chercheurs britanniques IPY I; l'étude de ces donnés n'a pas donné de résultats concrets, sans doute à cause de la proximité de la station de la zone aurorale.

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Naunairturtauhimanianuun aktiginiata nipiqarnaup najugaani nunainarnii nunaupluu igiraniagun qanurilivaguhia, pijauvaktuq German IPYkuriinin ilagivapkakin Kingua Fjordmi Baffin Islandmii, naunairturtauvapkamii qanurititlaanganik ilihimapjutikhamun nunap taafuma nujugaani. Hivuliituq nalunairtauvaktuq, 1882-mii hivutliuplunii taamna nakuurpiarpaktuq nalauhimapluniluu, aipaanikli, najugaqarhutik "nunaup iliquhimaria malikhugu" nunamii qairhugaami ujaraliamii. Atjikutaroianganiktauq huli uvani naunairtuivangmijun nipiqarnamik Ford Raemii ukuaa British IPY tapkuali hunatlaringmik naunairhihimangiqijauvaktun imaqaak, nuna najugarijaan piplugu arhaitlu igiraniinun.

Introduction

The remarkable series of geophysical observations made during the First International Polar Year (IPY I) of 1882-83 have never been completely analyzed. This is partly because of the difficulty of handling large data sets in the days before high speed computers, and partly because of a lack of theoretical models, for example, of the geomagnetic field and its variations in time, to which the observations could be compared. In this paper, we analyze a series of magnetic and electric measurements made at two IPY I stations located in Canada. The application, which is based upon theories of electromagnetic induction in the earth which were not available one hundred years ago, is directed toward the internal electric properties of the earth, rather than toward the external sources of magnetic disturbances.

While our results are chiefly of historical interest, partly in showing the high degree of internal consistency of IPY I observations, and partly in constituting the "oldest" electromagnetic geophysical sounding in North America, we are able in addition to draw some conclusions about the earth's crust in the vicinity of one station, in southern Baffin Island. No other electromagnetic sounding in the vicinity has yet been performed, although magnetic field measurements were made by the Earth Physics Branch in 1982 as part of the IPY I centenary observance (Newitt and Dawson, 1984).

We begin with an outline to the type of electromagnetic data available from IPY I stations, and follow this with a very brief account of the modern methods for studying the interior of the earth from the electromagnetic point of view. These sections are followed by a discussion of the methods of analysis and interpretation which we have been able to make.

Magnetic Observations During IPY I

In a programme dedicated to the elucidation of polar phenomena, it was natural that observations of changes in the earth's magnetic field should play an essential role. Karl Weyprecht, the proposer of the First International Polar Year, emphasized their importance, and also pointed out the advantage of making all observations with compatible instruments and according to an agreed-upon time schedule. His suggestions were codified for the expeditions by the International Polar Conference, which specified that, from 1 August 1882 to 1 September 1883, absolute measurements of three magnetic elements (horizontal intensity, declination, inclination) be made each hour of Göttingen time, while on selected "Term Days" (the first and fifteenth of each month), the variations of the three magnetic components be observed every five minutes during the entire 24 hours of the day. It is difficult for us today, in an age of automatic recorders, to appreciate the tremendous dedication that was required of the participating scientists, to fulfill these schedules through manual observations in unheated, temporary observatories. The hourly magnetic observations were utilized, for many decades following IPY I, in global studies, on the changes with time of the earth's magnetic field. The Term Day observations were intended to determine the relation between magnetic disturbances and visual auroral displays, and while they frequently confirmed a general correlation, it is safe to say that this wealth of observational materials has never been fully utilized.

In addition to making the "obligatory Observations", expeditions were encouraged to make other measurements on a voluntary basis. At a number of stations, including Kingua Fjord (now Clearwater Fjord), the natural electric currents induced in the earth by magnetic field changes were recorded, by means of long cables grounded at each end and connected to galvanometers. During periods of earth current observations, parties were encouraged to record both the electric field changes and magnetic variations at intervals as short as 30 seconds.

