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RECORD No. 1968 / 54

Visit to USA and Canada, 1966

by

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SUMMARY

The author spent approximately three months (June 13 to September 21) in North America during 1966. Visits were made to Universities, government institutions, geophysical contractors and mining companies in the United States of America and Canada to study recent developments in mining geophysics. Detailed accounts are made of these visits, and where possible they have been subdivided into different fields of interest (e.g. electrical or electromagnetic methods) by subheadings. Recommendations are made for modifications to field and interpretation techniques as used by the BMR and for the purchase of new equipment; suggestions are made for future investigation and development.

1. INTRODUCTION

During 1966 the author, a geophysicist with the Metalliferous Section of the BMR, made an official visit to North America for approximately three months. The object of the visit was to study recent developments in mining geophysics both in Universities and Government Institutions and in large American and Canadian companies who conduct their own research. Developments in instrumentation, field techniques, and interpretation, mainly in the fields of electromagnetics and induced polarisation, were to be studied, but other geophysical methods applied to mineral exploration, were to be investigated also.

The author left Australia on June 13th and returned on September 21st. Most of the time was taken up by visits to field parties in the south-western United States (where geological conditions and the associated geophysical problems are similar to many encountered in Australia) and to north-eastern Canada where many new geophysical techniques have been developed. The rest of the trip was spent visiting geophysical research centres, instrument laboratories, geophysical contractors, and mining companies.

The timetable of visits to the various centres is shown in chronological order in Appendix 1. The organisations visited at the various centres are shown in Appendix 2.

2. SAN FRANCISCO

University of California, Berkeley

Professor S.H. Ward had a group of graduate students working in mining geophysics at the Berkeley campus of the University of California. I visited this group on June 15th and 16th. Professor Ward was absent but two of his graduate students (R. Phillips and B. Fuller) were able to show me around.

The group was very active in mining geophysics and very computer oriented. They were apparently restricted by a lack of opportunity for field work and most of their time was spent analysing a limited amount of data exhaustively. Several topics were discussed.

E.M. model tests. The group had worked with simple models and horizontal coplanar coils (Slingram configuration) and several other methods. One student had modelled thin sheets in a uniform field and replaced them by a wire loop which could be treated theoretically. This led to quantitative interpretation theory which could be extended to cover AFMAG results (Parry, 1966).

Tests with a rotary field e.m. technique were made in the laboratory by D.C. Fraser. Model tests with this apparatus led to the prediction of a practical field unit with a transmitter-to-receiver range of up to two miles and a depth penetration of 1000 ft (Fraser, 1966).

IP model tests. An IP model test programme was under way but had not progressed very far. Physical models were placed in a water tank and measurements were made with a.c. to give frequency effects. Details were not available but the main problem appeared to be inductive coupling, which suggests that relatively high frequencies were being used.

Magnetotellurics. The Berekely group had experimented for some time in magnetotellurics and had built a mobile laboratory for recording both magnetic and electric fields. This had been used in experiments over sedimentary basins and in mineral exploration. Results were geared for computer analysis and a lot of theoretical work had been done. Interpretation, particularly in sedimentary basins, was extended by treating the propagation of plane e.m. waves through an n-layered earth. If the number of layers, their thicknesses, and resistivities were known at a base station, the same characteristics could be deduced at field stations.

AFMAG. Professor Ward was mainly responsible for the development of the AFMAG method. The group has investigated audio frequency natural fields in several areas and field-tested AFMAG under a variety of conditions (Ward et.al, 1966).

Computer analysis. Electromagnetic and magnetic interpretation has been made less subjective by the introduction of computer methods to search for anomalies amongst field observations. Techniques include frequency filtering (high-pass, low-pass, and band-pass) in an attempt to remove regional or local effects or both, strike filtering to select only anomalies which persist in a certain strike direction, and auto-correlation to separate anomalies of a predicatable type from noise (Fraser, Fuller, and Ward, 1966).

Borehole e.m. An e.m. unit was under development to measure borehole orientation. A transmitting coil was lowered down the hole and a receiving coil, held at the surface, was oriented to detect the maximum signal. In the absence of interference from secondary currents the orientation of the transmitter coil could be deduced.

IP research. Fraser, Keevil, and Ward (1964) have made a series of laboratory investigations into the IP effect in rock samples. They have studied conductivity spectra from 0.1 to 1000 c/s and investigated electronic polarisation, membrane polarisation, clay effects, etc.

Two-layer structure from dipole-dipole measurements. A paper has been produced outlining theoretical methods of resolving resistivity and IP effects in a two-layer structure from dipole-dipole measurements if the resistivity of the surface layer is known. If the surface layer resistivity is not known a numerical method may still permit an estimate of the resistivities and depth to the interface (Fraser and Ward, unpublished).

Magnetics. Co-operation with Varian Associates has made possible some experimental work with Varian magnetometers. Several static anomalies were investigated and micropulsations in the magnetic field, which are independent of remanent magnetism, were recorded simultaneously by two Varian rubidium vapour magnetometers. After traversing the anomalies and analysing the results it was possible to determine the proportions due to remanent and induced magnetisation. If the shape of the magnetic body could be estimated from the static anomaly and drilling results it would also be possible to estimate its average magnetic susceptibility (Goldstein and Ward, 1966).

Varian Associates, Palo Alto

Following a letter of introduction from E. Burnside of McPhar Geophysics Ltd to Mr L. Langan of Varian Associates a visit was arranged to Varian's Quantum Electronics Division at Palo Alto on Friday June 17th. The main purpose of the visit was to see, and discuss applications of, Varian's two basic types of magnetometer - the proton precession type and the relatively new optically pumped magnetometer using rubidium or caesium vapour as sensing element.

The proton precession magnetometer. This type of instrument is now in general use as an airborne or ground magnetometer in several forms but Varian claim to have invented the first one and have developed several very sophisticated models with accessories for a variety of applications. The proton precession magnetometer measures the intensity of the total magnetic field by the precession frequency of hydrogen atoms aligned at an angle to it. The hydrogen atoms must be realigned for each reading so a continuous measurement is not possible by this method. The instrument itself is basically simple and rugged, the sensor can be aligned in almost any direction and a sensitivity of ±0.1 gamma can be obtained if necessary. In most applications a sensitivity of ± 1 gamma is considered sufficient.

The most recent model of the Varian proton magnetometer, the V4937, is of a completely solid state design with digital readout (± 1 gamma) and advanced modular construction. According to the selection of accessories it can be used for ground, airborne, or marine or as an observatory instrument. Special types of proton magnetometers have also been developed by Varian for use in rockets and satellites. The variety of uses for this instrument includes archaeological prospecting, searching for skiers buried under avalanches, and locating submarine pipelines.

I was shown over the Varian laboratories where several of these instruments were being constructed, tested, and calibrated, and shown some of the accessories developed for use with them. The proton magnetometer is very versatile and is widely used for airborne and marine applications. In ground work it suffers from the limitation that it cannot be used in extremely steep gradients as the variations in magnetic field across the sensor make it impossible to obtain a reading (tests by Ward's group at Berkeley, using the M49 model, showed that it cannot be used when the horizontal gradient of total intensity exceeded 110 gammas/ft, but was quick and convenient to use otherwise). The V4937 has world-wide range, an accuracy of ±1 gamma, and a sampling rate as short as once every two seconds. The BMR proton magnetometer seems to compare favourably for sensitivity, sampling rate, etc., but does not have the very sophisticated ancillary equipment and versatility of the Varian model.

Optically pumped magnetometers (Rb, Cs, etc). These magnetometers are a recent development enabling highly accurate, continuous measurements of total magnetic intensity. Measuring accuracy of ± 0.01 gamma is readily obtainable but the instrument has a larger orientation 'dead zone' than the proton magnetometer. The operating principle of this instrument has been described by several authors (e.g. Bloom, 1962).

These instruments can be used directly as magnetometers, but in this application the high sensitivity is not used to its best advantage. Small anomalies are hidden by magnetic noise coming from distant sources. It is desired to separate these small anomalies from the noise in prospecting (either airborne or ground). The instrument is particularly well suited for use as a gradiometer. Two sensors, a fixed distance apart, can be coupled together and the difference between the field intensities measured. In this configuration, short-term fluctuations from distant sources are cancelled out and a relatively noise free, highly sensitive record is obtained.

The simplest application for a highly accurate, continuous magnetometer like this is as an observatory instrument. A continuous record, including noise from distant sources is obtained and the data can be stored or analysed by computers in various ways. A development of this application is the Automatic Standard Magnetic Observatory with Remote Recording (ASMOR), which can be set up at a remote location and left to run automatically. The ASMOR has two pairs of Helmholtz coils to bias the total field at the sensor, which then measures small variations in the declination and inclination of the total magnetic field. By taking a series of five measurements with various biases the instrument effectively records the magnitude and direction of the total magnetic field every ten seconds. The data can be recorded on the spot or transmitted by telephone to a central recording laboratory for reduction and analysis.

The magnetometer has also been used as a ground prospecting tool (e.g. searching for skiers buried by avalanches; archeological prospecting in Italy) and as an airborne magnetometer. Because the orientation angle with respect to the total field is so important it has been necessary to mount the airborne sensor in gimbals to allow the orientation of the sensor to be varied during flight. The ground instrument can easily be oriented for each reading but so far a satisfactory arrangement for marine work has not been developed.

The combination of two sensors in a gradiometer has been used on the ground and in the air. For ground work two sensors are mounted on a horizontal staff approximately ten feet long and carried manually. The sensors can be tilted into the appropriate orientation with respect to the staff and maintained at an operational angle provided the staff orientation remains approximately constant. This set-up has proved satisfactory for archeological prospecting on the Plain of Sybaris in Italy, where both proton and rubidium magnetometers have been used.

An airborne gradiometer has also been developed. It comprises two 'birds' suspended beneath a helicopter and separated vertically by 100 ft, and measures both the total field and the vertical gradient. The additional information obtained from this instrument makes possible a much more detailed interpretation of magnetic anomalies. Although developed for petroleum exploration it could also be a valuable aid in mining geophysics. A marine gradiometer has not yet been developed but is probably the next step provided problems of turbulence and sensor 'dead angles' can be solved.

Finally, the optically pumped magnetometers could be used for laboratory measurements of magnetic susceptibility of samples (Breiner, 1965). Apparently the high sensitivity of these instruments cannot be fully utilised in such an arrangement and other methods can give more accurate results. Possibly future developments, particularly in optimising detector/sample geometry, will enable more profitable use of the optically pumped magnetometers in this field.

3. SALT LAKE CITY

I flew from San Francisco to Salt Lake City on Sunday June 19th and used Salt Lake City as a base until July 6th. During this time I was primarily associated with The Anaconda Company; I had discussions at their geophysical headquarters in Tooele and visited field crews in Nevada (June 22nd to June 24th) and Arizona (June 28th to June 30th). In Salt Lake City I spent one day with Kennecott Copper Corporation (June 21st) and one with ASARCO (June 27th). I also spent one day with Heinrich's Geoexploration Co. in Tucson (July 1st).

The Anaconda Company

On June 20th, I visited Anaconda's geophysical laboratory at Tooele and had discussions with Mr E.O. McAlister (Chief Geophysicist) and Messrs Jack Corbett and Mark Halvorsen (Geophysicists). Although Anaconda have used various geophysical methods their main emphasis is on induced polarisation (IP) where they have developed their own techniques and constructed their own equipment.

Anaconda work in the time domain and measure IP effects with their own parameter 'phase angle', which is analagous to 'chargeability'. The phase angle, A, is defined by $\tan A = V_d/V_{in}$ where V_d (the 'out of phase' voltage) is the decay voltage after the current is turned off and V_{in} (the 'in phase' voltage) is the voltage during the current pulse. Thus the IP effect is regarded simply as a change of phase of the input waveform. The ratio V_d/V_{in} is usually small so that, in most cases $A \approx \tan A$ = chargeability. Values of V_d and V_{in} are measured in various ways by all time domain IP systems, usually averaged over a time interval by some kind of integrating system. Anaconda's approach is slightly different but the end product is practically the same.

Most IP work in the south-west United States is directed towards the search for large, relatively low-grade, porphyry copper deposits, which may be very deep and are almost certainly covered by a low resistivity overburden. Under these conditions IP measurements must be made with large electrode separations, which reduces the magnitude of the received signals and increases the possibility of dispersion (inductive coupling in the frequency domain). The received signals, in extreme cases, are small enough to be seriously affected by telluric noise, which introduces random variations in the received voltage. This effect can never be eliminated completely but it can be reduced by increasing transmitter power and optimising electrode arrays. Dispersion is affected by ground resistivity, electrode separation, and frequency. The ground resistivity is fixed and electrode separation is determined by other factors (depth of target, telluric noise, etc.) although some flexibility in electrode array is usually possible. The frequency or, more appropriately in the time domain, the time interval for measurement of V_d, can be varied to reduce dispersion effects.

Anaconda U.L.F. equipment. The Anaconda Company has developed several high powered, flexible IP transmitters which can be used with a number of different types of receiver. The U.L.F. (ultra low frequency) receiver used pulses as long as 20 seconds in normal operation and occasional longer ones in more difficult areas. The received voltage (after 'backing off' the self-potential) is amplified and recorded on a 'Rustrak' chart recorder (see Plates 1 & 2). The record is made in two stages because of the difference in magnitudes of V_d and V_{in}, the gain is increased to record V_d and synchronised with the ripple on the transmitted pulse to leave no trace during the current 'on time'. V_{in} can then be read directly from the chart record and the value of V_d at the end of the decay curve (where dispersion effects should be a minimum) is related back to the area under the decay curve to give an average V_d. V_{in} is used to calculate resistivity and combined with V_d to give the phase angle, a measure of the IP effect.

After discussions in the laboratory at Tooele, I visited a field crew in Nevada for three days and saw the U.L.F. equipment in action (see Plate 2). The problem was to detect mineralisation underneath a volcanic flow estimated to be several hundred feet thick, using a pole-dipole array and a 25-kilowatt transmitter. In order to get sufficient depth penetration it was necessary to use as large an electrode separation as possible while still receiving a recognisable signal. In this case a receiving dipole of 400 ft and separations between current electrode and receiving dipole of 400 feet and 800 ft were used. Referring to the electrode configuration illustrated in Plate 1 the 'near leg' was omitted and the distance between 'forward current' and 'ground' was 400 and 800 ft. Current pulses of 15 seconds were used and decay curves recorded during 15 seconds 'off time'. The transmitted current ranged between 5 and 10 amps (depending on contact resistance) and this was sufficient to obtain interpretable records at nearly all stations. Over the middle of the basalt flow the received signal was weakest and interference from telluric noise became excessive. Some tests were made with one-minute charging time and four-minutes decay time but this was very time consuming and results were not significantly improved.

Both current and potential electrodes used in this area were hollow iron pipes of square cross section, buried in pairs and well watered. Although the ground was very dry little difficulty was experienced in obtaining suitable contacts. The high currents used caused the electrodes to dry out quickly and, if the readings were not completed in a few minutes, it was often necessary to re-wet the electrodes to maintain a good contact. Men stationed at the receiver and transmitter electrodes were in continuous radio contact to avoid accidents, and current cables were never handled until it was certain that the transmitter was switched off. Progress along the line was quite fast and the method had the obvious advantage that the chart records could be interpreted later in the laboratory, which removed the possibility of reading errors.

The U.L.F. receiver apparently had quite a low input impedance and it was necessary to check the contact resistance of the electrodes at each set-up. This was done by switching in 1000 ohms in series with the receiver and noting the change in indicated voltage. This test was made after each reading but, in the absence of broken leads, contacts were generally quite satisfactory.

The records from the U.L.F. work in Nevada were returned to Tooele for processing at a later date. I was not present for the reduction and interpretation but this appeared to be quite straightforward. Even when telluric noise was particularly bad the practice of reading a series of pulses made it possible to extract meaningful data from the random noise.

Conventional IP. The Anaconda Company also arranged for me to spend three days with a crew working near Miami-Globe in Arizona. The job was essentially a reconnaissance using a predecessor of the U.L.F. equipment and a 75-kilowatt transmitter. The electrodes (iron spikes similar to those used by the BMR) were set out in a pole-dipole array with an 800-ft potential dipole and pole-to-dipole separations of 1600, 2400, and 3200 ft. The transmitter, operating below full power, produced 8 to 12 amps in alternating square pulses at 1 c/s; this was generally sufficient to give recognisable signals at the receiver but telluric noise was a major problem.

The received voltage was fed to a galvanometer whose swing was calibrated by comparison with a standard pulse. The swing of the meter was then used to measure V_{in} and the decay voltage was measured by feeding a portion of the decay curve to the meter and balancing it against a standard voltage. The receiver amplifier was synchronised with ripple on the transmitted pulse to exclude the relatively high voltage V_{in} during measurement of the decay voltage. The synchronisation was frequently driggered instead by telluric noise and when portions of V_{in}, amplified by the same factor as V_{in}, reached the meter it oscillated violently.

