Effect of an Ocean Ridge Model on Geomagnetic Variations

AL DUBA[1] AND F. E. M. LILLEY

Department of Geophysics and Geochemistry, Australian National University
Canberra, Australia

The isotherm and composition model of Forsyth and Press (1971) for a mid-ocean ridge system is combined with recent data on the electrical conductivities of basalt and olivine. The response of the resulting two-dimensional conductivity model to geomagnetic variations is calculated by using the numerical methods of Jones and Pascoe (1971) for periods of 5 min, 1 hour, and 1 day. The results show that the electrical conductivity structure beneath such a ridge can be best detected by using magnetotelluric observations on the sea floor.

The natural variations with time of the geomagnetic field provide a very convenient energy source for measuring the deep electrical conductivity structure of the earth. Traditionally such measurements have been made on land, although the last ten years have seen the development of techniques by which observations can be made at sea. Technical and theoretical aspects of electrical and magnetic measurements at sea are discussed by *Schneyer and Fonarev* [1968], *Hermance* [1969], *Berdichevskiy and Van'yan* [1969], *Richards* [1970], *Bullard and Parker* [1971], and *Cox et al.* [1971].

This paper will test whether the structure beneath a mid-ocean ridge can be detected by using electromagnetic observations. A particular model for the composition and the thermal structure of a spreading ridge is combined with recent data on the electrical conductivity of the relevant materials. The response of this electrical conductivity structure to alternating primary horizontal magnetic fields is then computed by using numerical methods to solve the differential equations involved.

Only one model has been considered, and it should be noted that this model does not take into account the evidence of *Cox et al.* [1971] for relatively high conductivity beneath the sea floor. Further, although the model considered should evidently be easily detected by using sea floor observations, the practical problem of interpreting actual observations may be more difficult, since the inversion of data recorded over such a two-dimensional structure can be expected to be highly nonunique in solution.

[1] Now at Lawrence Livermore Laboratory, University of California, Livermore, California 94550.

UPPER-MANTLE MODEL

Figure 1 presents the model lithosphere containing an active mid-ocean ridge. The solidus region and the isotherms are adapted from the wet peridotite model of *Forsyth and Press* [1971]. Temperatures at depths of >100 km are those calculated by *MacDonald* [1965] for an oceanic mantle with uranium concentrations of 5.5×10^{-8} g/g and an opacity of 10 cm^{-1}. The model consists of four conductors with widely varying electrical properties. A 5-km ocean and sediment layer with an electrical conductivity of 4 mhos m^{-1} overlies a basaltic crust 8 km thick. Beneath the crust lies the peridotite mantle, which is taken to have an electrical conductivity equal to that of olivine because olivine is the major continuous phase present [*Tozer*, 1959]. Included in the mantle beneath the ridge axis is a zone of partial melting with an electrical conductivity equal to that of molten basalt. This model supposes that the molten basalt is a continuous phase within the solidus region and that it acts as an electrical shunt to the olivine of lower conductivity. If this assumption were invalid, the conductivity contrast at the ridge would be reduced. No allowance is made for the possible extension of the highly conducting zone to a depth of >70 km.

Figure 2 shows representative data for the

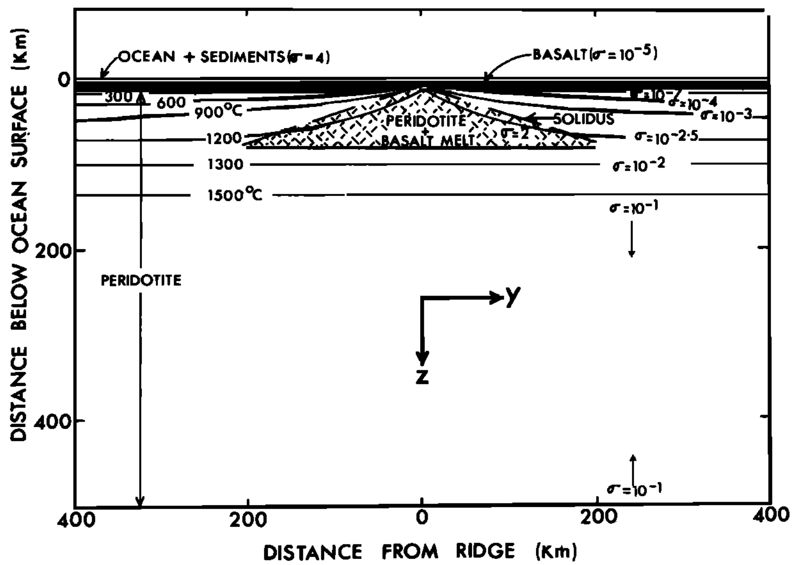

Fig. 1. Scale diagram of the wet peridotite model of *Forsyth and Press* [1971] showing composition and isotherms.