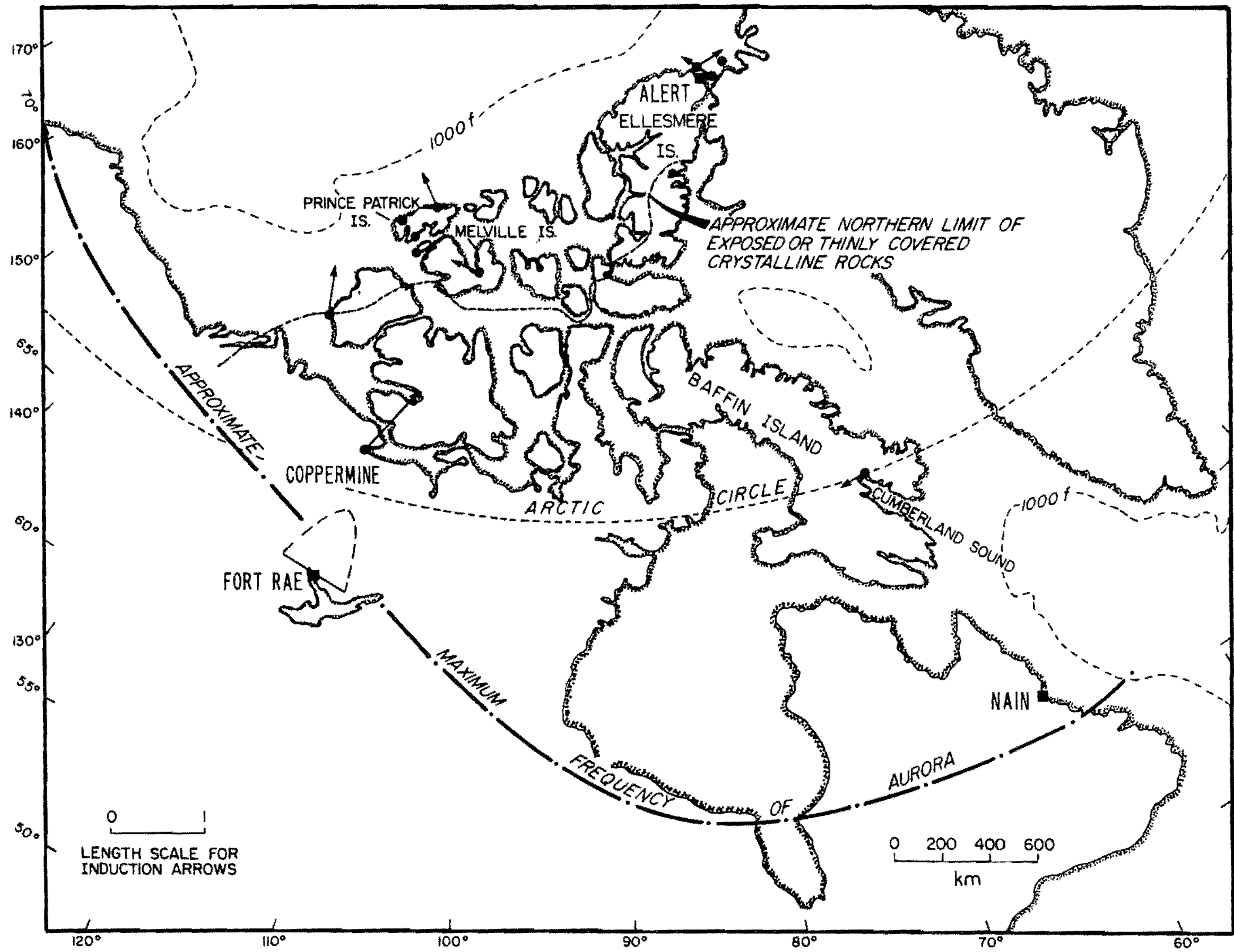

Figure 1. Location of Kingua Fjord (at the end of Cumberland Sound) and Ft. Rae stations in northern Canada. Typical induction arrows for a period of about fifteen minutes are shown, as are the locus of maximum and auroral frequency and ocean depth contours in fathoms.

The present study is concerned with an analysis of two types of observation: the five-minute interval Term Day magnetic field observations, and the simultaneous measurements of rapid changes in earth currents and magnetic field.

IPY I Stations in Canada and their Magnetic Observations

As is well known, the three IPY I expeditions occupying sites in Canada were those of Germany at Kingua Fjord, off Cumberland Sound, Baffin Island (Fig. 1) near present-day Pangnirtung; of Britain at Fort Rae on Great Slave Lake (Fig. 1); and, of the United States at Fort Conger, Ellesmere Island. Of these, the German and British parties observed the complete series of hourly and Term Day magnetic element variations, as laid down by the International Polar Commission, publishing these as tabular values and as graphs for each Term Day (Dawson 1886; Neumayer and Börgen 1886). The chapter in the latter work which deals with the magnetic variation and electrical measurements was written by W. Giese, who was in charge of the Kingua Fjord expedition. The magnetic observations of the United States party at five-minute intervals are incomplete, consisting, in general, of the declination only.

