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DEPARTMENT OF
NATIONAL RESOURCES

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD 1977/23

OVERSEAS VISIT TO INDIA FOR MAGNETOTELLURICS

SPONSORED BY AUST DEPT OF SCIENCE AND
GOVERNMENT OF INDIA (COMMITTEE FOR SCIENTIFIC &
INDUSTRIAL RESEARCH)

D.W. KERR

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* Copies of the figures for these lectures can be obtained from BMR.

INTRODUCTION

1.1 This report has been compiled at the conclusion of my visit to India under the India/Australian Scientific and Technological Agreement. I visited several geophysical organisation including the National Geophysical Research Institute (NGRI) between January 15 and February 26, 1977. The report is divided into several sections and appendices; these are listed on the contents page. The original proposal by Professor Vozoff (Macquarie University) for Indo/Australian co-operation in the field of magnetotelluric exploration is contained in Appendix A. The objectives of the proposed project were briefly as follows:-

(a) To train Indian geophysical and electronic personnel in the use of the Magnetotelluric (MT) method.

(b) To carry out reconnaissance MT surveys in Indian sedimentary basins.

(c) To ascertain the feasibility of MT surveys in the Himalayas.

(d) To study upper mantle conductivity in India.

1.2 I travelled to India under the first phase of the proposal in order to carry out the following:

(i) Select field areas in conjunction with NGRI, Oil and Natural Gas Commission (ONGC), and possibly the Geological Survey of India (GSI).

(ii) Lecture to NGRI, ONGC, GSI and Universities on the MT method, theory application and interpretation with emphasis on results obtained in Australian sedimentary basins.

(iii) Hold discussions with NGRI's instrumentation groups on MT instrumentation etc.

(iv) Hold discussions to ascertain the direction of future co-operative work.

A tentative suggestion for (i) above was a survey of a portion of the river plains between Delhi, Dehra Dun and Chandigarth with later extensions across the Main Boundary Fault into the Himalayan foothills.

RESULTS OF DISCUSSIONS CONCERNING FUTURE CO-OPERATION

2.1 Discussions in India fell into three general categories, these being:-

(a) those concerning future MT co-operation,

(b) those at a lower level than (a) concerning logistics, instrumentation etc.

(c) discussions related to geophysics unrelated to MT

(a) is considered here while (c) is contained in section 5 and (b) appears scattered through various sections and appendices.

2.2 Principal discussions concerning MT co-operation were between Dr Hari Narain (Director, NGRI) or Dr Sanker Narayan (Assistant Director NGRI) and myself. NGRI is very enthusiastic about MT and, in fact, the Director has for some time been wishing to start an MT section at NGRI. The impetus was provided by Professor Vozoff's discussions on MT and suggested co-operation in early 1975 and an MT group was formed at NGRI last year. This MT group in India is commencing design and construction of its own MT equipment and has competent geophysicists in Dr Sanker Narayan, Dr Sreepati Sarma and Mr Rakesh Kumar. Upon my arrival in Hyderabad it soon became evident that the original proposal of Professor Vozoff would need some modification to fit in with Indian planning and projects. Originally it was thought that NGRI would make the decision on whether or not to take up MT on a large scale at the end of the MT co-operation; however they have decided that MT is a necessary technique for their repertoire and are thus at the stage with instrumentation and data processing that we expected several years hence. I drew up a modified tentative proposal for the co-operation in MT and we used this as a basis for discussion with the various concerned groups; this proposal is essentially contained in section (3) and Appendix (B). Some of the anticipated improvements resulting from the modified proposal are as follows:

(a) BMR could not afford to be without its MT and data processing equipment (Also used in Engineering Seismic applications) for a large percentage of each of the three consecutive years mentioned in the original proposal. The modifications proposed ensure that the BMR equipment would only be in India once for a period of 6 months and as this period is from November to April would have a minimal effect upon other field activities. Most BMR field activity appears to be concentrated between late March and October. The BMR equipment would not be "on loan", being in the care of an experienced officer of the Bureau. Surveys would be carried out on a co-operative basis as has occurred in the past with Australian MT work in conjunction with Macquarie University and the South Australian Department of Mines.

(b) It may be seen that the co-operative project comes at a very good time for the Indian side - just as they are commencing to build up expertise in all facets of MT work; BMR's and Macquarie University's experience here will be of great assistance. Australia will benefit from the classic MT situation in the Deccan Traps and the unique opportunity of obtaining MT information across the Boundary Fault in the Himalayan foothills. Indian geophysicists are very strong in theoretical geomagnetic work and it appears that this co-operative MT work will pave the way in the future for Indian assistance to Australia in theoretical work; this is difficult for us due to lack of manpower.

(c) Costs in the modified proposal have been spread fairly evenly over the next 4 financial years (Appendix B) and only one major item appears against each year; this should make the Australian Department of Science's job a little easier and it will be noted that the costs have been reduced somewhat over the original estimate. Labour and transport costs for the two Indian surveys have been included in the summary of expenses for the Indian side but no inclusion for any equipment development has been made (this is in accordance with the general guidelines laid down by Department of Science). It will be seen that cost estimates are $A31 000 for India and $A33 000 for Australia, including the visit which resulted in this report.

(d) NGRI's instrumentation capability is good, although they lack availability of some components; if they follow the specifications suggested for their equipment (Appendices F and G) then the resulting equipment should prove to be better than that commercially available now from the USA (BMR equipment) or Germany. I feel that there could be interest in Australia in purchasing what would be relatively cheap, good quality equipment. A little more is said on equipment in the summary of this report (Section 7 and Appendix F).

2.3 It is Dr Narain's wish, if possible, to try and have Department of Science and DST/CSIR (Department of Science and Technology/Council for Scientific and Industrial Research) sign for a complete co-operative proposal covering the whole of Appendix (B). This is probably not as Department of Science would wish due to financial constraints etc but would make organisation very much easier for both sides. Professor Vozoff also supports this view.

PHASES 2 AND 3 OF CO-OPERATIVE MAGNETO-TELLURIC (MT) INVESTIGATIONS BETWEEN INDIA AND AUSTRALIA UNDER THE SCIENCE AND TECHNOLOGY AGREEMENT

PHASE (2) VISIT BY TWO GEOPHYSICISTS TO AUSTRALIA

3.1 The second phase of the magneto-telluric (MT) investigations conducted under the India-Australian Scientific Agreement calls for practical experience to be gained by two Indians in an Australian sedimentary basin; the experience to be gained is expected to include field work for the collection and preliminary analysis of data plus final processing and interpretation of that data. Insight will be gained into the practical aspects of MT exploration, instrumentation and all phases of analysis. The original proposal suggested that an Indian geophysicist and an electronics engineer visit Australia. Following the discussions between Mr Kerr and NGRI's MT and Instrumentation groups, it is felt that an electronics engineer would not benefit sufficiently from the visit to justify the costs involved. It is felt that two geophysicists whose interests in MT span the broad spectrum from instrumentation and field work to data processing and two-dimensional interpretation of results would be the most suitable participants in an Australian MT activity. Obviously choice of participants will depend essentially on NGRI and the extent of involvement by ONGC and/or GSI.

3.2 Discussions between Mr Kerr and the supervising geophysicist (Mr Kailasam) and the Director-General of GSI have been completed. Dr S.V.S. Sarma of NGRI and Mr Kerr have also had discussions with members of the ONGC at Dehra Dun and have been able to finalise locations for the survey sites in two Indian localities. Both GSI and ONGC are anxious to have one representative in Australia this year. I believe that, in view of the short time between now and the proposed survey starting date, it would be unwise to vary the original proposal of two people to visit Australia. Comments on visits to each of GSI and ONGC are as follows:

3.3 If it is desirable for 3 Indians to visit Australia and funds can be obtained from some other source for the third member, then no problems will be experienced in involving all concerned in the Australian activity.

(a) GSI: The supervising geophysicist was very keen that one of his people participate in the MT programme. At the present time, GSI's interest is largely academic because the types of surveys and MT equipment proposed for India will be applicable to depths between 1 km and 150 km, of which the first 2-10 km are of interest mainly in petroleum exploration. For mineral exploration, interest is normally in the shallow section of 0-1 km; this normally implies audio-frequency MT equipment in the 100 to 20 000 Hz frequency range (BMR's current equipment and NGRI's proposed system operate in the frequency range 0.00025-50 Hz). GSI has some interest in the application of MT to crustal geophysics over the whole of India. A letter from BMR was sent to the supervising geophysicist, GSI, before finalization of Mr Kerr's itinerary to inform that Dr Narain (NGRI) was organizing, co-ordinating etc, the visit. GSI's Director-General said that if it could be shown that GSI should be involved and was too late to participate in this current programme, then GSI might make available all funds necessary for the participation of one of their personnel either in this or some other programme of activity.

(b) ONGC: The supervising geophysicist (Mr T.S. Balakrishnan) reserved his decision on interest by ONGC in the proposed visit to Australia and future Indian developments in MT until after the series of MT lectures and discussions on sites and possibilities of success of the MT method in ONGC's applications. Deputy Superintending Geophysicist, Dr S.K. Chowdhury had been corresponding with Australia about MT prior to Mr Kerr's visit and had in fact asked Professor Boyd (Australia) and Dr Narain to include ONGC in the preliminary discussions on MT. At the completion of talks with the Director (Dr Talukdar) and Mr Balakrishnan, the latter decided that he would like one of his staff (Dr Verma) to come to Australia if possible for Phase 2 of the MT co-operation. Of the two areas chosen for MT field work in India, one is of commercial interest to ONGC and the other is of interest but the commercial prospects are totally unknown.

3.4 The Australian MT survey scheduled for the next financial year (1977/1978) will commence in the Canberra Area (A.C.T.) on 26/9/77 and run until approximately 18/10/77. It is suggested that the Indian geophysicists participate in the whole three weeks of the survey and remain in Canberra for one week to assist in and study data processing, presentation and one-dimensional interpretation of data. The final three weeks would be spent on two-dimensional interpretation, modelling etc, at Macquarie University, Sydney.

3.5 It is suggested that the Indian geophysicists fly to Sydney from Hyderabad (via Bombay/Perth) arriving in Sydney on Saturday 24/9/77; upon arriving at Sydney they would meet with Professor Vozoff and then fly to Canberra, hence to the survey area via road after one day rest. At the completion of the survey, the Indians would return with Mr Kerr to BMR in Canberra for a period of one week and then to Sydney with Professor Vozoff for the final three weeks, prior to their return to Hyderabad. Total estimated cost for the visit is $A3 000 - $3 400 for India (Rs. 27 000 - Rs 31 000) and $A3 000 for Australia (Rs. 27 000).

PHASE (3) FULL COMPONENT MT SURVEY IN INDIA

3.6 It is desirable that this phase of the MT project be planned now to facilitate commencement of the survey in the Australian financial year 1978/1979. This survey will be the first undertaken in the country and will give important information in two different areas; details are briefly as follows:

(a) Approximately 16 survey sites in the Saurashtra Basin (west of the commercially viable Khambhat basin) will map the thickness of mesozoic sediments between the Deccan Trap and basement. (The Deccan traps consist of resistive basaltic lava flows 300-800 metres) separated by thin (i.e., 3-10 metres) weathered layers which are conductive. The Deccan traps are covered by recent tertiary sediments which vary in thickness between a few metres and 1200 metres. The mesozoic sediments are believed to vary from zero to 1.5 km. Seismic, gravity and magnetics have so far failed to provide information about the sediments which have so far only been mappable by drilling. Examination of well logs from the area indicates that the MT method should respond well to the problem which reduces to the detection of a conductive layer sandwiched between two resistive layers and sometimes covered by conductive overburden (usually thin in the areas of interest). The ONGC has a strong interest in this basin and has commissioned a DSS (Deep Seismic Sounding) section across it. Part of the MT set of traverses will be on the DSS line. Deep crustal and depth to mantle information should be obtainable in this area.

(b) Survey sites in both the Punjab and Ganga basins were originally planned on the basis of limited information; the visit to ONGC has considerably clarified the situation as follows:

3.7 Extensive coverage of both the aforementioned basins by seismic, gravity and aeromagnetics has provided a very clear and apparently accurate picture of the stratigraphy and lithology of the basins. Commercial interest in the basins is currently zero. Pakistan has oil on its side of the Punjab basin, but this is known to occur in marine sediments which thin out and disappear before the Indian side. The strip in the foothills between Punjab/Ganga and the Himalayan tectonic zone is known to have generated hydrocarbons but the viability or extent of commercial deposits has not been established yet. The Sivalik sediments in the basins thicken considerably towards the foothills and depth to basement near Mohand (drilled) is greater than 6.5 km. Use of seismic in this area detects the top of a limestone layer on the basement but cannot resolve the basement interface. A study of well logs from the area shows that MT should resolve the limestone/basement interface as the limestone has quite a low constant resistivity of the order of 130 Ohm metres. It is hoped by the use of several MT traverses (18 sites) from the Punjab basin into the structurally disturbed area of the foothills to trace basement and possibly confirm the existence or otherwise of the Great Boundary Fault. It is also hoped to map thickness of the Sivaliks across the foothills. Seismic cannot be done in the area due to logistics problems and interpreted gravity/magnetic results are inconsistent with known geology and structure in the area. An attempt is to be made in the future to shoot a DSS traverse across the mountains. There is no knowledge of how well MT will work in the foothills and what if any information will be provided. Some preliminary modelling will give some ideas but not sufficient to allow any predictions in advance. Logistics will be moderately difficult in that short electrode distances will need to be used and topography will have to be taken into account; there appear to be sufficient flat spaces in the foothills to allow satisfactory traverse lines. This part of the survey will be unique in MT history in that all equipment will need to be man-handled into the area; for this, 25-30 men will be required to carry the presently used equipment from site to site. The success or otherwise of MT in this area will depend to a large extent on the 2 or 3 dimensionality of the structure (Strongly 3-dimensional situations may well not be interpretable). There may be economic interest for ONGC in the foothill area depending upon results. Interesting deep tectonic information should result from this survey. The survey will provide valuable information (0-80 km) necessary for the interpretation of Dr E. Lilley's (ANU-Aust Nat University) deep magnetic sounding results from the same area.

3.8 (b) and (a) above respectively provide classic test-book applications for MT in both its reconnaissance role and that of detailed mapping. The locations of the 3 or 4 sites in (b) and (a) have been decided after meetings with the ONGC. Modelling of the survey areas will possibly result in some slight variations to site location.

3.9 Australia hopes to be able to provide most of the equipment for the Indian survey together with one experienced geophysicist to supervise the field operations, field processing and field interpretation. To minimise freight costs, it is envisaged that Australia should provide the following major items. There is some doubt whether the computer & peripheral data acquisition equipment will be available.

(a) Six magnetic sensor coils, E and H pre-emplifiers, post-amplifiers, analogue chart recorder, all racks for equipment (3) and shock-mounted base plates. (Total wt. approx. 560 kg).

(b) Computer, tape-recorder, x-y plotter, A/D converter, moving head disc, thermal printer, casette recorder, 400 Hz power supply patch panel. (Total Wt. approx. 300 kg).

(c) All instrument cables, magnetic sensor cable (may not be necessary due to projected instrumentation improvements), chart paper, cadmium chloride, magnetic tapes etc. (Total wt. approx. 100-200 kg).

3.10 It is expected that India would provide the following:

(a) Two geophysicists, one electronics technician, four labourers (preferably with an interest in carrying out similar work in future years as these labourers will require some training). ONGC and maybe GSI will provide one geophysicist (to make a total of 3 or 4).

(b) One truck similar in size to the NGRI seismic truck, one truck for carrying cables, coils etc., two jeeps. If possible, the vehicles would be fitted with four-wheel drive. ONGC has verbally offered to provide jeeps for the survey.

(c) Twelve porous pots with glazed walls as used in DC resistivity and NGRI experimental telluric work. Eight cadmium electrodes with rubber stoppers.

(d) Four seismic cable winders each with 400-500 metres of plastic or rubber-coated wire. Some spare wire plus 8 x 300 metre lengths of twisted pair electrical wire.

(e) 5 KVA, 220-250 V.50 Hz. alternator with 150 m power cable; single phase is adequate and the alternator should not need to be trailer- or truck-mounted. Preferably one spare alternator if these are not designed for continuous operation.

(f) Theodolite or transit, shovels, 4"-5" auger (to 7 feet depth), spirit level, distance measuring wheel or chains/tapes, axes, saws etc.

(g) At times 25-30 bearers would be required for the porterage of equipment from site to site.

3.11 All the items provided by the Indian side would be eventually required for their own MT set-up or could easily be re-utilized in other geophysical fields. A suggested time-table for the survey would be briefly as follows:-

(a) Arrival of equipment and personnel in Hyderabad with 2 weeks checking and truck installations.

(b) 5 days travelling plus 16 sites over Deccan traps to the west Khambat Basin - 7 weeks and 5 days.

(c) 5 days to Punjab Basin.