The following sequence of operations was necessary to take a reading:

1. Calibrate the swing of the meter by feeding in a standard pulse.

2. Adjust synch. amplitude to its operational minimum to reduce the chance of triggering by random noise.

3. Switch off the receiver amplifier and read V_{in} from the swing of the needle (calibrated in 1)

4. Check the contact resistance by inserting a series resistor (similar to the U.L.F. unit).

5. Switch on the amplifier and synch. to feed an amplified portion of the decay curve to the meter. Oppose the decay voltage by adjusting variable potentiometers to minimise the meter deflection and read V_d from the potentiometer settings.

In practice the null position was quite broad and very difficult to read accurately. The meter deflections were erratic owing to telluric noise and if the synch. was triggered by noise a delay of several seconds ensued before the meter settled down. Noise was particularly bad after a short thunderstorm and readings were very difficult to obtain with the maximum separation (3200 ft. from current to potential electrodes) If the transmitter had produced 20 to 30 amps, as it should at full power, the noise problem would have been considerably reduced but electrodes would have dried out very quickly. Even at an operating level of 8 to 12 amps it was necessary to 'wet down' electrodes at frequent intervals.

A rough conversion from instrument readings to phase angles was made in the field as a check on progress. Typical results were as follows:

Current to potential separation	Phase angle
1600 ft	30-35 mins
2400 ft	40-50 mins
3200 ft	60-70 mins

The increase of phase angle with separation was probably due to dispersion and this would be checked at headquarters by comparison with calculated values. This equipment was superseded by the U.L.F. receiver described earlier.

Anaconda P.D.R. equipment. The Anaconda P.D.R. equipment represents a basically different approach and is designed mainly to remove or at least reduce the effects of telluric noise. It uses three potential electrodes: near leg, ground, and far leg (see Plate 1).

The signal received across far leg to ground is compared with that received accross near leg to ground and is balanced on a bridge circuit. If the two dipoles are equal in length the telluric noise cancels out almost exactly. In any case they oppose each other and noise effects are reduced. The small difference that cannot be balanced out on a non-reactive bridge represents the 'out of phase' component or IP effect (including dispersion). This can be balanced out reactively or read off the meter at minimum deflection to give a phase angle measure of IP effect plus dispersion. If readings are taken at two frequencies the proportion of the reading due to dispersion can be estimated and allowed for.

This instrument was used briefly in Arizona to provide some estimate of the magnitude of dispersion effects. Readings were taken with 0.2 and 1.0 second pulses. The array used had the near leg 25ft from the forward current electrode, where it was assumed to be relatively free of IP and dispersion effects. The receiver and ground electrode were 1600, 2400, and 3200 ft from the forward current electrode and the far leg was 800 ft further on. The instrument was quick and easy to read and telluric noise did not present any serious problems. Measurements were reduced to a phase angle at each frequency and the resulting estimates of dispersion were used in the interpretation of the conventional IP results.

Kennecott Copper Corporation

On June 21st, I visited Kennecott Copper Corporation's Exploration Services in Salt Lake City. This division of Kennecott provides exploration services (geology, geophysics, and geochemistry) to Bear Creek Mining Company and undertakes consulting, research, and development for branches of Kennecott throughout the world. I was shown over the group's building by the director Dr R.C. Holmer and met the geophysicist in charge of operations, Mr. Bob McDougal. Mr. Tom Mitcham is in charge of geological research and Mr Blair Roberts in charge of geochemistry. My main interest was of course geophysics, and considerable time was spent in discussions with Dr Holmer and Mr McDougal.

In common with other companies operating in the south-west United States, Kennecott use gravity and aeromagnetic data to a limited extent, mainly for mapping sedimentary areas in the basin-range country west of Salt Lake City. For more direct prospecting, various types of electromagnetic equipment, including AFMAG, have been tried but discarded. Conducting overburden reduces the depth penetration of these methods and makes them unsuitable for use in the arid south-west environment. The most extensively used method at the present time is induced polarisation.

Kennecott work primarily in frequency domain IP using conventional equipment developed by Dr T.R. Madden at M.I.T. For reconnaissance work they use a dipole-dipole array with up to 1000-ft dipoles and frequently have trouble with inductive coupling (dispersion in the time domain) when working in low resistivity environments. It is not possible to avoid inductive coupling effects in the frequency domain (in the time domain dispersion can be effectively avoided by delaying measurement of the decay voltage until the dispersion effects have disappeared) but, when present, they can often be recognised and allowed for. The increase of inductive coupling effects with dipole separation and frequency is used to recognise them. The effects become very pronounced and easily identifiable at large n values (see Plate 3). Kennecott normally read as far as n = 6, as is normal practice in the BMR, in contrast to McPhar who usually stop at n = 4.

Kennecott usually base their interpretation on percent frequency effect (P.F.E.) rather than metal factor although both are considered. This approach is used by several officers of the BMR but again it conflicts with the approach used by McPhar. Kennecott have a large I.B.M. computer in Salt Lake City and have developed a very flexible program for computing theoretical IP effects from models. The program can work with various arrays although dipole-dipole is the most common one in use in the frequency domain. Theoretical IP profiles are widely used in interpretation; for example in assessing depth penetration in the two-layer case with a conducting surface layer.

New equipment and techniques are continually being developed by Kennecott but a great deal of this work is classified. A new IP unit, suitable for either frequency or time domain, was under construction with the receiver reading directly in P.F.E. Dr. Strangway of M.I.T. and

Dr Holmer have experimented with thermal radiation as a prospecting tool (Strangway and Holmer, 1966); so far their experiments have not been very successful but they are hopeful that further work in this direction may prove rewarding. Finally, Kennecott are working extensively in tell-urics, using audio frequency natural electric fields as the basis of a prospecting method. This technique was not open to discussion.

ASARCO

Monday June 27th was spent with the American Smelting and Refining Company (ASARCO) geophysical division in Salt Lake City. I was conducted around their laboratories by the Chief Geophysicist (Mr. R.J. Lacy) and had discussion on geophysical techniques with him and with Mr. B.C. Morrison.

ASARCO use aeromagnetics, ground magnetics, and gravity for mapping sedimentary areas but the main emphasis is on IP and geochemistry for direct prospecting. They have done their own aeromagnetic work with a Varian proton magnetometer but found it unsatisfactory as a field instrument and now use an ELSEC proton magnetometer.

ASARCO have developed their own IP equipment for use in the arid south-west United States and northern Australia. The instrument is basic-ally conventional time domain equipment using 3-second alternating square pulses. In order to reduce dispersion effects, 250 milliseconds delay is allowed after the current is turned off and then the decay voltage is integrated for 750 milliseconds. A variation of Wenner configuration is normally used with three potential electrodes, making readings possible at two separations from the one set up.

The problems facing Anaconda and Kennecott, inductive coupling and telluric noise, are problems for ASARCO also. The Wenner array is chosen for maximum signal strength combined with reasonably small coupling effects. Coupling is usually avoided by the 250-millisecond delay and the main problem is telluric noise, which can give random variations several times as large as the required signal. Several pulses are normally averaged in an attempt to sort out telluric noise but it still remains a major problem with large spreads.

Clay effects have occasionally been encountered but these are comparatively rare. Chargeabilities of 10 mv/V compared with a general background of 2 to 3 mv/V have been attributed to a sandy clay mixture. Longer charging pulses can sometimes help to distinguish between metallic conduction and clay or membrane effects but in borderline cases prior geological information must be used to interpret such anomalies. ASARCO have investigated IP effects in laboratory samples and claim to be able to distinguish between different polarisers (e.g. graphite and sulphides) in samples but not yet in the field. Laboratory samples are set in plastic discs with faces ground flat and then inserted in a cylinder filled with liquid, with one current and one potential electrode at each end.

An interesting experiment with various electrical methods, (self-potential, equipotential, resistivity potential, etc) in boreholes, was carried out in 1961 by Messrs. C.K. Moss, B.C. Morrison, and G. Reinbold in order to try to determine the location of the best mineralisation bet-ween a pattern of boreholes at West Fork, Missouri. This experiment is described in a volume of ASARCO case histories held by the geophysical metalliferous section of the BMR. Several different techniques were used including the direct excitation of the orebodies by placing current electrodes opposite them in two boreholes and measuring potential in the remaining ones.

ASARCO have an extensive geochemical laboratory under development and they are working on a mercury detector, which they hope to use eventually as a field instrument.

I was most impressed by a device developed by a member of the staff in Salt Lake City for projecting colour slides on to the back of a transparent mapping table. Aerial photography was taken on colour film and stored as colour slides without any necessity for printing. The projected colour slides were used in the same way as conventional aerial photographs, with the addition of colour, and the whole projection system, with two projectors, was remotely controlled from the mapping table. The system appeared to work extremely well.

Heinrich's Geoexploration Company

On Friday July 1st, the Anaconda Company arranged for me to visit Heinrichs Geoexploration Company (Geoex) in Tucson, Arizona. This company undertakes contract geophysics, mainly IP and magnetics, in the south-west United States, Canada, and recently Australia. They have wide experience of work in a hot arid environment and hope to cope effectively with Australian conditions.

Geoex use frequency domain IP extensively and have constructed their own IP unit, which is very similar to the Geoscience unit used by the BMR. Their equipment transmits up to 5 kilowatts, at a maximum of 3 c/s and is air cooled for operation in hot climates. Inductive coupling is a major problem; it cannot be corrected for accurately but estimates of its magnitude (from Geoscience calculated model cases) can be used in interpretation. The staff in Tucson had constructed a laboratory IP transmitter for testing rock samples in conjunction with a normal field receiver. The transmitter was simply a square-wave generator supplying a constant current at the normal operating frequencies; I was unable to find out how the instrument was coupled to rock samples but apparently it was widely used for qualitative measurements of IP effects.

One of Geoex's most popular instruments was a mobile magnetometer, mounted in a truck, with the detector on a tail boom. Readings were recorded on a chart recorder with reading intervals and chart speed geared to the wheels or operating at fixed time rates. During my visit a Varian proton magnetometer was in use but other models had been used previously. The set-up had been particularly useful for rapid magnetic traversing on roads or tracks in the relatively flat terrain around Tucson. Plans were also underway to adapt a Varian proton magnetometer for airborne use in a Cessna.

Geoex also work with a variety of methods in conjunction with other companies. They were trying Hunting airborne e.m. in northern Australia during 1966 and are associated with the Anaconda IP equipment proposed for the tests over the Woodcutters Area, Northern Territory.

4. DENVER (USGS)

On July 4th, I travelled from Salt Lake City to Denver and spent Tuesday July 5th to Friday July 8th with the United States Geological Survey (USGS) and the Colorado School of Mines. The USGS was very helpful; they have done some research in methods and techniques in the laboratory but relatively little field work in mineral exploration. They have a programme of regional gravity and aeromagnetic survey work for public release. Groundwater investigations and deep resistivity probing are carried out in research projects, and airborne radiometric and electromagnetic facilities are being developed. Laboratory research on induced polarisation and electromagnetic model tests had been done but was not in progress during my visit.

Regional gravity and aeromagnetics

I met Don Mabey, in charge of regional geophysics, and discussed gravity and aeromagnetics with him. The USGS carries out regional mapping of the basin-range area of the western United States, partially duplicating a lot of the work already done privately by companies like Kennecott and ASARCO. The USGS makes the final release of data to the public.

An interesting result of this work has been the appearance of east-west lines of magnetic anomalies which cut perpendicularly across the north-south striking outcrops of the basin-range provinces. These magnetic anomalies correspond to areas of igneous activity and often include known mineralisation (e.g. Bingham Canyon, Utah and Ely, Nevada).

Resistivity

I spent some time with Adel Zohdi and Dallas Jackson, geologists with the USGS, who use resistivity extensively in groundwater investigations and large-scale crustal studies.

In groundwater investigations they have used their own d.c. equipment, which has a power output of approximately 2 kilowatts and is switched manually to provide current pulses in alternating directions for greater sensitivity. For crustal studies banks of storage batteries are used to supply high currents and more sophisticated switching apparatus is necessary. The potential is recorded on a chart recorder, normally using several pulses for each reading. Current electrodes are stainless steel spikes (or mats of braided copper wire for high current transmission); potential electrodes are porous pots and a variety of electrode configurations are employed.

The usual method of applying resistivity to the study of near-horizontal layers is a series of depth probes using expanding electrode arrays. In small-scale work (e.g. groundwater surveys) depth probes are spaced along a line and a subsurface cross-section can then be constructed. The usual electrode configurations employed are Wenner, Schlumberger, and various dipole arrays. The equatorial dipole array (see Plate 3) gives the same results as the Schlumberger configuration (i.e. the same interpretation curves can be applied to both) and these two are most commonly used by Zohdi and Jackson. Dipole methods are preferred because cables can be kept relatively short but they are very sensitive to faults and dipping beds are not always practical.

Dipole methods have been reviewed recently in the literature (L.M. Al'pin et al, 1966; Keller, 1966) and are widely used in the crustal resistivity studies conducted by the USGS (Keller et al, 1966; Anderson and Keller, 1966; Jackson, 1966). Zohdi has published several papers on shallower, groundwater investigations (Zohdi, 1965a & b) and he presented two papers on this subject at the 36th Annual International S.E.G. meeting in 1966.

Induced polarisation

I met Len Anderson, a geologist with the USGS and Dr George Keller, Associate Professor of Geophysics at the Colorado School of Mines, both of whom had studied induced polarisation in laboratory samples (Keller, 1960; Anderson and Keller, 1964). Anderson was still studying physical properties of rocks but with less emphasis on polarisation mechanisms.

Anderson and Keller have studied the factors affecting overvoltage effects in rock samples:

(a) Total percentage of metallic conducting particles

(b) Matrix resistivity

(c) Grain size of conducting particles

(d) Current density

(e) Distribution of conducting particles

They found a considerable overlap between effects and membrane polarisation effects, which suggests that the two could easily be confused in field measurements on rocks that exhibit pronounced membrane polarisation effects (e.g. shaly sandstone). Further studies showed that the relatively high current density used in laboratory tests led to reduced overvoltage effects and an over pessimistic estimate of the amount of metallic sulphide necessary for detection in such an environment. Low current densities and short charging times reduce membrane polarisation with the result that frequency domain IP generally avoids membrane effects in the field.

The laboratory IP work carried out by Anderson and Keller used IP equipment of their own construction operating in the time domain. Laboratory studies were supplemented by some field work but this was very restricted.

Dr Keller showed me over part of the geophysical laboratory of the Colorado School of Mines. He demonstrates IP effects in rock samples to students as a part of their course. For this purpose, samples are cut into flat discs and clamped between circular electrodes with a small potential electrode at the centre and a large annular current electrode around it.

Although errors can be introduced by electrode polarisation, this system produces a large signal, which is not much affected by noise.

Radiometry

I was introduced to Jim Pitkin and John Hand, geologists with the USGS, who were working with airborne gamma ray spectrometry. In early work Pitkin used six sodium iodide crystals (10 cm in diameter and 5 cm thick) and photomultiplier tubes connected in parallel. Only photons with incident energies greater than 50KeV were recorded and the measured count rates were automatically compensated for variations in altitude. With this set-up, several areas were flown at approximately 150 metres altitude and the results were correlated with geological maps in an attempt to develop the method as an aid to geological mapping (Pitkin et al, 1964). They concluded that this type of measurement could be a useful aid to geological mapping in areas where soil cover or glacial material had not been transported far and hence was still representative of the rock beneath it.

Pitkin and Hand were currently working with two sodium iodide crystals (11 inches in diameter and 4 inches thick) with seven photo-detectors on each. After calibration, correction for background, etc., count rates were recorded on three energy bands (corresponding to potassium, thorium, and uranium) and one total count band. This work was still experimental and results were being compared with those obtained with the old equipment in order to assess how best to use the additional information.

I also met Carl Bunker who had worked with a truck-borne gamma ray spectrometer in areas of hydrothermal alteration (Moxham et al, 1965). For this work a large sodium iodide crystal (11 inches diameter and 4 inches thick) with seven phototubes was used. Results were fed to a 400-channel analyser and used to estimate potassium, thorium, and uranium. An interesting result of this work was an apparent increase of potassium content and decrease in thorium near hydrothermally altered areas. Several mineralised areas have been studied on the ground and it seems likely that increases in the potassium-thorium ratio in such areas should be detectable from the air. The continuing work by Pitkin and Hand will investigate this.

Electromagnetics

I spent some time with a group, under Frank Frischknecht, who had worked on electromagnetics (both model tests and field work) and were currently installing an airborne INPUT system to be flown with a gamma ray spectrometer (under Pitkin and Hand) and fluxgate magnetometer. Frischknecht is co-author, with Keller, of a recent textbook 'Electrical Methods in Geophysical Prospecting' and several papers on field applications of electromagnetics (Frischknecht, 1959; Frischknecht and Ekren, 1961 a & b; Frischknecht and Ekren, 1963).