In addition, the German expedition to Kingua Fjord measured natural earth currents. Because the typical associated voltage gradient along the earth's surface is of the order of millivolts per kilometre, it was realized that lines several kilometres long would be required, given the sensitivity of the available galvanometer, and the party was provided with some 10 kilometres of cable for this purpose. The galvanometer was to be calibrated at intervals during the observations by measuring its deflection due to a known voltage provided by a standard cell. However, because, in 1882, electric and magnetic units were not standardized to the extent they are today, a very interesting and fundamental intercomparison experiment was carried out during the winter months before the earth current lines were established. The complete length of cable was laid out upon the ice of Kingua Fjord in the form of a polygon whose area could be accurately measured. The voltage induced in the cable was compared with that of the standard cell on many occasions, simultaneously with measurements of the rate of change of the vertical component of the earth's magnetic field. Faraday's Law, that the induced voltage be equal to the rate of change of magnetic flux through the polygon, was then used to determine the voltage of the standard cell that was compatible with the magnetic units. It was not until the spring of 1883 that the cable was cut and laid out in two lines for earth current measurements. Although it was intended that these should be oriented respectively magnetic north and magnetic east and each 5 kilometres long, the rugged topography inland from the camp made this impossible. For, while the camp itself was located in a relatively flat beach adjacent to a valley leading into Kingua Fjord, the surrounding region is composed of Precambrian rocks, unmapped in detail away from the coast, but believed to contain numerous granitic intrusions (Geological Survey of Canada, 1969). This fact is relevant to the electromagnetic results to be discussed below. One cable was extended up the valley in which the camp was located, for a distance of 4 km in azimuth N18^{0}E, very nearly magnetic east, since the magnetic declination at the site was 72.5^{0}W. The second cable was carried westerly from the camp, over extremely rough terrain, for a distance of 2.5 km in azimuth N260^{0}E. The angle of this second cable with the magnetic meridian was thus 27.5^0, and the angle between the two cables, 118^0. At the outer end of the cables and at the camp, electrical contact with the earth was made by a method which is still in use today: holes dug in the soil were kept filled with saturated copper sulphate solution, and the bare copper of the cable was immersed in the solution.

Measurements were made on selected days in July and August of 1883 by connecting the galvanometer to one cable or the other. These measurements were made at intervals as short as 30 seconds, and were accompanied by measurements of magnetic field changes. For our purposes, to be described below, the observing procedure was not completely ideal probably because, as a series of "voluntary" observations, the programme had to be fitted in between "obligatory" observations. No single series of observations extends over more than one hour, and there were frequent gaps within this time. Thus, there is obviously an upper period limit to any possible spectral analysis. Secondly, the special short-interval magnetic observations were made between each successive earth current observation, rather than strictly simultaneously (probably because only one observer was involved).

Electromagnetic Induction in the Earth

The magnetic field variation measurements made during IPY I had as their chief purpose the study of relationships outside of the earth: correlation with auroral displays, and even a possible correlation with weather. It is our purpose in this study to utilize these obervations for the determination of electrical properties, and therefore structure, within the earth. This section will give a very brief review of the two methods used; more detailed discussions can be found in several geophysical works (Parkinson 1983).

Variations in the earth's magnetic field at all periods longer than 0.1 s and shorter than a few years have their primary cause outside of the earth, in charged particles from the sun and the resulting electric current flowing in the high atmosphere. These variations induce electric currents within the earth, since virtually all rocks are electrical conductors, although in greatly varying degree, and these induced currents produce secondary magnetic fields of the same period. Any magnetic measurement at the earth's surface is therefore a composite of a primary and secondary field; it is the secondary component which will give information on internal electrical conductivity.

When measurements of the variation of three magnetic components are available, as in the Term Day observations, statistical relationships between these components, even at a single station, can be used to indicate the magnitude of the internal effect. At the surface of a laterally uniform earth, at points removed from the overhead sources, variations in the vertical component are small because of cancellation effects. However, if an elongated structure in the earth concentrates current flow, (Fig. 2), the associated secondary magnetic field will have an appreciable vertical component to either side of the structure. Furthermore, since this vertical component is part of a magnetic field line around the current line, its variations will be found to be coherent with, and, in general in phase with, horizontal components variations in an azimuth from the station to the structure. This is the basis for a method of analysis introduced by Parkinson (1962).

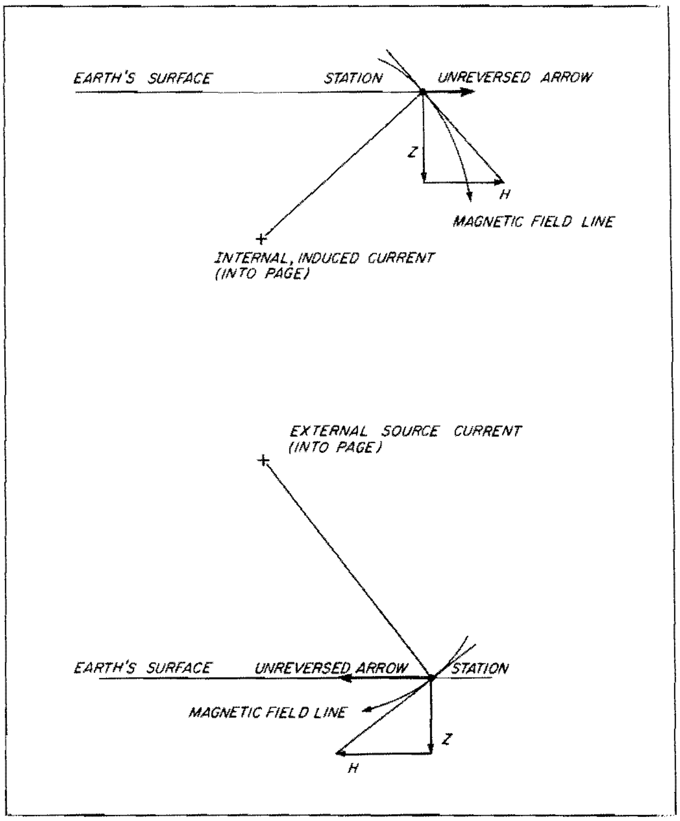

Figure 2. Induction arrow response produced by internal and external line currents.

