TECHNICAL REPORT. 1 Jul 75-30 Sep 80.

on

THE ELECTRICAL CONDUCTIVITY OF THE CRUST
OF THE EASTERN UNITED STATES.

11) 14 Nov 80

Institution: Department of Earth and Planetary Sciences
              Massachusetts Institute of Technology
              Cambridge, Massachusetts 02139

Principal Investigator: Gene/Simmons

Scientific Collaborators: Lou/Caruso and Frank/Miller

Contract Title: Physical Properties of Deep Crustal Rocks

Contract Number: N00014-76-C-0478

Period: 1 July 1975 through 30 September 1980

Submitted: 14 November 1980

THE ELECTRICAL CONDUCTIVITY OF THE CRUST OF THE EASTERN UNITED STATES

by
Gene Simmons,
Lou Caruso,
and
Frank Miller

Department of Earth and Planetary Sciences
Massachusetts Institute of Technology
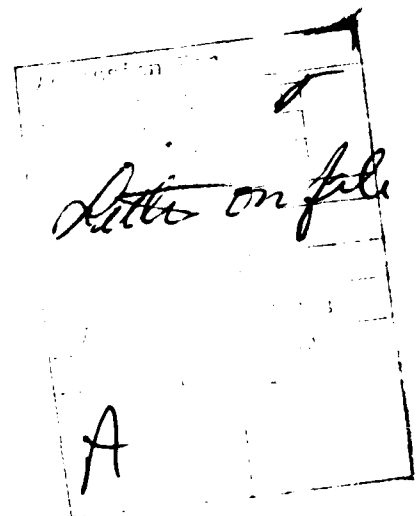Cambridge, Massachusetts 02139

14 November 1980

TABLE OF CONTENTS

INTRODUCTION

Knowledge of the electrical structure of the crust is important for both scientific and practical purposes. First, the electrical structure is likely the result of the tectonic history of a region and therefore reflects tectonic structures. Because our knowledge of both the electrical structure and the tectonic structure is incomplete, an increase in coverage in one data set can be used to fill gaps in our knowledge of the other data set. Second, the presence of a resistive layer at depth bounded above and below by rock of higher conductivity (which is likely for the eastern United States) might provide a waveguide useful for lithospheric electromagnetic wave propagation (see, e.g., Wheeler, 1961; IEEE, 1963; deBettencourt, 1966). The concept of using lithospheric waveguides an an integral part of hardened communications systems has obvious military applications. Third, departures from average conductivity for a region are useful in prospecting for minerals, oil and gas, and geothermal resources.

The electrical properties of the crust can be measured directly in the field or estimated for *in situ* conditions from suitable measurements made in the laboratory. Each approach has both advantages and disadvantages. Field measurements made from the surface of the earth are relatively expensive, must penetrate a conductive layer and then 'see' a resistive layer (that may differ by several orders of magnitude in conductivity), and are often affected significantly by large lateral changes in the conductivity of shallow rocks. In addition, because the rocks through which the electromagnetic waves propagate cannot be characterized adequately, the measurements made at one locality can seldom be extrapolated reliably to other geologic regions. By contrast, measurements made in the laboratory are relatively inexpensive, can be made rapidly, and the samples can be characterized with standard techniques. Unfortunately,

removal of rocks from their _in situ_ location often changes significantly the characteristics of the rock that control the electrical conductivity; modelling those characteristics has been uncertain in the past. Thus, the problems that are inherent in the use of data measured in the laboratory to infer electrical properties of rocks _in situ_ in the earth's crust are (1) preventing sample bias, (2) duplicating the condition of rock _in situ_ and at depth (including pressure, temperature, and several other variables), and (3) modelling the properties of the pore fluids.

In this paper, we report new data obtained in the laboratory for several representative samples from the eastern United States. We believe that we have modelled properly all characteristics of the samples that affect significantly the electrical properties. We use the data to estimate a standard electrical model for the upper crust of the eastern United States.

ELECTRICAL LOSSES IN ROCKS

Electrical losses in rocks over the frequency range 100-50,000 Hertz are dominated by three mechanisms: (1) electrolytic conduction through fluids that are present in microcracks, (2) interfacial polarization, and (3) thermally activated mechanisms. Each of these mechanisms is dominant in a different section of the upper crust. At shallow depths, where the microcracks are physically open, interconnected, and filled with electrolytes, the conductivity is high and conduction occurs mainly through the electrolytes. At intermediate depths, where the open microcracks are greatly reduced in both number and volume, the chief electrical loss mechanism is that of interfacial polarization. At depths where temperatures exceed approximately 300°C, thermally activated mechanisms dominate.

