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Résumé de l'article

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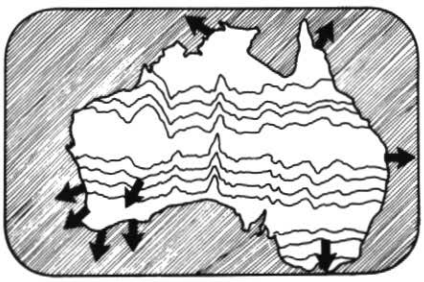
Conference Reports



Electromagnetic Induction in the Earth

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Summary
The study of electromagnetic induction in the earth has provided a geophysical method for using magnetic and electric field variations observed on the surface to interpret electrical conductivity and earth structure over a wide range of depths. Analysis of geomagnetic data on a world-wide basis has shown that both conductivity and internal temperature increase rapidly in the mantle, between depths of 300 and 1000 km. In addition many localized zones of high conductivity have been found in the crust and upper mantle. Important anomalies of this type are located in the Cordillera regions of North and South America, in the Japanese Arc, North Germany, and in the Canadian Arctic to mention only a few. These large anomalies, some of them many hundreds of kms in extent, are often found near continental margins or near old plate boundaries. They appear to be associated in a fundamental way with the development of mobile belts and their study is becoming important in our understanding of global tectonics.

Background
Nearly 100 years ago Horace Lamb formulated the problem of electromagnetic induction in a spherical earth by external geomagnetic field variations. A few years later Schuster applied this theory to the limited magnetic variation data available at that time. He was able to show that the variations observed on the surface could be divided into parts of external

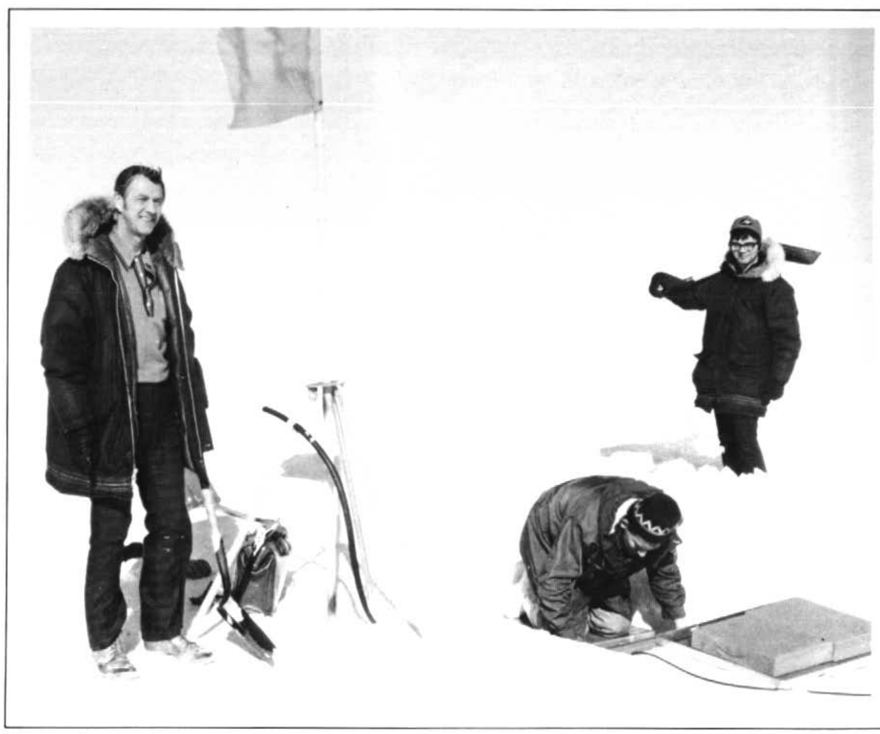

Figure 1
Installation of a recording 3-component magnetometer on sea ice. The photograph was taken at Hooker Bay on the south-western side of Bathurst Island in May 1973. The recording magnetometer is installed in an insulated aluminium box which is set on top of the sea ice and covered over with snow. In this way the instrument can maintain an operating temperature only a few degrees below 0°C regardless of air temperature. This was one of a profile of six similar stations set up between Resolute Bay and Isachsen to record simultaneously variations in the geomagnetic field. A large anomalous variation field (induction anomaly) was found on Ellef Ringnes Island during this experiment. The work was part of a program to study geomagnetic induction effects in the Canadian Arctic by the Earth Physics Branch, Department of Energy, Mines and Resources.

