orders of magnitude in σ. Further, the fayalite-poor olivine may be the better conductor.

2. In olivines with similar fayalite and impurity contents the amount of Fe^{3+} present determines the σ up to at least 800°C.

3. This study cannot claim to have determined an unambiguous pressure derivative because of experimental difficulties.

4. There is a large and reversible change in σ mechanism in olivine at about 1150°C. The activation energy and pre-exponential term for this mechanism, as determined by various laboratories, vary from 3 to 8 ev and 10^6 to 10^{22}, respectively.

5. For all natural olivines studied here, except the Fa 9.4, no change in mechanism indicated by a reversible change of slope was observed between 200° and 800°C. The Fa 9.4 and the Fa 0 have no change in mechanism between 500° and 1100°C.

GEOPHYSICAL APPLICATIONS

The present data on the σ of olivine single crystals can be used to estimate the temperature at depth in the mantle if (1) is solved for T (degrees Kelvin):

$$T = \frac{A_x \log e}{k(\log \sigma_x - \log \sigma_m)} \qquad (3)$$

where $\log \sigma_m$ is the σ of the mantle. Both the magnetotelluric σ profile of *Eckhardt et al.* [1963] and the geomagnetic profile of *McDonald* [1957] were used in these calculations.

If the pressure derivatives of A_x and $\log \sigma_x$ are substituted in (3), the temperature at depth T_p is

$$T_p = \frac{\left[A_x + \left(\frac{dA_x}{dP}\right)_T P\right] \log e}{k\left[\log \sigma_x + \left(\frac{d \log \sigma_x}{dP}\right)_T P - \log \sigma_m\right]} \qquad (4)$$

Figure 6 shows the temperature calculated from the present data for 40, 100, 200, and 400 km from (3) and (4). The calculations for Fa 10 olivines with no pressure effect yield temperatures that are significantly higher than those proposed for the mantle beneath both the oceans and the shields [*Ringwood*, 1966; *Clark and Ringwood*, 1964] at any depth. In fact, these temperatures are sufficient to activate the high-temperature conductivity mechanism that was observed for the Fa 9.4 and the Fa 0. Thus Figure 6 also includes calculations based on these high-temperature σ mechanisms.

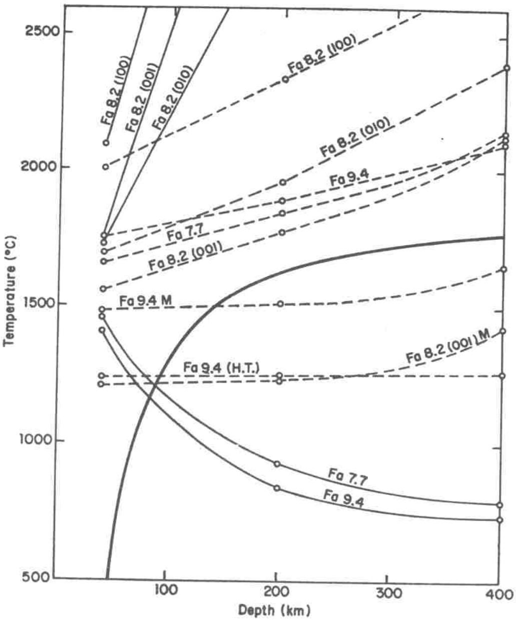

Fig. 6. Temperature distribution in the mantle. Heavy solid line is the oceanic geotherm of *Ringwood* [1966], extrapolated beyond the 250-km depth on the basis of data from *Clark and Ringwood* [1964]. The thin solid lines connect temperature points calculated by using the pressure derivatives obtained in this study and the Cantwell-McDonald profile of σ depth. Broken lines connect temperature points calculated without using pressure derivatives. *M* refers to temperature points based on the McDonald profile of conductivity depth, and H. T. refers to the temperature calculations based on the high-temperature mechanism observed in Fa 9.4. Composition of olivine is indicated above the line, and the numbers in parentheses indicate the crystal direction of the σ measurement.

The pressure effect observed for the low-temperature σ mechanism causes the calculated temperature to decrease with depth, except in the case of the Fa 8.2, and indicates a temperature at 400 km that is somewhat lower than has been proposed for the mantle beneath either the oceanic or the shield areas. The pressure effect observed for the Fa 8.2 yields a temperature distribution that is much larger than expected for the mantle.

This study shows that the σ is quite variable among olivines with compositions close to the assumed composition of olivine in the mantle (Fa 10). Thus, even if one neglects the uncertainties introduced by grain boundaries, the calculation of temperature distributions at depth based on magnetic and laboratory σ data [see *England et al.*, 1968; *Tozer*, 1959] is subject to large uncertainties. The uncertainty is further increased if the possible effects of pressure and the uncertainties in the σ distribution in the mantle [*Parker*, 1971] are taken into account.

