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# Workshop - Determination of the Minimum Conductivity of the Earth's Crust

Summary Report
(Final)

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# RECOMMENDATIONS OF THE WORKING GROUP ON ELECTROMAGNETIC METHODS

The report describes the results of

On February 10-12, 1972, a small working group which met in the Green Center on the campus of the Colorado School of Mines to discuss the problem of measuring the minimum electrical conductivity in the earth's crust, with special reference to the possibility of long-range communications through such a low-conductivity region. The working group consisted of the following members:

Forrest Dowling (Newmont Exploration, Ltd.)
Charles Swift (Kennecott Exploration, Inc.)
Adel Zohdy (U. S. Geological Survey)
James R. Wait (National Oceanic and Atmospheric Adm.)
H. Frank Morrison (University of California, Berkeley)
Charles S. Cox (University of California, San Diego)
Stanley H. Ward (University of Utah)
Francis X. Bostick (University of Texas, Austin)
H. W. Smith (University of Texas, Austin)
Mark Landisman (University of Texas, Dallas)
George V. Keller (Colorado School of Mines)
James I. Pritchard (Colorado School of Mines)
Richard Geyer (Colorado School of Mines)

The membership of the working group includes representation from academic groups with some capability for doing crustal scale electrical soundings, and from industrial organizations with experience in measuring electrical properties in the field.

The first item on the agenda was definition of the problem. Simply stated: is there a low-conductivity channel in the crust of the earth through which electromagnetic energy can be propagated with acceptable attenuation for distances of hundreds or thousands of kilometers? However, it was decided that there are two identifiable sub-problems. The first: how may we best determine the profile of conductivity in the crust? The second dealt with prediction of transmission losses once the electrical structure of the channel is determined.

Dr. J. R. Wait described the results of theoretical studies that have been made at NOAA for propagation of VLF electromagnetic waves along layered earth structures consisting of three or four layers. These studies indicated that the curst must have a zone five to ten kilometers thick with a conductivity of less than $10^{-6}$ mhos per meter in order that ranges of several hundreds of kilometers can be achieved. The conductivity would need to be lower than $10^{-7}$ mhos per meter to permit transmission to ranges of several thousand kilometers. The studies also indicate that the presence of irregularities in the cross section of the channel or of transitional boundaries at the top and bottom of the channel will usually reduce the range. It is clear that further analytical or model studies must be carried on as further definition of the geometry of the low-conductivity channel in the crust is obtained.

Previous attempts to determine the minimum conductivity in the crust using the conventional magneto-telluric and direct-current sounding techniques have in most cases been unable to determine whether or not the minimum value is less than $10^{-4}$ mhos per meter, although a few measurements have been interpreted to indicate that the minimum conductivity must be less than $10^{-5}$ mhos per meter. In order to determine whether the low values of conductivity required to permit long range electromagnetic propagation actually exist in the crust, it will be necessary to reduce the threshhold of conductivity which may first be discriminated from zero conductivity. Therefore, the committee addressed itself to the problem of the precision with which we can now first distinguish a non-zero conductivity in the crust from zero conductivity, using state-of-the-art surveying methods.

In discussing the merits of various field techniques, it was recognized that there are basically two classes of methods:

1. Methods which are capable of determining only the thickness of a resistant layer when it is embedded between much more conductive rocks; and

2. Methods which are capable of determining only the thickness-resistivity product of such a layer.

For convenience, we can term these methods either H-sensing (H being the thickness of a resistant layer) or T-sensing (T being the product of resistivity and thickness for a layer). The magneto-telluric method is the best known of the H sensing methods, while DC resistivity sounding is the best known of the T sensing methods. In principle, at least, it is possible to determine the minimum conductivity in a three-layer sequence by using both types of sounding method. In fact, the approach is not so simple, because the region of minimum conductivity in the crust is probably bounded above and below by transitional boundaries. When a discrete boundary interpretation is applied to data obtained from an earth with transitional boundaries, the equivalent discrete boundaries derived from the H-sensing and T-sensing methods will not lie at the same depths. This result usually leads to a pessimistic estimate of the minimum conductivity.