and internal origin and that the internal part must be attributed to electric currents induced in the earth by the external part. Calculations of this kind provide a means of estimating electrical conductivity of the earth's interior. Throughout the 1920s and 1930s Chapman, Whitehead, Price and Lahiri developed and applied the theory, first to a uniform earth and later to one in which the conductivity was allowed to vary with depth. In 1939 Lahiri and Price published a monumental study in which solar diurnal variations and the longer period storm-time variations were used to estimate the distribution of conductivity to a depth of about 1000 km in an earth assumed to be radially symmetrical. They concluded that the conductivity must increase rapidly at mantle depths near 700 km and that beyond this its value is one mho per metre or greater. This kind of anaylsis is now usually called global geomagnetic depth sounding. Interpretation is limited to depths of about 1500 km or less since long period geomagnetic variations of external origin are unable to penetrate further through the conducting rock.

A new and important phase of electromagnetic induction studies began in the early 1950s with the discovery of localized geomagnetic variation anomalies in Japan by Rikitake and his colleagues and in northern Germany by Bartels and his co-workers. These anomalies are characterized by large differences in recorded geomagnetic variations, especially the vertical component, over distances as small as 100 km and less. The observations indicate local disturbances in the pattern of induced currents flowing in the crust and upper mantle which are caused by prominent inhomogeneities in electrical conductivity. The large anomalous vertical component found in central Japan has been explained by assuming a depression of the highly conducting mantle beneath. This interpretation agrees well with the distribution of heat flow and seismic wave velocities observed over the Japanese Islands and also with current ideas concerning their tectonic evolution. The North Germany anomaly resembles the effect of a concentrated internal current flowing in the east-west direction. Its location was originally thought to be in the upper mantle at a depth near 100 km. Interpretation has been uncertain, however, because of the screening effect of highly conducting sedimentary rock near the surface and the possibility of electromagnetic coupling between the upper and lower conductors.

Since the pioneering studies in Japan and North Germany large electromagnetic induction anomalies have been found in many parts of the world and much effort has been made to understand their geophysical significance in terms of: 1) The structures and rock composition in the crust and/or upper mantle which cause the observed anomalous fields and; 2) the tectonic implications of their global distribution.

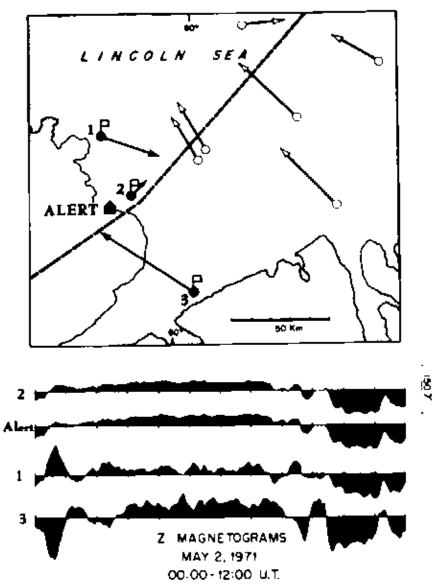

Figure 2
The Alert induction anomaly extends for over 600 km across the northern end of Ellesmere Island and beneath the continental shelf of the Lincoln Sea. It has been attributed to a massive elongated conducting body lying at a depth of several km in the crust. Electric currents flowing in this conductor produce the anomalous and strongly localized magnetic fields which are observed at the surface. The vertical component magnetograms above illustrate the anomalous effect along a profile of stations close to the Ellesmere coast. The Parkinson arrows at the various stations were derived from the recorded geomagnetic variation data and point toward the location of maximum current concentration.

An important class of induction anomalies, commonly called coast-effect, arises through the conductivity contrast across a land-sea boundary. Such anomalies have been demonstrated by Rikitake, Schmucker, Parkinson and many others during the last two decades. They are recognized by a strong enhancement of the vertical geomagnetic component at coastal stations and are attributed either to a concentration of currents flowing along a coastline in the conducting sea water or to more deeply seated currents located at the boundary between oceanic and continental blocks.