(d) 15-18 sites in Punjab plus foot-hills - 9 weeks.

(e) 1 week, return to Hyderabad.

(f) 1½ weeks, crating of equipment, then return to Australia.

Total time = 23 weeks = 5½ months.

3.12 All estimates have been made on the basis of 6 months to allow for unforeseen contingencies.

Two or three supervisory visits would be performed by Vozoff (2), and Kerr (1); exact details would be worked out later. Approximate costs on the Australian side would be freight ($A5 000) - (It is hoped to recover freight costs from some other agency, airline etc), air fares ($A4 500 - 6 000), consumable items etc ($A500). The total would thus be about $A10 000 - 12 000 or Rs 92 000 - 110 000.

Costs to India are estimated at Rs 110 000 or $A12 000.

3.13 Processing and interpretation of data would be performed predominantly in Australia with some work being performed in India. It is hoped that the NGRI MT system would be completed 1-1½ years after the survey with Australian equipment and that the second Indian survey could be carried out with the new NGRI system which should out-perform the Australian equipment. Detailed equipment specifications are being discussed and drawn up in conjunction with NGRI. One or two Australians should participate in the second survey field work and interpretation should be a co-operative project.

3.14 Under the collaborative proposal, it is hoped that Australia may acquire some micropulsation data from the Choutupal observatory near Hyderabad and from the similar equatorial station to the south. This would be digitized, processed and interpreted in Australia and a depth section (horizontally layered) computed for the two sites; the Indian geophysicists visiting Australia in August would co-operate in this activity and it is hoped that a joint India-Australia paper could be produced. Cost of this activity is effectively zero.

LECTURES, DISCUSSIONS ETC AT VARIOUS SCIENTIFIC INSTITUTIONS

4.1 The major scientific areas visited during my stay in India were as follows:

(a) National Geophysical Research Institute - Hyderabad (NGRI)
(b) Choudupal Micropulsation Observatory - near Hyderabad (65 km)
(c) Osmania University - Hyderabad
(d) Andhra University - Waltair Visakhapatnam
(e) Geological Survey of India - Calcutta (GSI)
(f) Oil and Natural Gas Commission - Dehra Dun (ONGC)
(g) Indian Institute of Geomagnetism - Colaba, Bombay (IIG)

4.2 Most (approx. 25 days) of my time was spent at NGRI. Apart from the meetings with Drs Narain and Narayan, I had discussions with members of the MT group on fieldwork, interpretation and processing of data. We obtained as much geological and geophysical information about possible areas for application of MT. I had discussions with the Instrumentation group responsible for the design of NGRI's MT system and was able to assist them in this work. The only MT work done in India so far has been a crude semi-quantitative interpretation of 2 magnetic and 2 electric field components being continuously recorded at the Russian donated Choudupal Observatory for micropulsation data near Hyderabad. We are now hoping to obtain sets of records from this observatory and hope to be able to quantitatively construct a one-dimensional depth section beneath Choudupal and produce a joint Indo/Australian paper on the subject (see Section 3). While in Hyderabad I hoped to visit ECIL (Electronics Corporation of India Limited) to see the state of advanced electronics in the country; however complicated security precautions prevented clearance arriving in time for the visit. I spoke with many other geophysical groups at NGRI and a summary of this information is contained in Section 5. NGRI is very keen to get its MT program under way. I delivered my four lectures at NGRI for NGRI & Osmania University and these were attended by approximately 130 people. While at NGRI I met and spoke briefly with Professor Nayudama, Director-General of CSIR, about MT.

4.3 I spent one day at the Choudupal micropulsation observatory. This observatory bears a very strong resemblance to a fixed Magnetotelluric recording station; a similar station (minus any electric-field recording) is situated at Etaiyapuram near the magnetic equator. The observatory equipment was donated by USSR and uses magnetic induction coil sensors with a sensitivity of approximately 1 V/n.T.Hz - which is approximately 150 times less sensitive than the magnetometers in use at BMR for MT. All electronic amplification is performed with optical amplifiers and sensitive light beam galvanometers with clockwork mechanisms. The equipment is beautifully made and could well still be performing in 200 years time!

4.4 I visited the Centre for Exploration Geophysics at Osmania and had some brief talks about MT and related subjects; they have done some telluric work but are not particularly interested in low frequency MT, being mainly concerned with very shallow mineral exploration. Some of the Osmania people attended my lectures at NGRI.

4.5 I spent one day at Andhra University at the invitation of Professor V. Bhaskara Rao, head of the geophysics department. Andhra University is situated on the East coast of India approximately 900 km SW of calcutta; its geophysics department has supplied a very large percentage of Indian graduates now scattered over the country. I delivered my lectures at the University to staff and tertiary students (total approximately 160) and had a look at the geophysical work of the University. I spent a long time signing autographs after the lecture! I will be sending copies of my lecture notes so that MT will in future be included in the geophysics courses. I spend about 20 minutes talking to the Vice-Chancellor of the University before leaving.

4.6 My two day visit to Calcutta went well although it was a little rushed. I gave the four lectures, had discussions with Mr L.N. Kailasam and Dr Swamiji. GSI was very keen to become involved in MT and this co-operative project in particular. Mr Kailasam has one person working on MT and was talking of developing his own equipment. I pointed out to Mr Kailasam that the type of equipment we use for MT is not satisfactory for shallow mineral prospecting (audio-Frequency range) even though the principle is identical; I advised him to consult with Dr Narain before doing anything as it would be a pity for everyone to be working in different directions. I told Mr Kailasam of the work being done by Professor Vozoff of Macquarie University on natural field audio-frequency magnetotellurics. Mr Kailasam is still keen to be involved in any MT co-operation with Australia and will hopefully keep in touch with Dr Narain. I met with the Director-General of GSI and talked about MT and applicability to GSI.

4.7 I spent three days at ONGC headquaters in Dehra-Dun (Himalayan foot-hills) and during that time gave four lectures, looked at the geology and geophysics of likely test areas and took a field trip through the Himalayan foothills to ascertain what logistic problems would be involved with MT work in that area. ONGC has a keen interest in MT; in fact Dr S.K. Choudbury, Deputy Superintending Geophysicist is presenting a paper (Early March '77) recommending the use of MT in the Deccan trap area of the Saurashtra Basin. ONGC has offered computing facilities (IBM 370/145) in conjunction with the co-operative proposal between Australia and India and will assist with logistics wherever possible. If the technique works in either of the two areas specified for MT (one is a simple classical case and the other more difficult) then ONGC will take up its own MT petroleum exploration using NGRI equipment and Australian developed processing and interpretation techniques. Everything went well at ONGC and I was able to obtain well logs, etc. to help in pre-survey computer modelling. There was some difficulty with topographic maps and air photos due to the proximity to the Chinese border; any of these maps or photographs coming to Australia will need to be classified. It was decided that the sites for the second of the two MT surveys in India would be in the Assam Basin in the North East of India (East of Bangladesh).

4.8 I broke my journey home from Hyderabad to Canberra for two days at IIG in Bombay. I gave a condensed lecture (about 2½ hours) there to mainly physicists and mathematicians who are interested in electromagnetism and have some interest in the physics of the solid earth.

I had interesting discussions with Dr B.P. Singh and Miss Nandini Nityanada who are interested in deep electromagnetic sounding; we have established the possibility of co-operating on some work involving coastal and source effects using two and three dimensional numerical modelling techniques. I had discussions with the IIG instrumentation group on techniques for the measurement of small magnetic field pertuabtions.

4.9 In general, all discussions and lectures went well. Keen interest was shown not only in MT but also in geophysical inversion techniques for the interpretation of data and in advanced instrumentation and computing techniques. I was able to meet with many scientists from all over the world during my Indian visit and was pleased to note that in the field of geophysical inversion techniques (numerical) the work of Jupp and Vozoff is definitely superior to what has been done in the US, Canada, Germany, Britain or USSR.

INFORMATION ABOUT INDIAN SCIENTIFIC ACTIVITIES OTHER THAN MT

5.1 I was impressed by the quantity and quality of work being performed at NGRI. Some of the items which I found of interest were as follows:

(a) Airborne Rubidium vapour (RV) and Electromagnetic (EM) prospecting equipment

(b) Deep seismic sounding (DSS) equipment and results for Crustal studies

(c) Hydrogeological modelling both analogue and digital

(d) Theoretical geophysics and electromagnetic laboratory modelling

(e) General indigenous electronic equipment

(f) Heat flow work

5.2 The NGRI aeromagnetic system is well thought out with an indigenously built RV magnetometer having a noise level while flying of ±0.25 nT. The NGRI also fly a radiometric system and pulse transient electromagnetic system; this latter system (NGRI design and built) operates concurrently with the RV magnetometer by the use of neutralising coils which locally neutralise the transient fields at the RV cell. The airborne EM system uses normalisation and time integration of the transient signals to enhance the difference between good and poor superficial conductors and looks to be impressive as a routine prospecting tool. The system is continuously being improved as a result of analogue model studies in the laboratory. While on the topic of aeromagnetic measurements, I was interested to note that NGRI is employing quite advanced techniques for the interpretation of magnetic data. NGRI is using two and three dimensional techniques for the inversion of magnetic data; the work being done is very similar to the work being carried out in USA and Germany. I had some interesting talks with Professor Hahn of the Federal Geological Survey of Germany about his work in magnetics. The German/US inversion techniques are not as sophisticated as those employed by Vozoff in MT but appear more advanced than anything that is happening currently in Australia. The Germans, according to Professor Hahn, are using magnetotellurics extensively in conjunction with magnetic data.

The NGRI uses a German donated ANA (atomic navigation array) system for aircraft positioning and radar altimeter system for height measurement in its aircraft. I learnt from Professor Hahn that the French have perfected the chemical polarisation technique for providing continuous precession signals in proton magnetometer applications.

5.3 NGRI has been using DSS techniques successfully for several years now. Basically DSS consists of shallow angle seismic reflection with the use of medium sized charges (50 - 150 kg) and sensitive modified geophones. The depth range obtained is from 2 km to 50 km at costs per line km which are lower than conventional seismic. DSS is now being used for reconnaissance over difficult areas such as basaltic flows and over large lateral distances up to 600 km. The equipment was donated to India by USSR and it is hoped to place some MT sites along DSS profiles for comparison of the two techniques.

5.4 The location and management of water resources in India is one of the largest problems facing India today, consequently much effort is expended on EM and DC resistivity work for the location of groundwater. NGRI carries out a lot of the groundwater search work and is now performing the equally important task of modelling the supply and usage of water in groundwater systems throughout the country. Modelling is currently being carried out on a large indigenously made analogue system with several thousand nodes. Resistors, capacitors and inductors are used in networks with DC supplies and signal generators to simulate static and dynamic cases in aquifer systems. A PDP 11 computer with two moving head discs, tape drives, printer etc has been purchased to assist in both analogue and digital modelling programs. Considerable success has been achieved in the experiments in prediction of well levels, flow rates, recharge etc.

5.5 NGRI has a very impressive theoretical geophysics group (of approximately 12 people) which carries out analytic computations for plane and non-plane wave electromagnetic techniques in the earth. Work is being carried out on both time and frequency domain techniques. A lot of analogue laboratory modelling work is carried out with the appropriate theoretical backup. Mathematical and numerical modelling is carried out by the theoretical group in all areas of geophysics and recently work has extended into the area of multi-dimensional inversion of geophysical data.

5.6 By virtue of its economy and natural resources position, India imports very little in the way of instrumentation and electronic components. I was very interested to see the high standard of indigenously constructed equipment which often displayed the result of considerable ingenuity in the surmounting of problems. Nearly all the geophysical equipment which I saw was "home made" and had been constructed in very short times at quite low costs. I feel that Australian R & D electronic laboratories would be surprised to see how much the Indians achieve in a short time with few people. I now feel confident that the NGRI will be able to build up a better than world standard MT system in a reasonably short time and would hope that it might be possible for Australia to contribute towards this project one or two items (i.e. digital cassette unit and some few electronic components, (total less than $A3 000) which are impossible to currently obtain in India. This would ensure compatibility between the NGRI and BMR MT systems and create considerable interest in what would then be a commercially very viable geophysical instrument.

5.7 NGRI has recently become active in heat-flow work with a geothermal group now numbering 5 persons. During my stay at NGRI I had many conversations with Professor Elena Lubimova who is a Russian heat-flow expert of international reputation; she was at NGRI in much the same manner as I was with MT. I was interested to hear that quite a lot of heat flow work is now being carried out in Russia and that this is now being interpreted hand in hand with the vast amount of MT data which the Russians collect. Agreement between heat flow & MT in the USSR has been very good. The NGRI heat flow group has recently published a heat flow map of India and is carrying out offshore work - mainly in conjunction with the offshore oil exploration.

5.8 Andhra University has very little money and consequently carries out mainly theoretical work in areas of gravity, magnetics and many aspects of groundwater. Most advanced work is being done in gravity and I was interested to see that a lot of the data being worked on was Australian gravity data; it was sad to see that they were using a 1938 geological map of Australia and I promised to try and obtain something a little more recent.

5.9 GSI has quite a small research group in geophysics, most of the work tends to be routine geological and geophysical field work. Principal geophysical research work is in field EM techniques where quite a lot of laboratory model work has been performed. I was presented with a beautiful set of EM model curves which I could unfortunately not fit in my baggage.

5.10 ONGC is a complete contrast to GSI in that it is an autonomous government body (GSI is a government department) whose primary task is that of oil and gas exploration and exploitation. ONGC also makes a profit thus making it a powerful organisation. ONGC is a highly efficient organisation employing 23 000 men; it concentrates primarily on exploration and exploitation.

Geophysical techniques employed are the traditional gravity, magnetics and seismics with, currently, a push for magnetotellurics. The organisational efficiency of ONGC is very good and there is a large amount of co-operation between ONGC and NGRI. ONGC currently has about 45 operational field parties - mainly seismic. It is interesting to note that ONGC has been so successful that it is doing contract oil exploration in the Persian Gulf, drilling and seismic in Iraq and drilling for gas in Tanzania.

5.11 The Indian Institute of Geomagnetism is a branch of the Indian meteorological department and runs most of India's magnetic observatories. The IIG is very old, having been established 230 years ago; I spent most of the time there talking to the people already mentioned as being concerned with physics of the solid earth. IIG is like Andhra University in that it suffers from lack of money; any work such as digitising must be done manually and I was able to assist in a small way with details of the type of automation employed in similar organisations in Australia. I had interesting discussions with Dr Singh on complex demodulation theory for spectral analysis work and we hope to be of some assistance to him by digitising some magnetic storms (this can be done in a few hours on our semi-automatic digitiser compared to 3 months for two Indians working manually). As previously mentioned, we will be undertaking some correspondence on coastal and source effects in electromagnetic techniques.

INFORMATION FOR FUTURE PATICIPANTS UNDER INDIA/AUSTRALIA AGREEMENT

6.1 I have prepared this brief section because prior to my visit under the India/Australia Scientific Agreement little was known about accommodation, expenses etc for people staying in India.

6.2 I should make it quite clear from the outset that the treatment I received in India could only be described as excellent. Accommodation at most scientific institutions is normally available in what are termed "guest houses". Provision is made for visitors who don't like the guest houses to stay in hotels. CSIR pays the accommodation expenses of the guest and the guest pays for all meals, laundry etc. The details of my visit were basically organised by NGRI and I found that this subsidiary of CSIR was far ahead of CSIR itself in arranging or organising things. CSIR

seems to be so large that confusion sometimes occurs with planning. Visitors under the I/A agreement will be given an allowance of Rs 75 per day for food, laundry and other expenses ($A8.30), Rs 15 for cigarettes and Rs 10 for "out of pocket expenses". The total per day is thus Rs 100 or $A11.
It can be seen that the allowance is sufficient to cover all meals and laundry (Rs 1-2 to wash & press a shirt, meals Rs 5 - Rs 25) whether accommodation is in a guest house or hotel. Visitors will have money left over if staying in a guest house. Guest house food is very good (except at the MEC = Mineral Exploration Corporation guest house in Calcutta). The only real difference between guest houses and hotels lies in the quality of plumbing; most guest houses have a shower (cold only) and a bucket is provided for washing and procurement of hot water. Visitors should take an adequate supply of toilet paper as the Indian Government recently issued an instruction cutting off the supply to government run guest houses. Toilet paper is often imported (e.g. from Sweden) and can be expensive and difficult to obtain. As a precaution against running short of money I took $A100 with me to India but spent very little of that.

6.3 Travel arrangements in India are good; most travel is by air with chauffeur driven cars at each end and cars can usually be made available at any time for visitors to attend official or unofficial functions, social events etc. Expenditure on travel would normally be close to zero. Baggage at airports is carried by porters at a common fee of Rs 1 per item. The optimum tip (often mandatory) is .5 to 1 Rs per item. Naturally you must have change and local currency for these items and this can be accomplished by changing a <u>small</u> (a few dollars cash) amount of currency at the airport. Taxi drivers will do their utmost to cheat you (and Indians) if you don't know exactly what route you need to follow. Fare is Rs 1-2 per km (10-20c).