All of these factors were recognized during earlier attempts to measure the conductivity in the crust, and therefore, the question as to how we might improve our capacity for recognizing the minimum conductivity was discussed by the group. The method first discussed was the magneto-telluric method. In this, the impedance of natural electromagnetic noise is measured, usually by recording 4 or 5 components of the electromagnetic field at a survey site. The usual frequency range over which such measurements are made is from a few Hertz to a few millihertz, or even less. The depth to which the electrical structure of the earth can be determined is controlled by the skin-depth for the frequencies used. (The relationship between skin depth, frequency and conductivity is shown graphically in Figure 1).

The resolution with which the properties of the low-conductivity portion of the crust can be determined is limited by two factors; one is the conductance of the layers overlying the resistant zone (conductance is defined as the product of conductivity and thcikness for these layers), and the other is the effect of lateral inhomo-

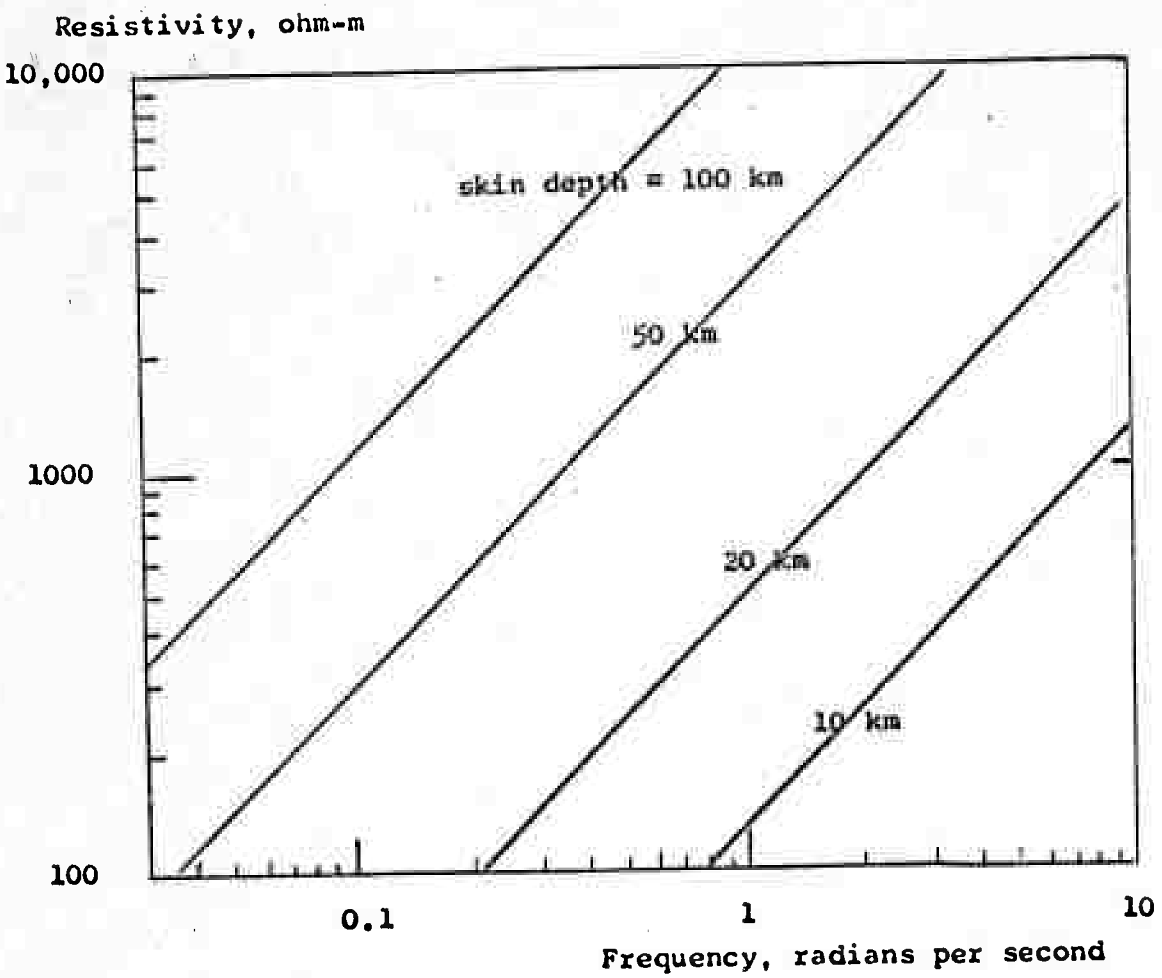

Figure 1. Skin depths for planar electromagnetic waves as a function of resistivity and frequency, in a uniform medium.