Electrolytic Conduction

Most rocks that occur at (or near) the surface of the earth contain abundant open, healed, and sealed microcracks. A typical example is shown in figure 1. The open microcracks are readily observed with the scanning electron microscope (Simmons and Richter, 1976; Richter and Simmons, 1977) and their effects on physical properties are well-known (for examples, see Birch, 1960, 1961; Brace, 1965; Morlier, 1971; Feves et al., 1977). Formerly open microcracks, seen as surfaces of fluid inclusions, or as thin volumes that are partially or completely filled with new mineral growths, occur ubiquitously (Simmons and Richter, 1976; Richter and Simmons, 1977). In the earth, the open cracks, filled with electrolytes, provide the paths for large conduction. The sealed and healed microcracks, on the other hand, do not contribute to the conductivity through electrolytic conduction.

The open microcracks in laboratory samples can be closed readily with the application of hydrostatic pressure - a technique that has been used extensively

Figure 1. Typical microcracks in igneous and metamorphic rocks. This micrograph was obtained with a scanning electron microscope using backscattered electrons. The mineral grains are readily distinguished by contrasts in mean atomic number, revealed by differing brightness in this micrograph. From highest to lowest Z, brightest to darkest, the minerals are garnet, feldspar, amphibole. Abundant microcracks can be seen at this magnification; they are all completely sealed with 'new' mineral growths. In other rocks open microcracks have similar appearances but do not contain sealing minerals.

to determine the effect of pressure on various physical properties of rocks (Birch, 1960, 1961; Brace, 1965; Simmons et al., 1974; Siegfried and Simmons, 1978, for example). If the microcracks that are present in the rocks in situ behaved exactly as the microcracks in laboratory samples, then the application of pressures in the laboratory would provide the basis for an exact analogue experiment. However, the abundance of healed and sealed microcracks in all rocks provides evidence that the microcracks in the earth when closed mechanically also become 'closed chemically'. They fill either with the same mineral as the host grain (and are termed healed) or a different mineral from the host (and are termed sealed). The chemically closed microcracks differ significantly from the open and mechanically closed microcracks in their effects on certain properties (for example, electrical conductivity and hydraulic permeability). The mechanically closed cracks have two surfaces (and therefore surface conduction). Because the opposite sides never match perfectly, thin films of interconnected electrolytes are present throughout the rock. Therefore, the laboratory experiment in which microcracks are closed mechanically only is not a satisfactory analogue for the measurement of electrical properties of rocks in the earth. An indirect means must be used to obtain satisfactory estimates of the variation of electrical conductivity with depth in the earth.

In figure 2, we show a typical curve of the pressures at which cracks close mechanically in the laboratory. The curve was derived from precise strain measurements as a function of pressure. The technique, termed differential strain analysis, is described by Simmons et al. (1974) and Siegfried and Simmons (1978). It has been used to measure the closure properties of cracks in approximately 200 samples. The curve in figure 2 indicates the volume of cracks, at pressure P=0, that will close mechanically between P and P+dP. Most cracks in basement-type rocks are closed by a pressure of 200 to 300 bars;
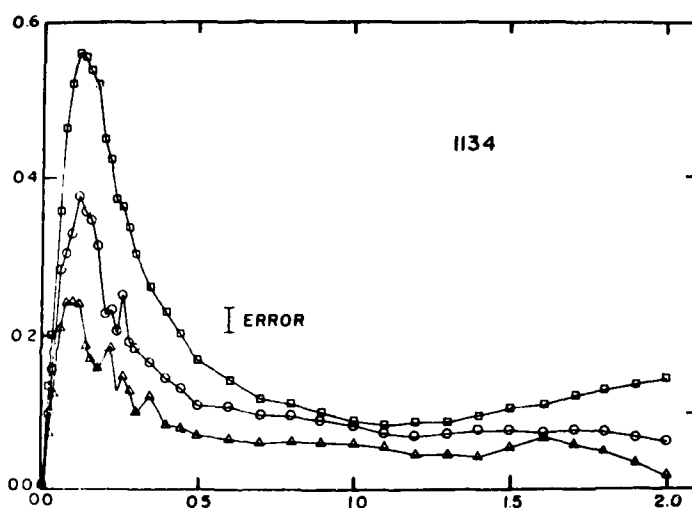
Figure 2. Crack closure spectra in three orthogonal directions for the Westerly granite. The abscissa is the crack closure pressure in units of kilobars and the ordinate is $\nu(P) = P(d^2\hat{\varepsilon}/dP^2)$ in units of per megabar where $\hat{\varepsilon}$ is the difference in strain between the sample and fused silica. Note that $\nu(P)$ dP is the porosity at zero pressure due to cracks closing between pressure P and P + dP. The total area under the three curves is the total crack porosity. The interpretation of these curves is that the area under each curve between pressures P and P + dP is the strain (at P = 0) of all cracks that will close mechanically between pressures P and P + dP. (After Feves et al., 1977.)

all cracks are closed by a pressure of approximately 1 kilobar. Therefore, the cracks in rocks would be mechanically closed at depths corresponding to approximately 3 to 5 km. The exact depth depends upon the rock type, nat re of cracks in the rock, and the pore pressure present in the rock _in situ_. The data used to obtain the curve of figure 2 can also be used to obtain the crack porosity that is present in the rock at pressure. If we convert pressure to depth according to the relation $P = 267 H$, where H is depth in kilometers and P is pressure in bars, then we obtain the typical curve for crack porosity as a function of depth shown in figure 3. The proper interpretation of this curve is that it shows the volume of cracks present at a given depth in the earth on the basis of laboratory experiments. Many of the cracks would become completely and chemically closed in a geologically short interval of time (say a few years to perhaps a few hundred years). Therefore, the curve shown in figure 3 represents the maximum crack porosity that one would expect to obtain _in situ_.