Frischknecht had conducted extensive electromagnetic modelling tests using mainly a moving-source Slingram configuration but with some Turam measurements. A copy of a report on these tests (Frischknecht and Mangan, 1960) was made available to the BMR. It includes a collection of profiles across various models and a short interpretative text. All model test profiles were plotted as in-phase and out-of-phase components (real and imaginary); field profiles were normally plotted in this form also. This contrasts with practice in the BMR where, although Slingram results are plotted as real and imaginary components, Turam is normally left in the form of ratio and phase profiles.

The INPUT unit, being fitted during my visit, was a conventional Barringer unit, but had two receiving coils, one vertical and one horizontal, in the bird. The plane was also fitted with the gamma ray spectrometer being used by Pitkin and Hand and a fluxgate magnetometer in a tail boom. I was shown over the plane but the equipment was not operational and it was not possible to see it in action.

Aeromagnetic measurements were recorded digitally on magnetic tape (at intervals of one-tenth of a second) and reduced on a computer. The computer output presented the results as contour intersections on traverse lines and the contouring was later completed by hand. It was intended to record INPUT and radiometric results in conventional paper charts. Both methods were experimental and a more sophisticated treatment of results was evidently not being attempted at this stage.

Geochemistry

A brief visit was made to Mr. F. Ward who helped develop a mercury vapour detection system which has subsequently been modified and developed by several companies (e.g. Barringer Research, Toronto). A standard mass of the ground sample is heated and the hot vapours given off, including mercury, are passed over gold foil, where the mercury is absorbed. After the system has cooled and the smoke has cleared the gold is heated and the mercury vapour released passes between an ultraviolet lamp and a willemite screen. Atomic absorption causes a shadow on the willemite screen and this can be detected by a phototube. The maximum signal detected by the phototube is taken as a measure of the mercury content of the sample. Measurements normally take about three minutes per sample and are apparently accurate down to 100 parts per billion (10^9).

5. TORONTO

I spent several weeks(July 9th to August 27th)based in Toronto, where I visited several geophysical contractors and mining companies to discuss techniques and interpretation and arrange visits to field parties. During this time I was absent from Toronto from July 26th to August 2nd, August 8th to August 19th, and August 24th to August 26th visiting field parties in Nova Scotia, New Brunswick, the Timmins district of Ontario, and near Minden, Ontario. Some time was also spent at the International Nickel Co. geophysical laboratories at Copper Cliff near Sudbury. The assistance given by the main geophysical contractors in arranging visits to field crews was not as great as was expected from some very optimistic correspondence, and a lot of my time was spent co-ordinating these visits. Mining companies (Kennco, INCO, COMINCO, etc) were generally very cooperative but the high pressure on contract crews to get the job done during the summer months necessitated rapid movements from job to job in the field and I found it difficult to catch up with some crews.

Barringer Research Ltd

I spent July 12th at Barringer Research Ltd near Toronto. The company had recently established a section devoted to geophysical exploration under John Boniwell and most of my time was spent with this group.

The group was primarily interested in airborne geophysics using instruments developed by the company. Contract work was flown in association with Canadian Aero Mineral Surveys of Ottawa and several Barringer crews were engaged in ground geophysics as a follow up.

Airborne geophysics. The airborne system consisted of INPUT transient e.m, a Barringer nuclear precession magnetometer, and a gamma ray spectrometer. The INPUT system (Barringer Research Ltd, 1966) was originally developed by Barringer Research Ltd for Selco Exploration Company Ltd, but has subsequently been modified and improved to give greater depth penetration and sensitivity. Research has indicated the possibility of distinguishing between different types of conductors (e.g. shallow overburden and orebodies) by the shape of the decay curve, and it has been suggested that induced polarisation effects can be detected and used to distinguish between ionic and electronic conductors. While this latter claim is a controversial one, the method itself has many advantages (reduction of orientation noise, high sensitivity, and depth penetration) and appears to work very well.

The Barringer nuclear precession magnetometer (Model AM-101A) was developed by Barringer Research in Toronto and is combined with the INPUT system on a time sharing basis. This instrument takes readings once per second with one gamma accuracy. Another model (A102) has been developed primarily by Barringer Research (Australia) in Sydney but, to date, its use has been restricted to straight aeromagnetic work in Australia. This model reads to one gamma, twice per second, is much lighter, and incorporates more advanced electronics. The airborne system also includes gamma ray spectrometer recording potassium, thorium, uranium, and total count. The results are recorded on the same chart as INPUT and magnetics.

Apart from typical survey results, as illustrated in the handbook, I was particularly interested in the results of a survey over the Gulf of Bothnia, where INPUT was used to detect a magnetite orebody beneath 75 ft of seawater. The instrument was first flown over deep seawater and the sensitivities were adjusted to keep the six traces parallel during variations in altitude, thus cancelling out the effect of the seawater. Next the instrument was flown over the known magnetic anomaly in 75 ft of sea water, at constant altitude, and an anomaly due to the presence of the conducting magnetite orebody showed up quite distictly.

Ground Geophysics. For ground follow-up, the company have a dip angle e.m. system (Model L.E.M.2) and a portable nuclear precession magnetometer (GM-102) of their own manufacture. The dip-angle e.m. system, typical of many in use in Canada, has moving source and receiving coils without a connecting cable and operates on 1000c/s. The receiver is tilted until a null is observed and the angle of tilt is recorded. This type of system is used widely in Canada, mainly for ground location of airborne e.m. anomalies; it is very difficult to do any quantitative interpretation on the results (e.g. conductivity, depth, width, etc) and I don't think it would prove very useful in Australia. The portable nuclear precession magnetometer reads to ± 10 gammas and is apparently quite rugged and reliable but not a particularly convenient field instrument. In addition, Barringer Research uses a Huntec 7.5-kilowatt (time domain) IP unit as a more diagnostic follow-up to INPUT, a Sharpe gravimeter, and a Mandrell E.R.75, 12-channel refraction seismic unit for specialised applications. The Huntec IP unit will be discussed in more detail later.

Geochemistry. I made a short visit to the geochemical laboratory under Dr John Walker, where I was particularly interested in the mercury detector (Model BNL-1200 Trace Mercury Spectrometer). This instrument uses the 2537-Å line from a mercury vapour light source as a sample beam and another beam with adjacent wavelength (not absorbed by mercury) as a reference beam. The two beams are passed simultaneously through a sample chamber containing vapours from the heated sample, the differential absorption giving a direct measure of the mercury content. The instrument takes about one minute per reading and can detect down to 5 p.p.b. in a 100-mg sample. It is a more advanced design than similar instruments I saw at ASARCO in Salt Lake City and the USGS in Denver.

McPhar Geophysics Ltd

During my stay in Toronto I visited McPhar Geophysics Ltd on several occasions (July 13th, 20th, and 25th and August 3rd and 25th) and had discussions with several members of their staff, mainly Dr P. Hallof and Mr D. Sutherland, geophysicists, and Mr J. Sevenhuysen, electronics engineer. McPhar are involved in most branches of mining geophysics, as contractors, consultants, and instrument manufacturers. I was able to discuss electromagnetic methods (airborne, ground, and borehole applications as well as scale modelling), AFMAG (airborne and ground), and induced polarisation (field equipment, scale modelling, and interpretation).

Electromagnetics. Several airborne electromagnetic nunits have been developed by McPhar for clients, all of them using continuous wave methods and measuring a variety of parameters. I was able to learn a little of the techniques involved and later saw one of these systems in the field with International Nickel Co. A related method, the airborne AFMAG unit, was built by McPhar for their own use and had been tested in Tasmania during the summer of 1965/66. The Tasmanian results were disappointing, as the fields were low and anomalies often obscured by noise. Its main application appears to be in searching for structural features (e.g. major shear zones) which may act as ore controls; it has not proved very useful in detecting orebodies directly. A recent paper by Ward et al (1966) has examined the advantages and limitations of the method.

McPhar have a wide range of ground e.m. units available and several of these were inspected in the laboratory. Nearly all of these units employ a vertical transmitting loop (or coil with horizontal axis) and measure dip angles with the receiving coils; the main differences are power output and operating frequencies. Low power units have a portable, hand-held transmitting coil and high power units use a large loop, mounted on a collapsible frame; operating frequencies range from 70 to 5000 c/s. One unit, operating at 600 and 2400 c/s, can also be used to measure in-phase and out-of-phase components, similar to the Slingram or E.M. Gun used by the BMR.

Ground AFMAG equipment is manufactured and used by McPhar. It has the advantage of one-man operation and greater depth penetration than conventional e.m. units but the disadvantage of an unreliable power source. Some attempts have been made to use power line fields as a power source but I could not get details of these experiments.

Several borehole e.m. units have been developed by McPhar but evidently not widely used. Various models are:

(a) D655 - Receiver down hole, transmitter at surface, measuring dip angles, frequency 1400 c/s.

(b) D651 - Receiver and transmitter down adjacent holes, measuring in-phase and out-of-phase components at 375 and 1050 c/s.

(c) D661 - Receiver and transmitter in the same hole, measuring in-phase and out-of-phase components at 375 and 1050 c/s.

The last of these units was still experimental at the time of my visit but I was led to believe that the first two were fully operational. They can all extend the range of information collected by a drillhole but interpretation is still not well developed.

To aid interpretation of conventional ground e.m., McPhar have constructed e.m. model test apparatus for use with various two-coil configurations (not including Turam) which measure in-phase and out-of-phase responses as well as dip angle. This is a very versatile apparatus capable of reproducing most of the instrumental and geological conditions encountered in the field; it operates on any frequency from 200 to 200,000 c/s with scaling factors from 1/50 to 1/400. I was able to see one of these units under construction but not in operation.

Induced polarisation. McPhar have a large number of frequency domain IP crews operating all over the world and have a continuous construction programme under way. I was able to see some of this work and discuss both the model P654 sequential transmission unit (which the BMR uses) and the model P650 simultaneous transmission unit. This second unit (sometimes called a lightweight model) is generally lower powered and is used in a completely different operating sequence as both high and low frequencies are transmitted together. Two of these units were later inspected in the field and will be discussed later.

The IP model test apparatus, built as part of an IP interpretation research programme (partly supported by the BMR) was inspected but was not in operation during my visit. The apparatus has been described in the volume of scale model cases produced by McPhar (Hallof, 1967).

Originally, models were constructed from gelatine and copper sulphate with supporting skeletons of bakelite but this proved rather unstable when suspended in water. To maintain a constant conductivity contrast it was necessary to circulate the water continually. Several other types of models were used in order to obtain different properties and greater stability including copper sulphate in plaster of paris blocks and powdered carbon suspended in plastic. Initial calculated cross-sections used vertical dykes from the surface with infinite strike and depth extent; the analogue models were of course of finite size and could be used to study end effects, bodies not reaching the surface, and the effect of finite depth extent. Two volumes of model profiles, one calculated and one using physical models, have been produced by McPhar and copies are held in the BMR Library (Hallof, 1965 and 1967).

I also had several opportunities to discuss IP problems and interpretation with Dr. Hallof. Inductive coupling, which often becomes a problem in frequency domain work in low resistivity environments (e.g. large areas of Australia) cannot be corrected effectively. Values of coupling effects can be calculated for various frequencies and electrode arrays, for some simple resistivity models (e.g. uniform earth, two-layer earth). These can then be used as a guide to indicate where coupling effects may become important but true resistivity patterns in the field are so complex that quantitative corrections to observed frequency effects are not practical. The error introduced by assuming a uniform earth with true resistivity equal to the apparent resistivity seems small in all but extreme cases (this can be deduced from a comparison of uniform earth, and two-layer earth, calculated cases) and tables of inductive coupling effects based on the uniform earth model give a useful indication of the magnitude of coupling effects. Dr. Hallof pointed out that time domain IP work generally avoids serious coupling effects; most electrode arrays used in time domain work are analogous to a dipoledipole configuration with n = 1 (e.g. three array) and, at this separation, frequency domain IP is usually unaffected by coupling also.

Dr Hallof prefers to base his IP interpretation on 'metal factors' rather than frequency effect. He emphasised, to me, that frequency effect and resistivity are strongly interdependent and consideration of frequency effect without allowing for resistivity can be very misleading. The use of 'metal factors' is a controversial point and while most IP workers recognise some interdependence of frequency effect and resistivity, in my experience, very few are prepared to rely on 'metal factors' as heavily as Dr Hallof.

Heath Steele Mines Limited

On August 1st and 2nd I visited Heath Steele Mines Limited, New Brunswick, after an introduction by McPhar. The discovery of this mine was attributed to geophysics and the area was of considerable interest to a mining geophysicist. The geology of the area was not well known owing to a thin layer (approximately 10 ft) of glacial overburden, and geophysics had proved invaluable. Orebodies of pyrite, chalcopyrite, pyrrhotite, galena, and sphalerite occurred but structural and stratigraphic controls, if present, were not understood.

Interest in the district started with airborne e.m. anomalies. These were followed up with ground e.m. (vertical loop, dip angle) to locate the anomalies accurately and, if two frequencies were used, to estimate conductivity. Only good conductors were considered important and gravity was used to try to differentiate between dense ore minerals and graphite. Gravity anomalies over orebodies were small and, in general, difficult to interpret. Ground magnetics was also used to give additional data before drilling. I was able to discuss the history of the district with Mr. P. MacFarlane (Geophysicist), to read several old reports, and to see the field results which led to the discoveries.

IP had largely superseded the methods described above and I visited a McPhar crew that was using lightweight IP equipment (see Plate 4) near the mine. The crew was using a dipole-dipole array with 100-ft dipoles, reading n = 1,2, and 3 to detail an anomaly which had been detected earlier with 200-ft dipoles. The transmitter and receiver were set up at one electrode and leads were run out to the others. The transmitter, powered by dry cells, transmitted 0.3 and 5 c/s simultaneously. After setting switch positions for the required dipole length and separation (a and n in Plate 3) the output current was adjusted to give a predetermined potential at the receiver electrodes. Resistivity was then read directly from the transmitter switch positions and frequency effect from the receiver.

A motor generator was available to boost the transmitter power if the resistivity should become too low. The resistivity in this area was close to the low limit ($\approx$100 ohm-ft/2π, i.e. 50 ohm-metres) for dry cell operation and readings at n = 3 were sometimes omitted. As part of the field procedure, the instrument was calibrated on a standard resistor after every third reading, but variations were quite small and such frequent checks were probably not necessary.

The position of the anomaly was known approximately and this additional work was intended to improve the interpretation. A frequency effect anomaly of approximately 15% and a resistivity 'low' were detected in the expected region.

Sharpe Instruments of Canada Ltd and

Harold O. Seigel and Associates Ltd

I visited the combined headquarters of Sharpe Instruments of Canada Ltd and Harold O. Seigel and Associates Ltd in Toronto on July 14th and July 19th. I was shown over the instrument workshops, saw a variety of instruments in construction and development, and met Dr H. Seigel and Dr R. Bosschart (Geophysicists) who specialise in induced polarisation and Turam respectively. A copy of Dr Bosschart's Ph.D. thesis on Turam model tests and interpretation (Bosschart, 1964) was made available to me and has been found particularly useful both as a guide in field interpretation of Turam results and as a complement to the BMR model test program.

Sharpe Instruments of Canada Ltd.

Sharpe produce a range of electromagnetic prospecting instruments including dip angle, in-phase and out-of-phase Slingram type, and a three-frequency Turam unit. All of these instruments use two coils (approximately 18 inches in diameter and 1 inch deep) one transmitting and one receiving (except for Turam, see below) and operate on a variety of frequencies. A summary of the instruments and their characteristics is given below.

Model	Operating frequency (c/s)	Connecting Cable	Parameters measured	Comments
SE 200	1250	NO	Dip angle	Both these units use a modulated signal which is evidently easier to separate from background noise (e.g. power lines) than a normal signal.
SE 250	1000	NO	Dip angle	
SE 300	400 1600	NO	Dip angle	An attachment is available for phase measurement with the addition of a connecting cable.
SE 600	1600	YES	In-phase and out-of-phase, or real and imaginary, components.	This instrument is similar to the ABEM Slingram or E.M. Gun; it can be used without the connecting cable to make dip-angle measurements.
SE 700	200 400 800	YES	Amplitude ratio and phase difference	This instrument is a Turam type; both coils act as receivers; the transmitter is fixed to a large stationary loop or grounded cable. Only one frequency can be transmitted at a time (c.f. ABEM Turam, which transmits two frequencies simultaneously).

The DHP-3 borehole e.m. probe was another e.m. unit designed to extend the zone explored by a borehole. A transmitting loop is laid out on the surface, transmitting 2000 c/s, and the signal is picked up by one down-hole probe and one reference probe at the surface. The signals are compared and variations in amplitude and phase angle indicate the presence of conductors. It should be possible to determine the approximate direction of any conductors causing anomalies by logging the hole with different positions of the surface loop and comparing responses.