geneities in conductivity, principally in the surface layers. As a consequence, one may state that a favorable area for determining the properties of the low-conductivity portion of the crust would be one with a minimum conductance in the surface layers. Typically, a magneto-telluric sounding curve should exhibit a maximum in apparent resistivity as one goes from the high-frequency end of the spectrum to the low-frequency end. In considering the requirements for a magneto-telluric survey, the curves shown in Figure 2 are useful; these indicate the frequency at which the maximum in apparent resistivity will be observed as a function of the conductance in the surface layers and of the combined thickness of the surface layers and the resistant zone. If surveys are to be made in areas with a minimum of surface conductance, say less than 1 mho, and if the depth to the more conducting rocks beneath the crust is 50 to 100 kilometers, as is usually the case, the middle frequency for the survey should be taken as 10 radians per second. Actually, measurements should be made over a frequency range covering about two decades on either side of this mid-value. This would mean that magneto-telluric surveys should be done using a somewhat higher frequency range than is now normally in use. The extension to higher frequencies should not represent any major development problem.

In northern latitudes in particular, the assumption of a plane-wave behavior for the natural electromagnetic field is open to question. In order to avoid difficulties caused by lateral changes in resistivity or by non-planar behavior of the electromagnetic field, it will be necessary to make numerous simultaneous magneto-telluric soundings over a region in which the conductivity-depth profile is under study. Simultaneous measurements can be used to study the structure of the incident electromagnetic field. Another advantage in using multiple