6.4 Water in most places is not suitable for Australians to drink although Indians do; even Indians need a month or two to acclimatise after being away from it. It is best to drink boiled water, tea or coffee if you are not staying for an extended period as being unable to work for a week could disrupt timetables. I contracted dysentery from unboiled water and it lasted 6 days with hot and cold fevers. I found that Lomotil and other commercial preparations were useless for dysentery in my case and it was necessary to seek medical advice; this was free, courtesy of NGRI and I recovered quite quickly. I did not lose any working days over the dysentery but felt very weak and ill. A good rule in India for this type of problem is to eat only curds and rice for 3-4 days. Most guest house attendants (unlike hotels) are very accommodating with regard to meal times and content; most will cook anything the visitor can think of. My personal choice was always Indian food, usually vegetarian because of the poor meat quality. If you can stand the pace, the social life is very good with a wide range of cultural activities and many opportunities to meet scientists and their families; the personal friendliness of the people is almost overwhelming at times.

6.5 Many places in India (Power stations, all airports and airfields, museums, some scientific establishments, military areas, bridges etc) are restricted for photography. One can usually carry a camera, but if you're caught using it this will mean loss of film and possibly camera. No photographs are permitted from aeroplanes at any time. There are no restrictions on currency into India but no nett currency may be taken out.

SUMMARY

7.1 In general I consider that my visit to India was successful; I feel it achieved the aims laid down and a few others. Several interesting avenues of communication can now be opened in some old and new scientific fields; specifically the proposed co-operation in MT, if supported, will be of great mutual benefit to both sides. The NGRI, ONGC, GSI have certainly given their total support and are looking for a similar expression on our side. We hope to gain experience in some unique and classical geological areas and obtain the co-operation of several very intelligent theoretical groups in the field of theoretical modelling and interpretation work in electromagnetic prospecting techniques. The Indians have much to gain in instrumentation, general expertise and computer programs/techniques. The combination of advanced technology, high cost of labour and shortage of theoreticians in Australia nicely complements the converse situation in India. Professor Vozoff agrees in suggesting that this co-operation should continue as summarised in appendix (B).

7.2 BMR, despite staff shortages and money should have little difficulty participating with Macquarie University, NGRI and ONGC in this co-operation as the whole thing will fit in nicely with BMR's proposed program; if necessary Australian MT work could still be performed in 1979 and probably not in 1978 giving a good "breathing space" for consolidation of report and paper preparation. I would like to suggest that BMR, Department of Science or someone else considers a permanent loan, donation or similar of a digital cassette recorder ($A2500) for the Indian MT system and possibly some few electronic components ($A300) unobtainable in India regardless of the future of the co-operative proposal.

7.3 It will have been noted in Section (3) that the work proposed in MT would be of great assistance in interpretation of Dr E. Lilley's (ANU) deep geomagnetic depth sounding data in India if the Lilley project is adopted by Department of Science under the I/A agreement. Dr Narain would like CSIR to sign with Department of Science for the whole co-operative MT project as a unit and has CSIR's support for this. Professor Vozoff also supports this if the Science Minister sanctions it and finances permit.

During my stay at the various scientific institutions in India, I was able to give a good overall picture of BMR activities with special emphasis on some particular areas of personal involvement or knowledge. NGRI's Director would like BMR's Director (Mr Noakes) to visit India and look at geological and geophysical work there; I feel he would find ONGC particularly interesting.

There is a possibility of an Indian lady interested in Information in the geosciences coming to BMR some time in 1977 or 78. Mrs Laxshmi Krishnan has been recommended by NGRI to stay in Australia for 1 year to work in this and related areas; first choice was CSIRO and second choice BMR. I believe this is something to do with International Women's year and is being financed by or under the Columbo Plan. Mrs Krishnan is very intelligent and a good organiser. I imagine there will be some communication with BMR if she is likely to come.

(D. KERR)
Geophysicist - BMR

14 March 1977

APPENDIX A

Original Vozoff Magnetotelluric Project - Summary

1. Institutions: Macquarie University, BMR, NGRI
2. Objectives of the Project:
   (a) To train Indian geophysical and electronic personnel in the use of the Magnetotelluric method.
   (b) To carry out reconnaissance Magnetotelluric surveys in Indian sedimentary basins.
   (c) To ascertain the feasibility of these surveys in the Himalayas.
   (d) To study upper mantle conductivity in India.
3. Duration: 5 years (-6/80)
4. Cost Summary:

- 6/76	$ 5 000
7/76 - 6/77	$12 000
7/77 - 6/78	$27 500
7/78 - 6/79	$21 000
7/79 - 6/80	$21 700
TOTAL	$87 200

5. Benefits:

To Australia: Experience in a variety of sedimentary basins. Scientific access to a classical geophysical area

To India: Training in, and computer programs for, Magnetotelluric measurements and analysis.

Revised 5/76

MAGNETOTELLURIC INVESTIGATIONS - COMPARATIVE STUDY OF AUSTRALIAN AND INDIAN SEDIMENTARY BASINS AND AN ATTEMPT AT APPLICATION OF THE METHOD IN THE HIMALAYA

Background

Macquarie University and the BMR have for three years been jointly using the magnetotelluric (MT) method to investigate some of Australia's sedimentary basins. The MT method has clear application to some of India's sedimentary basins, as has been recognised by the NGRI. We propose to carry out reconnaissance surveys in India while training Indian scientists in the procedures.

The MT method utilises natural ultra-low frequency electromagnetic signals to help map the distribution of electrical conductivity in the subsurface. Conductivity is directly related to porosity and fluid content in upper crustal rocks, and these are in turn directly related to age and likelihood of petroleum content. It is a relatively new method which is, however, used for exploration in North America and the USSR, as well as in Australia.

We propose that Indian personnel take part in the 1976 and (early) 1977 Australian programs, in preparation for India programs beginning in the last half of 1977. A suggested venue is the portion of the river plains between Delhi, Dehra Dun, and Chandigarh. An attempt would later be made to extend this work into the structurally disturbed areas - specifically across the Main Boundary fault northwards, along the line of country being investigated geologically by Professor Talent and his accosiates.

Program

First Year (- 6/76)

2/76 - 6/76 One Indian geophysicist to participate in Australian Officer Basin Survey. He will spend six weeks in the field, and three weeks each in Canberra (data processing) and Sydney (interpretation).

Second Year (- 6/77)

10/76 - 12/76	Professor Vozoff or Mr Kerr (BMR) to select field areas in conjunction with NGRI (and possibly Oil and Natural Gas Commission). Also to lecture on the method.

Third Year (7/77 - 6/78

8/77 - 1/78	Field measurements in India, involving two Australians full time (one senior technician, one geophysicist) and three supervisory visits by Professor Vozoff or Mr Kerr.
10/77 - 6/78	One Indian geophysicist in Australia, to assist in data processing and interpretation.
6/78	Review meeting (Hyderabad)

Fourth year(7/78 - 6/79)

8/78 - 12/78	Field season as in 1977. One full time Australian, two supervisory trips.
10/78 - 3/79	One Indian geophysicist in Australia, to process and interpret results.
6/79	Review meeting (Sydney or Canberra)

Fifth year (7/79 - 6/80)

As fourth year. Review meeting (final) in Hyderabad.

BUDGET

1st year	One airfare, Hyderabad-Sydney return	$1 000	
	Travel within Australia	$1 000	
	Subsistence in Australia 3 x 1000	$3 000	
			$5 000
2nd year	One airfare, Sydney-India return	$1 000	
	Subsistence in India, 16 weeks	$1 500	
	Two airfares, India-Sydney return	$2 000	
	Subsistence in Australia, 6 x 1000	$6 000	
	Travel in Australia	$1 500	
			$12 000

3rd year	Seven return airfares, Australia-India	$7 000	
	One return airfare, India-Australia	$1 000	
	Subsistence (transient) in India, 13 weeks	$3 300	
	Subsistence in Australia, 9 x 1000	$9 000	
	Shipping	$7 200	
			$27 500
4th year	Three return airfares, Sydney-India	$3 000	
	Three return airfares, India-Sydney	$3 000	
	Subsistence in India (transient) 5 weeks	$1 300	
	Subsistence in Australia, 6 x 1000	$6 000	
	Travel in Australia	$ 500	
	Shipping	$7 200	
			$21 000
5th year	Six return airfares, Sydney-India	$6 000	
	One return airfare, India-Sydney	$1 000	
	Subsistence in Australia	$6 000	
	Subsistence in India	$1 500	
	Shipping	$7 200	
			$21 700

ASSUMPTION

1. It is assumed that the following will be provided by the Government of India:

(a) Subsistence in the field for full time and visiting Australians.

(b) All expenses in India for Indians

(c) All internal travel costs in India

(d) Proper vehicles, field supplies, communications

(e) Sufficient field assistance

2. Minicomputer and other critical items of equipment will be shipped air cargo. The remainder will go by sea.

Revised 5/76

APPENDIX B
MODIFIED COOPERATIVE PROPOSAL

PROJECT SUMMARY	INDIA RESPONSIBILITIES	AUSTRALIA RESPONSIBILITIES
First Financial Year		
Phase (1) Visit by Mr Kerr to NGRI, ONGC, GSI etc, to lecture on MT method, select field areas, discuss design etc for instrumentation	Subsistence 1 person - 6 weeks + internal travel $700 Sub.	1 air fare
	$500 Air	$1500
1976 - 77 Jan-Feb (1977)		
Phase (2) Visit by two Indian geophysicists to Australia to participate in field work, processing interpretation of data etc	2 air fares	Subsistence for 2 people for 11 weeks each
	$3000	$6200
1977/78/August-September-Oct (1977)		
Phase (3) MT Survey in India using equipment from Australia; duration 5 months; 2 or 3 supervisory visits from Australia to India	Subsistence 1 Australian 5 months	3 or 4 air fares Freight and consumables etc
	Subsistence 2 or 3 transitory visits each of approx 2 weeks, internal travel	
	$3500	$6000
		$5000 (Frt)
1978-79/November - December (1978) Jan-Feb-March (1979)		
Phase (4) 1 Indian geophysicist in Australia for 3 months working on processing and interpretation	2 air fares	Subsistence 1 Indian, 3½ months,

PROJECT SUMMARY	INDIA RESPONSIBILITIES	AUSTRALIA RESPONSIBILITIES
of Phase (3). At the completion of this, review meeting in Sydney, 2 weeks, involving project co-ordinator from Indian side.	$3000	1 Indian, 2 weeks, Internal travel. $5200
1979-80/July-Aug-Sept-Oct (1979) Phase (5) MT Survey in India using new NGRI developed MT system for 4 months - area decided at review meeting of phase (4). Supervisory visits -2. Then 1 Indian in Australia for final program development etc, on NGRI's sofware system and some processing & interpretation of data from phase (4); (duration 1 month). 1 month for one Australian in India finalising survey results from phase (4), software etc., Final review meeting between all parties in Hyderabad including 2 Australians.	Subsistence 1 Australian for 5¼ months; another Australian for 3 weeks. 1 air fare to Australia. Internal travel $5800	Total of 5 air fares Australia-India. Internal travel. Subsistence 1 Indian for 1 month $9200
1980/81/Nov-Dec (1980), Jan-Feb-Mar-Apr-May (1981) Cost of 2 Indian surveys	$14000	
	$30500	$33100
Total:	$64 000	

APPENDIX C

MR D.W. KERR'S PROGRAM AS INITIALLY PROPOSED

15/1/77	Arrival in Bombay by QF.007 at 1.40 am. Arrival in Hyderabad at 1020 am
FIRST WEEK	Rest day Discussions on Indian Geology and Geophysical work at NGRI and visit to different groups in NGRI
SECOND WEEK	Discussions with NGRI Magneto-Telluric group, covering selection of possible sites for MT studies in India, data processing etc.
THIRD WEEK	Lecture week - To give lectures on selected advanced topics in Magneto-tellurics at NGRI.
FOURTH & FIFTH WEEKS	Visits to Geological Survey of India, Calcutta and Oil and Natural Gas Commission, Dehra Dun for detailed discussions on the application of Magnetotellurics for specific problems in india; visit to some field sites.
SIXTH WEEK	Discussions at NGRI to finalize the proposed MT survey program in India.
24/2/77	Departure to Bombay by flight IC120 enroute to Sydney.

APPENDIX D

ITINERARY & PROGRAM

15/1/77 Saturday	Arrival in Bombay by QF007 at 1.40 am Arrival in Hyderabad at 2.15 pm Some discussions with NGRI staff
17/1/77 Monday to 22/1/77 Saturday	Meetings with Director NGRI, visits to various groups in NGRI, discussions with MT and instrumentation sections. Various formal and social events etc.
24/1/77 Monday to 29/1/77 Saturday	Attended opening of groundwater symposium for developing countries; meetings with H. Narain, settled itinerary

	for remainder of visit. Studied available geology and geophysics for suggested MT field areas. Worked out design specifications for instrumentation, field logistics, costs etc. Attended lecture on heat flow techniques and palaeomagnetism by visiting experts. Attended meeting on geomagnetic sounding proposal under I/A agreement. Trip to Choudupal Observatory. Met Yovanda Narain (former adviser to King Nepal, Indian minister for family planning and Prof. Nayudama, Director-General CSIR).
31/1/77 Monday to 4/2/77 Friday	Gave lectures on MT to NGRI and Osmania University. Finalised proposal for Indo-Australian collaboration. Travelled to Vizag by air, gave lectures at Andhra University.
5/2/77 Saturday	Flew to Calcutta. Lectures and discussions at GSI.
8/2/77 Tuesday	Flew to Delhi then drove by car to ONGC at Dehra Dun (1 day's drive). Met Mr Talukdar, Director of Institute Petroleum exploration and Mr T.S. Balkrishnan chief geophysicist. Selected field areas after discussions and field trip for 1 day in mountains. Gave lectures.
12/2/77 Saturday	Drove back to Delhi. Visited Taj' Mahal in Agra by train on Sunday. GSIR failed to organise accommodation and transport, for stop in Delhi.
14/2/77 Monday to 19/2/77 Saturday	Back at NGRI. Visited Centre for Exploration Geophysics at Osmania University. Met theoretical geophysics group and talked about BMR and Macquarie University activities (i.e. MT, inversion, EM etc). Examined rock mechanics section and talked to EM prospecting group. Spoke with airborne group and Professor Hahn (Germany) on aeromagnetic interpretation. Attended lecture of Professor Hahn. Prepared report for Hari Narain on MT and my visit.

21/2/77 Monday to	Explained in detail computer-processing and inversion of MT data. Final talks with instrumentation group. Gave away copies of lecture notes, papers etc. Gave some computer programs for reference. Flew to Bombay.
25/2/77 Friday to 26/2/77 Saturday	At Indian Institute Geomagnetism Bombay. Gave lectures and had discussions on spectral techniques, complex demodulation etc. Talked to instrumentation and computer specialists. Took QF008 back to Sydney.

APPENDIX E

Summaries of 4 lectures*

LECTURE 1

An introduction to the MT method, its theory and application

Introduction

1.1 The magnetotelluric method is a geophysical tool for the mapping of subsurface conductivity, using surface measurements of natural transient magnetic fields and induced electric fields. The MT technique provides minimal environmental disturbance and is a very low-cost tool for the coverage obtained. MT results can often be successfully combined with results from gravity, magnetic and DC resistivity data to provide a more complete picture of the subsurface structure than could be obtained from any one of these methods considered independently; MT results are usually more definitive than those based on gravity or magnetic data as MT provides real depths, thicknesses and resistivities, not just anomalies.

Rapid advances in all areas of the MT technique over the last three years have brought MT away from the experimental arena and placed it at the disposal of scientists for the solution of geological and geophysical problems. Major advances in interpretation made by Vozoff and Jupp of Macquarie University, Australia, now allow two dimensional computer inversion of MT data in situations which were previously interpreted with the aid of forward modelling and often non-applicable one dimensional techniques.

* Copies of the figures for these lectures can be obtained from BMR.

The magnetic field

1.2 The MT technique depends on electromagnetic energy reaching the earth's surface from two major sources. Signals with a period greater than about one second are usually due to ionospheric currents at distances of 75 km or greater. Frequencies above 1 Hz are usually produced by atmospheric electrical activity. The magnetotelluric method relies on an assumption of plane waves reaching the earth or of curved waves with a radius of curvature greater than several skin depths penetration of the earth at that frequency. These conditions occur most of the time in most sedimentary basins. In practice, in Australia, it has been found that sometimes, (albeit rarely), plane wave conditions do not occur and that this has ramifications in the processing of the MT data; more will be said of this later.