In figure 4, we show an empirical relation between the electrical conductivity of rocks and the crack porosity. This curve is based on two sets of data. The first set, reported by Feves _et al_. (1977), was obtained by measuring the electrical conductivity and crack porosity of a suite of samples in which the only independent variable was crack porosity. Samples of Frederick (MD) diabase were heated to different temperatures in order to produce varying volumes of microcracks in the samples (see Simmons and Cooper, 1978). The second set of data was obtained by measuring both conductivity and crack porosity of natural cracks on a suite of igneous and metamorphic rocks. Both mineralogy and crack porosity were independent parameters and varied over significant ranges in this suite of samples. The first set of data shows considerably less scatter than the second set. In addition, we have shown two data points for the natural

8

Figure 3. Variation of crack porosity with depth for Westerly granite. This curve, derived from the same data as the curve in figure 2, represents the crack porosity for a sample in situ. It is obtained with the implicit assumption that no chemical sealing occurs in the cracks and the 'granite' curve therefore represents an upper bound on the crack porosity for rock in situ. Most other igneous and metamorphic rocks have smaller crack porosity at each depth.
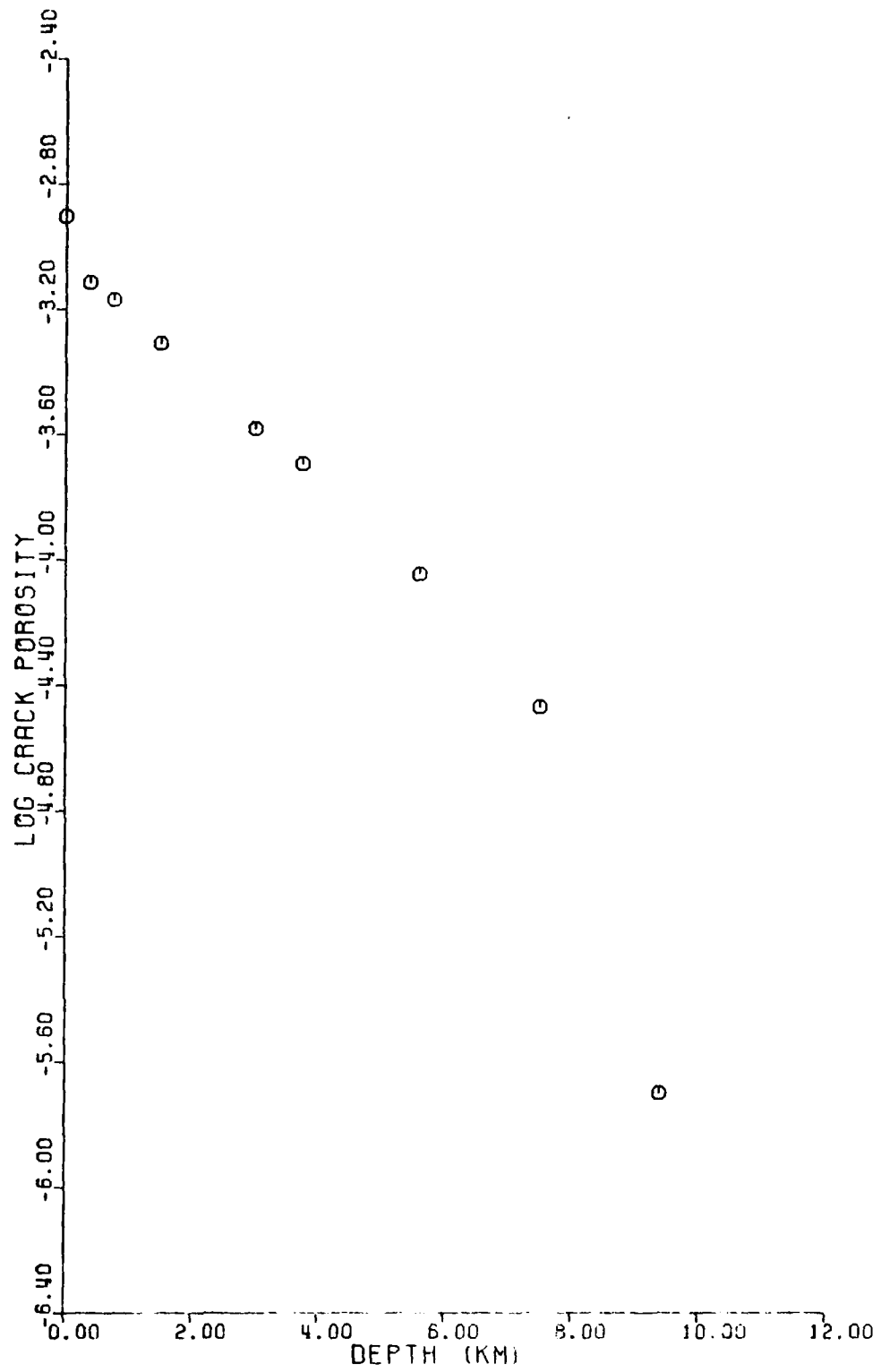
Figure 4. Electrical conductivity as a function of crack porosity. This *conductivity is due to electrolytic conduction in the microcracks.* A solution of 0.1N NaCl filled the cracks at the time of measurement. The circles are the original data of Feves et al. (1977); the triangles represent new data obtained on naturally occurring microcracks. The line is the original curve of Feves et al.
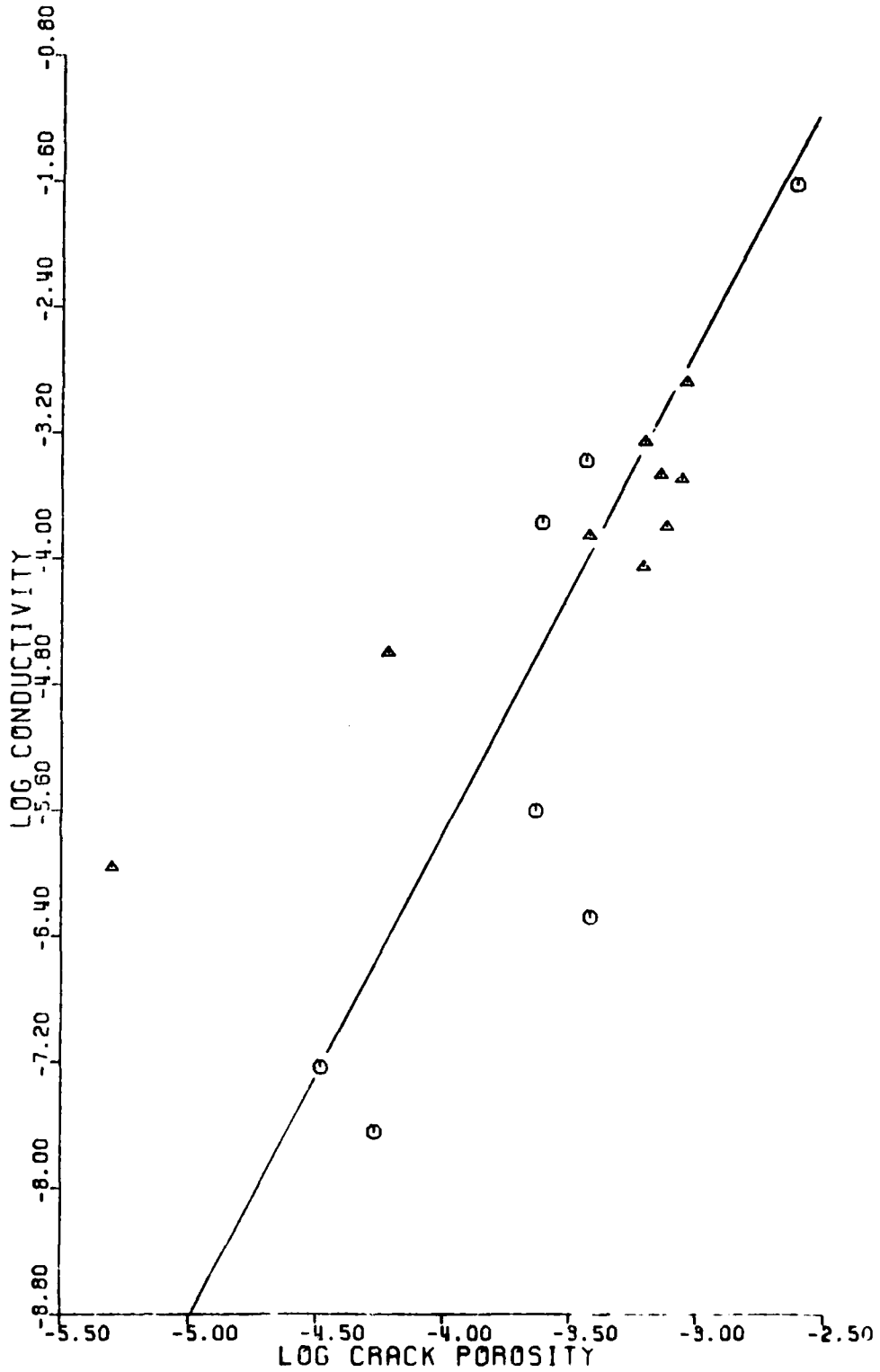
occurring cracks, but have neglected them in deriving the equation for the line. We suggest that the functional relation shown in figure 4 used with the curve for the distribution of crack porosity with depth, shown in figure 3, provides a realistic estimate of the upper bound on electrical conductivity as a function of depth for the rock in the earth's crust that is due solely to electrolytic conduction through the microcracks. The resulting variation of conductivity with depth is shown in figure 5.