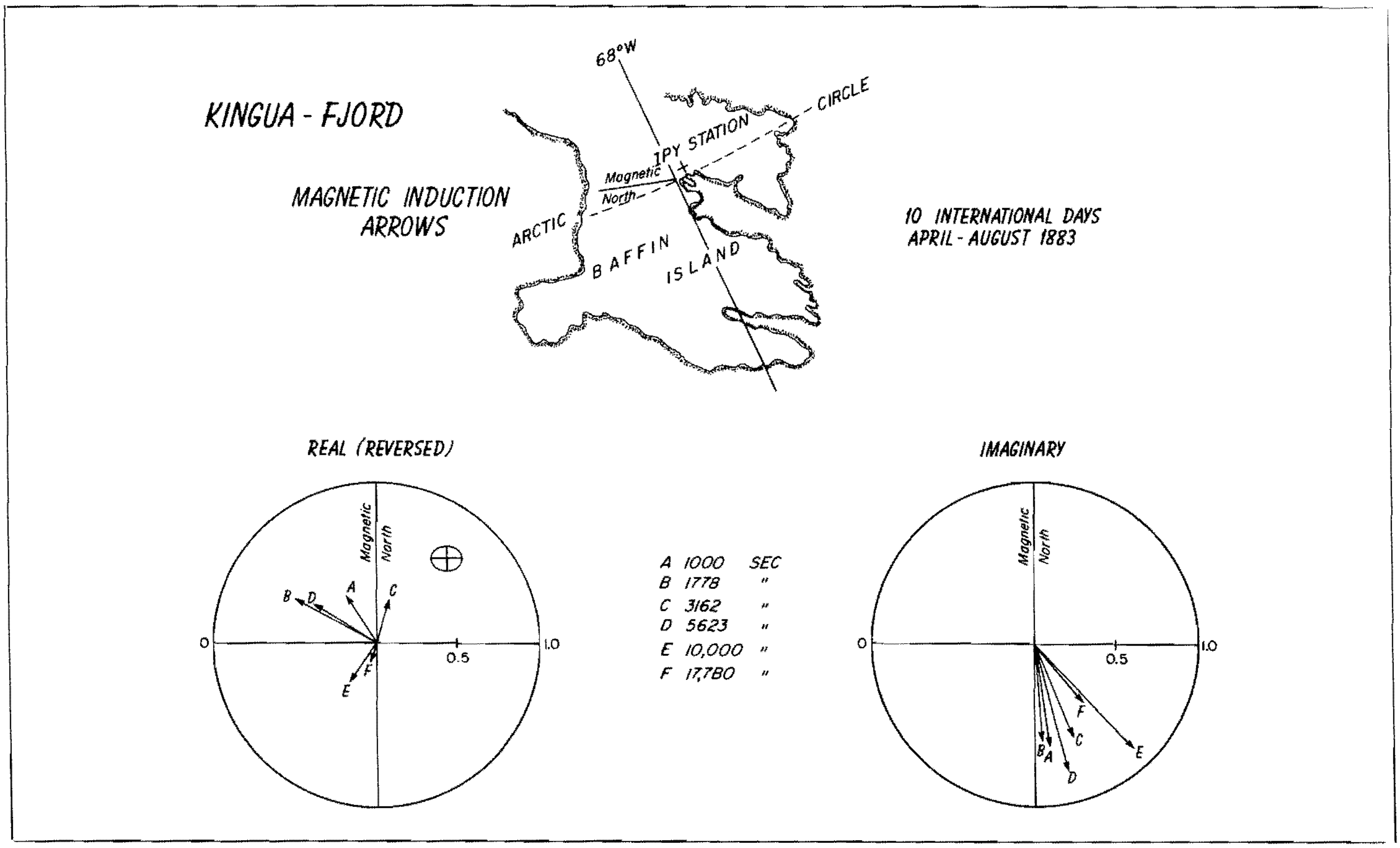

Figure 3. Induction arrows, Kingua Fjord, 1882-1883 observations.