I was able also to see Mark V, Seigel IP units, Sharpe gravity meters, and MFI fluxgate magnetometers under construction. The IP unit was later inspected in the field so is not described here, the other instruments are conventional and well known. Work was in progress in the development section on an improved fluxgate magnetometer (intended eventually to read down to 100 milligammas full scale) and a modification of the MFI fluxgate for use in borehole logging.

Seigel and Associates Ltd

Dr R. Bosschart is an expert on Turam interpretation and I was able to spend some time with him. All his Turam is done with large loops (as was the case with everyone else I spoke to in USA and Canada); grounded cables are considered extremely hazardous to interpret and rarely, if ever, used. He bases his interpretation, including depth estimates, mainly on ratio and phase profiles (not real and imaginary components as some workers tend to do) and gives equal weight to both positive and negative anomalies (both his own model tests and those carried out by the BMR have shown that dip alone can determine whether an anomaly is positve or negative). Negative anomalies are relatively rare, probably because the primary field becomes tilted, away from the source, by conducting overburden and it would then be necessary for a tabular body to dip at a shallow angle towards the source in order to cause a negative anomaly. Since orebodies or conducting shears are usually steeply dipping, these negative anomalies are not often encountered.

The main difficulty in Turam interpretation appears to be the effect of strike length, which can be ignored in Slingram or E.M. Gun interpretation because most conductors are large enough to be regarded as infinite. Variations in strike length can be allowed for by reference to sets of curves constructed from model test data and a response parameter λ ($= 10^3\rho/\nu d$, where ρ = resistivity, ν = frequency, d = thickness) for thin conductors can be derived from field results. Surveys at different frequencies can give some indication of conductor thickness, corrections can then be applied so that thick conductors can be interpreted in the same way as thin ones. Further details are included in Dr Bosschart's Ph.D. thesis (Bosschart, 1964).

Dr Seigel was a pioneer in the development of induced polarisation as a prospecting method. After early experiments with frequency domain equipment he discarded this method and now works exclusively in the time domain. He denied the existence of a strong interdependence between chargeability or frequency effect and resistivity and was strongly opposed to the use of 'metal factors'. He claimed that his equipment completely avoids significant coupling effects by delaying the measuring time sufficiently after the current is switched off and avoids telluric noise by averaging over several pulses.

I saw some field results from the Pine Point area where IP has been very successful. Typical results over the Pyramid No. 1 orebody showed very pronounced chargeability anomalies (15 to 20 milliseconds or millivolt-seconds/volt, with a background of 2 milliseconds), gravity anomalies of approximately 1 milligal, barely detectable resistivity anomalies, and no recognisable Turam anomalies. The orebodies in the Pine Point area are typically flat-lying with conductivity too low for detection by electromagnetic methods. IP has been the only successful method and Seigel had several crews in the area.

The main problem facing IP in Canada seems to be the masking effect of low resistivity gravel ($\approx$100 ohm-metres), which covers the highly resistive bedrock ($\approx$10000 ohm-metres) on large areas of the Pre-cambrian Shield. In order to penetrate the bedrock it is often necessary to use very large current electrode spacings (e.g. gradient array) and to put up with the corresponding reduction in signal strength. I was not able to visit any of Seigel's field crews but I did spend some time with a Canadian Aero Mineral Survey's crew near Toronto using the same equipment.

Huntec Limited

On July 14th and August 23rd, I visited Huntec Limited, who have taken over ground and marine contract geophysics and instrument research and development from Hunting Survey Corporation and Ronka Geophysical Instruments. I visited an IP crew working near Sydney, Nova Scotia, and discussed Huntec instruments and techniques with the technical staff in their Toronto office. The visit to the field crew will be described later; Huntec instruments and techniques are outlined below.

Induced polarisation. The Huntec IP unit is a time domain instrument with 2.5 or 7.5-kilowatt power output. It measures chargeability in a conventional way by integrating an area under the decay curve; the voltage obtained, divided by the voltage during 'current on' time gives a measure of the chargeability in milliseconds. The main advantage of the Huntec instrument over other similar equipment is the remote triggering of the receiver by the transmitter current pulse. This permits the receiver to be used away from the transmitter, and, in some cases (e.g. gradient array), several receivers may be used simultaneously. The receiver automatically compensates for self-potential without bucking out and has been operated successfully under quite noisy conditions.

IP effects in core samples have been measured by Huntec using copper wires wrapped around the core to form a miniature Wenner spread. This set-up was used with a normal field IP instrument, with slight modifications to the transmitter to permit smaller currents.

Ronka Horizontal Loop e.m. Ronka Horizontal Loop e.m. units have appeared in several models. They are all similar to the Slingram or E.M. Gun used by the BMR; they have a movable transmitting coil connected by a cable to the receiving coil and measure in-phase and out-of-phase (real and imaginary) components by nulling a bridge circuit. The two latest models, at the time of my visit, were the Mark III (dual frequency, 876 and 2400 c/s) and Mark IV (single frequency, 876 c/s). Both models claim a very narrow bandwidth, which helps exclude noise. A combination of in-phase and out-of-phase data is used to give an estimate of conductivity, information which is not readily available from dip-angle observations.

Field trip. I spent several days (July 27-29) with a Huntec IP crew at the Stirling or Mindanar Mine, Nova Scotia, under Mr Ed Gregotski (Geophysicist).

The Stirling had been worked twice in the past and abandoned. Ore consisted of galena, sphalerite, and pyrite in sheared, basic volcanics near a granodiorite intrusion. Extensions to the known orebody had been sought with various geophysical methods (airborne and ground e.m., gravity, magnetic, and self-potential) without success. A McPhar crew using lightweight IP equipment had surveyed the area during the winter of 1965/66 but results were unsatisfactory, possibly owing to interference from power lines. The Huntec crew were repeating the surveyed area using a 2.5-killowatt, time domain Huntec IP unit (see Plate 5).

The survey was initially using a three-electrode array with a = 200 ft (see Plate 3). Current electrodes were stainless steel spikes and potential electrodes were porous pots. The current lead from the transmitter and infinite electrode ran past the two potential electrodes and receiver and triggering of the receiver synchronisation was boosted by clamping a transformer on to the current lead and feeding the pulse directly to the receiver. A remote triggering facility using the received ground pulse for synchronisation was available but accidental triggering by noise was reduced by the use of direct triggering.

The transmitter produced 1500-millisecond pulses, alternating in polarity, with 500-millisecond 'off times' between pulses. The receiver measured Vp (voltage during 'current on' time) and Vs (voltage during 'current off' time) as two separate operations. Vp was measured by charging a condenser for 400 milliseconds during the current pulse, then discharging it into a bridge circuit during the next pulse while a second condenser was being charged. The two condensers were discharged automatically during alternating pulses and a value of Vp was obtained by nulling the bridge.

Similarly, Vs was measured by charging the condensers for 400 milliseconds while the current was off. Chargeability was calculated from the formula

$$\text{Chargeability} = \frac{Vs}{Vp} \times 400 \text{ millisecond}$$

$$\text{Resistivity} = \frac{4\pi Vp}{I} a$$

I was given the opportunity to operate both the transmitter and the receiver. Operation was quite straightforward but readings were slower than with conventional frequency domain equipment. A background chargeability of 2 to 3 milliseconds was measured and an anomaly of approximately 28 milliseconds coincided with the known mineralisation. The anomaly was quite sharp against a constant background and readings could be repeated without difficulty. No difficulty was experienced from power line noise.

Mr. Gregotski discussed interpretation techniques with me. By applying resistivity theory to standard shapes (e.g. sphere or layered medium) which approximate to the orebody, it is possible to calculate the true chargeability from the measured apparent chargeability. Tables have been drawn up relating true chargeability to sulphide content within broad limits (e.g. Wagg and Seigel, 1963) and these limits can be narrowed in a given area when drilling results are available for comparison with chargeability measurements. In this way it is possible to predict, approximately, the sulphide content in an orebody from its associated chargeability anomaly. This procedure has been applied in Australia (e.g. McArthur River) but it is generally regarded as hazardous.

Jalander fluxgate magnetometer (Type 46-65). The Jalander fluxgate magnetometer, manufactured in Finland and distributed by Huntec, is comparable with similar instruments made by Sharpe and McPhar. It has a reading accuracy of 10 gammas, is light and convenient to use, and is reputed to have very good temperature compensation. I rotated the instrument through 360° and observed only a 20-gamma reading variation.

Hammer seismic (Model FS-3). The Huntec, model FS-3 hammer seismic unit was being calibrated in the laboratory during my visit. This instrument records on pressure sensitive paper for up to 180 milliseconds after triggering and has been used to map refractors up to 200 ft deep and reflectors up to 300 ft deep.

Future developments. Huntec have an active research department and, although a great deal of their work was confidential, I was given some information.

A new e.m. system and a new IP receiver were under development. The IP receiver will incorporate automatic compensation and direct, possibly digital, readout.

A very interesting development was an IP interpretation system, announced at the Annual Meeting of the S.E.G. in November, 1966 (Dieter Patterson, 1966). A mathematical solution was derived for a conducting body of arbitrary shape in a uniform half space in the presence of a point source of electric current. A computer program is now available to solve the resistivity and IP effects, in three dimensions, measured with any electrode array, and a library of type curves for a selection of standard shapes is being built up. The method can be used for quantitative interpretation of field results where the model (an orebody in a uniform half space) is adequate. Future work may include more complex models (e.g. the addition of a conducting overburden layer).

Kennco Explorations (Canada) Limited

I visited Kennco Explorations (Canada) Ltd. on July 18th and August 3rd and met C.J. Sullivan (President) and H. Fleming (Geophysicist). The company is wholly devoted to exploration, using geology, geochemistry, and geophysics, and I was able to visit a contract IP crew that was working for them near Timmins, Ontario.

Most of Kennco's geophysical work is done by contractors, the most popular methods being Turam (with large loops rather than grounded cables) and IP. The usual problem is to detect sulphides in fresh bedrock, covered by up to 200 ft of glacial gravel with a resistivity of approximately 100 ohm-metres. ~~The bedrock usually has a resistivity of several thousand ohm-metres~~. The bedrock usually has a resistivity of several thousand ohm-metres so that IP depth penetration is seriously affected by the surface layer. Electromagnetic coupling and clay polarisation effects have not caused problems in this environment. Kennco generally us McPhar IP crews and base interpretation largely on metal factors.

Other geophysical methods used include AFMAG, which has not been very successful. Ground AFMAG is often strongly affected by noise, and airborne AFMAG only appears useful over major structural features. Gravity and magnetic measurements are often used as a routine cover, and reflection seismic was being used during 1966 to map sedimentary horizons enclosing potash evaporites in Saskatchewan. Kennco would like to use airborne INPUT but its use in Canada is restricted by Selco, who developed the method.

An interesting project had been under way for some years in the Timmins area, Ontario. Gold had been discovered in quartz boulders in an esker and it was hoped eventually to trace its origin. Sampling along the esker had narrowed down the area containing a possible source, and aeromagnetic work revealed a magnetic 'low' in this zone. Drilling confirmed the presence of a quartz porphyry in surrounding greenstone but so far no mineralisation. The zone of interest was covered by approximately 100 ft of glacial gravel and geophysical methods were being used in an attempt to locate the gold, probably accompanied by pyrite. Turam had been tried without success and an IP crew was surveying the area with McPhar lightweight equipment. I spent August 13th and 14th in the field with the IP crew and was able to operate the instrument (Plate 6) and become familiar with it. Operation was similar to the instrument I inspected at Heath Steele Mines.

The IP crew was operating with a dipole-dipole array, using 200-ft dipoles and four dipole separations ($n = 1$ to 4). The receiver and transmitter were set up together at a current electrode and leads were run out to the other current electrode and two potential electrodes. On the first day the transmitter was powered by a battery pack but the resistivity was so low (approximately 100 ohm-ft/2π) that current drain was sufficient to warrant the use of a motor generator on the second day. There was no difficulty in transmitting sufficient current to pick up the right potential at the receiver and good steady readings were obtained. Frequency effects were approximately 1% or less. There was no noticeable increase of resistivity or frequency effect with dipole separation and it seemed likely that, even with 200-ft dipoles and $n = 4$, the masking effect of the overburden was preventing significant penetration of the bedrock.

Crone Geophysics Limited

On July 21st, I visited Crone Geophysics Ltd, a small contracting and instrument development company, near Toronto. This company has developed an e.m. reconnaissance unit using the 'shoot-back' method (Grant and West, 1965); it gives dip-angle readings that are independent of topography and transmitter-receiver separation, line cutting is unnecessary and transmitter-receiver alignment is not critical. The instrument employs two coils, without a connecting cable, each of which can act as a transmitter or receiver. In practice, two readings are taken at each station with the coils exchanging functions; the algebraic sum of the two dip angles obtained gives a reading independent of topography. The instrument can be used as a normal, vertical loop, dip-angle e.m. unit if required, but the readings would then be affected by elevation in rugged terrain.

Crone Geophysics Ltd have also developed a borehole e.m. unit, similar to the instrument made by Sharpe. A large loop is laid out on the surface and the receiver is lowered down the hole. A serious difficulty has been insulation of the down-hole cables, which are subjected to high pressure in deep boreholes. If the insulation breaks down, the down-hole signal may be shorted out or galvanic effects may be picked up and so distort the signal. The instrument was not very successful and development was discontinued before it was completely operational. I saw some field results and interpretation was apparently very complex. The method has not been widely used.

The company also manufactures a time domain IP unit, using 2-second pulses and measuring chargeability by integrating the decay voltage for 1 second. The receiver is synchronised with the transmitter by reference to the received pulse so that no connecting cable is necessary. S-P must be bucked out manually and the receiver automatically resets at zero after sampling two pulses. Wherever possible the gradient array is used and in this configuration, several receivers can be used with one transmitter.

Moreau, Woodard, and Co. Ltd

I visited Moreau, Woodard, and Co. in Toronto on July 26th and met Mr M. Moreau. Moreau, Woodard, and Co. are wholly concerned with geophysical contracting, specialising in ABEM Turam but also using McPhar lightweight IP. Mr Moreau was associated with Dr Bosschart's Turam model tests and he has specialised in Turam interpretation.

The comapny has developed a streamline field routine for rapid coverage. To avoid galvanic effects, grounded cables are never used and 4000 x 2000 ft has been selected as the most convenient and useful size for a primary loop. If the area to be surveyed is much more than 4000 ft long, several loops are used instead of one large one, which would exaggerate the response of large features (e.g. major faults or shears) The method of covering an allotted area using a series of loops (as primary sources) is outlined in Plate 7.

Interpretation of Turam results involves determination of the response parameter from the ratio of real and imaginary components, and depth from the shape of the anomaly (see Bosschart, 1964). Because of the effect of strike length on the response parameter, interpretation is usually based on a strike length of 1000 ft and corrections are applied for deviations from this. Depth estimates based on real and imaginary components (see Bosschart, 1964 or the ABEM Turam handbook) are usually accurate to within 10% provided only one conductor is present; if several conductors are present, close together, interpretation is very difficult.

The International Nickel Company of Canada Limited (INCO)

I visited INCO'S headquarters in Toronto on August 4th to meet their Chief Geophysicist, Mr Ron Taylor and to arrange visits to field crews near Timmins and their geophysical laboratories at Copper Cliff. Mr Taylor had been associated with many of INCO's early experiments in e.m. using very low frequencies (< 100 c/s); he expected low frequency anomaly characteristics to help distinguish between orebodies and conducting shears and saw possible applications in Australia.

The main targets sought by INCO are pentlandite and pyrrhotite which occur together and which result in combined e.m. and magnetic anomalies. For many years INCO ignored e.m. anomalies that were not associated with magnetic anomalies; one of these was later followed up by Texas Gulf Sulphur Co. Inc., who drilled and discovered a massive silver-copper-zinc orebody near Timmins, Ontario. This discovery caused INCO, and many others, to alter their interpretation techniques and reconsider non-magnetic anomalies.

The standard techniques employed by INCO was to start with airborne reconnaissance (e.m. and magnetic) and follow up with vertical loop e.m. on the ground, and then possibly by drilling. INCO's airborne technique was developed about 1950 and they had several successes (e.g. Heath Steele Mines, New Brunswick) before competitive airborne e.m. systems became operational. Other geophysical methods have not been used extensively by INCO, but IP was being tested and considered.

It was arranged for me to visit an experimental camp at Texmont near Timmins, an airborne e.m. crew at La Sarre, Quebec, ground e.m. follow-up near Timmins, and INCO's geophysical laboratories and operational headquarters at Copper Cliff, Ontario.