Acknowledgments. This work was completed under the auspices of the Committee on Experimental Geology and Geophysics. Harvard University, during the tenure of a National Science Foundation post-doctoral fellowship. The support and encouragement of Professor John C. Jamieson, University of Chicago, is gratefully acknowledged. Dr. H. C. Heard and Dr. R. N. Schock, Lawrence Radiation Laboratory, Livermore, California, assisted with the experiments and contributed much to the interpretation of the data. Professor M. R. Chakrabarty and Professor E. Hanrahan, Marshall University, Huntington, West Virginia, and Professor R. C. Newton, University of Chicago, generously loaned equipment. Dr. Jun Ito, Harvard University, performed the wet chemical and spectographic analyses of the samples. (Donors of samples used are given in Table 1.) Professor T. J. Shankland and Dr. R. Stocker, Harvard University, read the manuscript and their comments were most useful.

Financial support for this study was provided by a National Defense Education Act Title 4 fellowship; the Rollin Salisbury Fellowship of the Department of the Geophysical Sciences, University of Chicago, NSF grant 1270; and Advanced Research Projects Agency grant SD-89.

REFERENCES

Akimoto, S., and H. Fujisawa, Demonstration of the electrical-conductivity jump produced by the olivine-spinel transition, *J. Geophys. Res.*, *70*, 443–449, 1965.

Banks, R. J., Geomagnetic variations and the electrical conductivity of the upper mantle, *Geophys. J. Roy. Astron. Soc.*, *17*, 457–487, 1969.

Birch, F., Density and composition of the upper mantle: First approximation as an olivine layer, in *The Earth's Crust and Upper Mantle, Geophys. Monogr. Ser.*, vol. 13. edited by P. J. Hart, pp. 18–36, AGU, Washington, D.C., 1969.

Bradley, R. S., A. K. Jamil, and D. C. Munro, The electrical conductivity of fayalite and spinel, *Nature*, *193*, 965–966, 1962.

Bradley, R. S., A. K. Jamil, and D. C. Munro, The electrical conductivity of olivine at high temperatures and pressures, *Geochim. Cosmochim. Acta*, *28*, 1669–1678. 1964.

Clark, S. P., Jr., and A. E. Ringwood, Density distribution and constitution of the mantle, *Rev. Geophys. Space Phys.*, *2*, 35–88, 1964.

Dekker, A. J., *Solid State Physics*, pp. 160–182, 305–346, Prentice-Hall, Englewood Cliffs, N.J., 1958.

Eckhardt, D., K. Larner, and T. Madden, Long-period magnetic fluctuations and mantle conductivity estimates, *J. Geophys. Res.*, *68*, 6279–6286, 1963.

England, A. W., G. Simmons, and D. Strangway, Electrical conductivity of the moon, *J. Geophys. Res.*, *73*, 3219–3226, 1968.

Fujisawa, H., Temperature and discontinuities in the transition layer within the earth's mantle: Geophysical application of the olivine-spinel transition in the Mg_2SiO_4–Fe_2SiO_4 system, *J. Geophys. Res.*, *73*, 3281–3294, 1968.

Getting, I. C., and G. C. Kennedy, The effect of pressure on the emf of chromel-alumel and platinum-platinum 10% rhodium thermocouples, in *Proceedings of a Symposium on the Accurate Characterization of the High Pressure Environment*, pp. 77–80, National Bureau of Standards, Washington, D.C., 1971.

Hamilton, R. M., Temperature variation at constant pressure of the electrical conductivity of periclase and olivine, *J. Geophys. Res.*, *70*, 5679–5692, 1965.

Harris, P. G., A. Reay, and I. G. White, Chemical composition of the upper mantle, *J. Geophys. Res.*, *72*, 6359–6369, 1967.

Hughes, H., The electrical conductivity of the earth's interior, Ph.D. thesis, Univ. of Cambridge, Cambridge, England, 1953.

Hughes, H., The pressure effect on the electrical conductivity of peridot, *J. Geophys. Res.*, *60*, 187–191, 1955.

Hutson, A. R., Semiconducting properties of some oxides and sulfides, in *Semiconductors*, edited by N. B. Hannay, pp. 541–599, Reinhold, New York, 1959.

Jander, W., and W. Stamm, Der innere aufbau fester anorganischer verbindungen bei hoheren temperature, *Z. Anorg. Allg. Chem.*, *207*, 289–307, 1932.

Kittel, C., *Introduction to Solid State Physics*, 3rd ed., pp. 301–330, John Wiley, New York, 1966.

Kumazawa, M., and O. L. Anderson, Elastic moduli, pressure derivatives and temperature derivatives of single-crystal olivine and single-crystal forsterite, *J. Geophys. Res.*, *74*, 5961–5972, 1969.

McDonald. K. L., Penetration of the geomagnetic secular field through a mantle with variable conductivity, *J. Geophys. Res.*, *62*, 117–141, 1957.

Mizutani. H., and H. Kanamori, Electrical conductivities of rock forming minerals at high temperatures, *J. Phys. Earth*, *15*, 25–31, 1967.

Noritomi, K., The electrical conductivity of rocks and the determination of electrical conductivity of the earth's interior, *J. Mining Coll. Akita Univ., Ser. A*, *1*, 27–59, 1961.