electrical conductivity of basalt together with all available data for olivine of a composition near 10 mole % fayalite, the most likely composition for olivine in the mantle [*Fujisawa*, 1968]. The range of the electrical conductivity data for basalt is less than an order of magnitude for most temperatures, and an average value of 10^{-5} mho m^{-1} at 300°C is used. For molten basalt an electrical conductivity of 2 mhos m^{-1} has been taken [*Watanabe*, 1970].

The olivine data are not so easily resolved, since they range over 3 orders of magnitude for most temperatures. This range is reduced by discarding the data for the Red Sea olivine and those of *Bradley et al.* [1964] for a synthetic olivine. Conductivity values obtained by averaging the bulk of the determinations in Figure 2 were used in the calculations for temperatures of <1200°C. From 1200° to 1500°C the Red Sea olivine data were used, since they are the only high-temperature data for olivine of geophysical interest and since they represent higher conductivity values than those that would be produced by extrapolating the lower-temperature data of other olivine. An upper limit of 10^{-1} mho m^{-1} was set for the electrical conductivity of the mantle at depth, consistent with the results of *Banks* [1969] and *Parker* [1970] from analyses of global geomagnetic variations.

The effect of pressure on electrical conductivity is not considered in these calculations. There is considerable disagreement among the literature values of pressure derivatives [*Duba*, 1972], and the effect of pressure on conductivity is likely to be small at the depths in the earth relevant to the present calculations.

COMPUTATIONS

Because a mid-ocean ridge is reasonably approximated by a two-dimensional structure, its electromagnetic response can be specified by just two separate cases: *E* polarization with a horizontal magnetic field across the strike and *H* polarization with a horizontal magnetic field along the strike. For these two cases great simplification occurs in the equations governing the electromagnetic phenomena [e.g., *Jones and Price*, 1970]. For a given horizontal source field the equations can be solved numerically once a suitable conductivity structure grid has been set up.

The numerical results of this paper were obtained by using the methods given by *Jones and Pascoe* [1971] and *Pascoe and Jones* [1972]. A grid of 40 × 40 conductivity units was determined from the thermal and compositional data in Figure 1 combined with the conductivity data in Figure 2. The horizontal and vertical spacings of the grid points used are listed be-