Texmont. I spent August 10th with an INCO crew at Texmont, south of Timmins, where they were experimenting with IP, S-P, and geochemistry on a pyrrhotite-pentlandite deposit. The area was rich in pyrite, and many unwanted anomalies were difficult to distinguish from the anomalies over orebodies. The crew were using a Huntec IP unit in different configurations (Wenner, gradient, and three-electrode arrays), generally triggering the reciver directly from the current lead because sudden variations in resistivity made the remote triggering unreliable. Resistivities had been measured from 100 ohm-metres to approximately 60,000 ohm-metres and chargeability anomalies were common. Some anomalies could be correlated with the nickel mineralisation but many others were probably caused by pyrite.

Self-potential measurements were made with a laboratory vacuum tube voltmeter. Anomalies similar to the IP were detected for much less time and trouble, but the magnitude of the anomalies seemed very dependent on rain. A week without rain was sufficient to reduce the magnitude of S-P anomalies markedly.

Geochemistry was being tested exhaustiviely, both soil samples and bedrock samples were taken and analysed for nickel. Pronounced anomalies had been detected but they were proving difficult to correlate.

It was suspected that drainage channels in the gravel had caused sharp lateral variations in metal content and these were difficult to analyse from the surface.

La Sarre. On August 16th, I visited an INCO airborne e.m. crew, grounded by bad weather at La Sarre, Quebec. The transmitting coils were inside the fuselage of a wooden framed Anson aircraft and the receiving coils were towed behind in a bird. A Varian proton magnetometer was mounted under one wing tip. For some time the e.m. receiver was mistaken for a magnetometer by competitors and INCO were able to operate in relative secrecy. Some historical and technical data have been included in a review by Pemberton (1962).

The INCO system used two frequencies (712 and 285 c/s in the plane at La Sarre) and two coil systems - coaxial and vertical coplanar. The received amplitude at each frequency was recorded - both signals sould respond similarly to changes in the orientation of the bird but should have different responses to conductors. The difference of the two received amplitudes was also recorded; it was less sensitive to orientation noise than either signal alone and was used in the interpretation. The ratios of this combined signal to the high frequency phase and low frequency phase (recorded separately) were used as a measure of conductivity to weight anomalies. The combined anomalies were compared with standard anomaly shapes for classification, then weighted by conductivity considerations and assigned a priority rating for follow-up work. Altitude, measured by a radio altimeter, and magnetic field were also recorded and used to weight the priority ratings. This system was still very sensitive to the orientation of the receiving coils and could not operate effectively in turbulent weather.

Vertical loop ground e.m. I spent August 17th with a ground crew that was following-up airborne e.m. anomalies near Timmins with vertical loop e.m. The airborne anomaly was located as closely as possible from its position on a photo mosaic and a large, triangular, vertical loop was set up on it and anchored to nearby trees (see Plate 8). The transmitter, a battery-powered oscillator, was switched on and commenced transmitting a pulsed 1000-c/s signal.

The receiver (see Plate 9), a small portable coil with amplifier, earphones, and clinometer, was taken 500 ft from the transmitter and traversed around a 1000-ft square with the transmitter at the centre. Dip-angle measurements were taken at approximately 100-ft intervals. All distances were measured by pacing and the transmitter loop was oriented so that its plane always approximately intersected the receiver. This orientation was not critical and, in thick undergrowth, it was sufficiently accurate to point the transmitter loop at the sound of the receiver operator's voice.

When a dip-angle anomaly or crossover was located, the transmitter was shifted to this spot and the procedure repeated. Dip angles could be read to 1° and anomalies of the order of 10° were expected over average conductors. During the day I spent with the crew, the largest anomaly detected was approximately 3° but it was considered that the main airborne anomaly had not been located.

Copper Cliff. I spent August 18th and 19th at INCO's geophysical research laboratories and field operations headquarters at Copper Cliff.

At the research laboratories I saw conventional e.m. dip-angle equipment under construction and several other instruments under development.

A borehole magnetometer (a modified version of the Sharpe MFI fluxgate) had recently been acquired and preliminary tests were under way. The sensing head of the instrument was designed to go down-hole while batteries and instrumentation stayed at the surface. The readout was a digital counter with one unit equal to 25 gammas. On its first test the instrument gave widely fluctuating readings owing to the presence of magnetite in the walls of the borehole. Plans were being made either to damp the instrument or to smooth the results to aid interpretation.

I was shown a temperature probe developed by INCO for logging structural holes in the Sudbury Basin. The probe contained batteries and associated electronics and a thermocouple sensor, enclosed in a protective cage, at the bottom. The probe had been quite successful and temperatures could be measured to a fraction of a degree.

The INCO airborne e.m. system was being modified to fit on a Twin Otter as the wooden framed Ansons were going out of service. The transmitting loops had to be mounted outside the metal skin of the Twin Otter but otherwise the original e.m. system was to be maintained. The proposed scheme was to erect a mast on top of the fuselage and string one loop between the mast and tail and the other between the mast and wingtips. The system would remain relatively sensitive to orientation noise but results would be useful.

I spent some time in the operations headquarters where airborne anomalies were interpreted and classified. In principle this was similar to the field interpretation I saw at La Sarre but final decisions on follow-up work were based on geological information and other factors affecting interest in the area. Anomalies were assigned priorities and the first six grades were transferred to photo mosaics. The first three grades were always followed-up and lower grades were left until time was available or interest in the area had increased.

The Consolidated Mining and Smelting Company of Canada Ltd (COMINCO)

I visited the Toronto office of COMINCO on August 5th and met Mr George Tikkanen, a geophysicist with the company. COMINCO used IP extensively; they owned a McPhar lightweight IP unit and contracted work out to McPhar and Huntec. Both McPhar and Huntec had worked over the same orebody at Pine Point and I was able to see a comparison of the results.

The McPhar results showed a pronounced metal factor anomaly which was later drilled and shown to coincide with the ore. Huntec used several different electrode arrays (Wenner, gradient, and three-electrode array) but failed to get chargeability anomalies as sharply defined as the McPhar results. In addition, the asymmetry of the three-electrode array apparently caused the anomaly to be laterally displaced.

The Huntec results did not include resistivity measurements, which may have been a major reason for the improved definition of the McPhar results. The dipole-dipole array used by McPhar appeared to give better depth penetration than the Wenner and three-electrode arrays used by Huntec but this may not be the case in other areas with different resistivity configurations.

Geonics Limited (Ronka)

I visited Geonics Limited in Toronto on August 5th and met their chief designer, Mr Vaino Ronka, who had previously designed several of the e.m. systems used by Huntec. The company was producing two e.m. units, the EM15 and EM16, and developing an IP system at the time of my visit.

E.M. 15. The E.M. 15 was a small, hand-held e.m. instrument consisting of two coils, 33 inches apart in a rigid frame, with associated electronics. The instrument transmitted and received a 16-kc/s signal and the magnitude and polarity of the real component of the secondary field was indicated on a meter.

The instrument was claimed to have a useful depth penetration of 30 ft and the presence or absence of magnetic material could be indicated by the polarity of the secondary field. The high operating frequency and limited depth penetration of this instrument would limit its usefulness in Australian conditions but applications have been found for it in Canada.

E.M. 16. This instrument used V.L.F. radio transmitters, with vertical antennae and horizontal fields, as a power source. Several such transmitters, operating in the 15 to 25-kc/s range, were available in Canada and USA; similar sources are available in Europe and in Australia. Plug-in modules, tuned for the selected frequencies, were used to adapt the instrument for use in different areas.

The instrument contained two receiving coils, one vertical and one horizontal, and associated electronics. The received signal was nulled by orienting the two coils independently and compensating the out-of-phase components electronically. The final result gave the in-phase and out-of-phase components of the vertical field as a percentage of the primary horizontal field.

The designer, Mr Ronka, claimed that the instrument could be used up to 2000 miles from the transmitter and had detected conductors 500 ft below the surface. The direction of the field is such that vertical bodies (striking towards the transmitter) give the best anomalies, and horizontal bodies (e.g. conducting overburden) give relatively small responses. Conducting overburden can however distort anomalies due to vertical bodies beneath it and thus affect interpretation. It is theoretically possible to estimate depth and conductivity from the shape of an anomaly; however, practical considerations may prevent accurate estimates.

Induced polarisation. Future instrument developments by Geonics include a time domain IP unit. This instrument will measure the IP effect by the slope of the decay curve five milliseconds after the current is switched off. The transmitter operates on only 300 watts but was claimed to be as sensitive as a 3000-watt instrument using conventional measuring techniques. The principle had been tested and a prototype field instrument was under construction.

6. OTTAWA

Canadian Aero Mineral Surveys Limited (C.A.M.S.)

I spent August 25th and 26th with a Canadian Aero Mineral Survey Ltd IP crew near Minden, Ontario, quite close to Toronto. On August 27th I travelled from Toronto to Ottawa and spent a week there with C.A.M.S. and the Geological Survey of Canada.

Minden. The IP crew led by geophysicists John Carson and John Irvine used Seigel 1.2-kilowatt, time domain equipment. Both geophysicists were staunch supporters of the pulse method, which they claimed was vastly superior to the variable frequency method. The conditions that prevailed over most of the Canadian Shield (glacial overburden with a resistivity of approximately 100 ohm-metres covering fresh bedrock with a resistivity of approximately 10,000 ohm-metres) made depth penetration a major problem. This problem was attacked by using large current dipoles (as in the gradient or pole-dipole arrays) in time domain methods; frequency domain methods were usually restricted to dipole-dipole arrays to avoid inductive coupling.

A gradient array was employed at Minden; progress was fast and efficient in the field and the set-up seemed ideal for rapid reconnaissance. Current electrodes (steel spikes) were set up 5400 ft apart and potential electrodes (porous pots) 200 ft apart were moved along traverses parallel with a line joining the current electrodes. Traverses were 3400 ft long, midway between the current electrodes so that potential electrodes were never closer than 1000 ft to the current spikes. Potential electrodes could be closed up to 100 ft or less if signals were sufficiently large and more detail was required. The transmitter and receiver were set up together in a tent near the centre of the area and a direct connection was used to synchronise the receiver with the transmitted pulses. Two men carrying reels of wire and maintaining telephone communication with the operator moved the potential electrodes along the traverses.

Self-potential was bucked out and the transmitter produced alternating, 1500-millisecond square pulses separated by 500-millisecond pauses. V_s was measured by integrating the received voltage for fixed time intervals during the current pauses. Normally four pulses were integrated cumulatively and the total divided by four; this automatically removed the effect of any uncompensated self-potential and reduced the effect of random noise. The transmitter was switched to continuous transmission, once in each direction, to give two measurements of V_p. The average of these two measurements was also unaffected by any residual self-potential.

Resistivity was calculated from $\rho_A = KV_p/I$ and tables of the geometrical factor K, computed for the layout described, were provided to facilitate field reduction. Chargeability was calculated from the ratio V_s/V_p.

ρ_A = apparent resistivity

V_p = potential with current on

V_s = integrated potential with current off

I = transmitted current.

During my visit, apparent resistivities were approximately 20,000 ohm-metres, typical for large areas in the Canadian Shield, and chargeabilities were very small ranging between 0.7 and 1.2 milliseconds. No anomalies were detected.

The instrument seemed rugged and reliable and readings could be repeated accurately; however, the equipment was very bulky and the necessity to keep transmitter and receiver together was a severe restriction.

<u>Ottawa</u>. August 31st was spent at C.A.M.S. headquarters in Ottawa, where Mr Arthur Rattew reviewed airborne operations and Mr Peer Norgaard discussed ground geophysics with me.

Airborne e.m. systems had been in use for some tine (Pemberton, 1962) when C.A.M.S. entered the field with a system developed by Newmont Mining Corporation. This was a helicopter-borne system using vertical coaxial coils 65 ft apart and a frequency of 390 c/s. The system measured in-phase and out-of-phase components of the horizontal field, an advance over many previous systems which only measured out-of-phase. This made conductivity estimates possible and improved the response to good conductors. The rigid framework supporting the coils on the helicopter prevented excessive, spurious, in-phase anomalies generated by changes in coil coupling (such anomalies occurred in the INCO system where the receiver was towed in a bird). The coil configuration was chosen to give maximum coupling with vertical bodies when flying perpendicular to the strike. The helicopter also carried a Gulf Mark III total field magnetometer and a scintillation counter.

This system was later fitted to a Canso (PBY) flying boat and the coil separation increased to 83 ft. The fixed wing system was faster but restricted to greater altitudes than the helicopter, otherwise the system was relatively unchanged.

The next addition to C.A.M.S.'s range was a vertical coplanar coil developed by Rio Tinto and fitted to the wingtips of a De Havilland Otter. The coils were 62 ft apart and the system operated on 320 c/s measuring in-phase and out-of-phase horizontal components. The coupling between coils was less rigid than in the Canso but, with coplanar coils, the system was less sensitive to the effects of movement. In addition to e.m. the Otter carried a total field magnetometer and scintillometer.

Finally, C.A.M.S. was licensed to use the Barringer INPUT system (Barringer Research Ltd., 1966) and all three systems were in operation during my visit. INPUT has no orientation noise, since measurements are made while the transmitter is off, and this was regarded as the most advanced airborne e.m. system of all.

In all of these systems, anomales were classified by conductivity and magnetic association as well as geometrical configuration. The continuous wave methods estimated conductivity from the ratio of in-phase and out-of-phase responses; INPUT used the rate of decay of e.m. response (from measurements in successive channels). Conductive overburden was usually marked by wide anomalies with low conductivity and graphite beds by anomalies with long strike and high conductivity, neither having magnetic associations. Sulphide orebodies were usually good conductors, with small physical dimensions and often were associated with magnetic anomalies. Geochemistry has often been used as a follow-up to investigate suspected graphite anomalies and ground e.m. has usually been necessary to locate drill targets.

The only ground method I discussed with C.A.M.S. was IP. They used exclusively time domain Seigel equipment with either gradient array or three array (See Plate 3). Gradient array was considered ideal for reconnaissance; it was fast, with good depth penetration, but could not be used to give information on depth, sulphide content, etc. The three array was the most widely used configuration and could be used to give estimates of depth and sulphide content (Seigel,1959 and 1962; Wagg and Seigel, 1963). In many areas on the Canadian Shield large electrode separations were needed with the three array to achieve sufficient depth penetration and this reduced resolution; gradient array offered possible advantages in these conditions.

Chargeabilities of 3 or 4 milliseconds, measured along stream beds or eskers, had been attributed to clay effects but these had never presented serious problems. Provided current and potential leads were kept apart, electromagnetic coupling effects had never been serious in Canada. C.A.M.S. was the only company I visited which insisted on sending out a trained geophysicist with each field crew and I think this had more influence on the quality of their results than either the instrument or method (frequency or time domain) employed.

Geological Survey of Canada (G.S.C.)

Department of Mines and Technical Surveys

I spent August 29th and 30th and September 1st and 2nd with the Geological Survey of Canada in Ottawa. The Chief Geophysicist, Mr. L. Morley, helped arrange my programme and then handed me over to Mr. L.S. Collett, in charge of a section working on electrical methods, where most of my time was spent.

Mr. Collett, and several others, had been engaged in groundwater investigations using ground resistivity, airborne INPUT, and laboratory resistivity measurements on samples. These methods had been used in the Winkler area of Manitoba where drilling results were available for comparison. The ground resistivity measurements, which took three months, detected differences in conductivity between clays, tills, sands, and gravels and outlined the aquifer with reasonable accuracy.

In order to correlate field resistivity measurements with definite lithological groups it was necessary to conduct laboratory resistivity measurements on samples. The accurate measurement of sample resistivity, without unnecessarily disturbing the sample, was a major problem, and inductive methods were being studies by Mr. Bill Scott. Eventually he hoped to extend resistivity measurements to include a complete specification of the electrical properties of samples, including IP effects, over a range of frequencies.

Airborne INPUT measurements were made over the Winkler area, flying traverses one mile apart, at 500 ft. The survey was completed in three hours. The INPUT equipment recorded on six channels and gave information on the relative conductivities encountered as well as locating actual anomalies. The results from each channel were contoured independently and compared with the ground resistivity map. The aquifer was outlined best in the first channel but subsequent channels gave additional information on conductivity. The INPUT results defined changes in lithology at least as well as ground resistivity results.

Individual decay curves were plotted from the INPUT anomalies and showed surprising deviations from the expected exponential shape. This was possibly due to the layered nature of the conductor and was being studied in more detail. Future INPUT experiments were planned, using 12 channels to obtain more detail in the decay curves and horizontal or vertical receiving coils to maximise the response to horizontal conductors.

Dr. Alex Becker and Mr. John Slankis were developing techniques for using magnetotellurics as a shallow exploration tool. The project was not very far advanced; telluric measuring devices had been constructed to operate on 8 c/s and some preliminary tests were being made.

The instruments in use consisted of two identical units (see Plate 10), each of which was connected across two earthed electrodes (steel or brass spikes) 75 to 150 ft apart. The incoming signals (generated by telluric currents) were filtered to select 8 c/s, rectified and the resulting voltage integrated and stored in a large condenser. After a fixed time interval, the potential across the condenser was a measure of the integrated electrode potential. In use, one instrument remained stationary at a base and the other was moved about. The ratio of the two readings (field/base) gave an indication of the relative resistivities. The field and base dipoles were always kept parallel and the operators maintained radio contact to synchronise measurements. Normally, two sets of readings were taken at each station with dipoles in two perpendicular directions. Without accompanying magnetic measurements, no absolute resistivites could be determined but preliminary studies were being made on the relative apparent resistivities.