With three-component variation data, it is possible to determine, for any assigned period of variation, the azimuth of horizontal changes which are coherent with the vertical variations. The results (Fig. 3) are plotted as "induction arrows" whose length is made proportional to the ratio of vertical to horizontal variations field. Since arrows would point away from internal currents, they are reversed in plotting so as to be directed toward internal sources. In regions close to overhead primary sources, reversed arrows tend to point away from these, so that the separation of internal and external effects is not complete. With data in digital form, and the availability of a computer, the calculation may be extended to provide phase information, separating that part of the horizontal field which is 90^0 out of phase (or in quadrature) with the vertical. The resulting induction arrows in this case are known as "imaginary" arrows. The latter tend to be directed toward shallow, moderately good as opposed to very good, conductors in the earth. With the sign convention we adopt in the analysis, imaginary arrows are plotted without reversal (Lilley and Arora 1982).

A second method of investigating earth structure, known as magneto-telluric sounding, is possible when simultaneous earth current and magnetic field observations are available. It was pointed out by Cagniard (1953), that orthogonal measurements of electrical field E and horizontal magnetic field H lead to an "apparent resistivity" of the earth, pâ, where

$$pâ = 0.2T\,(E/H)^2$$
ohm.m.

Where E is in mV/km, H is in nanoteslas and T, the period of the variation, is in seconds. Over a horizontally-layered earth, the apparent resistivity at short periods T approximates the true resistivity of near-surface material, while for increasing values of T, it tends toward the true resistivity of deepest formation. The form of the curve of pâ against T therefore gives an indication of the location in depth of changes in electrical properties, and an indication of those properties. In comparison with D.C. resistivity sounding, in which current is applied to the earth through electrodes, this effect with increasing period is analogous to that of increasing the electrode separation.

The calculation of pâ can be carried out with a single pair of orthogonal values of E and H. When measurements of both fields are available in two directions, two values of pâ are available. Over an isotropic earth, these will be identical, but on the real earth, they are normally different, and the difference is taken to be a measure of anisotropy in the ability to conduct electric current. Measurements over the Precambrian Shield, for example, nearly always show anisotropy, the current flowing preferentially along the local tectonic grain.

Analyses and Results

(a) Induction Arrows

The variations in declination, horizontal intensity and vertical intensity available at five-minute intervals were used to compute induction arrows for twelve Term Days, 1 March to 15 August 1883 inclusive. Computations were carried out for the period range 100 s to 4.45 hours, which is reasonably within the limits imposed by the sampling interval (5 minutes) and the length of each observing period (24 hours). For Kingua Fjord, results from individual Term Days were remarkably consistent. In Fig. 3 are plotted the mean arrows for the twelve days. Also shown is the 68% confidence ellipse for the end points of the arrows, computed from the day-to-day scatter. All real arrows are fairly small (Z/H 0.5), and tend to rotate with period within the northwest (magnetic) quadrant. They are certainly not demonstrating the coast-line effect which is found at many coastal stations and which results in the arrows pointing toward the nearest deep sea water. Nor could they be construed as pointing away from source currents associated with the axis of the auroral zone which lies some 900 kilometres south of Kingua Fjord (Fig. 1), although the scatter in direction may be source-related. They may indicate a moderate anomaly in electrical conductivity lying under the central axis of Baffin Island, but the overall impression is that Kingua Fjord is a normal, continental station free of any very marked local anomaly in electrical properties.

The imaginary arrows are somewhat larger and more confined in azimuth, toward the southeast. This is the direction of central Cumberland Sound from the station, and we are probably seeing here the typical response of a shallow conductor, for the Sound is not deep. Their smaller scatter in direction, as compared to the real arrows, is probably due to the freedom of the quadrature response from direct source effects (Alabi et al. 1975).

As mentioned previously, a party from the Earth Physics Branch reoccupied the Kingua Fjord site in 1982, in order to repeat the absolute magnetic field observations. During the course of this work, variation measurements of the three magnetic components were made at the 1982 camp, which was located 25 km west of the 1882 site. These measurements were recorded at intervals of 1 minute, for the period August 20 to August 25, 1982. Transfer functions computed from these observations are shown in Fig. 4. Because of the shorter observing interval (1 minute as opposed to 5 minutes for the 1882 data), arrows for shorter period than those shown on Fig. 3 are included but the general agreement is immediately apparent. The imaginary arrows in particular are virtually identical, while the real arrows, although directed somewhat more toward magnetic north, rather than

