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Preliminary Report on Crustal Magnetotelluric Measurements

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Some preliminary work on the determination of the earth's electric conductivity structure through simultaneous measurements of the natural electric and magnetic fields is reported in this letter. *Cagniard* [1953] coined the name 'magnetotelluric' for studies of this type. The present work was confined to frequencies of .005 to 1 cps, having skin depths distributed through the crust.

Magnetotelluric studies have been underway in the M.I.T. Geophysics Laboratory for several years. *Nevés* [1957] studied two-dimensional effects, and more recently the measurements described here were made [*Cantwell,* 1960]. Further field investigations are under way at this time, and will be incorporated in a more complete paper in the near future.

The idea of using geomagnetic and geoelectric measurements in combination to elucidate the electric conductivity structure of the earth is one that a number of investigators have studied. *Cagniard* [1953, 1956] has perhaps put the theory in its most satisfactory form. Useful field results have not been numerous in the literature, and field magnetotellurics is still in the developmental stage. This letter reports on some field measurements made in the latter part of 1959 and incorporates an analysis of the data based on two-layer master curves by *Cagniard* [1953].

To treat the magnetotelluric fields and their interaction with the earth, we assume them to consist of plane waves. The validity of the assumption depends on having these fields uniform over wide areas, and evidence for this uniformity has been summarized by *Cagniard* [1956] and reported by others.

The magnetotelluric method allows each measurement to be independent of other measurements. The impedance normal to the earth is defined as the ratio of the tangential electric field intensity to the tangential magnetic field intensity, and it is these tangential fields that are measured. For a plane wave incident on a uniform earth the ratio of tangential E to tangential H is given by

$$E_x/H_y = (\rho\mu\omega)^{1/2}e^{i\pi/4}$$

where ρ is the resistivity in ohm-meters, μ is the permeability in henrys/meter, ω is the radial frequency, E_x is the electric field in the x-direction (say north), and H_y is the magnetic field in the y-direction (say east). Determining this ratio for a uniform earth gives an interpretation of the conductivity, since μ is generally constant.

In the two-layer case the formula is modified so that the phase angle and the apparent resistivity vary as a function of the frequency. Master curves for this two-layer case were presented by *Cagniard* [1953].

Our field measurements were largely confined to Massachusetts, with the majority of the data

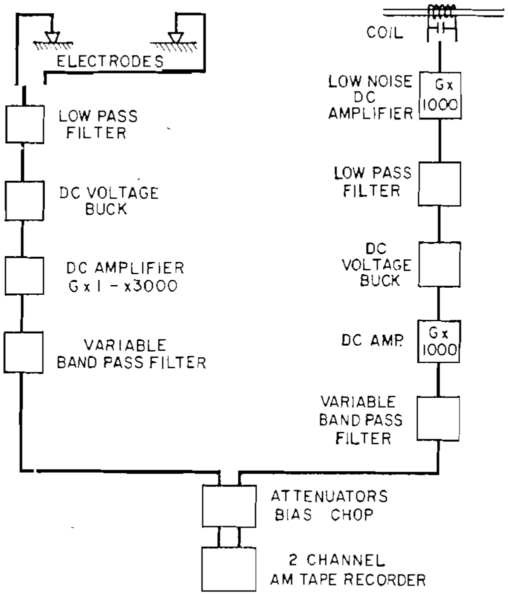

Fig. 1. Instrumentation for magnetotelluric field measurements.

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obtained at Littleton, Mass. The field instrumentation is shown schematically in Figure 1.

The electrode spacing was at least a kilometer, giving easily detectable electric fluctuations. The magnetic pick-up coil consisted of 90,000 turns of wire on a 5-foot, Permalloy bar, 1 inch in diameter. This produced 0.25 mv/γ/sec and the over-all sensitivity was .003 γ/sec in an octave band. In practice, this sensitivity was sometimes difficult to achieve owing to mechanical motion of the coil.

The instrumentation system was chosen to allow small signals to be extracted from a larger background of extraneous signals. The band-pass filters allowed examination of narrow frequency bands. Typical bands studied were .005 to .02 cps, .02 to .06 cps, .06 to .2 cps, and .6 to 1 cps. The system as tested in the laboratory had a dynamic range of 60db in the frequency bands of interest.

The magnetic tapes produced in the field were played back in the laboratory onto dual-channel paper-tape records. These records were then digitized for computer use.