Anomalies of the type discussed above usually involve induced current flow at various depths throughout the crust and upper mantle or in the deep oceans and their marginal shallow seas. The anomalous magnetic variations corresponding to these induced currents are seen on magnetograms in pulsations and bay-type disturbances, usually in the period range from 10 minutes to several hours. The North German anomaly is evidently strongly influenced by conducting sediments in a basin about five km deep; in Japan and in large anomalies discovered in the Canadian Arctic and in the North American Cordillera analysis has indicated that the conducting zones must lie deeper in the crust or in the upper mantle.

An important contribution to studies of electromagnetic induction in the earth began, again in the early 1950s, with the development of the magnetotelluric method by Kato, Tikhonov, Cagniard and Wait. This technique is particularly useful for the analysis of near-surface geological structures such as horizontally layered sedimentary basins or vertical faults and dykes. For its implementation electric (telluric) field variations recorded at one or more stations are required as well as geomagnetic variations. Structural interpretations are based on derivation of apparent resistivity for horizontally layered structures or of the impedance tensor for more complex anisotropic and/or inhomogeneous structures. Interpretation of geomagnetic variation anomalies and of magnetotelluric data usually depend on the simplifying assumption that source fields in the ionosphere are essentially uniform over the region under study.

Over the past 15 years the study of terrestrial electromagnetic induction effects has accelerated rapidly under stimulation from several sources. The International Upper Mantle Project created a need to exploit all possible geophysical deep sounding methods; international symposia organized by the International Association of Geomagnetism and Aeronomy (IAGA) at Berkley (1963), Madrid (1969), Edinburgh (1972) and Kyoto (1973) provided platforms and specialist audiences for reporting experimental results and theoretical advances. Instrumentation for measuring geomagnetic and telluric variations has improved greatly with the development of solid-state low noise amplifiers and portable digital recorders. Powerful new statistical techniques for time series analysis have been made possible by the general availability of large modern computers.

Much effort during this period has gone into deriving the electromagnetic response of various types of conducting models which are thought to resemble structures or formations occurring in nature. One can then compare the model response with that derived from field observations and subsequently adjust the model till reasonable agreement is obtained. For simple models such as 1–dimensional and some 2–dimensional cases the induction equations can be solved by purely analytical means. For many 2–dimensional and all 3–dimensional cases model responses are derived either by solving the equations numerically on a computer or by constructing scaled-down models in the laboratory which are then exposed to electromagnetic source fields of suitable configuration.

Modelling can be an expensive and laborious way of solving electromagnetic induction problems. The method contains no assurance that a particular model solution is the only one which can satisfy the data. During the last few years procedures for calculating conductivity distribution directly from the data have been developed; these are called inverse models because they make use of the mathematician's inversion theory for solving the induction equations. They are now widely used by seismologists in interpretating body and surface wave data and have been applied by geomagneticians to the problems of global distribution of conductivity with depth and interpretation of near surface anomalies. Solutions deived by inversion methods do not suffer in principle from lack of uniqueness; but in geophysical problems their successful application requires good data over a wide range of frequencies. Such data are difficult to obtain particularly for the global depth sounding problem.

The question of the geophysical significance of geomagnetic variation anomalies has attracted some attention during recent years. Law and Riddihough have pointed out that prominent anomalies are usually found in areas that can be identified as plate boundaries; either rift or graben zones, transform faults or continental margins. Why this should be so is not yet clearly understood. Some anomalies (Japan and the Cordillera of western USA) correlate well with regions of high heat flow and seismicity. On the other hand prominent anomalies in the Canadian Arctic and elsewhere occur in regions where neither heat flow nor seismicity are in any way unusual. A clearer association with other geophysical parameters seems to exist in relatively young mobile belts. In older regions such as the Arctic Innuitian Province the induction anomalies have remained long after tectonic activity has ceased.

The physical character and chemical composition of the high conductivity zones associated with geomagnetic anomalies is still largely a matter of conjecture. In the global problem it seems clear that the rapid increase in conductivity below a depth of a few hundred kms is associated with rising temperature and its effect on the semi-conduction process in olivine. In the case of local anomalies, partial melting, hydration of deeply seated structures and chemical inhomogeneities of a special kind may all be important. Laboratory results are now available which indicate that oceanic basalts may have much higher electrical conductivity than that usually associated with continental basalt.