When the plane electromagnetic waves strike the earth's surface they may do so at any angle and are then reflected at an angle equal to the angle of incidence and partially refracted at the air/earth interface (fig 1). The angle of refraction will depend on the angle of incidence of the wave and the relative velocity of the wave in the air and earth; typically this velocity ratio will be many orders of magnitude, so the refracted part of the wave will propagate downwards in the earth in a vertical direction. At the point of reflection on the earth's surface, the reflected magnetic component of the wave is in-phase with the incident component, while the electric field undergoes cancellation due to phase reversal at this point. At the air/earth interface, the magnetic field is thus nearly twice its value in free-space and the electric field component is reduced by many orders of magnitude over its free-space value and may be ignored. The MT technique relies on this vertically propagating alternating magnetic field and the measurements of currents induced in a conducting medium (the earth) by that field. Penetration of the wave is determined by its frequency of oscillation and the conductivity of the medium which together cause energy loss due to eddy current effects. The ratio of induced electric to magnetic field at various frequencies is used to calculate apparent resistivity as a function of frequency. Apparent resistivity curves may then be used for the production of 1 dimensional layered models and finally, in some cases, 2 dimensional resistivity models.

* Lectures 2 and 4 were discussions for which actual notes were not prepared Copies of the figures for these lectures can be obtained from BMR.

The Telluric field

1.3 As mentioned, the alternating magnetic field in a uniform earth induces an electric or "telluric" field at 90 degrees to itself. The telluric field gives rise to currents in the earth which are related by the differential form of Ohm's law:

$$\tilde{j} = \tilde{E}/\rho \qquad \text{where } \tilde{j} = \text{current density,} \qquad \ldots 1.3.1$$

$\tilde{E}$ = electric field

ρ = resistivity

The amplitude of current and field are given by the simple relationship

$$|\tilde{E}|^2 = 5\, f\, \rho_a |\tilde{H}|^2 \qquad \text{where } f = \text{frequency} \qquad \ldots 1.3.2$$

E = electric field in mV/km

H = magnetic field in nano-Teslas

A measure of the penetration of the earth by the plane wave is given by what is known as "skin depth"; this is the depth at which field amplitude has dropped to 1/e of its surface amplitude at a particular frequency. In a uniform earth, the skin depth is given by the following expression:

$$d = \sqrt{2/\omega\mu} \quad \text{metres}$$

where d = depth

μ = permeability = permeability of air in non-magnetic rocks,

ω = angular frequency

$$\simeq \tfrac{1}{2}\sqrt{\rho/f} \text{ km} \qquad \ldots 1.3.3$$

In a uniform earth, the induced electric field will lead the magnetic field by 45 degrees.

Equation 1.3.2. may be re-written in the following form:

$$\rho_a = \frac{1}{5f} \frac{|\tilde{E}|^2}{|\tilde{H}|^2} \qquad \ldots 1.3.4$$

The magnitude of a is known as the "apparent resistivity"; one must be careful in the use of a, which is the resistivity of a uniform earth which would give the measured E/H ratio, it is not necessarily the actual earth resistivity. The ratio E to H is the earth impedance at the measurement frequency; we will denote this Z and define the following relationship in a rectangular co-ordinate system:

$$Z_{ij} = E_i/H_j \quad \text{where } i, j \text{ may be } x,y \text{ or } y,x \qquad \ldots 1.3.5$$

The MT system in different earths

1.4 In the magnetotelluric measurement system, measurements are made of three mutually perpendicular magnetic field directions on the earth's surface and two induced electric fields at right angles to the measured H directions. The reasons for measuring vertical magnetic field will be discussed later. Measurement of both E and H components ensures that complete knowledge of both magnetic and telluric fields is obtained; this is essential to the interpretation of two dimensional structures. We will now look at the different types of earth model which may be experienced.

Figure (2) shows a uniform homogeneous earth of the type we have been discussing to this point. The magnetic and telluric fields are parallel to the earth's surface at all points and it is evident that the impedance is constant in all directions. It is evident that the apparent resistivity obtained from equation 1.3.4 would be a constant and equal the true resistivity at all points in the medium.

Figure (3) shows a one dimensional layered earth model. Here it will be seen that resistivity varies only in the z (vertical) direction and is constant horizontally at any particular depth. The apparent resistivity obtained from equation 1.3.4 will be constant in all directions at any frequency and will be related to the real resistivity.

Figure (4) shows the resistivity frequency distribution that would be produced from a measurement of E and H with this model. It will be noted that the asymptotes at the ends of the curve approach the true resistivity. If the resistivity in the one dimensional case varies with direction (not distance), the medium is said to be anisotropic.

Figure (5) shows a two dimensional structure (in this case an overthrust); here the resistivity varies vertically and horizontally in one direction with distance but is constant in the third direction. If the resistivity were to vary with distance in this third direction, the model would be three dimensional. In the two dimensional case, Z will obviously vary with direction at any particular location and frequency. Apparent resistivity versus frequency curves for the two dimensional model are shown in figure (6). At the present time, the forward model for the one dimensional situation may be calculated exactly for any number of layers, the two dimensional case may be calculated approximately, although to any required accuracy, given enough time and a large enough computer. At the present time Raiche (CSIRO Australia) and Honan (USA) have produced forward three dimensional models comprising arbitrary three dimensional shapes in a layered earth. Computer inversion techniques (Vozoff and Jupp) are now available for the production of one and two dimensional models directly from the processed MT data.

The MT measurement

1.5 I will now briefly describe the techniques involved in the MT measurement; we will then go on to discuss the manner in which the MT data may be utilised.

The methods used for recording MT data depend to a large extent on the spectra of the signals being measured; typical spectra are as illustrated in figure (7). To date the most common type of magnetometer employed in the measurement of the magnetic field component is the induction coil coupled to highly sensitive electronic amplifiers. This system has advantages over other forms of flat-response magnetometers in that the response increases with frequency whereas the natural fields decrease as 1/frequency, thus giving a large improvement in dynamic range. Recently, commercially available SQUID (superconducting quantum interference device) magnetometers have become more widespread in the measurement of H fields for MT work. A disadvantage of the SQUID magnetometer is the reliance on a supply of liquid helium.

A block diagram of a typical MT recording setup is shown in figure (8); a set of 3 induction coils connected by long cables to a set of sensitive amplifiers is buried shallowly in the ground. Two pairs of electrodes are buried 500 to 1000 metres apart in lines orthogonal to the horizontal induction coils; these are connected by cable to the electric field amplifiers and measure the electric field by measuring the voltage between the electrodes. Figure (9) shows a typical induction magnetometer, and the next slides show these being placed in the ground. The E field electrodes consist of cadmium rods inserted in supersaturated cadmium chloride solution in porous pots. The porous pots are placed in contact with moist earth, usually in a hole with a covering to protect against wind and animals. Wire similar to seismic cable is used to connect the electrodes to the amplifiers. Shielding is not necessary due to the low source impedances involved. The particular arrangement described for the electrodes is necessary to protect against polarisation noise. The wire to the electrodes must be covered with sand or clods of soil every few feet to prevent induced EMFs caused by wind moving the wires. The system for recording data is a digital computer based system and is shown diagrammatically in figure (10). There are two slides now showing the actual physical appearance of the equipment. The five incoming signals (denoted Ex, Ey, Hz, Hx, Hy) are converted to a digital signal in a 14 bit analogue to digital converter and are then processed in a digital computer. The computer buffers the data and records this onto magnetic tape for later processing; it simultaneously outputs the incoming information to an analogue chart recorder for monitoring. The computer is responsible for placing time, date, location, sampling information etc onto the tape, it also reads all functional switch positions on the input amplifiers and filters; these are converted to complex transfer functions and also recorded on tape. The computer breaks up the recorded data into blocks consisting of 512, 1024, 2048, 4096 or 8192 groups of data points for ease in later processing.

Recording at an MT site is performed in specific frequency bands for reasons of dynamic range and economy of number of data points. These bands are usually as follows

0.002 - 0.025 Hz
0.01 - 0.125 Hz
0.1 - 2 Hz
1 - 25 Hz
10 - 25 Hz

with a digital sampling rate of 0.03 to 350 Hz. The sampling rate and number of points recorded determines the maximum bandwidth which may be recorded. One site would normally be occupied for a period of 2 days, during which time up to 150 bands would be recorded on tape. It is normal to process at least some of the recorded data, on-site, before moving electrodes and magnetometers. The processing and interpretation of the data is the subject of a later lecture, however some of the basic underlying theory will be presented here.

Pre-processing of MT data

1.6 MT data is recorded in the time domain for conveience, however it has been noted earlier that the impedance is a function of frequency. The data records are therefore transformed to the frequency domain by means of the fast fourier transform.

The Cooley-Tukey algorithm is used to transform the demultiplexed data bands - these bands are normally of less than or equal to 2048 points (the primary limitation being the computer core memory size). The transformed data points are corrected for the frequency response and gain characteristics of the input amplifiers and filters; as mentioned previously, the transfer function of amplifiers and filters is calculated by the computer and stored with the data at the time of data acquisition. The corrected, transformed data points are stored at the end of the MT data tape along with sets of averaged cross power spectra (10 of) and averaged auto-power spectra (5 of). Spectra are averaged to ten points per decade of frequency to improve the statistics of the transformed data.

Cross-power spectra have certain interesting properties, some of which are as follows:

let $\langle x,y \rangle$ denote the cross spectrum of x and y. If the two spectra are completely correlated (i.e. equal or constant multiples) then $\langle x,y \rangle = \{\langle x,x \rangle \langle y,y \rangle\}^{\frac{1}{2}}$. If x and y are completely uncorrelated then $\langle x,y \rangle = 0$

The ratio $\frac{\langle x,y \rangle}{\{\langle x,x \rangle \ \langle y,y \rangle\}^{\frac{1}{2}}}$ is known as the coherency of x and y

so $$\text{COH}(x,y) = \frac{\langle x,y \rangle}{\{\langle x,x \rangle \ \langle y,y \rangle\}^{\frac{1}{2}}} \qquad ...1.6.1$$

it is evident that for highly correlated signals, COH (x,y) approaches 1 and that for uncorrelated signals, COH (x,y) approaches 0. Coherencies for all possible combinations of spectra are calculated by normalising the appropriate cross power spectra. It is evident from previous discussions that high coherency would normally be expected between orthogonal E-H pairs and low coherency between all other combinations (except possibly H vertical and the other H components - this will be discussed later). Figure (11) illustrates some of these points concerning coherencies with data from an Australian sedimentary basins.

You will recall that the apparent resistivity derived for either a uniform or horizontally layered earth was:

$$Pa = \frac{1}{5f} \left| \frac{\tilde{E}}{H} \right|^2$$

this may be written in terms of auto-power spectra as:

$$Pa = \frac{1}{5f} \frac{\langle Ex, Ex \rangle}{\langle Hy, Hy \rangle} \qquad ...1.6.2$$

this is known as the scalar or Cagniard apparent resistivity and has a phase which is the phase between the E and H fields at the particular frequency of interest. In practice, one often only ever looks at Ex, Hy and Ey Hx pairs that have high coherency, i.e. $> .95$. The cagniard resistivity is of use only in the horizontally layered case; in most cases conductivity changes laterally, so that in fact each field component is composed of a component produced by the orthogonal magnetic field and a component of current diverted by the structure from the other E/H pair. This situation is described analytically by the following equations:

$$Ex = Zxy\ Hy + Zxx\ Hx \qquad ...1.6.3$$

$$Ey = Zyx\ Hx + Zyy\ Hy \qquad ...1.6.4$$

where the Z^S, E^S and H^S are generally complex. In the layered or uniform earth case Zxx = Zyy = 0 and Zxy = Zyx. If one were to use a coordinate system lined up along strike, there would be no current deflection and Zxx and Zyy would be zero; in this case one of the Z^S would be a maximum and the other a minimum. In practice, strike direction frequently varies with depth and it is not convenient to attempt to line up one's coordinate system with the geology. The Zij (complex impedances) may be solved for in several different ways but the most common is as given by the following equations:

$$Zxx = \frac{\langle Ex\ Hx^* \rangle \langle Hy\ Hy^* \rangle - \langle Ex\ Hy^* \rangle \langle Hy\ Hx^* \rangle}{\langle Hx\ Hx^* \rangle \langle Hy\ Hy^* \rangle - \langle Hx\ Hy^* \rangle \langle Hy\ Hx^* \rangle} \quad ...1.6.5$$

$$Zxy = \frac{\langle Ex\ Hx^* \rangle \langle Hx\ Hy^* \rangle - \langle Ex\ Hy^* \rangle \langle Hx\ Hx^* \rangle}{\langle Hy\ Hx^* \rangle \langle Hx\ Hy^* \rangle - \langle Hy\ Hy^* \rangle \langle Hx\ Hx^* \rangle} \quad ...1.6.6$$

$$Zyx = \frac{\langle Ey\ Hx^* \rangle \langle Hy\ Hy^* \rangle - \langle Ey\ Hy^* \rangle \langle Hy\ Hx^* \rangle}{\langle Hx\ Hx^* \rangle \langle Hy\ Hy^* \rangle - \langle Hx\ Hy^* \rangle \langle Hy\ Hx^* \rangle} \quad ...1.6.7$$

$$Zyy = \frac{\langle Ey\ Hx^* \rangle \langle Hx\ Hy^* \rangle - \langle Ey\ Hy^* \rangle \langle Hx\ Hx^* \rangle}{\langle Hy\ Hx^* \rangle \langle Hx\ Hy^* \rangle - \langle Hy\ Hx^* \rangle \langle Hx\ Hx^* \rangle} \quad ...1.6.8$$

where * denotes complex conjugate

We may then rotate these impedances into a new frame of reference; the rotation is performed for each frequency and is carried out to minimise

$$|Zxx|^2 + |Zyy|^2 \quad \text{and maximise} \quad |Zxy|^2 + |Zyx|^2$$

this will give us the true strike direction for the two dimensional case or anisotropic layered cases. As in the Cagniard case, the apparent resistivity is given by:

$$\rho_{ij} = \frac{1}{5f} |Zij|^2 \quad ...1.6.9$$

where the Zij^S are rotated. Phase of the resistivity is given by the phase of Zij. For almost all MT interpretation work, the parameters used are the two components ρ_{xy} and ρ_{yx} of rotated tensor apparent resistivity given by equation 1.6.9 with their attendant phases (i.e. phase of Zij) and the rotation angle necessary to minimise the sums of squares of $|Zxx|$ and $|Zyy|$. The criterion for acceptance of a resistivity determined from 1.6.9 is known as the "rotated E predictability" or predictability of the E field in the rotated frame of reference. Equations 1.6.3 and 1.6.4 are used to predict a value for Ex and Ey in the rotated reference frame and a coherency is calculated between this predicted component and the rotated, measured E field; this coherency is what we call the "predictability". It should be noted that the rotation angle can only be calculated to within 90^{o} and some other information is required to resolve the ambiguity.

So far I have avoided talking about the "tipping vector" or "tipper" as it is more commonly known. This is dealt with in the following section and the relevance to strike determination will be demonstrated.

Tipping vector analysis

1.7 It has been previously mentioned that MT field measurements consist fundamentally of measurement of three components of the magnetic field and the two induced horizontal electric field components. It was seen that, in either a layered or uniform earth, all fields are horizontal; the vertical magnetic field can thus be used as an indicator of 1 dimensionality. It will be seen that two and three dimensional structures cause vertical magnetic fields to be generated and that the relationship between this Hz and the horizontal fields may be used in determining whether structure is two or three dimensional and for the determination of strike direction. In situations of lateral conductivity discontinuity, much larger currents flow parallel to strike on the conductive side than on the resistive side (figure 12); the result is a "tipping" of magnetic field lines around the conductive edge. The vertical H component is correlated with the current along strike and thus the orthogonal H component which is across strike. We can see then that the horizontal component of H across strike will be highly coherent with the H vertical field.

In practice, the horizontal components are rotated to find the direction of maximum coherency in a similar manner to that used for the tensor impedance rotation. A three dimensional rotation angle calculated on the basis of a three dimensional earth is also calculated; when the two angles differ, this is evidence of a three dimensional situation. When the two and three dimensional angles are the same or similar, this angle may be used in conjunction with the tensor rotation angle to produce a definitive strike direction. The equations used in the tipper analysis are as follows:

$$|T| = \left\{ |A|^2 + |B|^2 \right\}^{\frac{1}{2}} \qquad ...1.7.1$$

$$\delta = \frac{(ar^2 + ai^2)\tan^{-1}(ai/ar) + (br^2 + bi^2)\tan^{-1}(bi/br)}{T2} \qquad ...1.7.2$$

$$\varphi = \frac{(ar^2 + br^2)\tan^{-1}(br/ar) + (ai^2 + bi^2)\tan^{-1}(bi/ai)}{T2} \qquad ...1.7.3$$

$$\theta = \qquad ...1.7.4$$

$$A = ar + ia_i \qquad ...1.7.5$$

$$B = br + ib_i \qquad ...1.7.6$$

$$A = \frac{|Hy|^2 \langle HzHx^* \rangle - \langle HzHy^* \rangle \langle HyHx^* \rangle}{|Hy|^2 \; |Hx|^2 - \langle HxHy^* \rangle \langle HyHx^* \rangle} \qquad ...1.7.7$$

Assumption: Hz = AHx + BHy (2D model)

$$B = \frac{-\langle HzHx \rangle \langle HxHy \rangle + \langle HzHy \rangle \; |Hz|^2}{-\langle HyHx \rangle \langle HxHy \rangle + |Hx|^2 \; |Hy|^2} \qquad ...1.7.8$$

where T = tipper magnitude is an indicator of the size and tilt of the structure

δ = tipper phase

φ = 2 D rotation angle (with azimuth of coordinate

θ = 3 D rotation angle (system, gives perpendicular (to strike direction

The following slides illustrate some of the parameters discussed above:

MT Interpretation and Applicability

1.8 I will only outline briefly the interpretative techniques employed in MT as interpretation forms the basis for lecture number 5.