Interfacial polarization

Interfacial polarization is the process of accumulation of charge at boundaries between regions of differing dielectric properties. It is always present in composite samples. In the case of rocks, the losses due to interfacial polarization are usually smaller than the losses due to electrolytic conduction and to thermally activated loss mechanisms. However, if the conduction by electrolytes is small and the temperature is below 300°C, then the losses due to interfacial polarization dominate. In Table 1, we give the relative dielectric constant and the electrical conductivity at two frequencies (100 and 50,000 Hertz) for a set of 5 igneous and metamorphic rocks that are representative of a larger set (reported by Simmons et al., 1980). The dielectric losses at these frequencies for rocks with no microcracks and at temperatures below 300°C are chiefly due to interfacial polarization. The conductivities are of order of 10^{-9} and 10^{-7} mho/m at the frequencies of 100 and 50,000 Hertz, respectively.

Effect of temperature

Several authors, including Olhoeft (1980), have measured the electrical conductivity of rocks as a function of temperature. In figure 6, we show typical results for a granite (Olhoeft, 1980). At a temperature of 200°C, the conductivity is below the conductivity associated with interfacial polari-

13

Figure 5. Electrical conductivity (due to electrolytic conduction in micro-cracks) as a function of depth for Westerly granite. This curve was obtained directly from the curves given in figures 3 and 4. The conductivities of other igneous and metamorphic rocks are lower by 1 to 3 orders of magnitude at each depth.
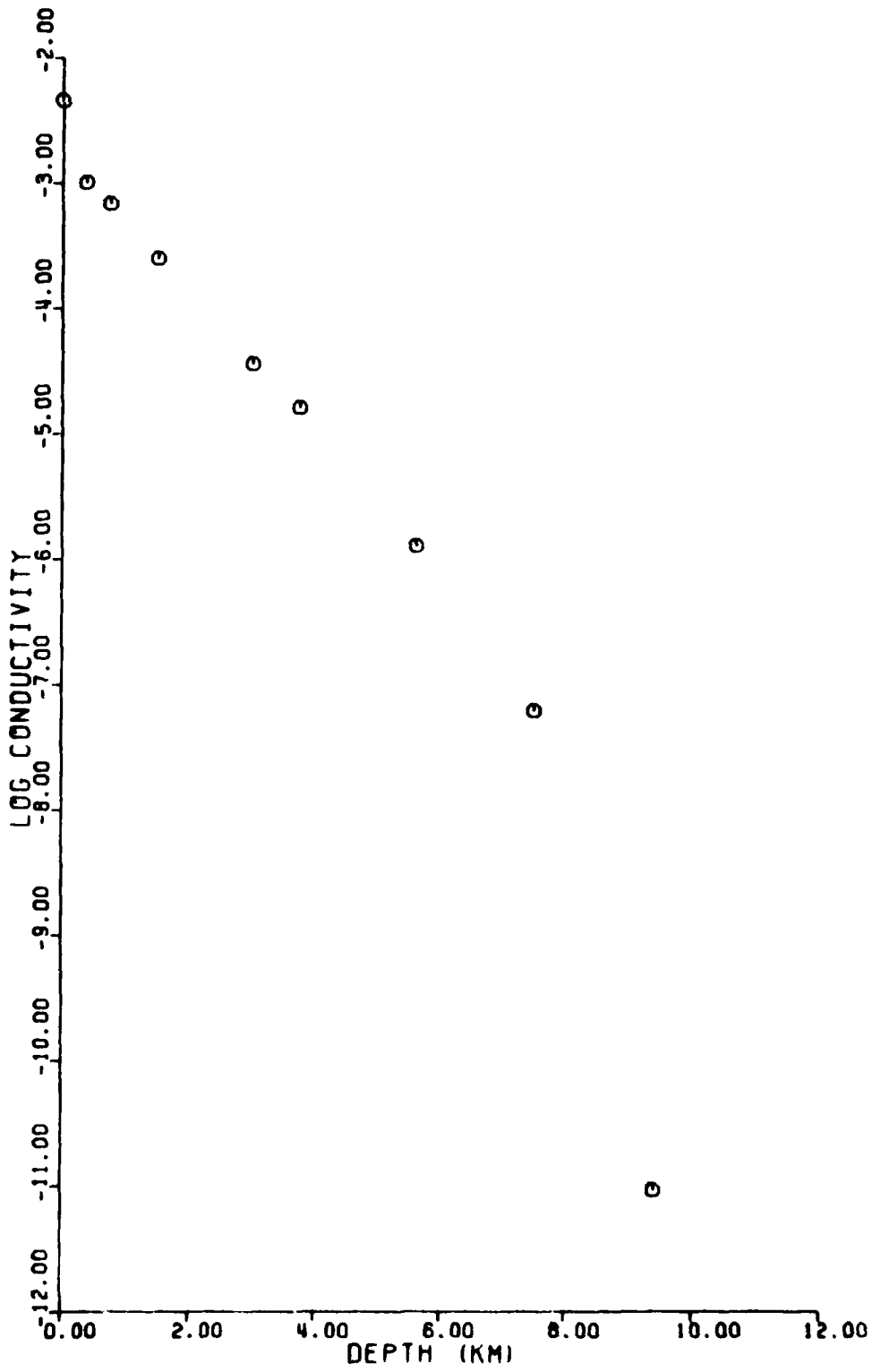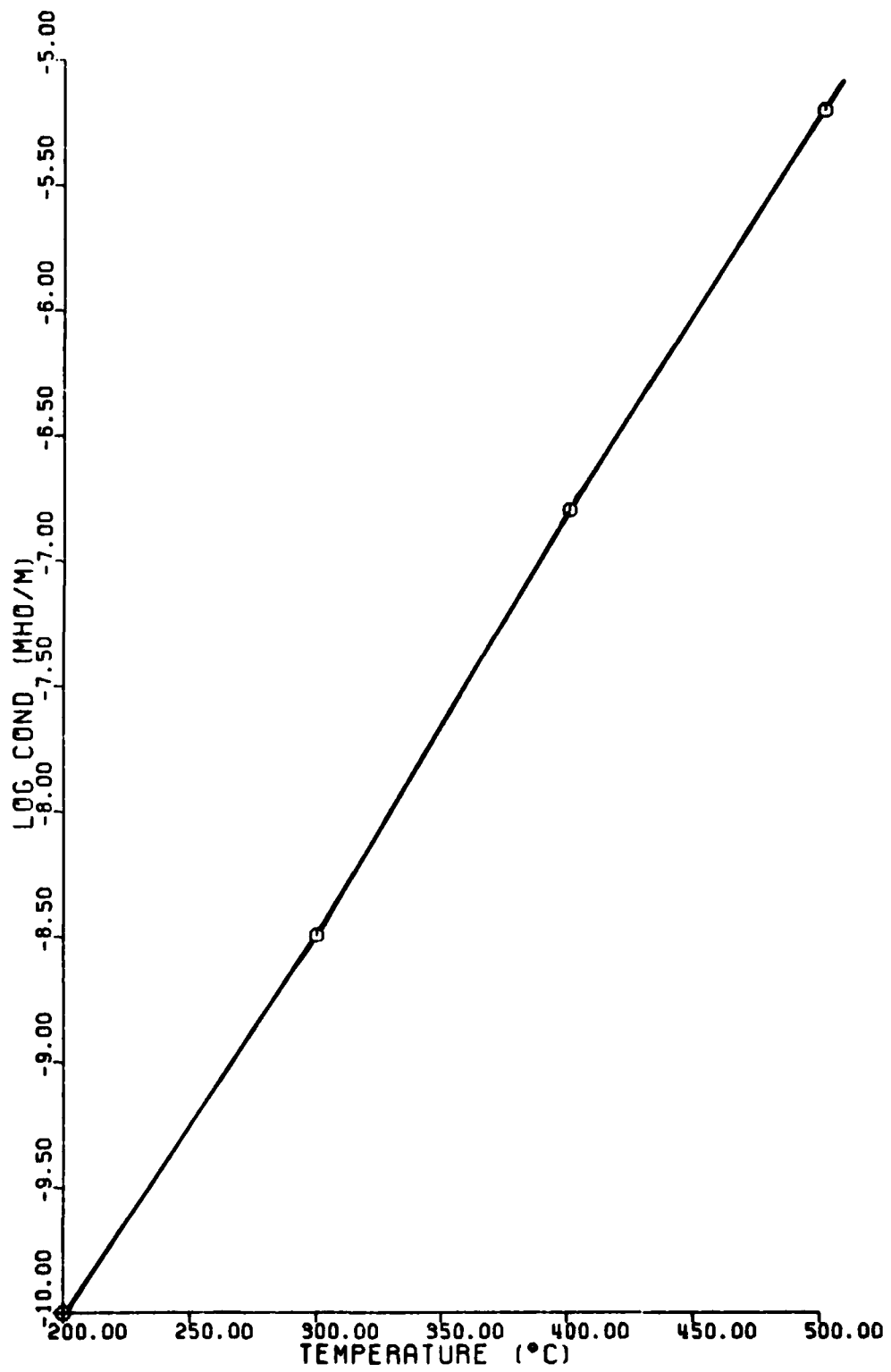
15

Table 1.

MIT Sample	Rock Type	f = 100 Hz		f = 50,000 Hz	
		K	$\sigma(\text{mho/m}) \times 10^9$	K	$\sigma(\text{mho/m}) \times 10^7$
2425	Metagranite	6.2	.91	5.6	2.6
2310	Garnet Granulite	6.5	1.2	6.0	2.4
1727	Amphibolite	10.9	4.1	8.3	9.3
83	Troy Granite	5.7	.29	5.2	.97
1410	Graniteville Granite	7.4	1.2	6.7	4.9

Figure 6. Conductivity as a function of temperature for a sample of granite. (After Olhoeft, 1980.)

zation (as measured by Simmons et al., 1980). At 300°C, Olhoeft's values are comparable to the values shown in Table 1. We conclude that the thermal effects begin to dominate the electrical conduction in rocks at a temperature of approximately 300°C.