The Ottawa Workshop

The Second International Workshop on Electromagnetic Induction in the Earth was arranged and sponsored by IAGA and its parent body, the International Union of Geodesy and Geophysics (IUGG). It was planned as a successor to the excellent meetings held in Edinburgh two years ago and was hosted on the Carleton University Campus by the Department of Energy, Mines and Resources. The five day meetings from August 22 to 28 attracted over 120 geophysicists from 15 countries, most of whom were specialists in problems of electromagnetic induction in the earth.

The meetings consisted of five symposia each organized around a selected topic with two or more review papers presented by the session leaders followed by contributed papers and informal discussions. The symposia and session leaders were:

1. The Inverse Problem; R. S. Anderssen, P. Weidelt
2. The Modelling Problem; B. A. Hobbs, O. Praus
3. Source Fields; S. Matsushita
4. Interpretation of Observed Fields; F. E. M. Lilley, I. I. Rokityansky, G. V. Keller
5. Geoelectrical Conductivity; T. J. Shankland, G. D. Garland, C. P. Sonett.

Full texts of the review papers and abstracts of all contributed papers were distributed to delegates on arrival. Arrangements have been made to publish the reviews in a special issue of Physics of the Earth and Planetary Interiors. In view of this only a brief resumé of the proceedings will be given here.

R. S. Anderssen's review gave a clear account of the limitations of inverse methods in the global problem, particularly the question of data sufficiency for generation of unique solutions. He reviewed previous inversion studies of global electromagnetic induction data and discussed their strengths and weaknesses in terms of uniqueness problem and the viable conclusions which may be drawn from them. P. Weidelt discussed the application of inversion theory to the interpretation of 2–dimensional local anomalies. He pointed out that exact solutions were available in only two special simple cases, and dealt in detail with the more general problems of finite conductors which require linearization before the equations can be solved. U. Schmucker's interesting contributed paper described his application of linearized inversion theory to Sq and D_{st} data to estimate deep conductivity structure beneath the continents. He found a sharp rise in conductivity at a depth of 500 km.

While inversion theory has only recently found useful application in induction problems, the classical approach has been to find analytic solutions for assumed models and to compare observed and calculated responses. B. A. Hobbs gave a thorough review of the basic equations and the solutions which have been achieved in global and local problems. O. Praus discussed recent developments in numerical and analogue modelling of induction effects in laterally non-uniform conductors. His discussion included 2–dimensional models, finite difference and finite element methods, the transmission surface analogy, and Soviet research in analogue model experiments.

S. Matsushita's review was concerned with the morphology of the slowly varying external fields Sq, L and D_{st} which are prime data sources for the global problem. The classical concepts of source currents for Sq and D_{st} in the dynamo region of the ionosphere are now known to be over-simplified and can be misleading in the study of currents induced in the earth. These source current systems are essentially 3–dimensional in character with important contributions from the magnetosphere.

Three excellent reviews were given in the session on Interpretation of Observed Fields. These were Magnetometer Array Studies by F. E. M. Lilley, Non-Synoptic Small Array Studies by I. I. Rokityansky, and DC Resistivity Methods for Determining Resistivity in the Earth's Crust by G. V. Keller. Each was concerned with a particular technique for observing and analysing local induction problems or conductivity-depth profiles. Magnetometer arrays are operations of many instruments (perhaps 30 or 40) simultaneously for the purpose of studying in detail a known anomaly or area of geological interest. Since 1967 fifteen such studies have been attempted in various parts of the world. Lilley gave a summary of these including methods used for analysis of the data and some of the results achieved. Non-synoptic small array studies include point observations of geomagnetic variations and profiles of a few (usually less than ten) simultaneous recording stations. In his review Rokityansky discussed anomalous variation fields for 2- and 3-dimensional models and new procedures for their interpretation. Keller's written review was concerned with DC resistivity methods of determining the conductivity profile in the resistive parts of the earth's crust. He provided an interesting summary of results achieved with the Schlumberger and dipole electrode arrays and with long high voltage direct-current transmission lines Keller's oral presentation also included a discussion of controlled source inductive methods which have an advantage over DC techniques in that they are better able to penetrate the high resistivity zone of the crust and permit analysis and profiling at outer mantle depths.