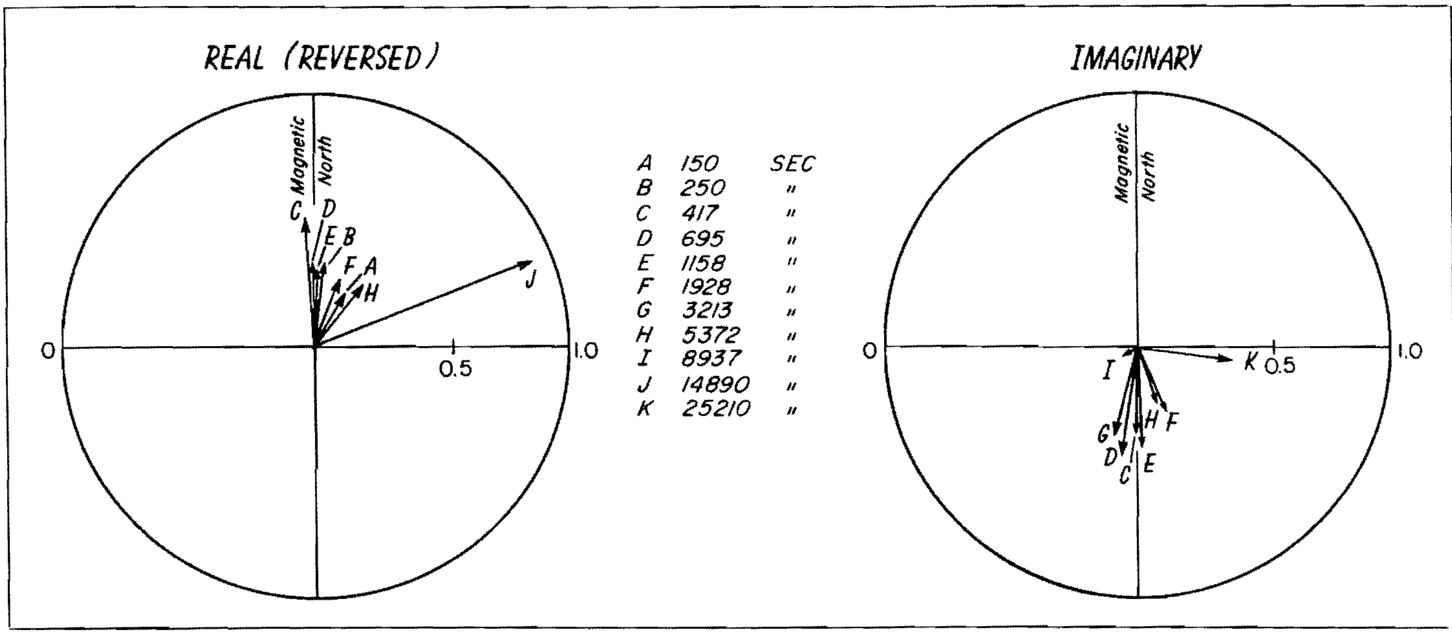

Figure 4. Induction arrows, near Kingua Fjord, 1982 observations.

magnetic northwest, are similar in magnitude. Considering the fact that the observing sites are separated by 25 km, the repetition of the experiment, with different instrumentation, yields a confirmation that is remarkable.

A treatment of the Fort Rae observations for the same Term Days as those used for Kingua Fjord yielded very different results. Fort Rae is very much closer to the axis of the auroral zone (Fig. 1), and it is evident that source effects predominate in the induction arrows. Results for any given period for the different days are so discordant that it is impossible to obtain a meaningful average. At shorter periods (10^3 seconds), there is a tendency for arrows to point in the northwesterly half-plane (Fig. 5); at longer periods, both real and imaginery arrows show even more erratic behaviour, with very large values of Z/H. We conclude therefore, that source effects are so great that it is probably impossible to infer anything about local internal electrical properties from the Fort Rae IPY I data, although this point will be discussed later.

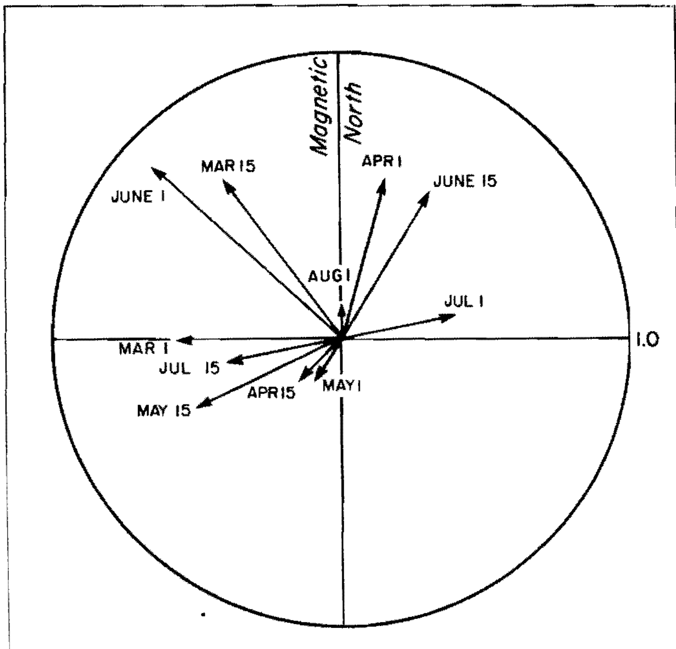

Figure 5. Behaviour of the induction arrow at Ft. Rae, for a period of 1000 seconds.