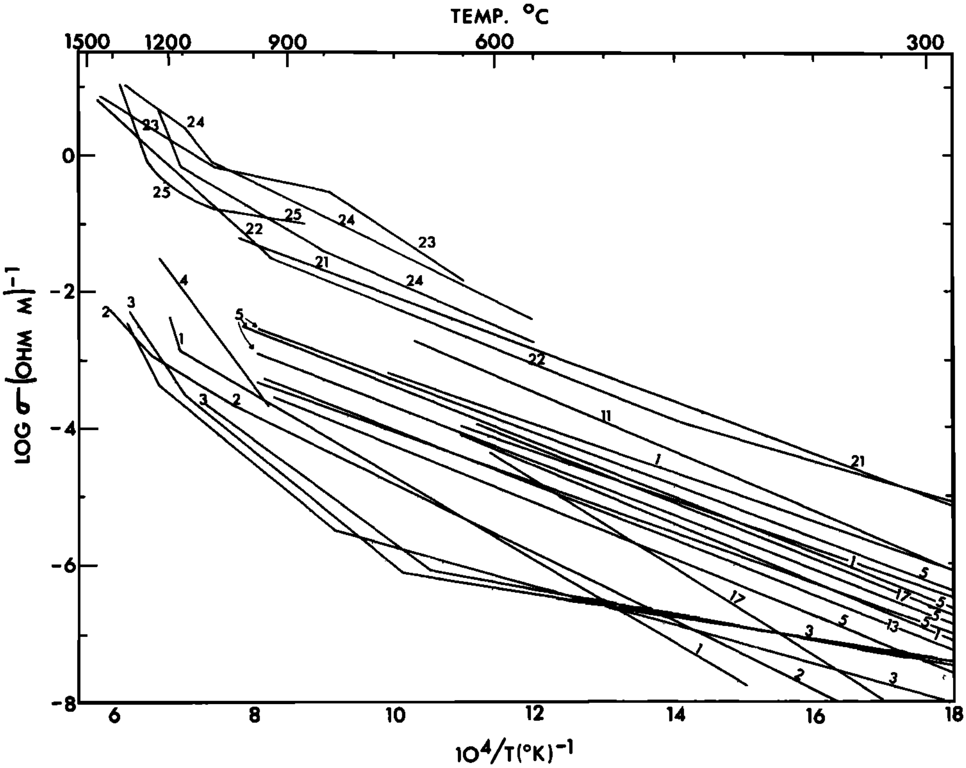

Fig. 2. Electrical conductivity for olivine with 10 mole % fayalite and some representative basalts. Numbers refer to the following studies. Olivine single crystals: 1, *Duba* [1972]; 2, *Duba et al.* [1972]; 3, *Hughes* [1953]; 4, *Hughes* [1955]; 5, *Kobayashi and Maruyama* [1971]. Olivine powders: 11, *Bradley et al.* [1964]; 13, *Hamilton* [1965]; 17, *Schult and Schober* [1969]. Basalt: 21, *Coster* [1948]; 22, *Watanabe* [1970] (dry); 23, *Watanabe* [1970] (wet); 24, *Khitarov et al.* [1970] (quartz tholeiite); 25, *Khitarov et al.* [1970] (olivine tholeiite).

low; the model is symmetrical about the ridge axis.

Horizontal grid spacings: 40 km, 17 intervals of 20 km, 4 intervals of 10 km, 17 intervals of 20 km, 40 km

Vertical grid spacings: 90 km, 50 km, 10 km, 5 km, 1 km, air-ocean interface, 6 intervals of 1 km, 18 intervals of 4 km, 7 km, 10 km, 15 km, 25 km, 40 km, 4 intervals of 50 km, 60 km, 70 km

The results for E polarization are presented graphically in Figures 3*a*–3*d*. Similar computations were also made for H polarization, but they showed no detectable effect over the spreading ridge.

Amplitudes are shown for the three E polarization components Ex, Hy, and Hz on both the sea surface and the sea floor. All values are normalized in terms of a surface horizontal magnetic field remote from the central ridge with an amplitude of 50 nT (1 nT = 1 γ).

Apparent resistivities are also computed according to the magnetotelluric formula

$$\rho_a = 0.2T\ |Ex/Hy|^2$$

where ρ_a is the apparent resistivity in ohm meters, T is the period in seconds, and Ex and Hy are in the practical units of millivolts per kilometer and nanoteslas, respectively.

Discussion

The surface horizontal field amplitude of 50 nT with which the results of Figures 3*a*–3*c* are normalized is reasonable for variations of periods of 1 hour and 1 day. Such an amplitude would be unusually large for variations of periods of several minutes, and so the amplitudes for the minute variations of Figures 3*a*–3*c* are probably greater than those that would occur in practice.

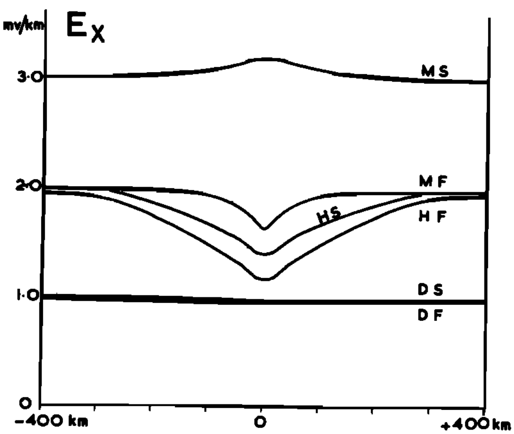

Fig. 3a.

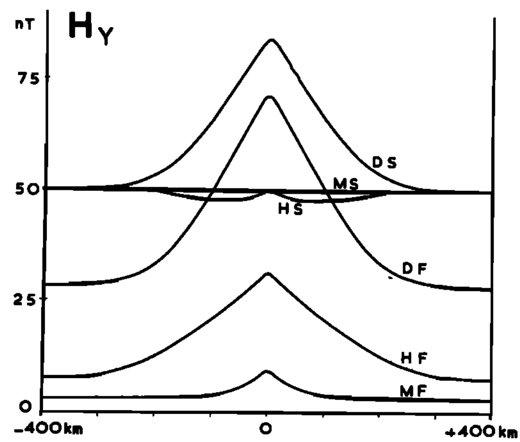

Fig. 3b.