The analysis of the records was done by performing power spectral estimates using standard statistical techniques [*Robinson*, 1954; *Blackman and Tukey*, 1958]. The most important advantage of these methods, which are based on the auto- and cross-correlations of the data, is that an estimate of the coherency between the electric and magnetic signals is obtained. It is possible for the signal received from the magnetic transducer to be not due to magnetic fluctuations, and it is also possible for the electric signals to be not due to current flow in the earth. Such spurious signals may be considered to be noise, and they would lower the coherency between the electric and magnetic signals. Noise tests performed in the field indicated that the magnetic system is the most likely to produce false signals. Most of this noise is due to mechanical instability of the coil mounts and can be reduced by proper supports. Robinson states that an expression for the coherency is

TABLE 1. Sample Coherency Analyses

Record No.	Frequency, cps	Δf, cps	Coherency Amplitude	Coherency Phase, deg
27-4	.010	.0025	0.89	−2
(.005-.02)	.012	.0025	0.82	−3
cps	.015	.0025	0.63	−70
	.017	.0025	0.76	−36
	.020	.0025	0.84	−31
27-5	.020	.005	0.91	−18
(.02-.06)	.025	.005	0.87	−19
cps	.030	.005	0.81	−26
	.035	.005	0.86	−36
	.040	.005	0.91	−42
	.045	.005	0.87	−38

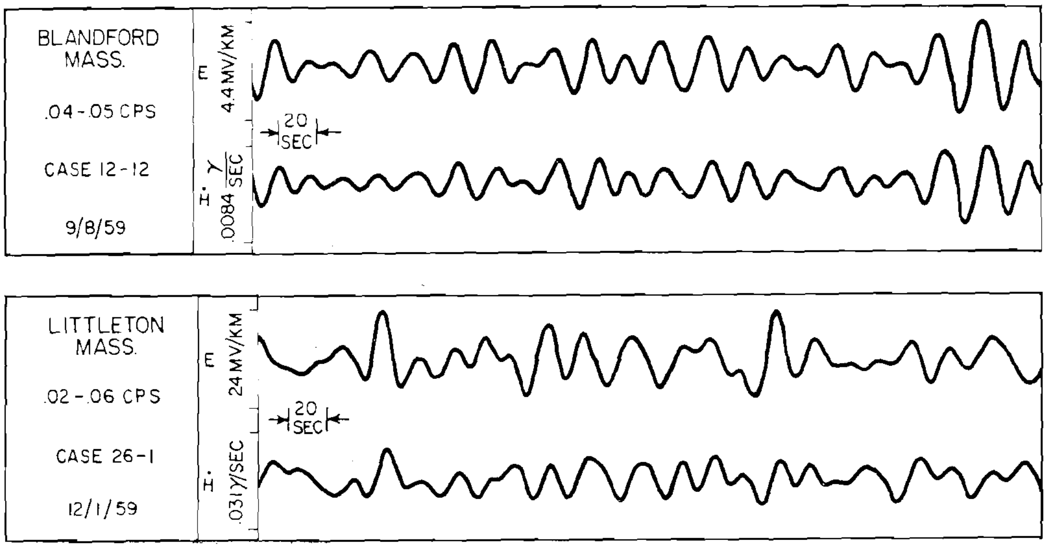

Fig. 2. Electric-magnetic records.

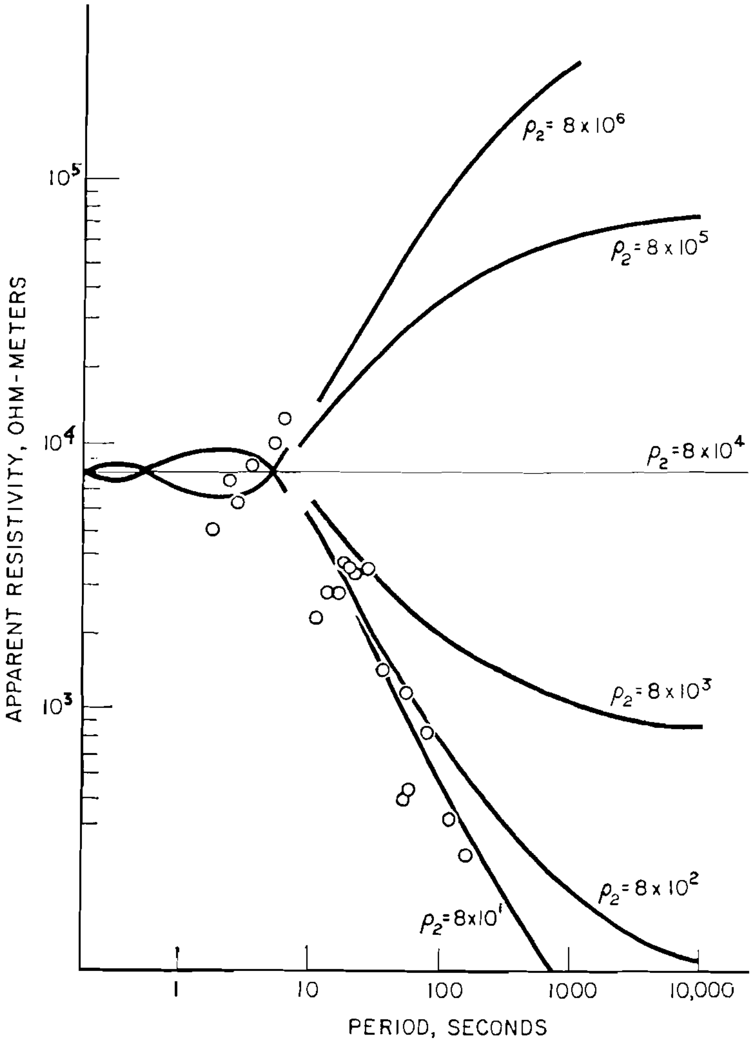

Fig. 3. Apparent resistivity versus (period)$^{1/2}$. Magnetotelluric data from Littleton and Cagniard two-layer curves.