The final session on Geoelectrical Conductivity covered a wide range of topics. T. J. Shankland reviewed recent results from laboratory studies on electrical conduction in rocks and minerals. For minerals the important parameters are temperature, oxygen fugacity, stoichiometry and iron content; for porous rocks they are the shape and interconnection of fluid-filled pore spaces. The manner in which these factors contribute to the bulk conduction process in the earth's interior are now becoming much better understood. G. D. Garland's paper entitled Correlations between Electrical Conductivity and Other Geophysical Parameters was concerned with the geophysical significance of conductivity anomalies in terms of their association with seismic, heat flow and gravity effects as well as geological structure and tectonic history. Major mantle and crustal anomalies in many different parts of the world were discussed in this context. In active or recent subduction zones, for example the Japanese Arc, the penetration into the mantle of a resistive lithospheric slab is probably responsible for the anomalous effects observed. Many crustal anomalies are also clearly associated with continental margins or with ancient plate boundaries. The final review paper in the session was Solar Wind Induction and Lunar Conductivity by C. P. Sonett. In this a summary of electromagnetic induction in the moon by the interplanetary magnetic field was presented. Lunar Surface Magnetometers installed during the Apollo landings have provided the basic data and a conductivity-depth profile between 0.9 and 0.6 lunar radii has been estimated. The conductivity appears to be about four orders of magnitude lower than that of the earth at comparable depths.

Many interesting contributed papers were given in the five sessions and these presented new methods and results in all the aspects of induction problems discussed above. The fourth symposium on Interpretation of Observed Fields also included some excellent papers on magnetotelluric results though a review paper on this topic was not given.

Highly specialized meetings of the type described here are becoming increasingly popular in the geophysical community, but have only recently been implemented at the international level. They have the advantage of being small enough to be arranged easily, and the participants have ample opportunity to get to know one another and to discuss problems of mutual interest. The Ottawa Workshop was organized under the chairmanship of Professor D. I. Gough of the University of Alberta, Edmonton, Canada.

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Symposium on Permafrost Geophysics

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The Canadian National Committee for the International Hydrological Decade (IHD) and the Permafrost Subcommittee of the National Research Council of Canada, Associate Committee on Geotechnical Research (ACGR) held a point Symposium on Permafrost – Hydrology and Geophysics in Calgary, Alberta on February 26 to 28, 1974. The hydrology section was sponsored and organized by the Canadian National Committee for the IHD. The geophysics section was sponsored and organized by the Permafrost Subcommittee of ACGR. This report will review the geophysical part of the symposium.

Fourteen invited papers were presented during the last day and a half of the symposium. The purpose of the presentations was to give an up-to-date account of geophysical techniques that have been tried in the northern regions of Canada and Alaska. Emphasis was placed on results of application of various techniques, rather than on model studies and equipment feasibilities and systems. This emphasis was appropriate in view of the specific nature and present interest in the subject and the interaction between hydrologists, geologists and engineering geologists.

The opening paper, "Geophysical Parameters of Permafrost" by L. S. Collett indicated that the electrical, seismic and gravity methods were the most useful methods applicable in the frozen ground environment. This is because electrical resistivity and elastic properties of earth materials exhibit the greatest change in frozen soils and rocks between 0°C and −10°C. The ratio between ice and water depends on the temperature gradient, porosity, dimensions of the pores, concentration of salt solutions and mineral composition of the soils and rocks. The gravity method is useful to detect ground ice and for estimating the thickness of excess ice but is of little use for the detection of the presence or absence of permafrost. The freezing of insterstitial water in rocks and soils has little or no effect on the magnetic permeability and radioactive parameters.

In the following paper entitled "Temperature and Heat Flux Measurements through Permafrost as a Geophysical Tool" by A. M. Jessop and A. S. Judge several points were brought out. The process of drilling a well disturbs the temperature in the ground around the well. The extent of this disturbance depends on many factors, including the temperature of the drilling fluid, the porosity of the surrounding rock, the thermal conductivity of the rock, and the duration of circulation of the drilling fluid. Of the two examples presented, a series of temperature profiles show that after six to eight years the temperatures are still continuing to return to equilibrium levels. At equilibrium level for the one example at Reindeer in the Mackenzie Delta, the temperature profile approximates two straight lines with different gradients, the change in gradient coinciding with the freezing boundary. The other example at Winter Harbour on Melville Island in the Arctic Archipelago shows very little change in the temperature gradient at equilibrium. The difference in behaviour between these two wells is accounted for by the fact that at Reindeer the porosity of the penetrated section was very high, and the ice contained in it was melted.