I spent August 30th in the field with a crew that was making telluric measurements along a traverse perpendicular to a steeply dipping fault which separated highly resistive granite from limestone and shale with much lower resistivity. The position of the fault had been established by geological mapping and by traversing with a Ronka E.M. 16. Initially, a base was set up with two 75-ft dipoles, one parallel and one perpendicular to the traverse. The other instrument was connected to a similar pair of dipoles and moved along the traverse taking readings at regular intervals. Several readings were taken at each station, using both longitudinal and transverse dipoles, until the mean ratios of field to base were established. Nearby thunderstorm activity affected the field and base dipoles differently and caused variations in the ratios. Changes in the world-wide thunderstorm activity distribution affected the main direction of the telluric currents and caused day to day variations in the ratio profile. The traverse had been repeated on several occasions and, although the anomaly magnitude varied considerably, the general shape was retained and the fault position was easily identifiable.

Dr Becker reviewed some standard telluric current theory with me. His immediate aim was to improve the repeatability of his results from day to day. The magnitude of the resultant of the two perpendicular measurements was expected to be less dependent on the direction of the telluric currents but small irregularities were a natural consequence of using finite (75-ft) dipoles and could not be avoided. Eventually he hoped to add magnetic measurements at the same frequency and measure absolute resistivity.

The Ronka E.M. 16 had been tested by Mr John Slankis over the fault described above (using a transmitter in Maine), and also over the aquifer at Winkler (using a transmitter at Seattle) where INPUT gave good anomalies. As expected, the near-vertical fault showed up quite clearly but the horizontal aquifer at Winkler gave no recognisable anomaly.

Mr Collett was interested in studying the general, low frequency, electrical characteristics of rocks, including IP effects. Interest was stimulated by observed irregularities in the shape of IP decay curves and attempts were being made to study these characteristics in the frequency domain.

Mr Roman Ahrens was constructing equipment to inject a 10-second sine wave signal with frequency sweep from 1 to 1000 c/s. The received signal, when analysed, was intended to yield a plot of the complex transfer function of the medium for various frequencies. Experiments were planned using various media in an attempt to correlate the shape of the transfer function curves with the physical properties of the media.

While at the G.S.C., I also made brief visits to the engineering seismic group, paleomagnetic laboratory, and aeromagnetic interpretation group. Aeromagnetic work was being flown on contract over most of the Canadian Shield. Processing was handled mainly by computers and final interpretation was done in Ottawa by officers of the G.S.C. The aeromagnetic contour maps produced were used extensively by mining companies and the geological interpretation was frequently published (e.g. Kornik and Maclaren, 1966).

7. WASHINGTON

United States Geological Survey (USGS)

I spent two days, September 6 and 7, with the USGS in Washington D.C. The sections of most interest to me had been moved to Denver but I was able to visit Dr Frank Seftle who was working on nuclear activation techniques, Dr Isidore Zietz in charge of aeromagnetic interpretation, and Mr Bill Fischer in charge of remote sensing.

Nuclear activation techniques. Dr Senftle had worked with both X-ray and neutron activation. The X-rays were relatively easy to generate and the resultant fluorescence could be readily analysed and identified but the method had very little depth penetration. Neutrons, with 20 to 30 inches effective penetration, sampled a much larger volume of rock and most of his work had been devoted to neutron activation.

The main problems in the detection of elements by neutron activation were the choice of suitable reactions that resulted in measurable gamma radiation, and the provision of a sufficiently powerful neutron source of the required energy. Dr Senftle found isotopic neutron sources too weak and built a small neutron generator using the reactions $^{2}H(d,n)^{3}He$, $^{3}H(d,n)^{4}He$ which produced 3.0 and 14.5-MeV neutrons, respectively. Both reactions were used to activate silver. The $^{3}H(d,n)^{4}He$ reaction produced a much higher neutron flux then $^{2}H(d,n)^{3}He$ but the 14.5-MeV neutrons also excited aluminium, which emitted a gamma spectrum line close to that of silver and resulted in a high background. The 3-MeV neutrons were more suitable and resulted in 0.44 and 0.66 MeV gamma radiation from silver with low background from other elements.

Dr Senftle constructed a portable neutron generator and gamma detector (Senftle and Hoyte, 1966) for the in situ detection of silver using 3-MeV neutrons. The equipment was mounted on a trailer or truck tailboard so that it could be towed into position and then lowered to the ground and operated by remote control to avoid the necessity for massive shielding. After a few minutes irradiation the neutron source was shut off and replaced by the gamma detector, which began recording within a few seconds. The results could be used to give an estimate of silver in situ. Variations in density of the rock caused variations in the volume sampled and introduced errors, which limited the accuracy of these determinations.

Dr Senftle expected to extend his experiments to the detection of other elements. In particular he planned to use 14-MeV neutrons to excite gold. A more powerful neutron source would be required and, in order to separate the 0.4 MeV gammas emitted by gold from the 0.44 MeV gammas emitted by silver, it would be necessary to delay measurement until the silver activity had decreased. A suitable routine might be to irradiate the required sites one day and return and record gamma activity the following day. Mercury also appeared suitable for detection by neutron excitation and was to be investigated.

Aeromagnetics. I met Dr Isidore Zietz and discussed aeromagnetics briefly with him. The USGS did most of its own aeromagnetic work with the plane I saw in Denver; some details of its operations had already been discussed with Don Mabey and others at the Denver office.

Most flying was at an altitude of 500 ft and half-mile intervals over selected areas of interest. For example, they had studied a great circle arc across the USA from coast to coast using seismic, gravity, and aeromagnetic measurements combined with geological studies (Pakiser and Zietz, 1965). There was no plan to conduct routine aeromagnetic surveys of large areas of the USA for public release as is done in Canada and Australia despite some pressure from the American Geological Institute and the Society of Exploration Geophysicists.

Remote sensing. I met Mr Bill Fischer, head of a section working on remote sensing and using radar, infrared, visible, and ultraviolet radiation. I had no experience in this field so he gave me a broad review of their work with emphasis on infrared.

Conventional infrared photography was used in the near-infrared region where most of the detectable radiation derives from the sun. Such photographs were particularly sensitive to features like bitumen roads, rivers, or vegetation. In order to study lower temperature radiation a scanning device was used to detect wavelengths not strongly absorbed in the atmosphere, and to build up composite pictures, similar to television pictures. These pictures have been used to map temperature differences due to sources other than solar radiation, such as buried river valleys, volcanic activity, and freshwater springs (e.g. along the coast of Hawaii, see "Time Australia", November 11, 1966). Mr Fischer was confident that electrochemical action on sulphide orebodies would produce temperature differences which could be detected, under favourable circumstances (time of day, degree of cloud cover, air temperature, etc.) by this technique. He suggested that an ideal time to make such measurements might be when a thin layer of snow covered the surface, as this would minimise background variations from solar radiation.

8. DANBURY

Newmont Exploration Limited

I spent two days, September 9th and 12th, with Newmont Exploration Ltd, at Danbury, Connecticut. I was shown round by Mr George McLaughlin, an electronic engineer, who was responsible for the design and construction of most of their geophysical instruments for both field and laboratory use.

The main topics discussed were:

(1) An analogue e.m. model test laboratory.

(2) Resistivity and IP measurements of drill core samples.

(3) A pulsed ground e.m. system developed by Newmont.

(4) The Newmont time domain IP unit.

E.m. model tests. The Newmont staff at Danbury have constructed an extremely versatile e.m. model test laboratory. Two coils, whose height, orientation, and separation could be easily varied, were mounted on rails suspended from the ceiling over a wooden frame where model conductors of various sizes and attitudes could be arranged. The instrument was operated remotely from a control console. The two coils were arranged as a tranmitter and receiver but Turam scale measurements could be modelled without any major difficulties. The signal used could be either a continuous wave (with frequency variable from 100 to 50,000 c/s) or a pulsed signal with the receiver sampling at up to 5 intervals after the pulse. The coil system traversed automatically and in-phase and out-of-phase component amplitudes were plotted on a chart recorder.

The system was in operation over a simple model using 1000 c/s continuous transmission and horizontal coplanar coils (a Slingram configuration). I spent some time studying the library of normalised results from a wide variety of model cases held in the laboratory and extracted copies of simple cases for comparison with similar tests conducted by the BMR.

Resistivity and IP in core samples. Newmont had constructed an instrument for measuring the resistivity of drill cores inductively. Two large coaxial coils produced a nearly uniform field with the core sample at the centre and two small receiving coils around the core. The received signal could be used to deduce core conductivity if the magnetic susceptibility was known. No electrical contact with the core was necessary and the sample was not disturbed in any way.

IP effects in drill cores were measured by clamping the sample between two current electrodes and introducing potential electrodes at intermediate points on the core. Current electrodes were flat plates and potential electrodes were glass tubes, similar to eye droppers, filled with $CuSO_4$ solution. Rock samples were prepared by soaking in water beforehand. Measurements could be made in either the frequency domain or the time domain but Newmont preferred the latter.

Pulse e.m. A pulsed e.m. system for ground use had been developed by Newmont and tested in the field. The system used a large transmitting loop (e.g. 2000 ft square) and transmitted very large current pulses for short periods before terminating at a linear rate. Secondary induced currents were detected by a receiving coil at intervals after the cessation of the primary current.

Tests of the instrument had been made in Cyprus and results were very encouraging. The system had much greater depth penetration than conventional e.m. systems and the effect of conducting overburden could be separated from deeper conductors. A similar system, possibly with a truck-mounted transmitter, may be tested in Australia.

Field IP. Newmont had developed a time domain IP unit incorporating several advanced design features. The instrument used two-second current pulses and two-second pauses during which the decay voltage was integrated in the conventional way. In addition, an analogous area above the decay curve was integrated and recorded. The ratio of the area above the area below the decay curve is ver sensitive to changes in the shape of the curve and this parameter was being recorded in field operations to see if it gave any useful additional information. It was hoped to assist in distinguishing different types of polarisation (e.g. metallic and membrane).

The IP receiver was synchronised with the transmitter by the ground pulse, similar to the Huntec instrument, and several receivers could be used simultaneously with the one transmitter. Normally, several pulses were integrated cumulatively on the instrument and this helped to reduce errors due to random noise. Self-potential was bucked out manually and possible errors due to residual self-potential were automatically removed by integrating an even number of pulses.

9. CAMBRIDGE, MASSACHUSETTS

I spent four days, September 13th to 17th in Cambridge, Massachusetts. Most of my time was spent at Geoscience Incorporated but Dr T Cantwell arranged for me to spend some time with Dr D.W. Strangway and Professor T.R. Madden at the Massachusetts Institute of Technology (M.I.T.).

Geoscience Incorporated

During my time with Geoscience I met the president, Dr T Cantwell, a vice president, Dr K. Vozoff and Dr G. Hopkins, an electrical engineer working on instrument design and development. Topics discussed are outlined below.

Field IP equipment. The BMR has used a Geoscience frequency domain IP unit (Models 5170 and 5260) for several years and I was able to discuss some of its field limitations with Dr Hopkins. This model had been superseded by a new receiver (Model 5280) featuring phase lock circuitry for improved moise rejection. The new receiver was evidently a big improvement on the earlier model and could be operated successfully near cities or mines and during magnetic storms.

Geoscience also manufactured a time domain IP system but this was not widely used.

Magnetotellurics. There was a lot of interest in magnetotellurics at several places I visited, including Cambridge. Apart from research projects at M.I.T., both Dr Hobson and Dr Vozoff had extensive experience in magnetotellurics, and Geoscience was constructing equipment for recording electric and magnetic field fluctuations for a client.

Dr Vozoff had spent considerable time investigating the possibility of detecting IP effects in magnetotelluric measurements (e.g. it was suggested that resistivity measurements at two frequencies could be used to compute a frequency effect) and he concluded that this was not feasible. Variations in frequency result in variations in skin depth and hence apparent resistivity. Such variations are generally much larger than the expected IP effects and cannot be separated from them.

Audio frequency telluric measurements were being used as a resistivity prospecting tool by Kennecott during 1966 and good depth penetration and a natural power source were evidently proving big advantages. Although essentially still in the research stage, and frequently veiled in secrecy, there was no doubt that magnetotellurics was regarded as an important potential tool for crustal studies, petroleum exploration and, on a smaller scale, mineral exploration.

Laboratory IP and resistivity measurements. Geoscience had devised a system for measuring resistivity and IP effects in rock samples by balancing complex impedances on a bridge circuit (Geoscience, 1965). Cylindrical rock samples were set up with two flat silver-silver chloride electrodes at each end. The inner two were used as current electrodes and the outer two as potential electrodes. Elaborate precautions were taken to avoid 60-c/s pick-up.

Signals from an oscillator were injected at a series of frequencies and the potential across the rock sample was compared with that developed across a known RC circuit. From the values of R and C used to balance the bridge, impedances at various frequencies could be calculated and hence a value for frequency effect could be obtained. If the area and length of the sample was known, resistivity could be calculated.

Computed two-dimensional IP and resistivity models. Geoscience had developed a very flexible computer program for calculating resistivity and IP cross-sections across theoretical two-dimensional models. The theoretical sections could be composed of up to ten different zones, in a variety of geometrical shapes, each having a specified resistivity and frequency effect. Results were usually computed for dipole-dipole arrays but the program could also include pole-dipole arays if desired. The program had been available on hire for some time for computing particular models and, in addition, several volumes of computed cases had been produced by McPhar as a preliminary to their model test programme, but McPhar's computer program was much less flexible. The Geoscience computer program was sufficiently versatile to cope with all likely two-dimensional cases, but it could not investigate three-dimensional effects as the McPhar model test programme does.

I spent some time studying the calculated cases and a practical application is described below. The model consisted of a surface layer representing conducting overburden, one dipole width thick, overlying country rock with a resistivity ten times that of the overburden. A vertical orebody, one dipole width across, with intermediate resistivity and 25% frequency effect, extended from the top of the country rock down to infinity. Using a dipole-dipole array and surveying out to n = 4 (see Plate 3) the orebody was barely detectable.

This model was not unlike the orebody being sought by a Kennco IP crew near Timmins, Ontario during August. The Kennco crew used 200-ft dipoles, so the overburden was approximately one half dipole width (100 ft) thick but the resistivity ratio between overburden and country rock was probably approximately 1:100. The model evidence suggested that any orebody one dipole width, or less, across would be extremely difficult to detect with the field set-up used. A more exact model could easily be computed to make a better comparison. Alternative electrode arrays (e.g. pole-dipole) or 400-ft dipoles could be modelled and used as a guide for the field work. The McPhar calculated models could not duplicate this case.

Inductive coupling. I had the opportunity to discuss field problems including inductive coupling with several geophysicists at Geoscience. In general, weak signals and interference from cultural noise or telluric currents were the main difficulties limiting the application of IP. Inductive coupling was very rarely a serious difficulty and not much attention was devoted to it. Some early work had been done at M.I.T. on inductive coupling effects in scale models and I obtained a copy of a report on it (Marshall, Fahlquist, and Neves, 1957).

Massachusetts Institute of Technology

I spent several hours at M.I.T. on September 15th with Dr D Strangway and Professor T. Madden in the Department of Geology and Geophysics.

Dr Strangway was devoting most of his time to studies in paleomagnetism but had worked with Kennecott from time to time on thermal measurements (Strangway and Holmer, 1966) and magnetotellurics. The search for ore deposits using thermal measurements revealed many conflicting causes for thermal anomalies; the work had been temporarily discontinued but Dr Strangway was still hopeful that the method might prove useful. Some oxidising sulphide orebodies had been shown to generate sufficient heat for detection at or near the surface and, in favourable conditions, new orebodies should be detectable. Dr. Strangway had used audio frequency magnetotellurics as a successful prospecting tool for Kennecott during the summer of 1966. The subject was not open to discussion but work in this field was certainly continuing.

Professor Madden had worked extensively in IP during its developing years but had recently become more absorbed in pure research in magnetotellurics. Several recording stations in the area were measuring electrical and magnetic field fluctuations and transmitting them by telephone to a central lab at M.I.T. Various frequencies (up to about 8 c/s) were being analysed and studied in an attempt to explain their characteristics.

Although no longer active in IP research, Professor Madden retained an interest in its development. He thought that if any further information could be extracted from IP measurements (e.g. the attempts by Newmont and Ronka to study details of the shape of IP decay curves) it could only come from very low frequency work (the 'tail' of the time domain decay curve). This was the direction taken by Anaconda, working with extremely long pulses.