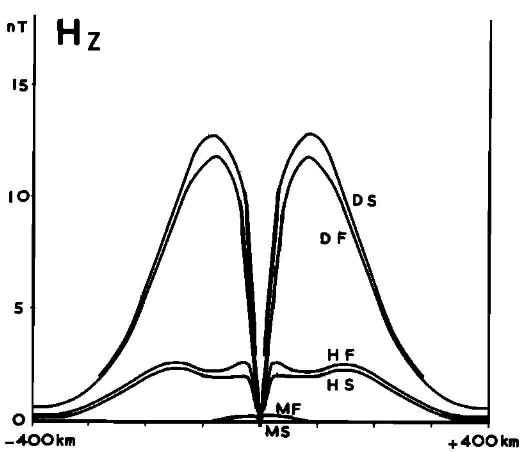

Fig. 3c.

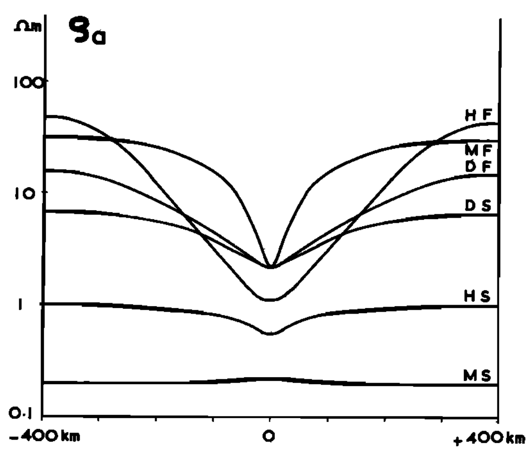

Fig. 3d.

Fig. 3. Response of the ridge conductivity structure to an alternating horizontal magnetic source field at right angles to the strike of the ridge. (*a*) Amplitude of the horizontal electric field *Ex* parallel to the ridge. (*b*) Amplitude of the horizontal magnetic field *Hy*. (*c*) Amplitude of the vertical magnetic field *Hz*. (*d*) Apparent resistivity computed by using *Ex* and *Hy*. Here M, H, and D stand for variation periods of 5 min, 1 hour, and 1 day, respectively, and S and F refer to calculations for the sea surface and the sea floor, respectively. In Figures 3*a*–3*c* the values are appropriate for a surface *Hy* field with an amplitude of 50 nT remote from the ridge structure.

The stronger anomalies in the central regions of Figures 3*b*–3*d* show that magnetic storms and bays with power in the period range of an hour or more would be useful in detecting the conductivity structure beneath a spreading ocean ridge. Using the diurnal variation and its subharmonics would also be possible, although the effect of these variations can be expected to be more complicated than that calculated here, particularly because the diurnal variation in many places has a strong vertical component [*Roden*, 1964; *Bullard and Parker*, 1971]. The strongest effects in Figure 3 appear to be in *Hy*, particularly on the sea floor; the greatest variation in the apparent resistivity data is for the hour sea floor case, and the observation of this variation by using sea floor magnetotelluric methods would be a worthwhile geophysical target.

The practical problems of carrying out such marine operations may be immense, particularly because of the topographical relief of a typical mid-ocean ridge. However, the types of deep-sea magnetic variometers developed by *Filloux* [1967] and V. Vacquier (personal communication, 1971) may have applications to this problem. It is even possible that at some places conditions would be appropriate for observing the variation anomaly by using the method of *Hill and Mason* [1962] in which a total-field recording magnetometer is floated on the ocean surface in a buoy.

The results of these calculations demonstrate that for variations of period of about an hour or longer, the effect of an active mid-ocean ridge system should be evident in both surface and ocean floor magnetotelluric measurements, particularly in the latter. Variations of shorter periods (several minutes) are too effectively shielded by the sea water to be useful.

Acknowledgments. Mrs. M. N. Sloane has given much valuable assistance in the work described, and we have benefited considerably from discussions with F. W. Jones, D. J. Bennett, and H. Y. Tammemagi.

The support and the hospitality of the Australian-American Educational Foundation in the form of a Fulbright-Hays postdoctoral fellowship is gratefully acknowledged by one of us (A. D.).