The depth range 2 to 20 km is that which is of most use in petroleum exploration and some hydrological applications at the present time. Depths from 20 to 200 km can be easily probed by the MT method and this region is becoming of more interest to crustal and structural geophysicists/geologists. The depth range from a few metres to 2 km may be mapped by a variety of active AC or DC methods and more recently by audio-frequency MT using artificial sources. Macquarie University, Australia, is currently working on a natural audio-frequency magnetotelluric system using a "home-made" SQUID magnetometer.

MT is the only method currently available which can routinely be used to map conductivity in the 2-20 km depth range and below. Conventional MT will often give information as shallow as 150 m. MT is frequently used in conjunction with gravity magnetic seismic and DC resistivity data; for instance, combining gravity and MT can distinguish between salt and shale as the cause of a gravity low and MT can provide an independent check on depth to basement for aeromagnetics. Because it measures a different parameter to seismic, MT may often be used in situations where seismic cannot due to problems of scattering, absorption or low contrast. In general, MT is another geophysical technique which complements several already existing techniques and has many advantages in terms of cost and coverage.

The first step in interpreting any MT data is to ensure that adequate good quality processed MT data is available and that one is acquainted with the geology of the area and any relevant geophysical data from other techniques. One and/or two dimensional forward MT models of the area of interest would normally have been prepared preparatory to carrying out the MT survey and these are normally used as a "first guess" in the interpretation process. The next step involves the plotting of sites on a geographic map and the computer calculation of 1 dimensional layered inversion models. In an isotropic layered medium, it is sometimes unnecessary to proceed any further than the 1 dimensional models if these are very similar in both components. If the two resistivity components at various sites differ with one another, it is obvious that the situation is either anisotropic, layered, two dimensional or three dimensional. An examination of Z_{xx} and Z_{yy} (the diagonal impedance tensors) relative to Z_{xy} and Z_{yx} will soon show if the problem is three dimensional; Z_{xx} and Z_{yy} should be small in the one or two dimensional case (i.e. 1/20 of Z_{xy} and Z_{yx}). The 2D and 3D angles from the tipping vector analysis will coincide for 2D cases, diverge for 3D cases and be undetermined in the 1D case. For the two dimensional situation, the 2D angle should be at 90° to the strike direction and the strike determined in this way should conform within the 90° ambiguity to the strike given by the rotation angle obtained from the tensor analysis.

At the present time, three dimensional inversion of MT data is not possible and three dimensional situations must be interpreted using two dimensional techniques and analogue modelling. Recent advances made by Vozoff and Jupp of Australia now enable stable two dimensional inversions to be carried out on MT data; a line of sites must be chosen which intersects the postulated structure at right angles. This is done by selection of a line of sites which lies on the perpendicular to the calculated strike direction; any other line of sites would produce a three dimensional situation. Both components of apparent resistivity and phase are fed in for all sites with a starting model; the computer produces a model which is the best fit to the experimental data, along with estimates of parameter influence. A typical starting model for a two dimensional inversion is shown in figure (13) along with typical output in figure (14). Several runs would normally be performed to obtain the best possible final model. It is sometimes advantageous to include DC resistivity data at the one dimensional inversion stage for surface control; this may be done with a joint inversion package developed by Vozoff and Jupp of Macquarie University. This latter technique has been used now on two Australian surveys with success.

I will be speaking in more detail of interpretation in two other lectures,

"The role of the digital computer in the acquisition, processing and interpretation of MT data" and

"Interpretation of processed MT data; one and two dimensional techniques".

LECTURE 3

3.1 To date, ther have been four major MT surveys in Australia; these surveys and aims have been as detailed hereunder:-

(a) Murray Basin test magnetotelluric traverse. This was a test survey to check out the MT analogue and digital equipment in an Australian sedimentary Basin.

(b) Cooper Basin test magnetotelluric survey. Aim was to check the results given by MT against well log predictions in the area. The location chosen for the test MT survey contains one of Australia's major reserves of natural gas, estimated at over 10^{14} cubic metres.

(c) "Wentworth Trough" MT survey in the Murray Basin. This was the first non-test survey which had the purpose of resolving ambiguity in unexplained gravity results in the area.

(d) East Officer Basin magnetotelluric survey. The aim here was to determine the structure bounding the north-east margin of the basin; a shallow-dip overthrust model had been postulated to fit the observed gravity data and interpreted aeromagnetic depth to basement. Seismic failed to penetrate the granite overthrust and MT was used to define sedimentary thickness beneath the overthrust and the overthrust extent and depth to basement. Petroleum potential was envisaged if a sedimentary section existed under the overthrust.

GENERAL BACKGROUND

3.2 Petroleum exploration in Australia is still in the early stages; most basins are covered by little more than gravity and some reconnaissance seismic, leaving a large amount of untested sediment. The magneto-telluric method is used for basin evaluation because it responds directly to the conductivity of the earth and hence its porosity. MT, unlike gravity and magnetic methods, does not suffer from the ambiguity of these techniques. Resolution of the MT method is comparable to that of refraction seismic or of interval velocity measurements from common depth point data. The MT method is often described as a technique for obtaining a smoothed electric well log without drilling a well. MT is not a method that will supplant other geophysical techniques - it provides new information (conductivity) which is simply another earth parameter such as density and magnetic properties are parameters. In some cases MT will provide information where other methods (e.g. refraction seismic) will not and in other cases, MT may well not provide any information at all. Some of the obvious uses and applications of MT are as follows:

(a) Basement profiling and determination of stratigraphy.
(b) Determination of structure such as dips, faults, overthrusts, contacts, dykes etc.
(c) Determination of composition in diapiric structures and deep ridges (i.e. sand, salt, shale etc) where structure may be defined by seismic but seismic cannot resolve the difference between, say, salt and shale.
(d) Determination of crustal thickness and depth to the base of the tectonic plate.

MURRAY BASIN SURVEY 1973

3.3 This was the first full-component (3 magnetic and 2 electric) MT survey area of a non-academic nature to be carried out in Australia and took place in mid 1973. The only other full component survey to be attempted in Australia was in the Terry Range of Western Australia in 1968; this latter survey ran into problems because one of the horizontal impedances could not be measured due to equipment failure.

The Murray Basin was chosen for experimental MT work for logistic reasons; it is situated in the south-eastern part of Australia enabling good access from most East Australian cities.

The equipment used in this survey and in the succeeding surveys mentioned in this paper is as described earlier in another lecture.

The operational crew for the MT survey consisted on average of four people each from Macquarie University and the Bureau of Mineral Resources (BMR); most of the manual labour for the survey was provided by postgraduate students from the University. In general, apart from the MT analogue amplifier system, equipment was borrowed from various parts of BMR. Equipment was housed in a shipping container which was bolted to the tray of a large 3 ton truck. A 20 KVA alternator was used for the supply of power and 1½ ton truck was used to tow this and to provide storage for all field equipment. Two four-wheel drive landrovers were used for carrying excess equipment and personnel.

Six survey sites were completed (see figure (1)) in a period of 3½ weeks and all four basic aims of the survey were achieved. The basic aims of the survey were as summarized below:

(a) To test the MT equipment

(b) To examine field procedures

(c) To examine the practicability of using minicomputer based systems in a field environment

(d) To attempt to obtain MT data for an Australian sedimentary basin

The results of the survey in terms of the aims mentioned above were briefly as summarized below:

(a) The MT and ancillary equipment performed well for the survey duration and many valuable ideas for improvement of instrumentation obtained. It was found essential to use digital recording techniques and to employ automatic digitization of operator-selectable functions (data from one site could not be used due to incorrectly recorded switch settings).

(b) It soon became obvious that site preparation, field procedures etc, for MT surveys must be systematized to avoid errors due to oversight or carelessness; surprisingly, incorrect coils were often buried in the wrong holes, wires incorrectly connected etc..

(c) The feasibility of using minicomputers in a field data acquisition system was established beyond doubt thus opening up many existing areas for application in field processing, checking and interpretation of data. Some data from this survey proved to be unsatisfactory due to contamination by noise produced by insufficient equipment earthing. The availability of a field processing system for the survey would have led to early detection of the earthing problem.

(d) As has been mentioned in 3.2.2., geophysical coverage of Australian sedimentary basins is not great and the Murray Basin falls into that category. Choice of sites was not dictated so much by geology or geophysics, but more by logistics; accordingly, the six sites chosen for recording were located at 50 km intervals along the accessible Darling river. It soon became apparent upon processing the data that very large variations existed from site to site and that a two-dimensional interpretation of data could not be made without more data at closer spacings. Interpretation was carried out using one-dimensional models for a broader scale of interpretation. Unfortunately the only well drilled in the vicinity of the MT survey was close to the one MT site where data could not be obtained due to misread switch settings. The interpretation from the next closest site agreed well with the well log measurements and provided good agreement on depth to basement and sedimentary resistivity. Depth to basement for the five good sites varied between 1 km at the southern end of the basins to the more common figure of 5-6 km towards the centre. These figures are in good agreement with seismic and aeromagnetic interpretation, although interpreted depth to magnetic basement appears to be erratic in the Murray Basin. Results from one site in particular, Lake Speculation indicate highly disturbed structure while one site (Pooncarie) is very nearly isotropic. On a deep scale, a persistent conductive boundary of 10-50 Ω M was detected at all sites with depths of 102, 80, 95, 106 and 200 km. The 200 km depth was observed at the structurally disturbed site (Lake Speculation) and is an erroneous result obtained by the applications of one-dimensional layered techniques to a three-dimensional situations. Lake Speculation is the only site where the tipping-vector analysis indicated three dimensionality. The range of periods successfully recorded on this survey was 0.1 to 1000 seconds. The conductivity of the layer observed at 100 km is in agreement with Swift's model (1967) but is low compared to Duba's model (1974). The depth to base of the tectonic plate agrees well with the work of Lilley and a deep seismic reflection shot which was carried out in the area by BMR in 1968.

COOPER BASIN MT SURVEY 1974

3.4 This survey represented the second "trial" for MT in Australia and in contrast to the Murray Basin survey was carried out in a Basin having good coverage from geophysics and containing 150 logged wells. The subsurface geology is quite well-known. The aim of this survey was to check agreement between MT and other geophysics. In this case electric well logs were chosen, interpreted and used for the production of anticipated layered MT curves.

Equipment for the survey was similar to that employed for the Murray Basin survey, but several refinements enabled the automatic recording of all manually set switches on the analogue equipment. Software improvements allowed the computation of power spectra (corrected for instrumentation response) Cagniard resistivities phases and coherences in the field. As the area of study was fairly isotropic, it was found possible to compare the Cagniard resistivities directly with the well log interpretations.

Many problems were experienced with equipment on this survey and these were entirely confined to the Geotronics analogue MT equipment and the diesel alternator (a spare unit was available). In total, 2 weeks was spent travelling, 2 weeks repairing the Geotronics equipment and about 12 days survey work. Access to many of the desired sites was denied because of river flooding and sites could only be occupied as flood waters receded. In total 5 sites were recorded although no low frequency data was obtained for the last site from one component due to cracked porous pots. MT data obtained from the survey agreed well with the electric well logs. Depth to transition beds for the sites was recorded as 1.3, 1.5, 1.45, 1.3, 1.35 km and agreed well with results obtained from wells in the area and sieismic soundings. Aeromagnetic depth to basement is not reliable in the area. As predicted, it was found not possible to detect the thin producing zone (PERMIAN Sediments), which have little resistivity contrast with adjacent layers; seismic picks up the Permian well but cannot detect producing or non-producing areas. Likewise with resistivity differences between producing and non-producing zones of only a few percent. Discrimination by electrical means is not possible. Two major structures were successfully detected by means of the tipping vector analysis.

Again in this survey, a conductive layer of 10-15 Ω M was measured at depths of 100, 130, 90, 86 km. MT site locations were about 900 km. north of the Murray Basin mentioned in (3.3). It has been mentioned that site access in the Cooper Basin was restricted by inaccessible roads. It was hoped that some of the MT sites might be located over some of the producing structures but this was not possible and fortunately led to some interesting observations concerning the analysis of the induced vertical magnetic field (tipping vector analysis). It is known that the tipper is a sensitive indicator of lateral structure in an isotopic medium;

vertical field is normally zero so provided one has sufficient equipment sensitivity, even small signals may easily be detected - whereas the perturbations of the inducing electric field are fractionally very small at large lateral distances and difficult to detect. In the Copper Basin results were very isotropic with only small differences between components thus leading to an undetermined rotation angle; the tipping vector on the other hand gave a strong tipper with very well defined direction for all sites. Within 30 km of structure, at frequencies corresponding to about 20 km skin depth, strike of structure could be accurately inferred to $\pm$ 5 degrees. It was found possible to locate direction of the two producing faults in the area of the MT work.

In connection with the isotropic nature of the resistivity curves, it should be mentioned that it was only possible to resolve differences in the components through the use of sophisticated inversion techniques. Dipping of the shallow layer was very slight, measured at 2 degrees, being influenced at greater depth by the two faults with indicated dips coming to approximately 15 degrees. At greater depth still, the four sites near the Gidgealpa fault show a gradual decrease in dip angle towards zero degrees, however the fifth site, located near the Big Lake fault, shows dip still increasing at 22 degrees (3000 second period).

WENTWORTH TROUGH MT SURVEY - MURRAY BASIN, 1975

3.5 This was our first MT survey which did not have the purpose of testing the MT method, equipment etc. The "Wentworth Trough" survey was in fact aimed at finding whether there was a trough. A 40 mgal gravity low in the Murray Basin area (near the centre of the first Murray Basin MT traverse) was guessed to be a sediment filled trough but there was considerable doubt as to whether this was the case or whether the gravity low was caused by low density basement uplift. A special set of detailed aeromagnetic traverses was flown over the "trough" but the profile showed very little variation in magnetic field (i.e. 15 nT). An MT survey was planned with 11 sites at 3 km intervals cutting the gravity anomaly centrally and at right angles.

Equipment was again the same as for the previous two surveys with some major additions to software (these additions were in fact carried out during the final stages of the Cooper Basin project). For this survey, at each site location, we were able to compute rotated apparent tensor resistivity, phase, coherency, rotation angle as well as all tipper information from the three magnetic field components. This processing of data enabled the best possible on-site evaluation of data yet possible; the only problems experienced were with the slow computer (1.6 cycle time), small memory (16 K words) and lack of mass storage facilities which limited the processing speed to about 1 output data point per minute. Much more data was collected on this survey than on any of our previous surveys with a total of 3.5 x 10^6 digitised samples from each of the E and H field components. Approximately 3 000 estimates were calculated for each component of the apparent resistivity at each site over five decades of period from .03 to 5000 seconds.

Results were isotropic at shallow depths becoming much less isotropic at depth (i.e. 10 km). One-dimensional layered inversion results looked like (fig. 2) thus indicating a basement trough filled with conductive sediment. It was obvious from the data that two-dimensional inversion would be necessary for the interpretation of the deep structure; this is still being carried out, but it will be noted from the layered result, (more resistive component), that there is disturbance in the crust which aligns well with the gravity anomaly. This is obviously not a true picture because the "structure" is closer to some sites than is the continuation of the same structure under them. It is believed that the crustal picture will explain the gravity anomaly as the trough itself is not the major factor. As in the previous Murray Basin survey, depth to mantle was again measured at 100 km approximately.

EAST OFFICER BASIN MT SURVEY, 1976

3.6 This survey was similar to that in the Wentworth Trough in that MT was used to solve a structural problem - although in this case there was an interest in petroleum potential. The Officer Basin lies slightly to the south of Australia's centre in and around desert area which suffers from extremes of heat, minimal rainfall and extremely sparse population density. An overthrust structure was postulated, as has been mentioned, seismic was very erratic in the area and MT appeared an ideal tool to solve the various problems which may be briefly re-iterated as follows:

(a) To determine if the structure was indeed an overthrust
(b) To determine overthrust extent
(c) To determine thickness and rate of thickening for the overthrust
(d) To establish depth to basement under and away from overthrust
(e) To establish the likelihood of a sedimentary section under the overthrust
(f) To establish depth to mantle as part of a long term project.