10. RECOMMENDATIONS

Induced polarisation

The BMR has used only frequency domain equipment, with a dipole-dipole array and conventional field techniques. Some limited use of other arrays may be useful in particular circumstances and I think we should experiment with them and become familiar with their use. I recommend that we purchase an additional set of IP equipment with a facility for work in the time domain. This would increase our flexibility and, although most geophysicists admit that time domain has no inherent advantage over frequency domain, in some particular field problems time domain electrode arrays can be more convenient. The same electrode arrays may not be practical in the frequency domain because of inductive coupling. Any investigations into details of the shape of IP decay curves, which may prove useful in the future, are more readily carried out in the time domain. It is not practical to recommend a particular type of equipment as new and better instruments are being developed continually.

Interpretation of IP is still based largely on experience and some relatively simple model studies. The BMR has supported, and plans to continue supporting, the McPhar model test programme; I recommend that we should also consider subscribing to the Geoscience calculated cases. The two programmes complement each other and both would prove useful.

Inductive coupling is often a major problem in low resistivity environments like most of Australia. A computer program has been developed, by the BMR to produce tables of inductive coupling effects on a uniform earth for various resistivities, frequencies, and electrode arrays. I think this work should be continued to cover other field situations that may arise, within the restriction of a uniform earth, and possibly for more complex geological situations.

Borehole IP has only been used to a limited extent and mainly in the time domain. In certain areas (e.g. Rum Jungle) it could prove a useful tool and I think we should experiment with the method. If it cannot be carried out satisfactorily with the present frequency domain equipment, this is an additional reason for the purchase of time domain equipment.

The rock testing laboratory has recently developed equipment for measuring qualitative IP effects in rock samples. Work is continuing to improve this facility and to put measurements on a quantitative basis.

Turam

Our field techniques should be modified to use large primary loops, in preference to grounded cables, wherever possible. We should benefit from the work of Bosschart and of Moreau and Woodard in our choice of loop sizes and field procedures but should conduct some tests of our own to find the optimum for our purposes. Some changes along these lines have already been made and further tests were included in the Strangways Ranges and Dobbyn surveys during 1967.

Reduction of Turam results from finite primary loops requires more complex reduction tables than for an assumed infinite cable. A computer program has been developed to produce these reduction tables for different loop sizes and coil spacings. The program remains available for any future needs.

The Turam model test programme, which is continuing in the metalliferous group, complements Dr Bosschart's work, and a study of his results is helping us to avoid unnecessary duplication.

Slingram

The Slingram model test programme at Darwin is similar to work done at several centres in the USA. Data collected from the USGS and Newmont have been forwarded to the Darwin group.

AFMAG

AFMAG has been a controversial tool for several years and its main application now appears to be as a guide to major structural features where the airborne version is particularly useful. Although tests in Australia have not been promising, the BMR is purchasing a ground instrument and will test it. The knowledge gained of the AFMAG method and experience working with audio frequency natural fields could serve as a useful introduction to magnetotellurics..

V.L.F. radio

The Ronka E.M.16 could prove useful in Australia as we have a suitable V.L.F. power source at North West Cape, WA. The method should be tested either by buying the instrument and conducting field trials or constructing our own experimental equipment from the V.L.F. receivers which may be available in the BMR on the completion of the Timor Sea Geophysical Contract Survey.

Magnetotellurics

The field of magnetotellurics is attracting a great deal of interest in the USA. The observatory group of the BMR is planning some experiments (using periods greater than one second for crustal studies) and the metalliferous group should try to extend these experiments into the higher frequencies of interest in mineral exploration.

Thermal measurements

The use of thermal measurements as a prospecting tool is still in its infancy. The engineering group of the BMR is experimenting with thermal measurements in groundwater studies and their techniques and results may prove useful in metalliferous prospecting.

Digital computing

Computers are already being used in increasing ways by most sections of the BMR. The metalliferous group has used them for calculating Turam reduction tables and IP coupling effects. Further developments will include routine checking of the reduction of field results (e.g. Turam and IP), reduction and analysis of Turam model test results, and some preliminary analysis of field results (e.g. calculation of real and imaginary Turam field components). It should also be possible to extend interpretation in e.m., gravity, magnetics, or resistivity by introducing various methods of smoothing, correlation, filtering, or trend analysis in particular problems. The use of computed, two-dimensional IP model profiles, either by developing our own program or subscribing to an established one, would improve our planning and interpretation of IP surveys.

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APPENDIX 1

TIMETABLE

Departed	Date (1966)	Arrived	Date (1966)
Canberra	13/6	San Francisco	13/6
San Francisco	19/6	Salt Lake City	19/6
Salt Lake City	28/6	Phoenix	28/6
Tucson	2/7	Salt Lake City	2/7
Salt Lake City	4/7	Denver	4/7
Denver	9/7	Toronto	10/7
Toronto	26/7	Sydney, Nova Scotia	27/7
Sydney	30/7	Moncton	30/7
Moncton	2/8	Toronto	2/8
Toronto	8/8	Timmins	8/8
Timmins	18/8	Sudbury	18/8
Sudbury	19/8	Toronto	19/8
Toronto	27/8	Ottawa	27/8
Ottawa	3/9	Washington	3/9
Washington	8/9	Danbury	8/9
Danbury	12/9	Cambridge	12/9
Cambridge	16/9	New York	16/9
New York	19/9	Canberra	21/9

APPENDIX 2

ORGANISATIONS VISITED

A.	San Francisco	University of California, Berkeley Varian Associates, Palo Alto.
B.	Salt Lake City	Anaconda, Tooele, Utah Kennecott, Salt Lake City ASARCO, Salt Lake City Heinrich's Geoexploration, Tucson
C.	Denver	USGS
D.	Toronto	Barringer McPhar Seigel Huntec Kennco Crone Moreau and Woodard INCO COMINCO Geonics
E.	Ottawa	G.S.C. C.A.M.S.
F.	Washington	USGS
G.	Danbury	Newmont
H.	Cambridge	Geoscience M.I.T.

APPENDIX 3

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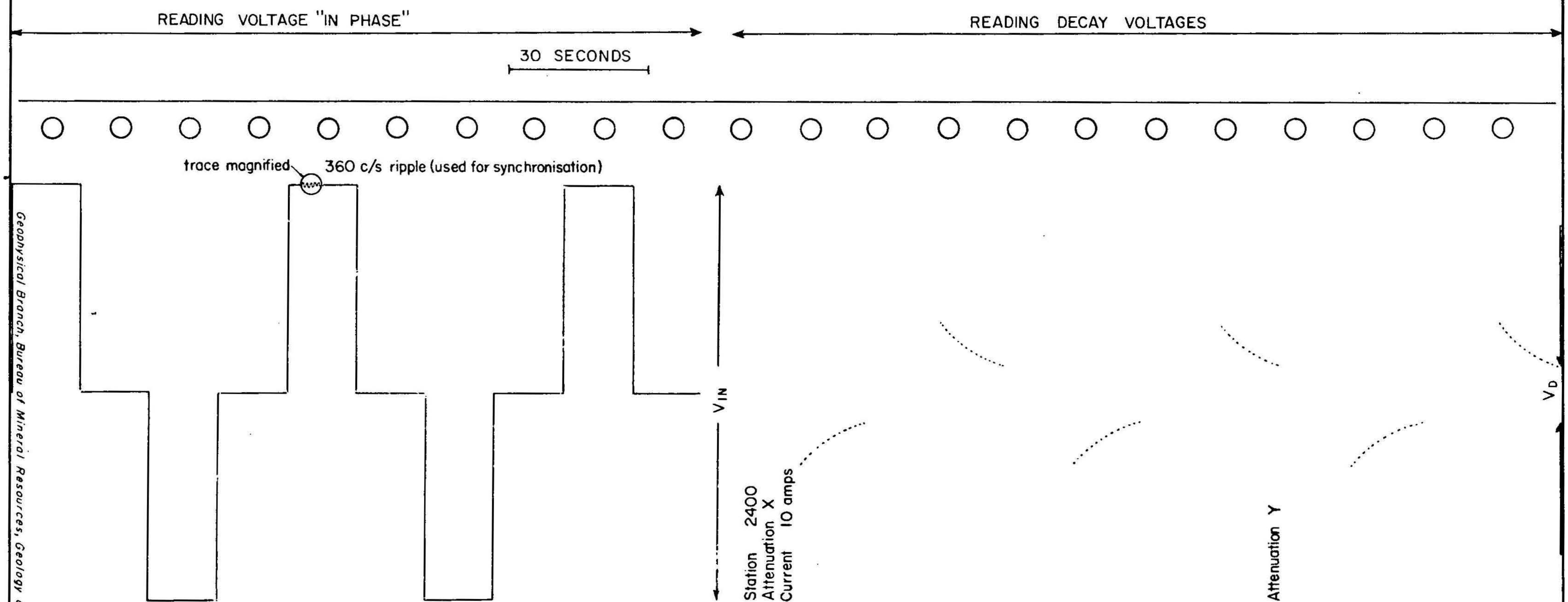
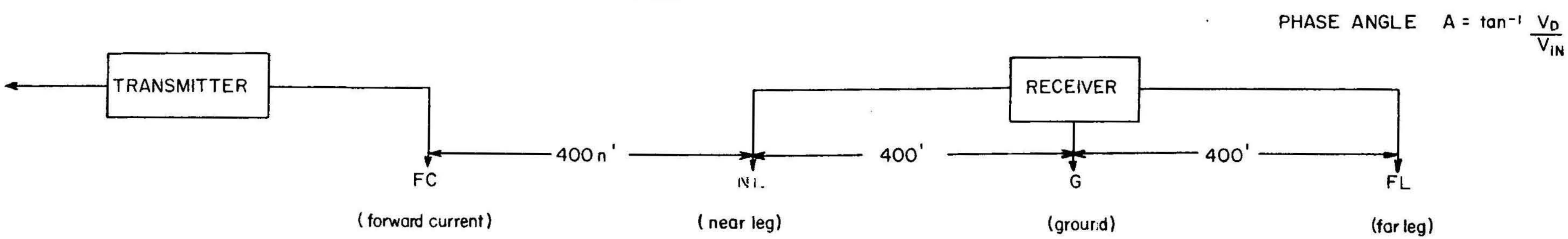
PLATE I



TYPICAL ANACONDA ULF RECORD

ANACONDA PDR ELECTRODE ARRAY



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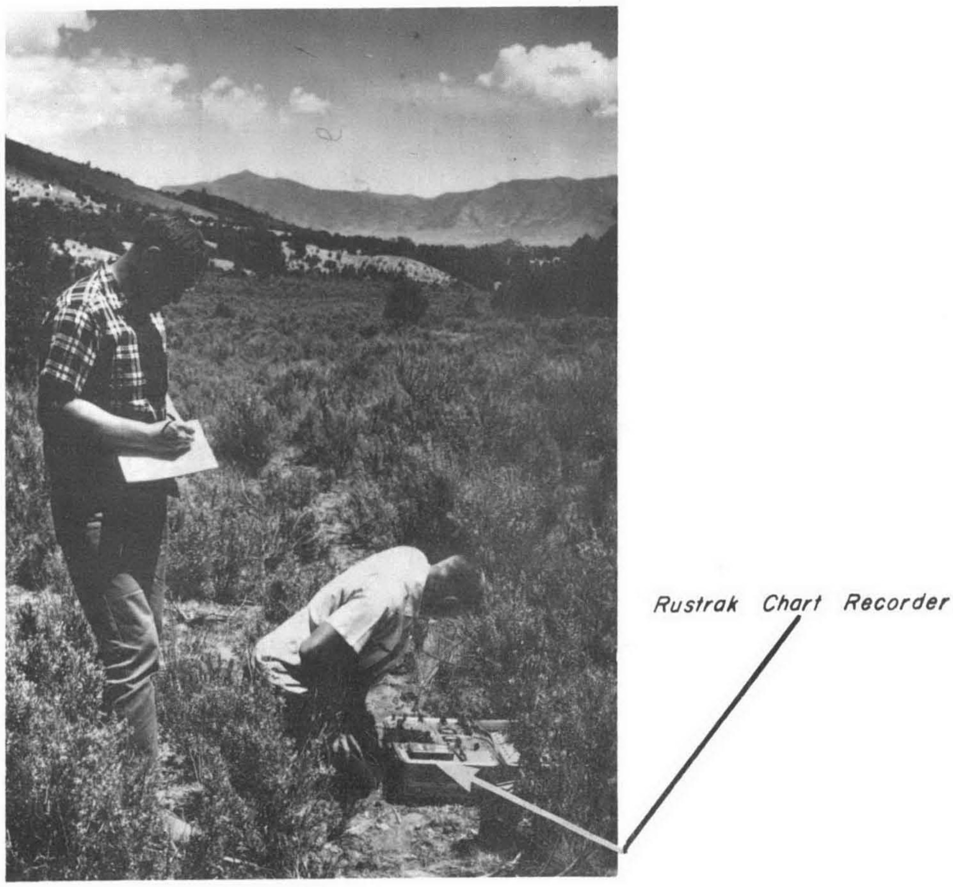
TO ACCOMPANY RECORD No. 1968/54