$$\mathrm{coh}_{xy}(\omega) = \Phi_{xy}(\omega)/\sqrt{\Phi_{xx}(\omega)\Phi_{yy}(\omega)}$$

where $\Phi_{xy}(\omega)$ is the power spectrum of the x-y cross-correlation and $\Phi_{xx}(\omega)$ and $\Phi_{yy}(\omega)$ are the power spectra of the autocorrelations. Perfectly coherent signals would produce a $\mathrm{coh}_{xy} = 1.0$. The magnetotelluric records often gave coherency values of 0.8 or better in the passband. Highly coherent magnetotelluric records have the following characteristics:

1. Different records at the same location give consistent estimates of the resistivity.
2. The apparent resistivities calculated are smoothly varying as a function of frequency.

Typical records are shown in Figure 2. Sample coherency analyses are shown in Table 1. The calculations were performed on the IBM 704 at the M.I.T. Computation Center.

Nine records having good coherency were used in obtaining the plot shown in Figure 3. This plot can be interpreted as is done in *Cagniard* [1953] if a two-layer model is assumed. The first step in such an interpretation is the assumption of a resistivity for the upper layer. The magnetotelluric data did not extend to high enough frequencies to determine the near-surface resistivities, but resistivity measurements made by *Slichter* [1934] and *Hauck*

[1960] indicate that a value of 8000 ohm-meters is not unreasonable [*Hauck,* 1960].

If this value is used for the resistivity of the upper layer, the two-layer interpretation yields a value of 70 km for the upper-layer thickness. The resistivity of the lower layer is estimated to be less than 80 ohm-meters.

The two-layer interpretation fits the data reasonably well, but it is not suggested that the earth's conductivity structure is as simple as this. The fit of the data does indicate that a rapid change of resistivity with depth must occur at around 70 km. The lower limits of resistivity cannot be determined until data involving lower frequencies are analyzed.

The interpretation is also subject to error because of the inaccuracies of the data and the complications of an inhomogeneous earth. Some preliminary calculations on the effect of horizontal variations of conductivity show that the ocean would not have much effect on the readings recorded. Superficial conductivity variations under the electric line can produce large errors, however. It is doubtful in this case that the apparent resistivity values can be assigned a standard deviation of less than a factor of 2. It is hoped that further work will improve the techniques.

Several interesting questions have arisen as to the validity of the interpretation. The assigning of the upper layer resistivity to be 8000 ohm-meters does not have much effect on the interpretation of the location of the apparent discontinuity in resistivity, but it does lead to implications concerning the electrical environment in the crust. If this low figure can be demonstrated to be valid, it would seem to imply that some porosity still remains in the deeper crustal rocks.

The sharp break in resistivity to a still lower value at a depth of 70 km may be explained on the basis of temperature effects. Using various temperature models given recently by *MacDonald* [1959] and laboratory data on mineral conductivities [*Hughes,* 1953], one can predict resistivity profiles not unlike the two-layer model. The near-surface conductivity must involve other conductivity mechanisms, however, which we believe to be attributable to a small residual porosity.

More data and better analysis of the data are necessary before attempting geologic interpretations of these magnetotelluric results, but the technique appears to hold some promise. Magnetotelluric investigation of the earth's electrical conductivity structure over a larger continental area is now in progress.

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REFERENCES

Blackman, R. B., and J. W. Tukey, *The Measurement of Power Spectra,* Dover Publications, New York, 190 pp., 1958.

Cagniard, L., Basic theory of the magnetotelluric method, *Geophysics, 8,* 605–635, 1953.

Cagniard, L., Electricite tellurique, *Handbuch der Physik, 47,* 407–469, 1956.

Cantwell, T., Detection and analysis of low frequency magnetotelluric signals, Ph.D. thesis, Geology and Geophysics, M.I.T., 170 pp., 1960.

Hauck, A. M., Deep structure resistivity measurements in Massachusetts, M.S. Thesis, Geology and Geophysics, M.I.T., 57 pp., 1960.

Hughes, H., The electrical conductivity of the earth's interior, Ph.D. Thesis, University of Cambridge, 1953.

MacDonald, G. J. F., Calculations on the thermal heating of the earth, *J. Geophys. Research, 64,* 1967–2000, 1959.

Nevés, A. S., The magnetotelluric method in two-dimensional structures, Ph.D. Thesis, Geology and Geophysics, M.I.T., 122 pp., 1957.

Robinson, E. A., Predictive decomposition of time series with applications to seismic exploration, Ph.D. Thesis, Geology and Geophysics, M.I.T., 255 pp., 1954.

Slichter, L. B., An engineering problem in geophysics, *Tech Engineering News,* M.I.T. Cambridge, Mass., 8–9, 1934.

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