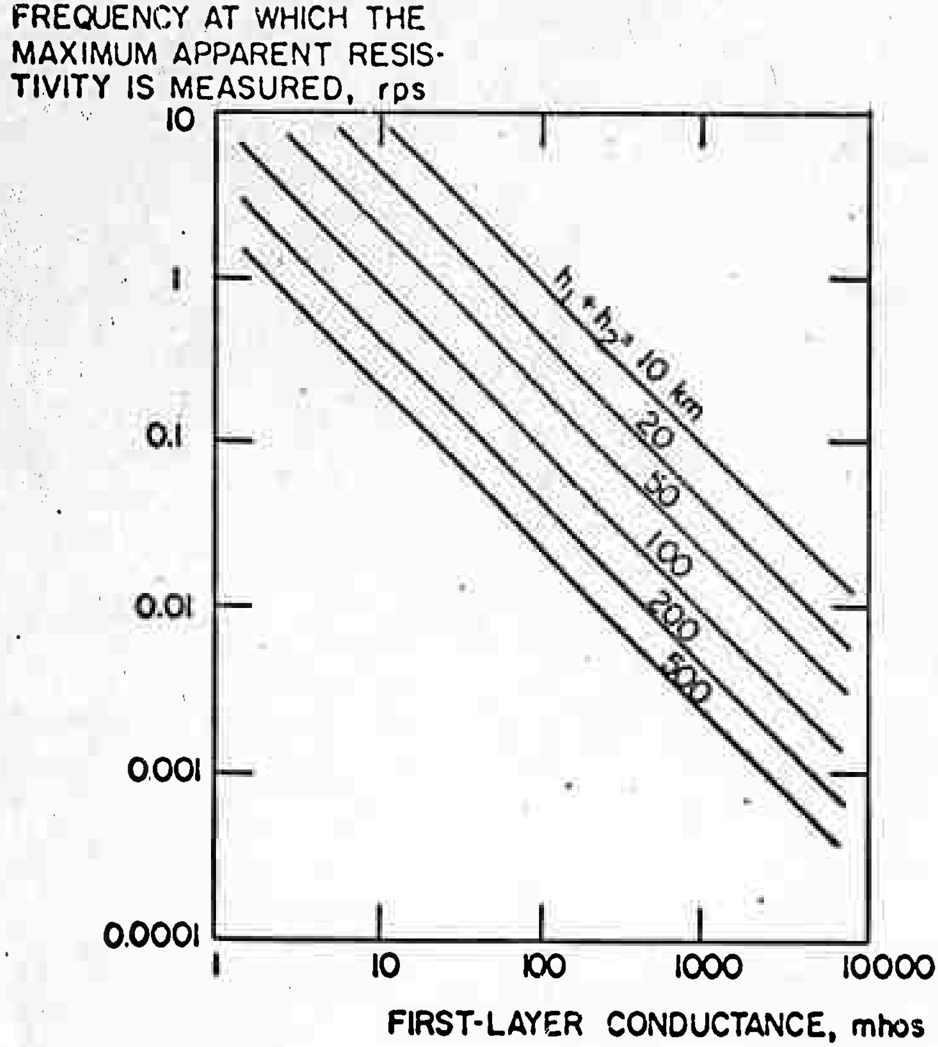

Figure 2. The frequency for which a maximum apparent resistivity will be observed on a magneto-telluric sounding made over a three-layer sequence in which the middle layer has a much higher resistivity than the other two.

magneto-telluric soundings lies in the capability for recognizing regions where lateral changes in resistivity have a minimal effect on the data, and there, interpretations in terms of planar boundaries may be applied.

The second method discussed was the direct-current sounding method and related electromagnetic methods for determining the resistivity-thickness product, T. According to the theoretical work reported by J. R. Wait, a resistivity-thickness product of $10^{10}$ ohm-meter$^2$ would be required to support minimal through-the-earth communications links, while a product of $10^{11}$ ohm-meter$^2$ would be required to achieve ranges in excess of 1000 kilometers. A number of direct-current soundings to large spacings, using both the Schlumberger array and dipole arrays, have been made in various parts of the world. In such soundings, the distance between the electrode contacts is gradually increased to provide information on the electrical structure at greater and greater depths. For a crustal-scale survey, one may expect the apparent resistivity to pass through a maximum value as spacing is increased, with the maximum value being determined by the resistivity-thickness product for the crust. As with the magneto-telluric method, the best resolution of the properties in the resistant part of the crust can be obtained when the conductance in the surface layers is low. The curves in Figure 3 show the electrode spacing (for a Schlumberger array) at which the maximum apparent resistivity indicating the presence of the low-conductivity portion of the crust is observed, as a function of $T_2$ and of the conductance in the overlying layers.