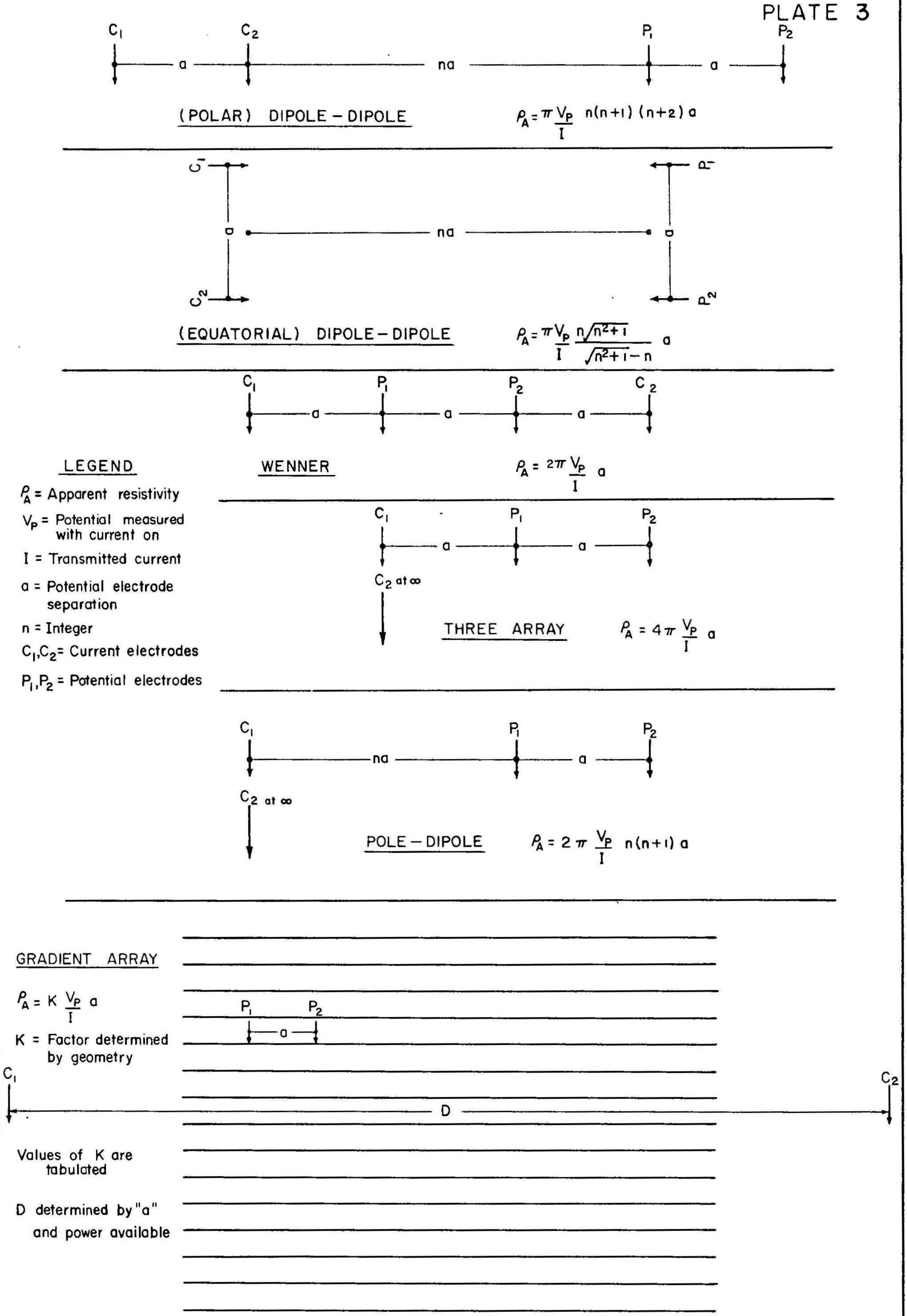
G 29—11

PLATE 2



ANACONDA U.L.F IP RECEIVER, NEVADA

PLATE 3



INDUCED POLARISATION ELECTRODE ARRAYS

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 29 — 12

TO ACCOMPANY RECORD No. 1968/54

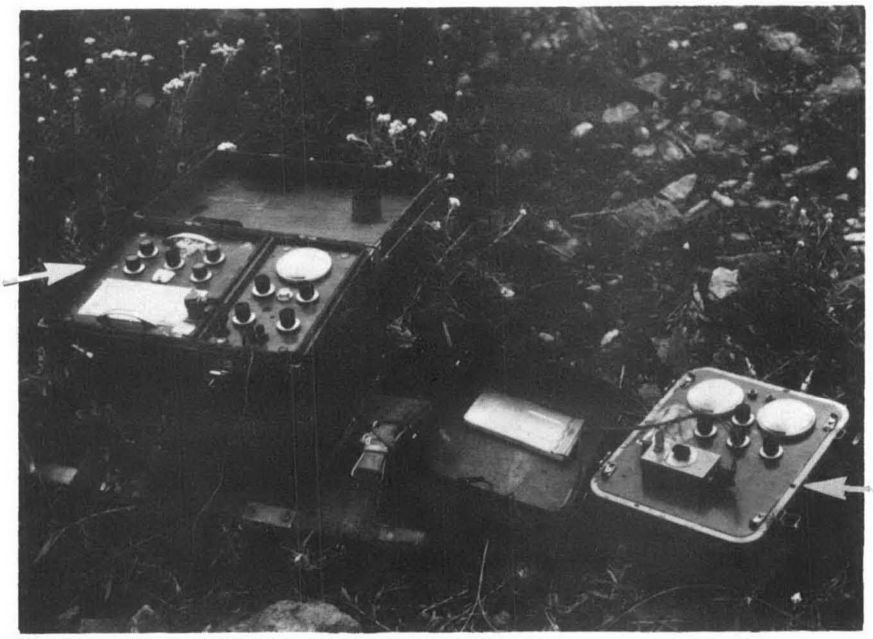


PLATE 4 Mc PHAR LIGHTWEIGHT IP UNIT

HEATH STEELE MINES, NEW BRUNSWICK

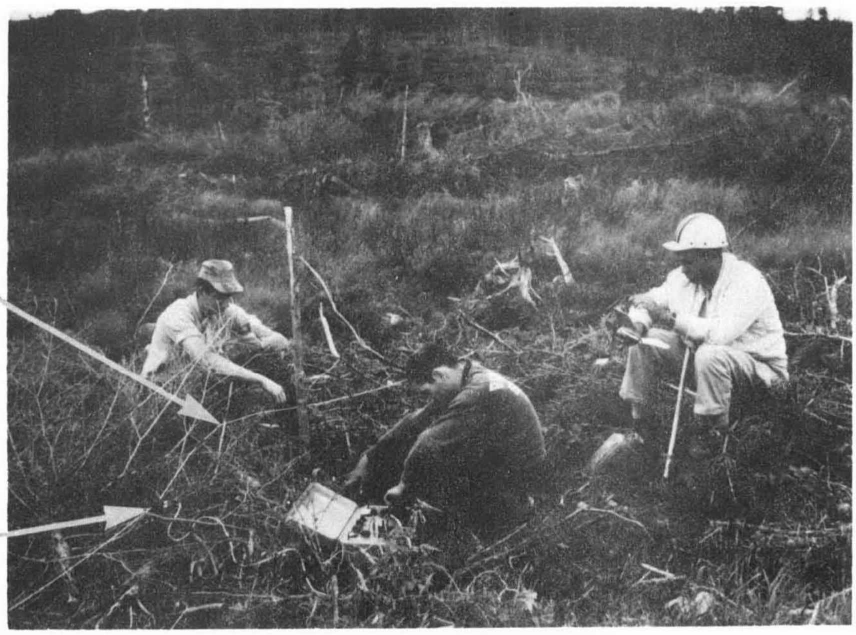
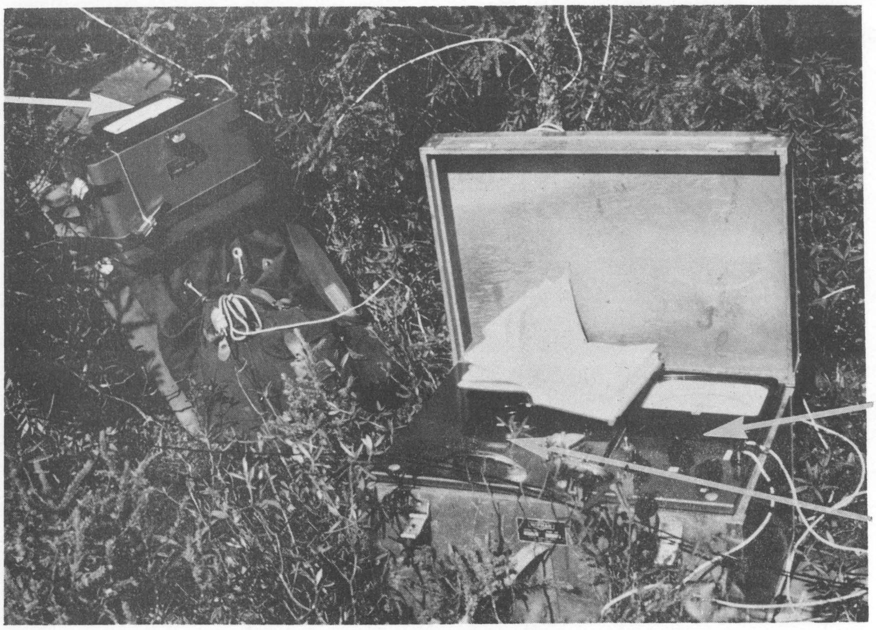


PLATE 5 HUNTEC IP RECEIVER

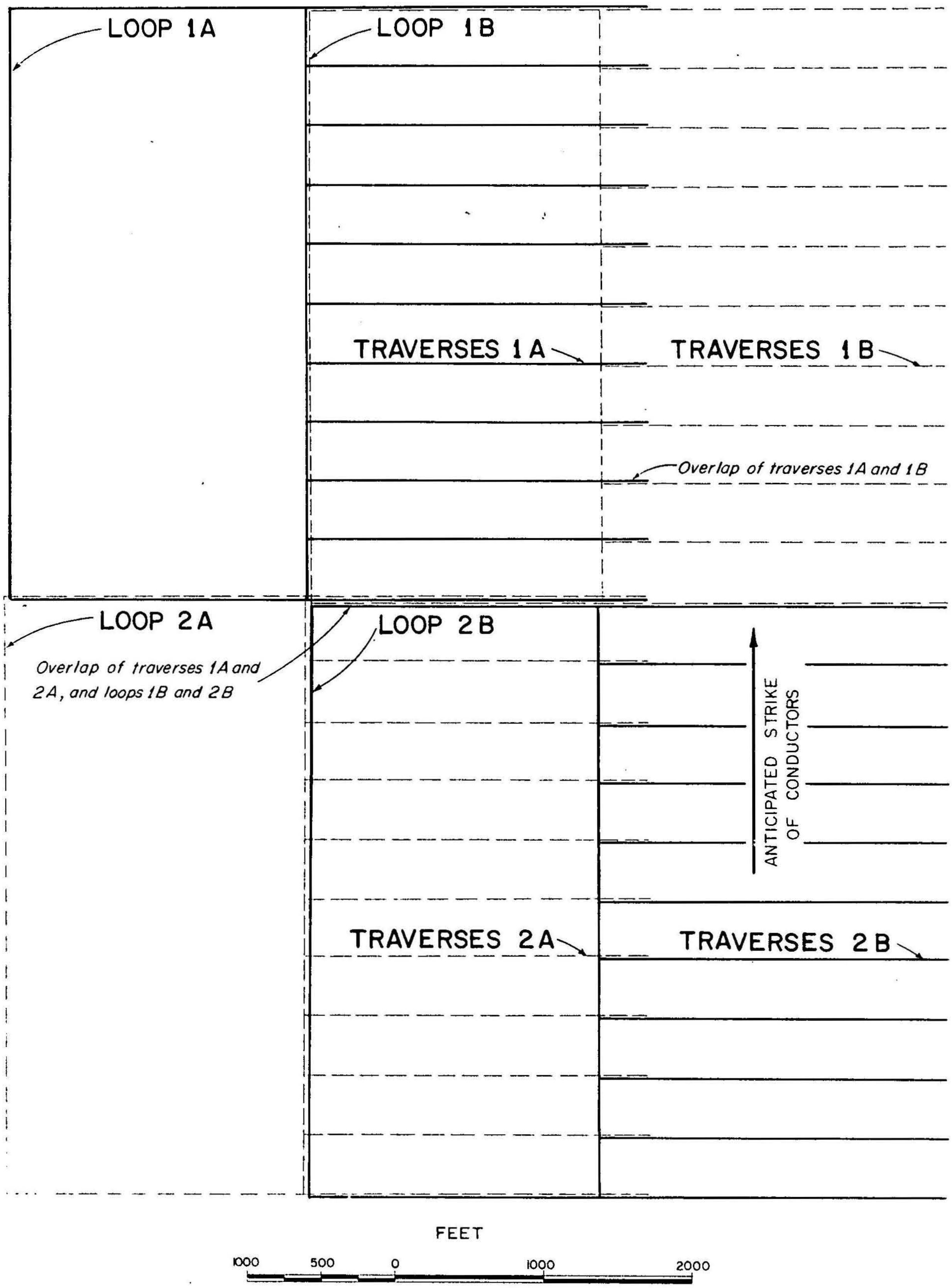
STIRLING, NOVA SCOTIA



McPHAR LIGHTWEIGHT IP UNIT

NEAR TIMMINS, ONTARIO

PLATE 7



TURAM FIELD SEQUENCE

(Used by Moreau, Woodard and Co. Ltd)

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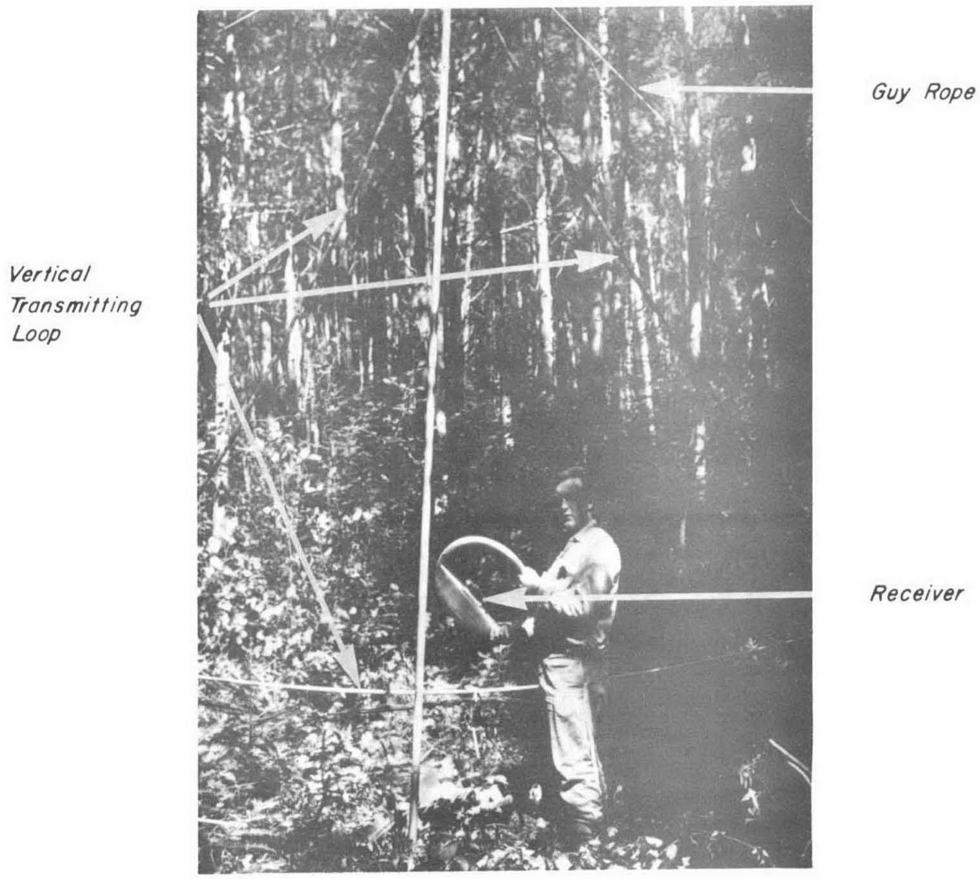


PLATE 8 INCO, VERTICAL LOOP, DIP ANGLE EM
NEAR TIMMINS, ONTARIO

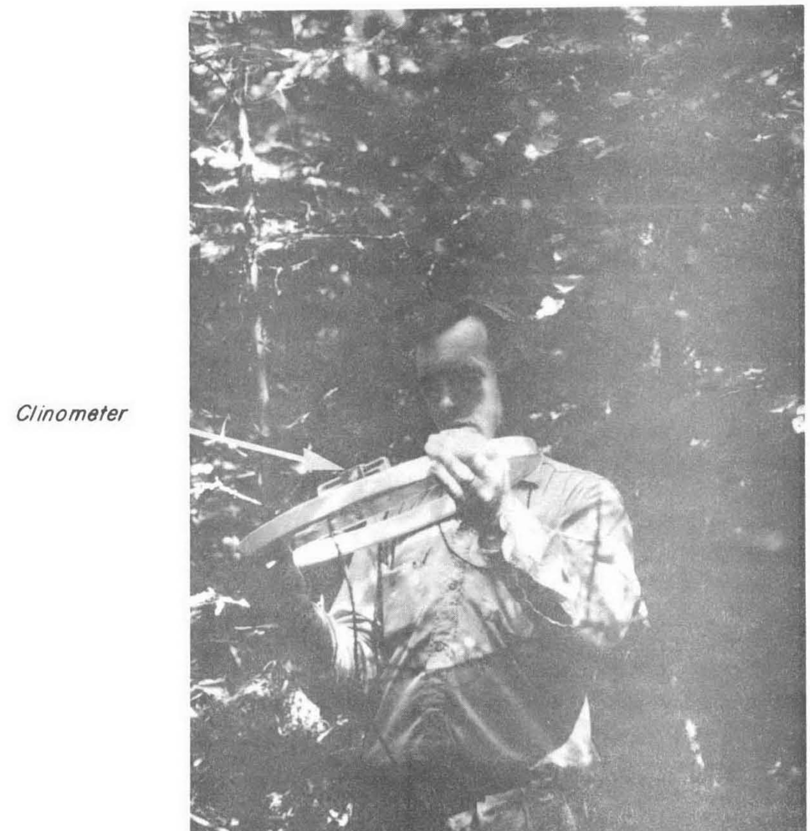
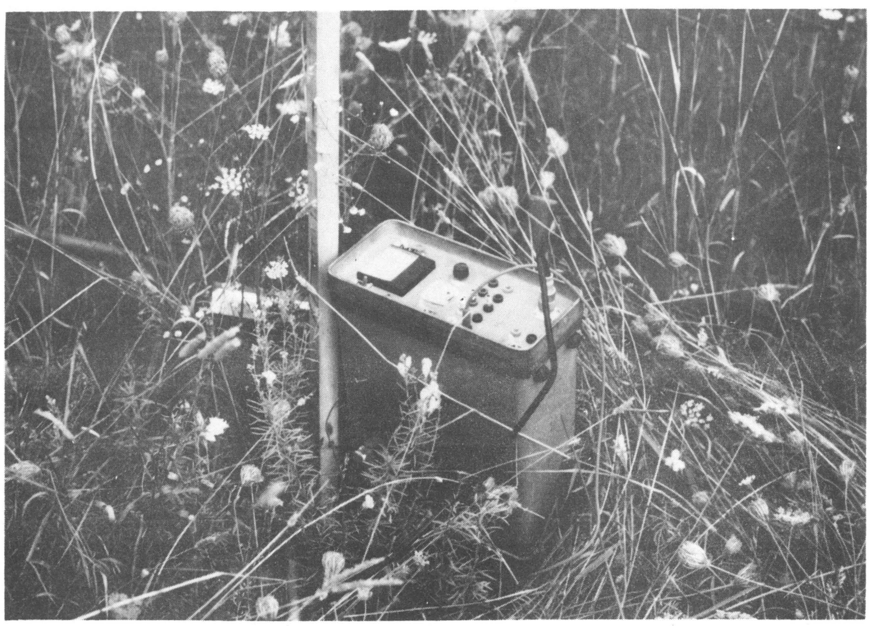


PLATE 9 VERTICAL LOOP EM RECEIVER TAKING
DIP ANGLE MEASUREMENT, NEAR TIMMINS, ONTARIO

PLATE 10



GEOLOGICAL SURVEY OF CANADA, TELLURIC FIELD RECORDER, NEAR OTTAWA, ONTARIO