The model fitting both magnetic and gravity results is shown in figure (3), and this was used as a preliminary model for initial two-dimensional MT modelling - this showed that the MT technique would resolve all the items mentioned in (a) to (f) above provided the overburden conductivity and thickness could be accurately ascertained (e.g. from deep DC resistivity). The MT survey was duly carried out using DC resistivity at each site for surface control. Even with the one-dimensional model we have been able to confirm (a) to (e) qualitatively and hope soon to have all the quantitative figures. Equipment problems were experienced on this survey due to poor condition of roads in the area. Field processing was carried out much faster on this survey than on previous surveys with the addition of a high speed moving head disc. We were able to calculate about 10 apparent resistivity/period points per minute.

LECTURE 5

Interpretation of processed MT data; one and two dimensional techniques

Interpretation

5.1 Interpretation of processed MT data is the production from that data of some sort of electrical model relating conductivity and spatial parameters such as distance depth and thickness. Stage two of the interpretive procedure consists of relating the electrical model to a geologic situation in a manner which depends on the original aims of the MT work. Stage one of the process is a less variable procedure than the second stage; for this reason I will discuss stage 1 here and stage two in a practical manner when discussing MT surveys in Australia (lecture 4).

Magnetotelluric interpretive techniques have changed dramatically in the last year with the development by Vozoff and Jupp (Macquarie University, Australia) of stable iterative inversion techniques for MT and joint DC/MT data in one dimension and MT data in two dimensions. The availability of an operational two dimensional inversion package means that "cut and try" methods of fitting forward two dimensional models to multi-site MT data are now a thing of the past, as is the non-valid approach of constructing two dimensional sections from one dimensional inversion models in non-isotropic situations.

First steps

5.2 Output from the final MT processing stage would normally consist of the following graphic output for each of several MT sites:

(a) Rotated tensor apparent resistivity and phase curves for each orthogonal component. Because of the large amount of data which can be collected from a computer based data acquisition system, this data is normally averaged to 10 points per decade in non-overlapping bands.

(b) Tensor rotation angle versus frequency; these would normally be averaged as in (a) above and consideration could sometimes be given to greater averaging on the basis that rotation angle usually changes fairly slowly with depth (frequency)

(c) Plots of tipper magnitude and phase angle versus frequency

(d) Plots of 2D and 3D tipper rotation angles.

Samples of the above plots may be seen in figures (1) to (6).

A preliminary examination of the resistivity plots will soon give an idea of whether the data is one or two dimensional. If the curves diverge as in the site shown in figure (7), the data is almost certainly two or three dimensional. With one dimensional data, i.e. figure (8), the orthogonal components coincide, the magnitude of the diagonal impedance tensor is close to zero, (figure (9)), and tensor rotation and tipper angles are undefined. It would be rather unusual to find a completely one dimensional situation, as modern MT techniques in sedimentary basins will frequently sound depths to 200 km (in this case the tipper could well resolve deep lateral conductivity changes over a 100 000 square km area. If the resistivity curves diverge from one another, a definite strike direction should be evident from the tensor rotation angle; this will be confirmed from the 2D and 3D tipper rotation angles. Large relative values for the diagonal tensor impedance components and divergence of the two tipper rotation angles indicate three dimensional structure which can only be approximated by two dimensional techniques.

In all but one-dimensional isotropic situations, a line of sites which crosses the indicated strike direction (from tensor rotation) at right angles is now required. The line of sites crossing the strike may have been obtained in one of three ways:

(a) By calculating and monitoring the strike direction in the field and adjusting site location accordingly; this is by far the most effective technique.

(b) By choosing sites in accordance with geological and geophysical data obtained from other methods.

(c) By choosing a grid of sites so that a line may be drawn at right angles to the strike direction, no matter what that direction may be.

Until field processing methods were developed (Kerr, BMR Australia), a judicious combination of (b) and (c) was usually necessary; this did not always produce satisfactory results in that the geology was sometimes poorly defined with little support from magnetics, gravity or seismic.

Pseudo - Sections

5.3 Once we have our line of sites across indicated strike, we may construct a particular form of two dimensional presentation called a pseudo-section. Sites are plotted horizontally on a linear scale and chosen resistivies are plotted vertically beneath the site positions on a logarithmic frequency scale; resistivities are then contoured.

Pseudo-sections should be drawn up for each orthogonal resistivity component and a third section for tipper magnitude, in place of resistivity values. Pseudo-sections are useful in that they tend to show current flow and can be used to identify lateral conductivity discontinuities. Figure (10) shows sections created from the results for a simple vertical conductive dike. It will be noted that the currents flowing across the dike (i.e. E perpendicular to strike) do not show the dike due to the thinness and high conductivity of the dike compared to the surrounding high resistivity. The component of resistivity due to E parallel to strike shows the dike well as the E parallel currents flow parallel to the conductive body for an infinite distance; in keeping with the behaviour of the MT method in providing a smooth gradual response to conductivity variations the dike appears as a "valley" when looking at E parallel. That it is not a valley is indicated by the lack of a response in E perpendicular. It will be noted that a significant tipper is produced by disturbance of the currents flowing parallel to strike and that, in fact, the tipper is the best diagnostic of lateral conductivity variations. In most cases we would use the E parallel pseudosection as the first step in obtaining a "general" two dimensional section comprised of horizontal layers (this is because of the continuity which would normally be expected between sites because of the type of continuous response exhibited by the E parallel pseudo-section as in figure (10)). If the example of the conductive dike is replaced by that of a resistive dike, then E perpendicular currents will be impeded and the E perpendicular pseudo- section will show the dike. A dike would not normally become apparent in both pseudo-sections until the dike was tilted more than 45^{o} (to give a larger type response).

Horizontal Layered Models

5.4 The next stage in the interpretation consists of one dimensional modelling for each component of each site; by now the nature of the final model would normally be becoming apparent (i.e. one dimensional, two dimensional, location and general shape of structure etc); At this stage we generally screen the data to produce the best statistically significant curves; the apparent resistivity/phase data is fed into a one dimensional computer inversion package modified to run on a small scale mini-computer from the program developed by Vozoff and Jupp of Australia. The inversion package produces a layered model for each of the components at each site; with two dimensional data, it is frequently necessary to invert on resistivity alone and not include phase as in these cases, both resistivity and phase are not generally compatible with the layered situation. If the situation was fairly isotropic as indicated by similar E parallel and E perpendicular pseudo-sections, the one dimensional inversion results may be drawn as a resistivity depth section; the course of action at this point would normally depend upon the type of problem being solved (structural, sequence identification, depth to basement etc) and several different examples will be given in the lecture on Australian MT surveys.

It is convenient at this point to examine the information which may be obtained from the one dimensional inversion package:

Inversion consists of the fitting of model derived data to experimental data in an iterative fashion such that at each iteration the relative root mean square error between model and data is minimised. The Jacobian or influence matrix (matrix of partial derivatives of the model data with respect to parameters) determines the effect that any particular model parameter will have upon model values. The inverse Jacobian is applied to the measured and model data to generate a correction vector which may be applied to the model to bring the model data closer to the measured data. Numerical stability of the inverse problem is obtained by classifying model parameters as Important (large effect on model data), Unimportant (small effect on model data) and irrelevant (no effect on model data); this classification is obtained from the magnitude of the partials in the appropriate column of the Jacobian i.e. large, small and zero. Unimportant and irrelevant parameters could have a highly unstable effect on the inversion if not controlled, so irrelevant model parameters are not allowed to change during inversion and unimportant parameters are only allowed to influence the inversion in the final stages so as to reduce the final least squares error. A form of "tapered damping" is applied during the process so that only the most major parameters of the model are altered in the early stages of inversion. It may be seen from the above that if the inversion converges to a solution which is close to that indicated by the measured data, then the Jacobian may be used as a good guide to those parameters which are well defined. Important variables would normally be described as those whose normalised singular value was greater than 1% at the 1% damping level.

The final item of interest in the inversion process is the "V" matrix or parameter space eigenvectors; this matrix defines the relationship between the original and transformed parameter spaces and is derived from the singular value decomposition of the Jacobian. The V matrix allows one to decide which parameter combinations are "important" (e.g. resistivity thickness products etc).

It may be seen from the above general discussion that the inversion process may be easily modified to allow parameters to have more or less influence during the inversion simply by applying weighting factors to the appropriate elements of the Jacobian. For instance, parameters may be "fixed" by zeroing the appropriate column of the Jacobian or given more "weight" by applying a linear multiplication term.

The advantages of the one dimensional inversion technique over previous manual methods and even more primitive inversion techniques are as follows:

(i) Curve fitting is the best so far obtainable and quantitative error estimates are available quickly at each point and over the whole curve.

(ii) The inversion is stable.

(iii) The model parameters and combinations of these may be categorised into "resolvable", "barely resolvable" or "unresolvable".

(iv) Inversion may be carried out simultaneously on apparent resistivity and phase with any form of linear weighting between the two.

(v) Individual data may be weighted (quite simply) in very many ways.

(vi) Likely error in the final model may be estimated and there is little danger (because of (iii) above) of quoting models with superfluous or unresolvable layers.

2 Dimensional Techniques

5.5 In most cases MT data will be either two or three dimensional; two dimensional techniques and intelligent use of limited three dimensional models is the only way of currently handling the three dimensional problem.

As has been previously mentioned, Vozoff and Jupp have now developed a successful 2D inverse computer program designed on the lines of the one dimensional package; as may be expected running costs are considerably higher and amount to approximately 3000 seconds of CPU time on a 1.5 microsecond computer. Considerations of core storage space and central processor time currently limit some of the capabilities: For instance, the only variable parameter allowed is resistivity - it is necessary that the model dimensions remain fixed. The above is not as serious as it may sound because the two dimensional model is built of resistivity "blocks" with two spatial dimensions plus the parameter of resistivity figure (11). If the inversion makes the resistivity of a block the same as that of an adjacent block the boundary between the blocks disappears and the two become one. We can see then that by judicious manipulation of the starting model and a number of re-inversions that one can finally arrive at a satisfactory two dimensional inversion result. In Australia we are just starting to use the two dimensional inversion which is essential to the interpretation of our last two surveys. Output from the two dimensional package is very similar to that of the one dimensional program described in 5.4 and the techniques of using it are similar; obviously the major difference is that a line of sites, both components and phases, are fed into the two dimensional inversion.

LECTURE 6

Site selection and field procedures for MT surveys; the importance of preliminary modelling

Pre-survey planning

6.1 The MT method relies on the measurement of three mutually orthogonal magnetic field components at the earth's surface (the inducing field) and two horizontal electric field components (the induced telluric field). These measurements are carried out at very many frequencies in the spectral range 0.0004 to 100 Hz. The theory surrounding these measurements is covered in lecture (1). It will be assumed that the equipment used in the MT survey is as briefly described here (6.3) and as more comprehensively described in lectures 2 and 4. The initial stage of any magnetotelluric survey consists of defining the problem or problems to be solved by the technique; MT will not solve all problems and even though it will not always be practicable, it is often possible to conserve time and effort by modelling the problem and the predicted magnetotelluric response in advance. Two particular Australian problems in which the magnetotelluric method has recently had application are illustrated in figures (27) and (28). In the first problem, the aim was to find if the observed 40 mgal anomaly was caused by a sediment filled trough in the basement or basement intrusion covered by recent sediments. It would be expected that the sediments would be considerably more conductive than the basement/intrusion and that MT modelling in each case would produce significantly different results. The second example is taken from another Australian sedimentary basin - the Officer Basin; in this example, an overthrust structure was postulated to try and explain observed gravity and magnetic data on the North-Eastern boundary of the basin; seismic surveys over the postulated overthrust ran into problems seeing beneath the granite and only partial reflections were obtained from basement beneath the sedimentary column. Questions which it was hoped would be resolved by the MT technique were as follows:

- (a) To determine if the structure was indeed an overthrust
- (b) To determine the extent of the overthrust
- (c) To establish thickness and rate of thickening of the overthrust
- (d) To establish rate of thinning of the sediments under the overthrust
- (e) To establish depth to basement near and under the overthrust
- (f) To establish depth to mantle in the area as part of a long term project.

Let us then take as an example of a typical problem that of the overthrust described above. A very rough first approach to modelling the situation would be to take a layered one dimensional model of a part of the overthrust and observe the effect on the model output data of varying the various model parameters. This has in fact been done for the model in question; the model used is illustrated in figure (12) and some of the output curves are shown in figures (13) to (14). Figures (15) to (18) show that the overburden resistivity and thickness have a significant effect on the MT apparent resistivity curves; furthermore, due to the high frequencies involved, the MT method cannot adequately resolve this layer. Figures (19) to (24) show variously that the thickness of the top resistive section (overthrust) is easily resolvable and that the resistivity is rather unimportant as long as it is high. In a similar way, the depth to basement may be resolved without the conductivity of the sediments having a significant effect. It can be seen from figures (25) to (26) that the mantle resistivity and depth, have very little effect on the apparent resistivity curves in the period range of interest for the other model parameters. Exactly the same information provided by this empirical method of calculating parameter resistivity could be obtained in a more elegant form by calculating the partial derivatives of the model response at all frequencies of interest (the Jacobian) and then looking at the significant terms. The Jacobian could be easily calculated using the layered model inversion program in its forward mode; this provides not only the Jacobian, but also the V matrix (described in the Interpretation lecture). The V matrix will provide information about the effects of parameter combinations (i.e. conductivity thickness products) on the model. To be strictly accurate, the pre-survey modelling described should be carried out using a two dimensional forward model; when this is done, it is seen that, in this case, the layered modelling does agree well with the more resistive component of the 2 dimensional model. Response of the 2 dimensional model figure (29) at different sites is shown in figures (30) and (31).

Survey Planning

6.2 Planning of the survey proper may commence once the initial modelling has been carried out and evaluated. Section 6.1 shows that in the example quoted there would be a good chance of an MT survey providing the answers to questions 6.1 (a) to 6.1 (f) providing the surface layer can be defined; equally importantly, an MT survey may well not succeed if steps are not taken to look at the overburden. The solution in this case is to take DC resistivity measurements at the same locations as the MT. Regional gravity contours of the overthrust area show that a 2 dimensional MT interpretation should suffice. Site choice and spacing should depend upon the type of survey; for the type of non-reconnaissance detailed MT survey required in the example used here, a tentative line of sites at 90 degrees to strike would be chosen with site spacing closest near the detailed parts; 2 dimensional model data is very useful in eliminating redundant sites. Suitable site spacing in the example would be 8 km away from the overthrust and 4 km closer in to the lip.

Some of the logistics required for MT surveys become fixed from survey to survey. Some of the requirements from Australian experience are detailed below:

(a) Personnel requirements: 2 geophysicists, 1 technician, 2 unskilled field hands. A motor mechanic is often required but only sometimes available.

(b) Vehicles: one recording ruck in the 1½ to 3 tonne range, two 1½ tonne trucks for carrying camping equipment, MT gear etc, one long wheelbase landrover as personnel carrier, survey vehicle, etc. As many as possible of these vehicles would be equipped with four wheel drive, low range gears, winches and supplementary water and fuel; these options are normally mandatory when operating in rough unpopulated desert areas of Australia.

(c) Major MT equipment: 3.75 to 5 kVA motor alternator 240V/50 Hz. Prismatic compasses, level, 6 MT coils, 10 electrodes, cables, theodolite measuring wheel, power or hand auger or both, bush saw, shovels, axes, mattocks, picks, sledge hammer. Equipment mounted in recording truck.

Before proceeding to talk about site preparation and layout, I will briefly describe the MT equipment and procedure for recording the MT signals.

The MT equipment

6.3 The MT recording equipment may be divided into two sections, these being the analogue data acquisition system and the digital data acquisition system and monitoring system.

The analogue portion of the equipment consists of the complete commercial magnetotelluric system designed, manufactured and marketed by the Geotronics Corporation of the USA. Plans are currently in hand at the Bureau's design and development laboratories to replace the final amplifiers and filters used as part of the Geotronics system. The three components of the magnetic field are sensed by highly permeable induction magnetometers which, coupled with matching preamplifiers provide mid band sensistivities of 0.1, 1.0 and 10.0 volts per nanotesla. The electric field is sampled as a voltage difference between two non-polarizing electrodes implanted in the earth's surface; distance between these electrodes is measured with a measuring wheel. Two components of electric field are measured, these being orthogonal to the two horizontal coil alignments. A set of 3 (1 spare) electric field pre-amplifiers provides output sensitivities of 10, 100, 100 volts per volt of input. The five (3H, 2E) preamplifiers all have 3 gain positions as well as a switchable low pass or notch filter characteristic. Output from the preamplifiers passes through a set of five identical postamplifiers; these postamplifiers provide switchable high and low cut filter responses plus gain control of 20, 50, 100, 200, 500, 1000 and 2000 times. It can be seen that the final maximum E field sensitivity for a 1 volt output is 0.5 microvolts and for H, 0.00005 nano-teslas at 2Hz. The output of the postamplifiers feeds a fast analogue to digital converter with 15 bits resolution (resolution, LSB = 0.3 mv). The A/D converter is commanded by the computer to sample the five channels at discrete time intervals; these are determined by the frequency range being recorded and are selected by the equipment operator. The computer is responsible for initiating and conducting acquisition of blocks of data; the data is recorded in files on 9 track half inch phase encoded magnetic tape. Each data file recorded on tape consists of the transfer function of all the equipment, (as determined by the computer which monitors all switch positions on the analogue equipment), information about file size, digitising interval, channel arrangement etc and the five channels of data (multiplexed). The computer maintains an output record of the data on a 6 channel Gould analogue chart recorder. The operator is responsible for monitoring the data recording, initiating changes in recording bandwidth and sampling rate and finally for the maintenance of a handwritten recording log which contains information pertinent to the recording site and each file or group of files being recorded.