The thermal gradient in the eastern United States has been measured in a few hundred locations. The results of Birch et al. (1968), Diment et al. (1965), Sass et al. (1976), and Combs and Simmons (1973) are typical of the larger data set. The gradient for most of the area is between 15 and 25°C/km. We can use these gradients and figure 6 to obtain the variation of electrical conductivity with depth in the earth where the conductivity is due to thermally activated mechanisms.

STANDARD CRUSTAL MODEL

We can obtain a standard crustal model for the eastern United States if we assume (1) microcracks become closed chemically as well as mechanically in the earth's crust, (2) the mechanical behavior of microcracks in the laboratory (figure 2) is exactly analogous to the mechanical behavior of microcracks in rocks in situ, (3) the relation between electrical conductivity for electrolytes in microcracks and the crack porosity obtained in the laboratory (figure 4) is exactly analogous to the relation between electrical conductivity due to electrolytes in microcracks in rocks in situ, (4) the functional relationship between electrical conductivity and temperature as obtained in the laboratory (figure 6) is identical to the relationship that exists for rocks in situ, (5) the effects of interfacial polarization measured in the laboratory (Table 1) are exactly analogous to the effects of interfacial polarization in rocks in situ. We use figure 5 to obtain the variation of electrical conductivity due to electrolytes in microcracks and the relationship shown in figure 6 for the thermal effects. In figure 7, we show the resulting proposed standard model for the variation of electrical conductivity with depth in the eastern United States. The conductivity decreases rapidly with depth from the surface due to the chemical closure of microcracks and the resulting decrease in electrolytic conduction paths. At a depth of 2 to 5 km, the conductivity associated with interfacial polarization becomes the dominant conductivity. The exact depth is dependent on rock type, geographic location, and so on. The effects of interfacial polarization remain approximately constant with depth and produce a conductivity of 10^{-7} mho/m. At a depth of 15 to 25 km, thermal effects become significant and the conductivity increases with depth at greater depths.

Figure 7. Standard curve for conductivity as a function of depth in the eastern United States. This curve was obtained from the curve of figure 5, a thermal gradient of 20°C/km, and the data of Table 1. This model is based on laboratory data. The rapid decrease between surface and 4 km is due to the decrease of porosity. The value between 4 and 16 km is controlled by inter-facial polarization. The rise in conductivity at depths greater than 16 km is caused by thermal mechanisms.
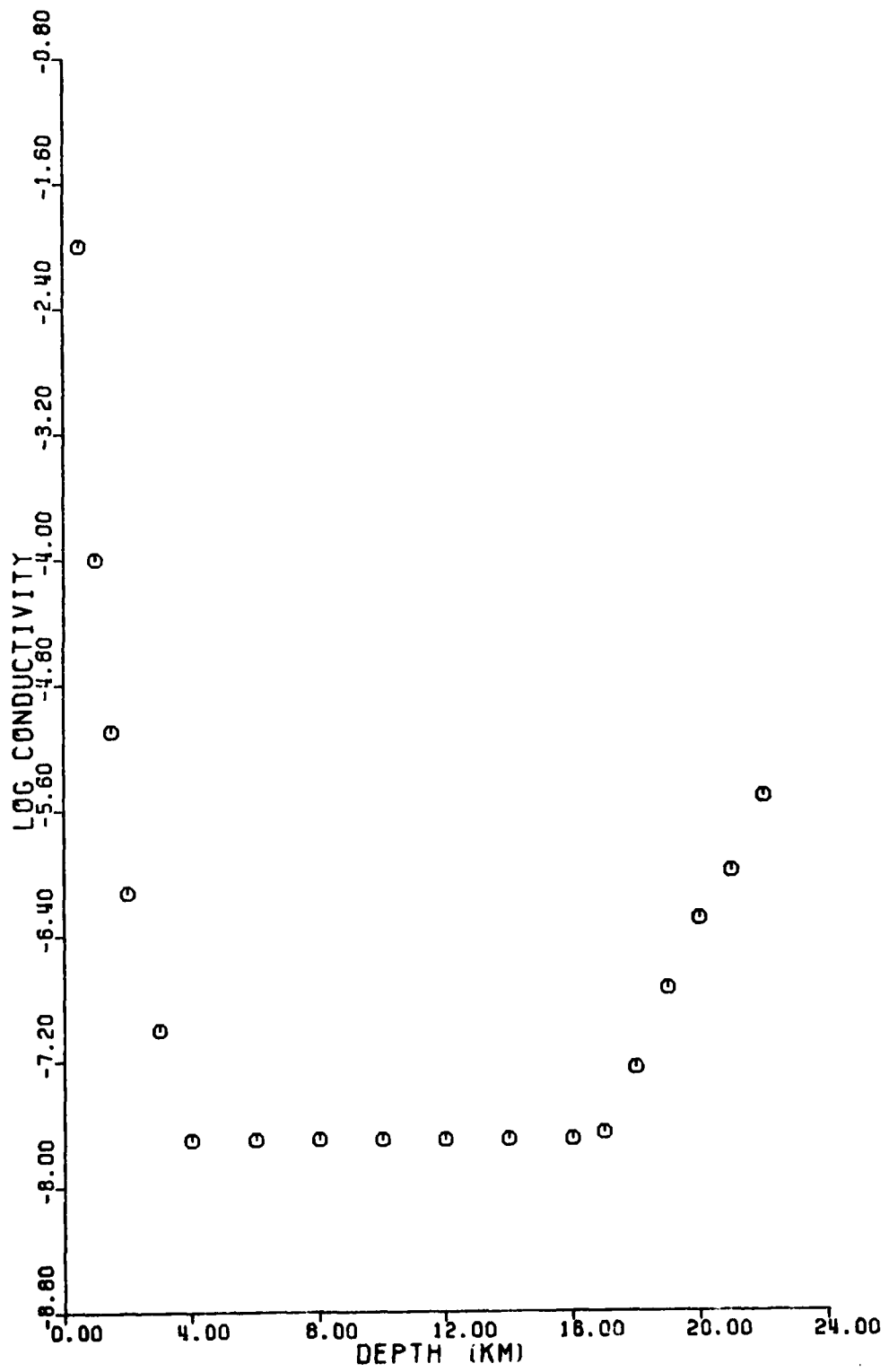
ACKNOWLEDGEMENTS