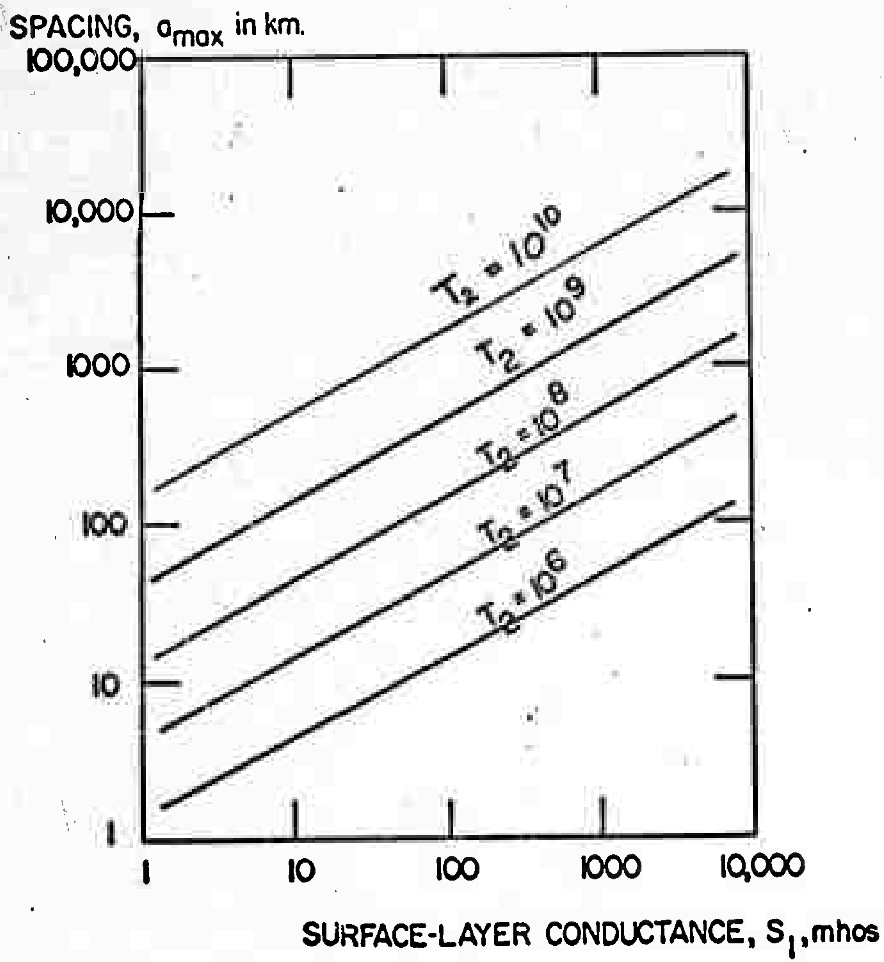

Figure 3. The spacing of a Schlumberger array that would be required to reach the maximum on a three-layer sounding curve measured over a section in which the second layer is much more resistant than the other two. This spacing depends on the conductance in the surface layer, $S_1$, and the transverse resistance in the second layer, $T_2$ (in ohm-$m^2$).

Practical considerations limit the maximum electrode spacing that is likely to be obtained to several hundred kilometers. Considering the curves in Figure 3, it is apparent that surveys must be made in areas with less than 1 mho surface conductance in order that the existence of a T product of $10^{10}$ ohm-meter$^2$ or greater can be established.

As with the magneto-telluric methods, a second factor limiting the resolution of direct-current sounding methods is the effect of lateral changes in resistivity. Over distances of several hundred kilometers, such effects are common. If a survey is done in an area with low surface conductance, the most common type of lateral change in resistivity is one in which the surface conductance inreases at the larger spacings. This will result in measuring a maximum apparent resistivity at too short a spacing, and yield an erroneously low value for T, the resistivity thickness product. All of the large-scale resistivity soundings done to date have yielded resistivity-thickness products only of the order of $10^9$ ohm-meter$^2$, but there is a reasonable probability that all of these values are low. This problem may be minimized by making redundant measurements -- that is, by making measurements at a single receiving site from multiple transmitter locations, as well as the other way around. Then, the effects of lateral changes in resistivity may be recognized, and to some extent, avoided. Still another alternative is to do a detailed survey of the near-surface variations in resistivity before laying out a deep resistivity probe. This may be done effectively using airborne electromagnetic surveying, which is capable of detecting zones of anomalous near-surface conductivity to depths of some tens of meters.

To summarize the preceeding discussions, the following strategy for determining the minimum electrical conductivity in the crust using electrical sounding methods was evolved:

1. Two sets of surveys in the same area are required, one an H-sensing survey (probably magneto-telluric soundings) and the other a T-sensing survey (probably direct-current soundings).

2. The surveys must be carried out in an area which is favorable for producing data from which a high-resolution interpretation may be made. This requirements can be translated to one in which the surface conductance must be less than 1 mho, and preferably, less than 0.1 mho. (For example, a five-kilometer thick surface sequence with a resistivity of 5000 ohm-meters would have a conductance of 1 mho). From this requirement, it is apparent that the survey will need to be carried out in an area of basement outcrop.

3. The surveys must be carried out in an area where it is likely that the zone with minimum conductivity in the crust will have as low a minimum as is reasonable to expect. This requirement translates to one in which we require a relatively low heat flow and relatively low fracturing of the crustal rocks. It is presumed that this information may be obtained from existing geological and geophysical data, or from appropriately designed seismic surveys.