(b) Magneto-Telluric Sounding at Kingua Fjord

The simultaneous earth-current and horizontal magnetic field variations at Kingua Fjord were used to deduce the relationship between apparent resistivity and period, according to the method of Cagniard. Peculiarities in the arrangement of the electric lines, described above, required some modifications to the standard procedures. Thus, while the "East" electric line was very nearly perpendicular to the magnetic meridian, the "North" electric line made an angle of 27.5^0 with the meridian. Changes in horizontal magnetic field in an azimuth perpendicular to the "North" line had first to be computed, from the observations of changes in horizontal intensity and declination, before an apparent resistivity could be extracted. In the end, two values of apparent resistivity were obtained for each period, but these two values do not relate to orthogonal directions.

The second complication concerned the sampling of the data. While observations for several days at a sampling interval of 30 seconds are available, the longest single observing period is one hour; many of the days have gaps without observations in the middle of the day. These factors severely limit the range of

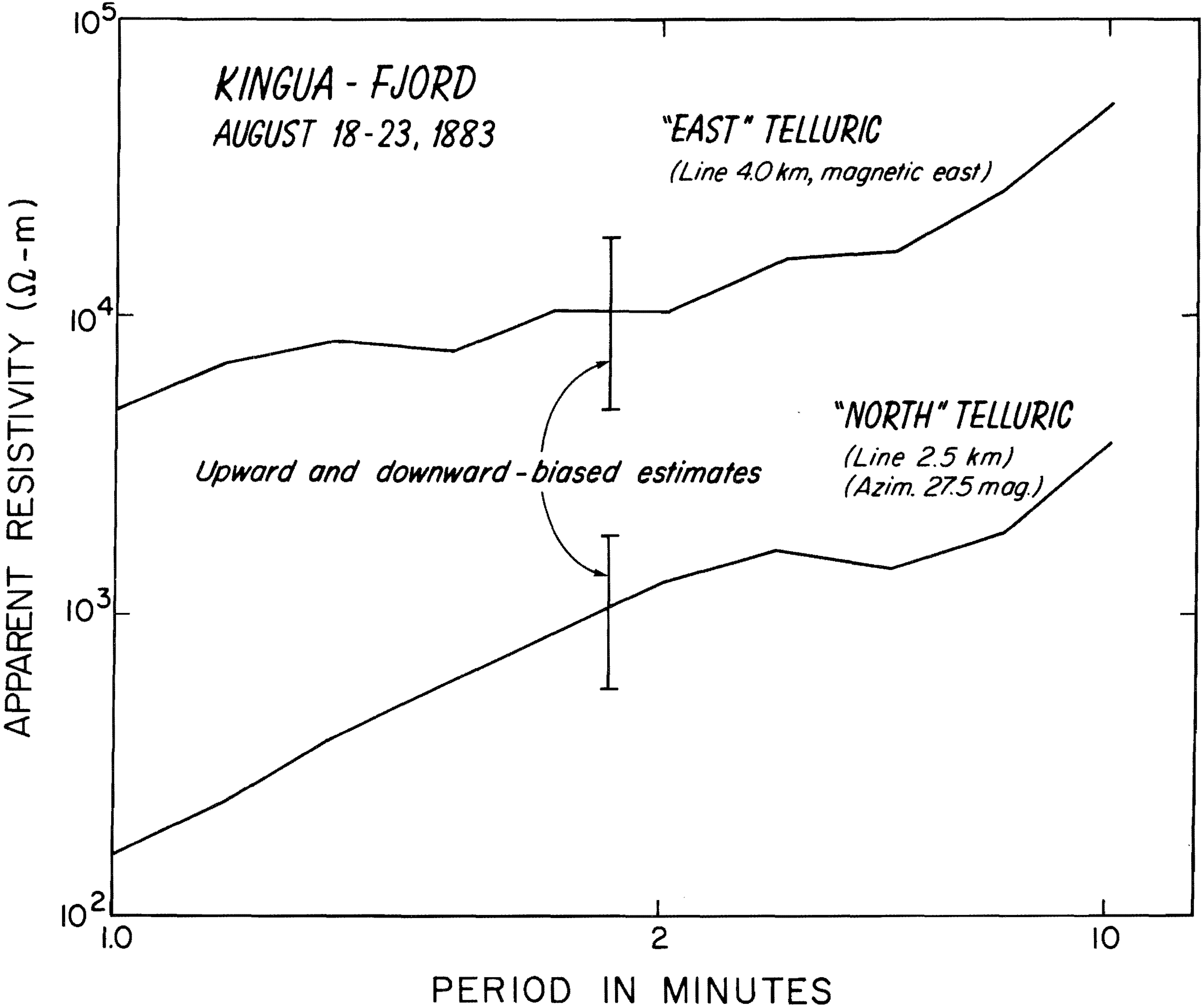

Figure 6. Magneto-telluric sounding, Kingua Fjord, 1883 observations.

periods for which spectral analysis, and therefore calculation of apparent resistivity, is possible. We have taken a period range from 1.0 to 10 minutes, computed apparent resistivities for six individual events, and produced the mean curves shown in Fig. 6. The scatter among the individual days permits an estimate of the uncertainty of the mean, which is shown graphically on Fig. 6, as the spread between upward and downward biased estimates.