REFERENCES

Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 1, J. Geophys. Res., 65, 1083-1102, 1960.

Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 2, J. Geophys. Res., 66, 2199-2224, 1961.

Birch, F., R. Roy, and E. Decker, Heat flow and thermal history in New England and New York, in: Studies of Appalachian Geology: Northern and Maritime, edited by E. Zen, W.S. White, J.B. Hadley, and J.B. Thompson, Jr., Interscience Publishers, New York, 437-451, 1968.

Brace, W.F., A.S. Orange, and T.R. Madden, The effect of pressure on the electrical resistivity of water-saturated crystalline rocks, J. Geophys. Res., 70, 5669-5678, 1965.

Combs, J. and G. Simmons, Terrestrial heat flow determinations in the north central United States, J. Geophys. Res., 78, 441-461, 1973.

deBettencourt, J.T., Review of Radio Propagation below the Earth's Surface, paper presented at Sessions of Commission II, XVth General Assembly (1966), Munich, Germany, 1966.

Diment, W.H.R., R. Raspet, M.A. Mayhew, and R.W. Werre, Terrestrial heat flow near Alberta, Virginia, J. Geophys. Res., 70, 923-929, 1965.

Feves, M., G. Simmons, and R. Siegfried, Microcracks in crustal igneous rocks: physical properties, in: The Earth's Crust: Its Nature and Physical Properties, Geophys. Monogr. Ser., vol. 20, edited by J.G. Heacock, AGU, Washington, DC, 95-117, 1977.

IEEE, Transactions on Antennas and Propagation, Special Issue on Electromagnetic Waves in the Earth, AP-11, May, 1963.

Morlier, P., Description de l'etat de fissuration d'une roche a partir d'essais non-destructifs simples, Rock Mech., 3, 125-138, 1971.

Olhoeft, G.R., Electrical properties of granite with implications for the lower crust, J. Geophys. Res., accepted, 1980.

Richter, D. and G. Simmons, Microcracks in crustal igneous rocks: microscopy, in: The Earth's Crust: Its Nature and Physical Properties, Geophys. Monogr. Ser., vol. 20, edited by J.G. Heacock, AGU, Washington, DC, 149-180, 1977.

Sass, J.H., W.H. Diment, A.H. Lachenbruch, B.V. Marshall, R.J. Monroe, T.H. Moses, Jr., and T.C. Urban, A new heat-flow contour map of the conterminous United States, U.S.G.S. Open File Report 76-756, 24 pp., 1976.

Siegfried, R. and G. Simmons, Characterization of oriented cracks with differential strain analysis, J. Geophys. Res., 83, 1269-1278, 1978.

Simmons, G., R. Siegfried, and M. Feves, Differential strain analysis: a new method for examining cracks in rocks, J. Geophys. Res., 79, 4383-4385, 1974.

Simmons, G. and D. Richter, Microcracks in rocks, in: The Physics and Chemistry of Minerals and Rocks, edited by R.G.J. Strens, Wiley-Interscience, New York, 105-137, 1976.

Simmons, G. and H. Cooper, Thermal cycling cracks in three igneous rocks, Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., 15, 145-148, 1978.

Simmons, G., L. Caruso, and F. Miller, Complex dielectric properties of several igneous and metamorphic rocks, technical report for Office of Naval Research, 1980.

Wheeler, H.A., Radio-wave propagation in the earth's crust, J. Res. National Bureau of Standards, 65D, 189-191, 1961.