4. Once an area favorable from both viewpoints has been located and the appropriate electrical soundings made, the uniqueness of the interpretation of the variation of conductivity with depth may be improved by using auxilliary methods to determine the probable rates of change of conductivity with depth at the top and bottom of the zone of minimum conductivity. The transition at the top

is probably controlled by the rate at which fractures close with increasing overburden pressure, in which case, there is some possibility that careful seismic measurements may be used to provide the required information. The transition at the base is probably temperature-controlled, and will depend to some extent on the mineralogy of the rocks. In this case, data on heat flow combined with all available information -- seismic, electrical and gravity -- on the probable lithology may help in determining the rate of change of conductivity with depth. Using only electrical sounding data, it is possible only to interpret the resistivity as a step-function of depth, even though the mathematical techniques for use with other functions are available. Using the additional information available from other type surveys, the electrical soundings may be interpreted in terms of linear transitions in resistivity, providing a more realistic representation of the actual earth.

There was considerable discussion of reasonable sites for making the necessary surveys. Areas of low surface conductance may be identified as consisting of the Canadian shield area, the batholiths of the western United States and Canada, and the Appalachian folded belt. It was felt by the group that the Canadian shield offers the best chance of finding an area of sufficient size (radius of 100 kilometers or more) for carrying out the surveys described above. One area which appears to be particularly favorable is the Barren Grounds in the northern districts of Keewatin and McKenzie, in Canada, with advantages including a virtual lack of conductive cover as a consequence of glacial scouring and of the presence of permafrost in the first few hundred meters of rock. However, rather than confine initial interest to an area so far north, alternate areas in the southern Canadian Shield, in Minnesota, Wisconsin, New York and Ontario are also considered as worthy of consideration. A higher surface conductance is to be expected in these regions because of the presence of glacial till at the surface, and it is well known that parts of the crystalline basement in these states contain highly conductive rocks.

The program of attack on the problem discussed by the group would consist of a first phase directed towards an immediate determination of a favorable site for the existence of a meaningfully low value of conductivity in the crust, a second phase involving further delineation of the favorable area if the first phase is not sufficiently definitive to warrant immediate drilling, a third phase consisting of drilling deep enough to verify the mininmum conductivity predicted from the surface-based studies, and a fourth phase consisting of drilling several holes so that a propagation experiment may be carried out. It was the feeling of the group that only the propagation experiment would provide a positive confirmation of the minimum conductivity in the crust. Also, it should be clear that at the end of any phase, there is the possibility of a negative result that would negate carrying the program further.

It was anticipated that the first phase would require 15 to 18 months to complete, inasofar as the electrical field surveys are concerned. The facilities available among the university groups and the projected costs of participation are included at the end of this report. The duration of the second phase would depend on the results obtained during the first phase, but would probably be 12 months to provide the necessary amount of geological and engineering data about a proposed drill site. It is recommended that initially a single hole be drilled to a depth of 4 to 6 kilometers, so that high-resolution electromagnetic surveys may be made in the borehole before the program is committed to drilling very deep holes for a transmission experiment. If surface-based surveys indicate that there is a high likelihood for the existence of a zone with conductivity of $10^{-6}$ mhos or less at a prospective drilling site, the accuracy and reliability with which the conductivity profile in the crust can be determined can be much improved by making measurements of electromagnetic field properties at the base of a hole that penetrates through most of the surface conductive material. Probably, the most effective experiment of this sort would involve the use of an electromagnetic field generated at the surface near the hole, with measurements of wave impedance being made at the bottom of the hole.

Once the capacity of the various surface-based measurements for determining the minimum conductivity in the crust has been determined, it is anticipated that such studies will be extended into areas along proposed communications paths to determine the continuity of the properties of the channel. Presumably, such surveys will have to be done in areas less favorable to the use of electrical methods. In this case, the use of other techniques, such as seismic velocity studies and heat flow measurements, would become more important in determining the properties of the channel with confidence.

One region where the existence of a useful communications channel would be of considerable interest and where the use of the conventional approaches outlined in the preceeding would be difficult is the world's oceans. Any attempt to measure the minimum conductivity in the crust with electromagnetic surveys made on the ocean surface will be frustrated by the very great conductance in the sea water (20,000 to 25,000 mhos, typically). Successful techniques for measuring conductivities with equipment on the sea floor have not yet been developed.