The curves shown in Fig. 6, are remarkably "normal" for a site located on crystalline igneous rock. There is certainly anisotropy, as indicated by the different curves of apparent resistivity obtained for the two electric lines, but anistropy is found, for example, at virtually all sites located on the Precambrian Shield. The apparent resistivity is lower when computed from the field values obtained with the "North" earth-current line, that is, for current flow in a true azimuth of N 260^0 E. This is therefore the direction of easier current flow in the earth, and could be expected to be parallel to the structural grain of the region. The higher values of apparent resistivity, determined from "East" earth-current line, correspond to current flow in a true azimuth of N 18^0 E. Near the station, this direction corresponds to that of the small valley, on the side of which the camp was located, and if the valley were structurally controlled, current flow parallel to it could be expected to be easier, rather than more difficult. But an examination of aerial photographs, and also the generalized structure lines shown on the Tectonic Map of Canada (Geological Survey of Canda, 1969) both indicate a tendency toward a northeast-southwest structural grain in the vicinity. The effect of this, therefore, appears to predominate over that of the valley itself.

For the period range available (1.0 to 10 minutes), the apparent resistivities are influenced most by conditions in the upper crystalline portion of the earth's crust. The influence of very near-surface material would be seen only at shorter periods, while evidence of the lower resistivities that are believed to exist in the upper mantle would require information at considerably longer periods. In addition, the values must be considered to be averaged horizontally over at least the length of the earth current lines, that is, 2.5 to 4 km, about the station. Under these conditions, the range of values of apparent resistivity seen, approximately 10^3 to 10^4 ohm-m., is completely normal for the continental crust. It follows that the IPY I electrical observations made at Kingua Fjord, as well as the magnetic observations, are remarkably consistent. They were obviously obtained with a high degree of competence and dedication.

Comparison with Other Induction Studies in Northern Canada

We have presented evidence, based on the IPY I measurements, that the electrical properties in the vicinity of Kingua Fjord are typical of those at a "normal continental site". It is of interest to contrast this with the situation at other stations in northern Canada. Figure 1 summarizes the information, by showing in-phase induction arrows, for periods in the range between 600 and 900 seconds, (results are not available for identical periods from all studies) at a number of sites. Remarkably, within the map area, five distinct types of behaviour are found.

In the vicinity of Alert, on northern Ellesmere Island, induction arrows at nearby stations show an almost complete reversal in direction (Niblett et al., 1974), pointing toward an axis, which happens to be near the centre of Robeson Channel. The effect is an example of the classic case of a linear concentration of current along some narrow conducting channel within the earth. It would be tempting to associate such a channel with a structure related to Robeson Channel, but in fact the current axis has been found to diverge westerly from it, to pass beneath Ellesmere Island. The precise cause of the conductivity anomaly remains unknown.

A number of stations on Prince Patrick Island and Melville Island are shown, with no induction arrow indicated. At these points, for the period concerned, the ratio of Z/H was found to be so small (DeLaurier, et al., 1974), that no arrow could be computed.

Severe attenuation of the vertical component in a limited period range is diagnostic of a horizontal layer of very high conductivity somewhere within the upper crust. In this case, the conductive layer probably lies within the sedimentary rocks of the Sverdrup Basin, although the authors quoted were unable to satisfy, quantitatively, the observations with a simple model. At the other stations of the western Arctic islands, the induction arrows tend to point to the deep ocean to the northwest. The arrow at Coppermine is particularly long, and this station, which is closer to the axis of the auroral zone, may show a combination of a coast and a source effect; that is, the arrow points both toward salt water and away from the external source currents in the auroral zone.

The results at Fort Rae have been discussed above. Because of the proximity to the sources, and the consequent erratic behaviour of the magnetic fields, it is impossible to compute stable induction arrows. On Figure 1, the half-plane in which the arrow was found to lie for a period of 1000 sec. is shown. The reason for the orientation of the boundary of the half-plane is not clear. While the station is too close to the auroral zone and therefore to complicated overhead current systems, for the simple rule that arrows point away from external sources to apply, it is difficult to see why the arrow deduced from our data set, is apparently constrained to point northerly. It is just possible that an internal conductor north of the station is able to exert some influence over this complicated behaviour.

In summary, therefore, this region of northern Canada contains stations which exhibit virtually all of the classical induction arrow responses: "normal" continental, linear current channel, extreme vertical component attenuation by a horizontal conductor, coast-line effect, moderate source effect, and extreme source effect.

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