Site selection and preparation procedure

6.4 This section deals with the actual physical selection of MT sites; normally, approximate site locations will have been chosen by prior consideration of the results of preliminary modelling. Site selection in the field will be influenced by the following considerations:

(a) Previous decisions on site location

(b) Any changes to (a) brought about by unexpected or more positive field results obtained from processing data from previous sites

(c) Considerations of physical access (i.e. if the site is in a swamp some difficulties may be experienced)

(d) Bad site locations sometimes occur, outcrop should be avoided and it is important to avoid noise sources such as vehicles, people, earth tremors etc. Earthed metal conductors such as fences etc must be avoided as these cause local conductivity disturbances. Civilisation should be kept many kilometres away as electrical mains interference can wreak havoc with the measurement of the small signals.

Once a site is found which fulfils all the requirements mentioned above, a check should be made to see that two perpendicular electric field directions can be laid out in a cross shape from a central point approximately half way between the electrodes in each case. Each arm of the cross will be from 250 to 500 metres in length and orthogonality would normally be to within ± 1 degree with an azimuth measurement to ± 2 degrees. A theodolite or transit is most useful for aligning E field directions and is often the best means of discovering an optimum direction through heavily timbered areas. Once a suitable central point has been found for the site, wires are run out in the four directions; we use pre-measured lengths of wire which are run out to the fullest extent. Holes (about ½ metre deep) are dug at the end of the wires and a mud slurry is prepared at the bottom of each hole and allowed to settle for some time (usually 12 to 24 hours). Porous pot electrodes figure (32), are filled with supersaturated cadmium chloride solution (some of which is poured into the hole) and the pot is placed with its porous base in the mud slurry. A plastic bag and bucket are used to cover the electrode and provide protection against small animals. The wire joining each electrode to the centre point of the wires is weighted down every few metres with clods of earth, sticks etc to prevent excessive wind movement of wires in the earth's magnetic field from generating electric noise currents. The distance between each of the two pairs of pots is measured as accurately as possible (usually better than 1%) and these figures are recorded (usually on a peg at the site and in the recording log). We usually denote the direction which is closer to the North/South as the "x" direction and the other as the "y" direction. The three induction magnetometers (which weigh 42 kg each and are 2 metres long by 10 cm across) are placed near the site centre. The vertical magnetic coil is buried in a hole made by an auger; there is quite an art in aligning this hole within the required ± 2 degrees of vertical, especially when hard rock is encountered half-way down! The other two magnetometers are aligned so as to be perpendicular to the electric field directions and are buried in trenches approximately 35-45 cm deep. Positioning of the coils should be to within ± 1 degree if possible and should be accurately levelled to approximately ± ½ degree or better. The coils are all covered with a layer of earth to minimise noise induced by wind, thermal variations etc. Trees within about 30 metres should be avoided to prevent the roots from moving the ground in a wind. It is interesting to note that we once experienced large noises on Hz (of the order of 0.001 nano-teslas); at the particular site, it had been impossible to bury the H vertical magnetometer which ended up in the centre of a very large man-made mound of earth. The noise was found to be caused by a magpie (not very large Australian bird) walking on the sides of the earthmound! The recording truck wherever possible should be aligned to be as far from the site centre as possible, usually diagonally between two of the electrode wires; figure (33) shows a typical recording set-up. Connections between the recording track and magnetometers is by means of three sets of shielded twisted pair cables and electric field connection is accomplished with unscreened wire similar to that used in seismic work; screening of the electric field cables is found to be unnecessary due to the relatively large voltages being measured and the noise-free environment. E fields are of the order of 1 mV per kilometre. The interelectrode resistances between each pair of E electrodes is adjusted by means of moisture content and ground connection in the holes to be less than 1000 ohms. The input impedance of the E field preamplifiers is 100 000 ohms. Inter-electrode resistances are measured on a regular basis (i.e. once/24 hours) and the "pots" are normally checked and topped up with electrolyte each morning.

Wherever possible MT sites are set up in advance - i.e. while one site is being recorded, the previous site is "dug-up" and coils, electrodes etc are moved to the new site and installed; it is sometimes possible to have preliminary site work completed 2 or 3 sites in advance. Once the recording truck is moved into a new site, a 2 day schedule of recording and processing is undertaken; this schedule requires one person and in some remote areas it is possible to have the site unattended while the computer acquires the data (normally during the acquisition of long period data). Data is normally acquired in six operator selectable bands which are as follows:

(a) 0.002-0.025, (b) .01-.125, (c) .1-2.0, (d) 1.0-2.0, (e) 1.0-25.0, (f) 10.0-25.0

hz

The overlap in the last few bands is used to obtain as much data as possible in the often critical high-frequency area. A normal recording schedule would include three or four similar sets of recordings each of which would contain the following number of individual data files: 1 of a, 4 of b, 8 of c, 12 of d, 15 of e and 15 of f. It can be seen that the total number of files recorded comes to between 150 and 200. The operator monitors the progress of data recording on the analogue chart recorder to ensure that amplifiers do not saturate and that the signals all look "reasonable" - in Australia difficulty is often experienced with animals (such as rabbits and rats) eating the electrode cables. On one memorable occasion, rabbits succeeded in eating through 2 layers of tough plastic coating, copper shielding braid and then the two wires contained inside the shielding braid! Needless to say, the H field signals obtained via these cables were decidedly "sick"! Facilities are available on the computer based system to edit data files on the magnetic tape.

Field processing of the data

6.5 Field processing of the MT data is carried out, usually when recording cannot be carried out due to checking and reparing of cables, checking electrodes etc. As has been mentioned in the lecture which deals with processing, the processing is divided into three passes which are as follows:

(a) Fourier transform data, correct for instrument response, calculate cross and auto powers then average the data.

(b) Calculate "raw" coherencies, Cagniard resistivities, unrotated tensor resistivities and then rotated tensor resistivities.

(c) Display data for the whole site on an incremental plotter.

(c) above has been implemented at BMR in a laboratory environment but has not yet been used in the field. Processing and displaying 20 data bands in the above manner would normally take 40 minutes for pass (a), 12 minutes for pass (b), 3 minutes for pass (c). All the computations are performed with the assistance of a disc memory; a backup system is available which uses magnetic tape, as a mass storage medium and takes approximately 5 times as system using the disc. In the future, it is hoped to overlap all processing and acquisition of data in the computer so that display of rotated apparent resistivity may be accomplished in close to real-time. The field processing of MT data is regarded as the only satisfactory economic method of deciding when sufficent data has been acquired from a site and of deciding whether or not the sites are being located correctly with regard to structures etc. If desired, it is now possible to compute layered inversion models in the field; these will not always be strictly accurate and may be misleading for strongly 2 or 3 dimensional structure, but are still useful for deciding whether features are being resolved.

APPENDIX F

TELLURIC PRE-AMPLIFIER

The following represent suggest design specifications for the E field or telluric pre-amplifier section of the proposed NGRI magneto-telluric system. In general, two high performance low-noise pre-amplifiers are required for the amplification of low-level signals in the 5 uV to 100 mV (peak to peak) range; these amplifiers should be mounted in a single container with suitable magnetic and electrostatic shielding. Output signals may be single-ended and should appear on individual connectors. BNC or similar connection would be satisfactory. If the amplifiers are to be operated by an external AC supply, the system should be organized so that AC power does not enter the amplifier unit; one suggestion would be to have a separate unit capable of accepting 250V 50Hz and supplying DC power to E, H and post-amplifiers. If possible, the power supply unit would be designed to accept 115 V 400 Hz as an alternative power source. 400 Hz alternators are much lighter than their 50 Hz counterparts and removal of extraneous 400 Hz is also much easier than at 50 Hz. The following operator accessible features should be available on the front panel:-

(a) Gain switch with switchable gains of 10, 100, 1000 for each amplifier.
(b) Low pass filter switch with roll off commencing at 25 Hz or 100 Hz; (may be ganged).
(c) "Bucking controls" for the removal of polarization voltages from the pairs of electrodes.

(d) Some sort of indication of nulling for (c) above; either 2 LEDS or small meter.

(e) Input terminations for the amplifiers; most good quality connectors (e.g. BANANA SOCKETS) would be satisfactory. Differential connection plus a "guard" and earth terminal should be provided for each amplifier.

(f) Latching peak indicating device (such as a L E D) with re-set facility to indicate when transients may have caused output saturation on the preamps.

The amplifiers should have an input impedance of no less than 100 000 ohms; more than this is undesirable from the point of view of noise. Amplifier input should be differential and common node rejection should be 100 db if possible; 80 dBCMR is the lowest acceptable figure in most circumstances. It is suggested that amplifiers should be chopper-stabilized and have a response extending downwards in the frequency spectrum to DC. The chopper frequency should be carefully chosen with the possibility of 50 Hz and its harmonics in mind. The 25 Hz and 100 Hz filters should be 1st or 2nd order filters and may be controlled for both amplifiers by a ganged control. Noise referred to the input of the amplifiers should be as good as possible; a figure of 2 uV P to P in the range .001 to 20 Hz may be considered good at the amplifier input. Filters should appear fairly early in the amplifier to prevent possible saturation problems (from 50, 100, 150 Hz). Cross-talk between channels should be 120 dB or below. Perodic DC drift (due to temperature etc) should not exceed 2 uV PP or the noise figure (whichever is greater) over a one hour period of time. Gains should have an accuracy of $\pm$ 0.1% at any time the amplifiers are being used for data acquisition. Filter stages should be made as insensitive to component variations as is possible commensurate with economic considerations; phase response is a particularly sensitive area.

Binary coded switch outputs (0 to 5V) or (0 to 12 V) positive true should be provided via connectors at the rear of the unit for gain and filter switch settings. Dynamic range of the amplifier should be such that the input signal will not saturate the amplifier at other than the final stage for any gain setting. Output voltage capability should be $\pm$ 10.0 volts and linearity should be 0.1% or better for a 1 volt output signal. A DC Bucking voltage should be provided for the removal of pot polarization voltage. Range should be $\pm$ 60 mV and should be stable (i.e. compared to deift performance figures).

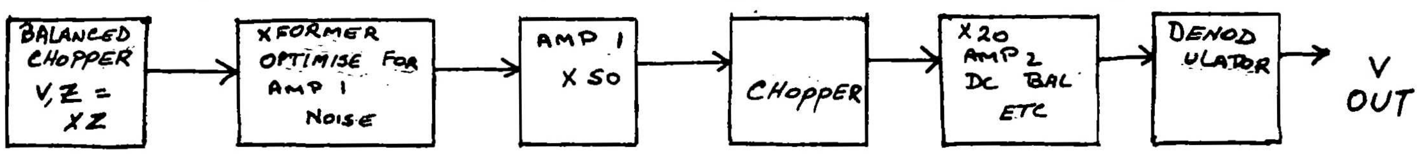
MAGNETIC FIELD PREAMPLIFIER

The amplifier is required to be a state-of-the-art unit exhibiting ultra-low noise figures at very high gain levels (2×10^3 to 2×10^5 typically); it presents special problems in the nature of the source which is reactive. It is suggested that input impedance be no less than 3 times the final coil DC resistance to avoid undue losses in signal level. For the purpose of instrument design, the power density (in nT^2/Hz) of the magnetic field measured field measured in magnetotelluric work may be approximated by the expression:-

$$\delta = 10^{-(2.4 \log_{10} f + 6)} \quad \ldots \quad \ldots \quad 7.1$$

where f is in Hz. The best coil constant which may be hoped for is between 100 and 150 V/^{nT} Hz. The Geotronics MT system deliberately rolls off the coil response at about 2 Hz to reduce saturation problems caused by 50 Hz pick up; this is performed by swamping the .001MF winding capacitance with a 10uF capacitor. It is believed that the noise problem (Most 50 Hz noise is picked up in the shielded cable) may be solved by placing the first gain stages (x600 x3000) at the coil itself. If this is done, the coil roll off may be altered from 2 Hz to approximately 20 Hz, thus improving S/N radio in the critical 1-30 Hz signal area (It should be noted that the input impedance of the amplifier is about 800 Ω at 10 Hz and 1.4 KΩ at .01 Hz. for the Geotronics preamplifier design).

MT data is normally collected in constant bandwidths so as to give 10 bands per decade; at 5 Hz this bandwidth would be approximately 1 Hz. so that the equivalent signal level would be 0.004 uV for the horizontal coil. For the vertical magnetometer and a 2 degree dipping structure signal levels of 0.0002 uV could be expected. It may be seen then that a noise bandwidth figure of 0.0002 uV/ $\sqrt{}$ Hz at 5 Hz is desirable - this equates to a figure of 0.004 uVPP in the 1 to 25 Hz band. If 20 to 30 periods are averaged in the fourier transform, a noise level of approximately 0.02 uVPP would be satisfactory. Similar calculations to the above for the range 0.001 to 1 Hz show that signal will be three times as good as the high frequency result. A consideration of thermal noise at 24°C shows that best possible theoretical noise figures would be 0.04 VPP for 30 Hz bandwidth and 2 input impedance. Geotronics equipment in the 0.002-25 Hz. range has a theoretical noise level of 0.03μV for 1.45 K source impedance and an actual noise level of 0.2 μVPP. The best possible amplifier that could be built would be limited to about .08μ VPP with present technology. One of the problems experienced if the initial pre-amplification is not situated at the coils is that of common mode noise which would often be large compared to signals of, say, .5 uV. Geotronics provide a common mode rejection ration of 150 dB; this is achieved by use of a balanced chopper input stage isolated from the following stage by a pulse transformer which also achieves impedance transformation; the chopper is a balanced type with a voltage transfer ratio of 1:2 when coupled with a transformer. The chopper + transformer provide a voltage step up ratio of 6.3 : 1 (also impedance) and feeds directly into a 725 operational amplifier (low noise) connected as a non-inverting amplifier with gain = 101 and input impedance of 30 K. It is felt that the design philosophy in this first stage of the Geotronics equipment is good but that much better operational amps than the 725 are available as far as noise is concerned or that a hybrid IC/transistor op amp may be constructed. The exact NGRI design will obviously depend upon the inductance of the coil, its DC resistance and the resonant frequency. It is felt however that design work could proceed assuming L = 600 H , R = 500Ω and C = .01 uF. MOS choppers will obviously be required for the front end. The following condensed block diagram is a suggestion for the NGRI amplifier.



As noted, the transformer may be chosen so that amplifier 1 operates at its optimum noise/impedance point which should be optimised for the 1-30 Hz band (i.e., source impedance in this passband). Geotronics provide a balance control for removing contact potentials from the coil/cable connections; this control has not been used in our system, and for the NGRI system it is suggested that an accessible balance control in the form of a trimpot is all that is necessary - this could be part of the final preamp stages situated away from the coils/preamps. Gain required before the post amplifiers and after the coil preamps will be between 1 and 100. Three decade gain positions (i.e. 1,10,100) will be found to be satisfactory for all situations. Geotraonics organise their gains to be .1, 1, 10 volts/nT Hz but this is not essential providing the gains are known and stable. Low-pass filters may be provided as for the E field preamps, however it may be found that these are not necessary dut to natural coil roll-off. It is suggested that this may be evaluated at the prototype stage.

It has been demonstrated in the first few paragraphs that even with the best coils and minmum theoretical noise levels that S/N ratio in the 1-30 Hz band may well be inadequate; this does not imply that the system will not work but only that more data must be gathered in this range so as to record the larger signals which occur at times.

The other less demanding specifications for the magnetic preamplifier are similar to those for the E preamps; i.e. terminations, cross-talk, saturation indicator, power supplies etc coded switch outputs should be provided as with the E preamplifiers.