A possible approach to studying the electical properties of the oceanic crust may consist of measuring ELF electromagnetic noise on the sea floor in places where it could only have diffused out from a lithospheric channel. The deep ocean, being about 40 skin depths deep for 10 Hz signals, is opaque to noise generated above the ocean surface, and so, any electromagnetic noise seen at the bottom of deep oceans would be propagating through the ocean floor from the nearest landfall and then upwards into the ocean. The attenuation of electromagnetic noise introduced into basement rock on dry land will be less than the attenuation of electromagnetic noise traveling downward from the ocean surface for a distance from land which depends on the resistivity in the oceanic crust. If the crust

| has an effective resistivity of: | attenuations will be equal at distances equal to |
|---|---|
| 100 ohm-meters | 20 times the ocean depth |
| 1000 ohm-meters | 63 times the ocean depth |
| 10000 ohm-meters | 200 times the ocean depth |

The oceans have average depths of 4 to 6 kilometers, so that the corresponding distances from shore would be 100 to 1000 kilometers. The resistivity along the sub-ocean path must include some low resistivity material as well as the high resistivity part of the crust. The ELF electric field in the ocean should be parallel to the sea bottom, and may best be detected with a horizontal wire. The ultimate limitation to the sensitivity with which the electric field can be detected on the sea floor is the level of ELF noise from sources other than propagating electromagnetic fields.

Our recommendation for the ELF studies is in two phases. The first would involve instrument development and near shore tests to see if adequate sensitivity can be obtained, or whether electrical noise generated by wave action or microseismic action is important in limiting the sensitivity with which measurements may be made. The second phase would involve exploration of the sea bottom for ELF noise in places where it is most liekly to be found. It is thought that an area in the tropics may be best from the point of view that electrical storms on shore may be particularly effective in developing fields to propagate into the earth. An area of crystalline rock outcrop near a shoreline that is not tectonically active should provide the best geometry favoring propagation of electromagnetic waves beneath the sea. The most favorable areas for detection are areas where the conductive sea-bottom sediments are thin. Thus, suitable oceanic sites are at low latitude, close to continental batholiths which are part of the same lithospheric plates, and underlain by thin oceanic sediments. It appears that sites which satisfy these requirements may be found in the Atlantic near Brazil and Ghana and in the Pacific near Australia.

Other approaches to determining the electrical properties of the crust beneath the oceans which should be investigated further include magneto-telluric measurements on the sea floor and measurements which may be obtained by logging in deep drill holes in the sea floor. Such studies are already planned by other groups, but their significance with respect to communications should be followed. Still another alternative for measurements at sea which may be investigated further is the measurement of the leakage of natural currents from the sea through the resistant part of the crust.

A schedule of operations is given in Figure 4. The timing for the first phase can be estimated with some assurance. The schedules for later phases are subject to greater uncertainty partly because the lengths of time required to make the decisions at the end of each phase are unpredictable, and partly because the time required for drilling cannot be estimated until the drill site has been selected.

It was the strong feeling of the Electromagnetic Workshop that a firm management plan be instituted early in the program, if it is undertaken. In the case of electromagnetic studies, it will be important to coordinate the activities of each group so that on one hand, they do not interfere with one another, and on the other hand, an adequate redundancy of measurements is made at any prospective site. Coordination of the electromagnetic sounding program with the activities of other investigators, namely the seismologists, the heat-flow group and the laboratory group, along with any other peripheral studies, is even more important because the manner in which these programs can be used to augment the determination of conductivity in the crust is still somewhat experimental.

### Figure 4: Schedule of operations

| | | July 1, 1972 | July 1, 1973 | Preparation of phase 1 report | Decision with respect to site and drilling | July 1, 1974 | July 1, 1975 |
|---|---|---|---|---|---|---|---|
| 1. | Electromagnetic field studies | x x x x | x xxxxxxxx<br>xxxxxxx<br>xxxxxx | | | x x x x | |
| 2. | Direct-support refraction surveys | x x | x x x | | | x x x | |
| 3. | Airborne electromagnetic surveys | x | x x | | | | |
| 4. | Engineering and support studies at site preparatory to and along with drilling (seismic, geologic, magnetic, thermal, etc) | | | | | xxxxxxxxxxxxxxxxxxxxxxxxxxx<br>xxxxxxxxxxxxxxxx<br>xxxxxxx | |
| 5. | Development of advanced seismic interpretation schemes for determining conductivity in covered areas | x | x xx | | | x xxx | x xxxxxxxxxx |
| 6. | Drilling | | | | | x(earliest) | x(latest) |
| 7. | Laboratory studies | continuing, accelerating if drill cores become available | | | | | |
| 8. | Marine studies | continuing, accelerating if positive results are obtained | | | | | |
| 9. | Theoretical studies | continuing. | | | | | |