REFERENCES

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

Berdichevskiy, M. N., and L. L. Van'yan, Prospects for deep magnetotelluric sounding in bodies of water, *Izv. Acad. Sci. USSR Phys. Solid Earth,* no. 11, 701–703, 1969.

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.

Bullard, E. C., and R. L. Parker, Electromagnetic induction in the ocean, in *The Sea,* vol. 4, edited by A. E. Maxwell, pp. 695–730, Interscience, New York, 1971.

Coster, H. P., The electrical conductivity of rocks at high temperatures, *Mon. Not. Roy. Astron. Soc., 5,* 193–199, 1948.

Cox, C. S., J. H. Filloux, and J. C. Larsen, Electromagnetic studies of ocean currents and electrical conductivity below the ocean-floor, in *The Sea,* vol. 4, edited by A. E. Maxwell, pp. 637–693, Interscience, New York, 1971.

Duba, A., The electrical conductivity of olivine, *J. Geophys. Res., 77,* 2483–2495, 1972.

Duba, A., H. C. Heard, and R. N. Schock, The lunar temperature profile, *Earth Planet. Sci. Lett., 15,* 301–304, 1972.

Filloux, J. H., An ocean bottom, *D* component magnetometer, *Geophysics, 32,* 978–987, 1967.

Forsyth, D. W., and F. Press, Geophysical tests of petrological models of the spreading lithosphere, *J. Geophys. Res., 76,* 7963–7979, 1971.

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.

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

Hermance, J. F., Resolution of ocean floor magnetotelluric data, *J. Geophys. Res., 74,* 5527–5532, 1969.

Hill, M. N., and C. S. Mason, Diurnal variation of the earth's magnetic field at sea, *Nature, 195,* 365–366, 1962.

Hughes, H., The electrical conductivity of the earth's interior, Ph.D. thesis, 131 pp., Univ. of Cambridge, Cambridge, England, 1953.

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

Jones, F. W., and L. J. Pascoe, A general computer program to determine the perturbation of alternating electric currents in a two-dimensional model of a region of uniform conductivity with an imbedded inhomogeneity, *Geophys. J. Roy. Astron. Soc., 24,* 3–30, 1971.

Jones, F. W., and A. T. Price, The perturbations of alternating geomagnetic fields by conductivity anomalies, *Geophys. J. Roy. Astron. Soc., 20,* 317–334, 1970.

Khitarov, N. I., A. B. Slutskiy, and V. A. Pugin, Electrical conductivity of basalts at high T-P and phase transitions under upper mantle conditions, *Phys. Earth. Planet. Interiors, 3,* 334–342, 1970.

Kobayashi, Y., and H. Maruyama, Electrical conductivity of olivine single crystals at high temperature, *Earth Planet. Sci. Lett., 11,* 415–419, 1971.

MacDonald, G. J. F., Geophysical deductions from observations of heat flow, in *Terrestrial Heat Flow, Geophys. Monogr. Ser.,* vol. 8, edited by W. H. K. Lee, pp. 191–210, AGU, Washington, D.C., 1965.

Parker, R. L., The inverse problem of electrical conductivity in the mantle, *Geophys. J. Roy. Astron. Soc., 22,* 121–138, 1970.

Pascoe, L. J., and F. W. Jones, Boundary conditions and calculation of surface values for the general two-dimensional electromagnetic induction problem, *Geophys. J. Roy. Astron. Soc., 27,* 179–193, 1972.

Richards, M. L., A study of electrical conductivity in the earth near Peru, Ph.D. thesis, Univ. of Calif., San Diego, 1970.

Roden, R. B., The effect of the ocean on magnetic diurnal variations, *Geophys. J. Roy. Astron. Soc.*, *8*, 375–388, 1964.

Schneyer, V. S., and G. A. Fonarev, Some results of observations of magnetic variations at the surface and bottom of the ocean, *Geomagn. Aeron.*, *8*, 479–480, 1968.

Schult, A., and M. Schober, Measurement of electrical conductivity of natural olivine at temperatures up to 950° and pressures up to 42 kilobars, *Z. Geophys.*, *35*, 105–112, 1969.

Tozer, D. C., The electrical properties of the earth's interior, *Phys. Chem. Earth*, *3*, 414–436, 1959.

Watanabe, H., Measurements of electrical conductivity of basalt at temperatures up to 1500°C and pressures to about 20 kilobars, *Spec. Contrib. Geophys. Inst. Kyoto Univ.*, no. 10, 159–170, 1970.

(Received May 17, 1972;
revised August 28, 1972.)