

Electrical Conductivity of Olivine<sup>1</sup>AL DUBA<sup>2</sup>*Hoffman Laboratory, Harvard University, Cambridge, Massachusetts 02138*

The electrical conductivity  $\sigma$  of single crystals of olivine of 0, 7.7, 8.2, 9.4, and 26.4 mole % fayalite has been measured up to 1200°C and 7.5 kb. Samples from different localities with approximately the same fayalite content and impurity levels have electrical conductivities that differ by 2-3 orders of magnitude. It is proposed that the oxidation state of the iron in the natural olivines determines  $\sigma$  below 1100°C. No reversible change in activation energy was noted for any sample below 1100°C. In this temperature range activation energies for different samples vary from 0.7 to 2.0 ev. At 1150°C there is a reversible increase in  $\sigma$  with a poorly determined activation energy of 7-8 ev. Mantle temperatures calculated from the present data on olivines with almost the same fayalite content differ by more than 700°C at any depth. The temperature difference becomes even larger with depth if the pressure effects noted in this study are used.

The distribution of electrical conductivity  $\sigma$  in the mantle has been calculated from geomagnetic and magnetotelluric data by using inversion techniques [Banks, 1969; Price, 1967; Eckhardt et al., 1963; McDonald, 1957]. With these models of mantle  $\sigma$ , limits can be set on the temperature distribution in the mantle, provided that the  $\sigma$  of mantle constituents is determined as a function of temperature and pressure.

The geophysical and geochemical evidence that olivine is the major phase of the earth's upper mantle is overwhelming [Wyllie, 1970; Birch, 1969; Ringwood, 1969; Harris et al., 1967]. Although the entire range of the forsterite-fayalite solid solution ( $\text{Mg}_2\text{SiO}_4\text{-Fe}_2\text{SiO}_4$ ) occurs in metamorphic and igneous rocks, the most common composition of olivine in ultramafic intrusions, nodules in basalts, and kimberlites is  $\approx 10$  mole % fayalite (Fa 10) and thus is probably the composition of the olivine in the mantle [Fujisawa, 1968].

Because the major continuous phase in any mixture of minerals determines the  $\sigma$  of the mixture [Volarovich et al., 1966; Tozer, 1959; Hughes, 1953], the investigation of the  $\sigma$  of

mantle constituents can be limited to olivine. This limitation simplifies the experimental procedure, because small thin single-crystal specimens can be used. Thus the problems of large temperature gradients across representative rock samples and the shunting effect of the larger sample holder required for large specimens are eliminated.

In line with the above considerations three olivines with compositions of about Fa 10, an olivine with a composition of Fa 26, and a Linde synthetic forsterite were studied. The concentration on the Fa 10 composition was deliberate, because this composition of olivine in the mantle is most likely. Also the largest unzoned inclusion-free samples could be prepared from olivines of this composition. The high-fayalite sample and synthetic forsterite were chosen to permit evaluation of the effect of fayalite content on the  $\sigma$ . (These samples are described in Tables 1 and 4.)

Previous studies of the  $\sigma$  of olivine have concentrated mainly on synthetic and natural powders [Akimoto and Fujisawa, 1965; Bradley et al., 1962, 1964; Hamilton, 1965; Jander and Stamm, 1932; Pluschkell and Engell, 1968; Schult and Schober, 1969]. The use of powdered samples permits study of the entire olivine solid solution and the utilization of solid-pressure media to achieve pressures up to 65 kb. Unfortunately grain-boundary effects and compaction problems may cause powder data to be nonrepresentative of the electrical properties of

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the single crystals [Rodgers *et al.*, 1966; Hutson, 1959].

Work on single crystals has been limited to a study by Hughes [1955] of gem-quality peridot up to 8 kb from 1060° to 1240°C, atmospheric-pressure studies of natural olivine by Hughes [1953], Noritomi [1961], and Mizutani and Kanamori [1967], and studies of forsterite grown by the flame-fusion method and doped with small amounts of iron [Shankland, 1969]. (The literature data on the conductivity of single crystals are included in Figure 3.)

If the logarithm of the  $\sigma$  of olivine is plotted against reciprocal temperature, the data lie on nearly straight lines or straight-line segments. Thus  $\sigma$  can be expressed as

$$\sigma = \sigma_x \exp(-A_x/kT) \quad (1)$$

where the coefficient  $\sigma_x$  is independent of temperature,  $A_x$  is the activation energy,  $k$  is Boltzmann's constant, and  $T$  is the temperature in degrees Kelvin. The subscript  $x$  indicates that more than one conductivity mechanism may be operating. These mechanisms include ionic conduction and extrinsic and intrinsic electronic semiconduction. For a more complete description of the various  $\sigma$  mechanisms possible in olivine see Hamilton [1965]. Kittel [1966] and Dekker [1958] describe in considerable detail the  $\sigma$  of semiconductors. Olivine may be classified in this category.

#### SAMPLE PREPARATION

Single crystals of olivine were cut in thin slices (<0.02 cm) by a 0.006-inch diamond wheel turning at very slow speeds with low feeding pressures to minimize crystal damage. These slices were then carefully hand-lapped with a final alumina grit of 0.05  $\mu$ . The olivine sections were cleaned thoroughly with acetone and washed ultrasonically in a soap solution and in ethyl alcohol to ensure a clean surface on which to apply the conductive coating of platinum. Before being plated with platinum, the crystals were examined optically for flaws such as cracks, inclusions, and alteration products.

Two methods of platinum plating were used. Crystals from the San Carlos Indian reservation were painted with Liquid Bright, a platinum paint produced by DuPont de Nemours Company. Repeated applications of the paint and firing to 600°C in air resulted in a thick

platinum coat on the crystal surfaces. An uncoated thin section of olivine showed no color change during this procedure; thus it is assumed that there was no oxidation of olivine during this coating process. The remaining samples were placed in a bell jar, evacuated to about  $10^{-6}$  atm, and ion-bombarded to ensure a clean surface on which to deposit platinum. The crystals were then heated to 800°C by a tantalum-strip heater, and platinum-charged tungsten wires 4 cm above the crystals were heated sufficiently to evaporate platinum onto the crystals.

The platinum-coated plates of olivine were then cut into parallelograms whose lateral dimensions were in most cases at least 10 times their thicknesses to avoid boundary effects. Thickness and area were measured with a traveling microscope marked in 0.0001-inch intervals.

The orientation of the olivine samples was determined by the Laue back-reflection technique to within 0.5° and was checked by precession techniques. Table 1 lists sources, localities, and chemical compositions for samples used in this study.

#### EXPERIMENTAL APPARATUS

Figure 1 shows the sample-holder assembly with the primary and secondary heaters. The assembly was designed so that its conductance, which increases with temperature, would not interfere with the conductance measured for the olivine. Thus care was taken to ensure that no contact was made between the ceramic parts that carried the electrodes contacting the sample or between either ceramic piece and the furnace in the hot regions. This lack of contact was accomplished by making the inner parts of the assembly as concentric as possible with the furnace and by allowing relatively large clearances in the central parts and little clearance at the ends.

The leakage conductance between the electrodes with no sample inserted was measured in two separate runs and is given in Table 2, with data from the measurements of olivine conductance for comparison. Only conductances greater than the leakage conductance by at least 2 orders of magnitude were considered in the  $\sigma$  calculations. For the Fa 0 and the Fa 9.4 this leakage conductance was not negligible