In a large part, the capability for doing the electromagnetic sounding program exists in several university research programs. The facilities available and projected costs for participating in Phase I of the study outlined here are as follows:

1. University of California, Berkeley, has controlled-source equipment capable of making electromagnetic soundings and direct-current soundings with source-receiver separations of 100 kilometers or more, using frequencies from .001 Hz to 100 Hz. Prof. Morrison estimates that the cost for one year of operation, including a field program with the dipole-dipole sounding technique, using 20 to 30 transmitter stations, would be approximately $40,000.

2. University of Texas, Dallas, has equipment for magneto-telluric studies and for controlled-source electromagnetic studies. Both systems may require some modification to provide the desired data from basement outcrop areas, so that field programs might not be undertaken until the latter half of phase 1. The cost, including modification of equipment, would be between $100,000 and $160,000.

3. University of Texas, Austin, has equipment for undertaking magneto-telluric studies. This equipment may need to be modified to some extent to extend the range of frequencies analyzed up into the low audio frequency range, as is required for magneto-telluric soundings over basement. The projected costs for participation

would be approximately $40,000.

4. University of Utah, Salt Lake City proposes preliminary surveys in Northern Canada using induced polarization equipment that is relatively portable to determine whether or not the apparent advantages of this location actually exist. If the surface conductance is as low as appears to be the case, the initial work would be followed up with deeper soundings using the dipole-dipole array with spacings up to 200 kilometers. However, this large scale sounding would require development of equipment capable of delivering enough current to provide a signal detectable at 200 kilometers distance. Such equipment is being designed at the University of Utah to operate over a frequency range from .001 Hz to 1 Hz. The equipment will be capable of measuring induced polarization response as well as resistivity, and Prof. Ward feels that this will be a useful supplement in identifying rock types. The cost of the initial reconnaisance of the northern Canada area is estimated to be about $50,000, but this does not include development of equipment or field operations for the large-spacing surveys.

5. Colorado School of Mines, Golden, has equipment for combined direct-current resistivity surveys and electromagnetic soundings capable of use at spacings up to 100 kilometers. The cost for a program lasting 15 to 18 months with measurements being made in an area such as the southern Canadian Shield would be between $80,000 and $100,000.

In addition to these facilities which pertain to the immediate use of electromagnetic techniques to determine the conductivity profile in the crust, certain support studies would be required, in addition to the other lines of attack detailed in the output of the Multi-disciplinary workshop. Two items of support to the electromagnetic sounding program during phase 1 would be:

Airborne electromagnetic surveys. It is possible to measure conductivity to a depth of only a few tens of meters from the air. However, such surveys may markedly reduce the effort required in ground-based surveysby providing information about the locations of surficial conductive areas. Such areas can be used as locations for controlled-source equipment, and such areas must be avoided with both the controlled-source and natural-field receiving equipment. A reasonable reconnaisance of areas where deep soundings are planned might require the expenditure of from 50,000 to $100,000 for airborne electromagnetic surveying.

Seismic refraction surveys. It has been suggested that refraction surveys may be extremely useful in interpreting electrical sounding data if the depth of surface fracturing can be estimated from the seismic data. An adequate amount of seismic refraction surveying should be combined with the electromagnetic sounding program to evaluate this possibility.

If the above estimates are combined, one arrives at the conclusion that an electromagnetic sounding program with its immediate supporting studies would cost between $500,000 and $850,000 during phase 1. Such a study should provide reasonably clear evidence about the probability of conductivities less than $10^{-6}$ mhos per meter existing at several sites. This information might then be used in making a decision to drill, if the presence of a zone with a