POST AMPLIFIER AND FILTERS

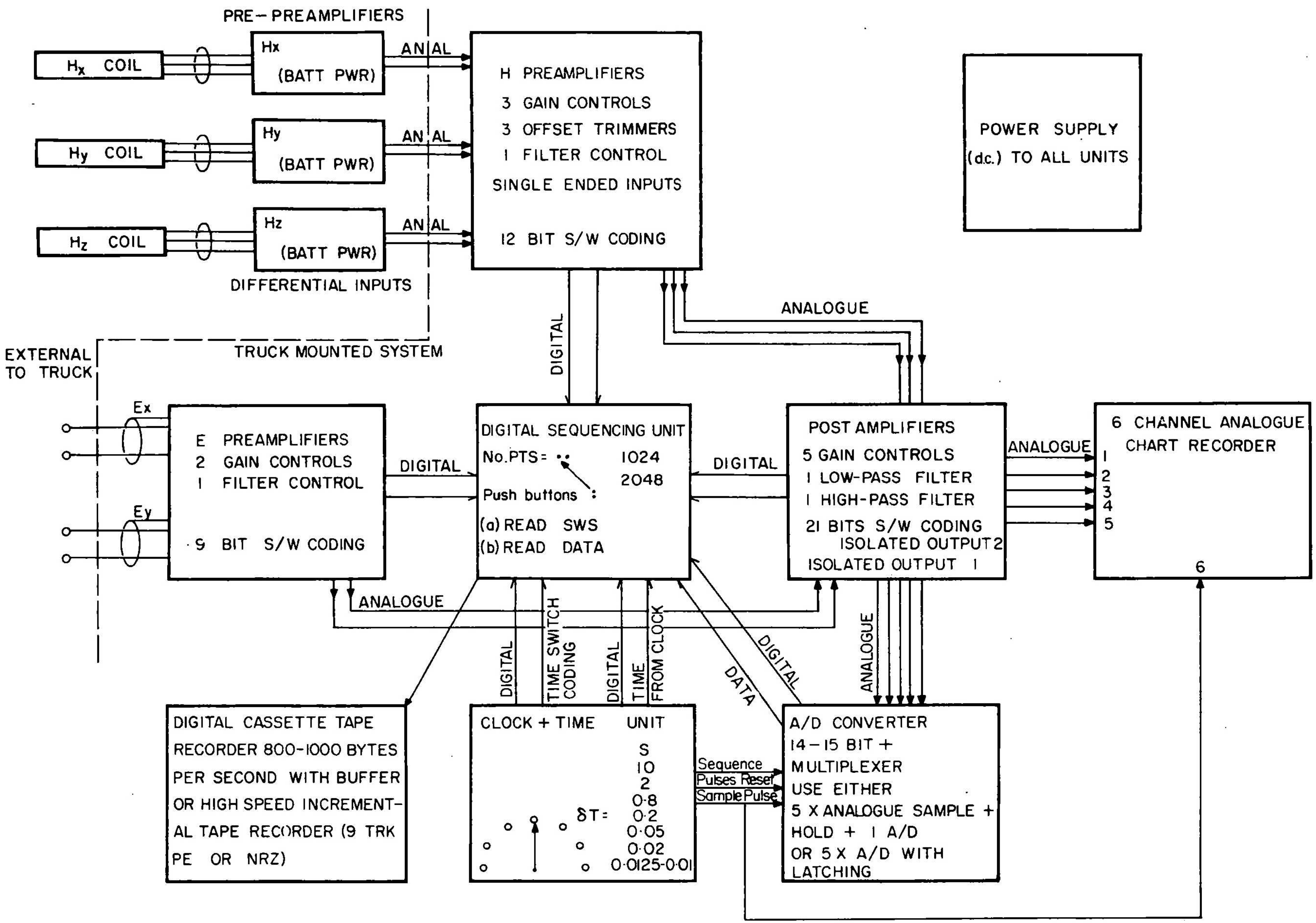
In magneto-telluric recording, filters are used for several reasons. One of the most important functions is to prevent the aliasing of high frequency signals by ensuring that these are small at the digitizing frequency. Filters provide an improvement in the dynamic range by selecting only a small portion of the spectrum for digitising at any particular time. Noise may be reduced by use of the narrow passband but is increased again later with the application of the inverse/filter transfer-functions. The reduction of high frequencies outside the particular passband being used is the most important of the filter functions, high cut filter characteristics should therefore be of third order (i.e. 60 dB/ decade or 20 dB/octave). If possible, placement of the high cut filter before the low cut filter will result in any signals aliased into the lower part of the passband being reduced more than if the filter order was reversed. Wherever possible, filters with a large time-constant should be placed before variable gain stages to prevent transients with a large associated time constant being produced every time gain is altered. Noise input for the post-amplifiers should be commensurate with pre-amplifier noise output. At minimum gain of x 10 for the preamplifier, output noise will be approximately 10-20 uV peak to peak in the 1-25 Hz range. An input noise figure of 5-10 uV peak to peak would then be satisfactory for the postamplifier when fed from the preamplifier output impedance (which would normally be 5-100 approximately). Drift criteria are as stated for the E-field preamplifiers and would normally dictate chopper stabilization. There is no need for a response extending to DC in the postamplifiers and the required response would be conveniently provided by a high-pass characteristic at 0.001 Hz (the suggested minimum filter break-point).

Suggested filter breakpoints are as follows for low-pass: 0.012, 0.033, 0.12, 0.55, 2.5, 5.0, 25.0 Hz and for high-pass; 0.001, 0.01, 0.03, 0.1, 0.55, 1.0, 5.0 Hz.

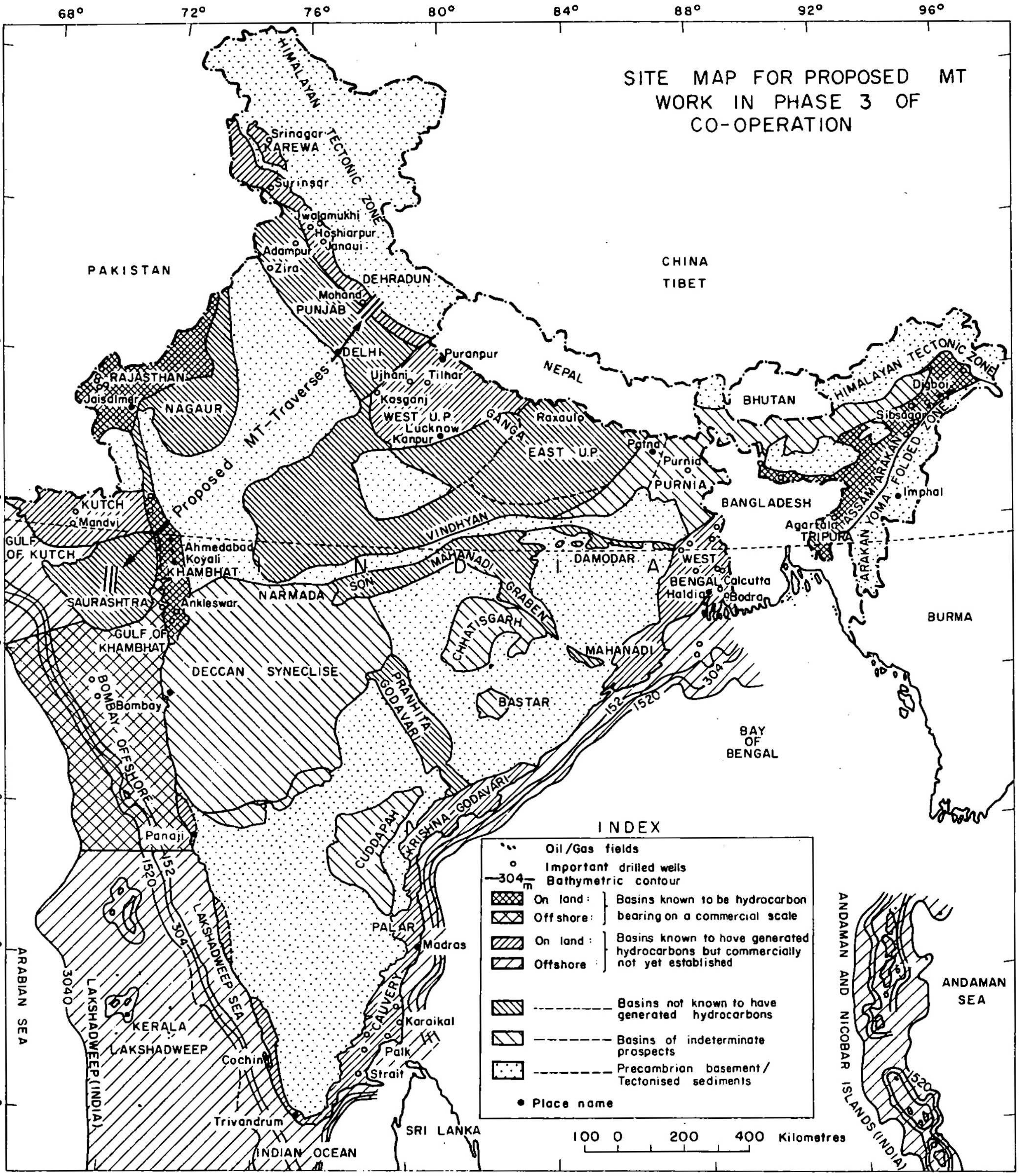
It is only necessary (unlike with the Geotronics equipment) to provide one high-pass and one low-pass filter switch for the amplifiers. As with the E and H preamplifiers, coded switch outputs should be provided for high-pass, low-pass and the five gain switches; to preserve cross-talk and stability performance, it is suggested that the coded switch outputs be used to drive miniature reed relays for filters and gain switching; a similar procedure may be employed with the E & H preamplifier.

Suggested post amplifier gains are 3, 10, 30, 100, 300, 1000. These should be adjustable to $\pm$ .1% as with the other amplifiers. Power supply for the post-amplifiers should be externally provided as for the E field preamplifiers. Output should be via good quality connectors (e.g. BNC) and two isolated outputs should be provided - one set for visual monitoring via a chart recorder and the other for feeding the A/D converter for data acquisition.

DIGITAL MT DATA ACQUISITION SYSTEM



Appendix H



SITE MAP FOR PROPOSED MT WORK IN PHASE 3 OF CO-OPERATION
68°
72°
76°
80°
84°
88°
92°
96°
36°
32°
28°
24°
20°
16°
12°
8°
HIMALAYAN TECTONIC ZONE
Srinagar
KAREWA
Surinsar
Jwalamukhi
Hoshiarpur
Janauri
Adampur
Zira
DEHRADUN
Mohand
PUNJAB
DELHI
PAKISTAN
CHINA
TIBET
NEPAL
BHUTAN
HIMALAYAN TECTONIC ZONE
Digboi
Sibsagar
ASSAM ARAKAN YOMA FOLDED ZONE
Imphal
RAJASTHAN
Jaisalmer
NAGAUR
Proposed MT-Traverses
Puranpur
Ujhani
Tilhar
Kasganj
WEST U.P.
Lucknow
Kanpur
GANGA
Raxaul
EAST U.P.
Patna
Purnia
PURNIA
BANGLADESH
Agartala
TRIPURA
KUTCH
Mandvi
GULF OF KUTCH
Ahmedabad
Koyali
KHAMBHAT
SAURASHTRA
Ankleswar
VINDHYAN
NARMADA
SON
MAHANADI
GRABEN
DAMODAR
I N D I A
WEST BENGAL
Calcutta
Haldia
Bodra
BURMA
GULF OF KHAMBHAT
DECCAN SYNECLISE
CHHATISGARH
MAHANADI
BASTAR
PRANHITA GODAVARI
BOMBAY OFFSHORE
Bombay
152
1520
304
BAY OF BENGAL
KRISHNA-GODAVARI
CUDDAPAH
Panaji
ARABIAN SEA
3040
LAKSHADWEEP SEA
LAKSHADWEEP (INDIA)
KERALA
LAKSHADWEEP
Cochin
Trivandrum
INDIAN OCEAN
PALAR
Madras
CAUVERY
Karaikal
Palk Strait
SRI LANKA
ANDAMAN AND NICOBAR ISLANDS (INDIA)
ANDAMAN SEA
INDEX
Oil/Gas fields
Important drilled wells
304 m Bathymetric contour
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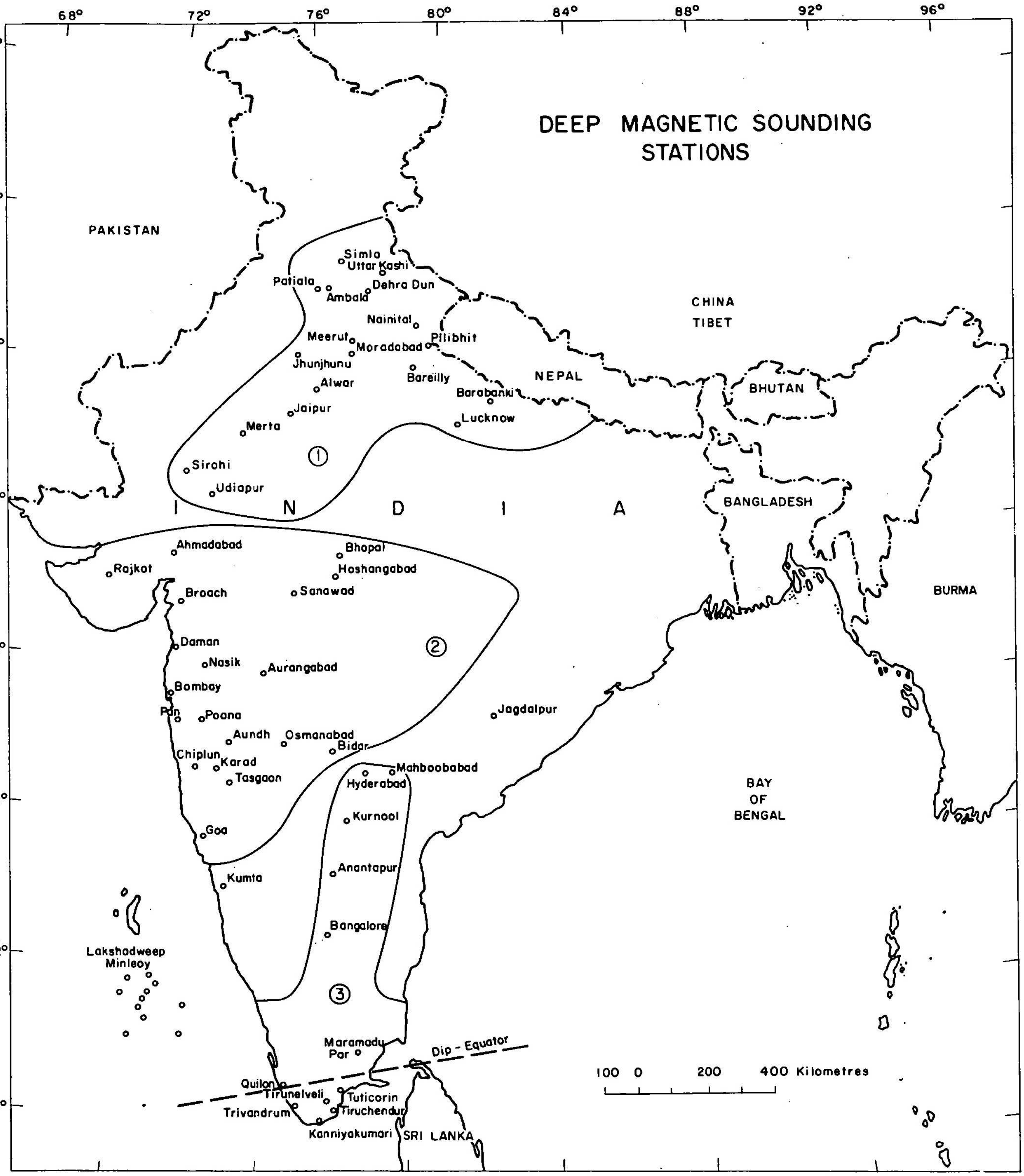
On land: Offshore: Basins known to have generated hydrocarbons but commercially not yet established
Basins not known to have generated hydrocarbons
Basins of indeterminate prospects
Precambrian basement/ Tectonised sediments
Place name
100 0 200 400 Kilometres


DEEP MAGNETIC SOUNDING STATIONS
68° 72° 76° 80° 84° 88° 92° 96°
36° 32° 28° 24° 20° 16° 12° 8°
PAKISTAN
CHINA TIBET
NEPAL
BHUTAN
BANGLADESH
BURMA
I N D I A
BAY OF BENGAL
SRI LANKA
Lakshadweep Minicoy
Simla
Uttar Kashi
Patiala
Ambala
Dehra Dun
Nainital
Meerut
Moradabad
Pilibhit
Jhunjhunu
Alwar
Bareilly
Barabanki
Jaipur
Lucknow
Merta
Sirohi
Udiapur
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Aundh
Osmanabad
Bidar
Chiplun
Karad
Tasgaon
Mahboobabad
Hyderabad
Kurnool
Goa
Kumta
Anantapur
Bangalore
Maramadu Par
Quilon
Tirunelveli
Tuticorin
Trivandrum
Tiruchendur
Kanniyakumari
Dip - Equator
① ② ③
100 0 200 400 Kilometres