Electrical Conductivity of Olivine at High Pressure and Under Controlled Oxygen Fugacity

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Electrical conductivity σ in the [100] direction has been determined for the Red Sea olivine (Fo 91) to 1440°C and 8 kbar in argon. No systematic variation of σ with pressure was observed. The effect of an 8-kbar variation in pressure over the 1270°–1440°C range is equivalent to a temperature uncertainty of ±5°C. We have also determined σ on the same sample up to 1660°C with controlled oxygen fugacity f_{O_2} at 1 bar of total pressure. By using published σ-depth profiles and assuming olivine as the major phase in the earth's upper mantle with $f_{O_2} = 10^{-6}$–10^{-8} bar, temperatures of the upper mantle are calculated as a function of depth. The temperature uncertainty due to possible pressure effects is 2–5 times smaller than that resulting from the ambiguity in published σ-depth profiles.

It is now generally accepted that the major phase in the earth's upper mantle is olivine with an approximate composition $Mg_{1.8}Fe_{0.2}SiO_4$ [*Fujisawa*, 1968]. Published values of electrical conductivity σ of olivine of this composition (either single crystal or polycrystalline) at high temperatures show very poor agreement [*Duba and Lilley*, 1972]. In many instances the difference can be attributed either to trace cation impurities or to different Fe^{3+}/Fe^{2+} ratios [*Duba*, 1972]. Calculations of geothermal profiles are often based upon the combination of σ values derived from magnetic field measurements with laboratory σ data. Since the oxygen fugacity f_{O_2} with which olivine is in equilibrium has a significant effect on σ [*Duba and Nicholls*, 1973], such calculations require laboratory data obtained under controlled f_{O_2}.

The pressure dependence of σ must also be considered in estimating temperature-depth profiles for the earth's upper mantle. Previous attempts to measure the effects of pressure on σ of olivine have yielded ambiguous results and with the exception of the work of *Hughes* [1955], *Schober* [1971], and *Duba* [1972] have been restricted to temperatures less than 1000°C. For polycrystalline samples prepared from powders it is difficult to separate intrinsic pressure effects from changes in sample dimensions due to compaction [*Bradley et al.*, 1964; *Hamilton*, 1965]. The possibility of slight oxidation of the olivine during σ measurement, as well as thermocouple deterioration [*Duba*, 1972], and uncertainty due to the high leakage conductance of the sample assembly [*Hughes*, 1955] make the pressure derivatives obtained from those single-crystal measurements suspect.

In this paper we report σ values measured over a wide range of conditions on a single sample of olivine from the Red Sea area (St. John's Island). This olivine was selected because of its composition ($Mg_{1.81}Fe_{0.19}SiO_4$), which is near that assumed for olivine in the mantle, and its low Fe^{3+}/Fe^{2+} ratio [*Duba et al.*, 1973]. Measurements were made up to 1440°C and 8 kbar of argon [*Duba et al.*, 1972] and to 1660°C under controlled f_{O_2} (1 bar total pressure). Results from this study are compared with available single-crystal data. Finally, by assuming an f_{O_2} variation with depth and using available σ-depth profiles, we construct temperature-depth profiles for the upper mantle.

EXPERIMENTAL PROCEDURE AND RESULTS

The Red Sea olivine (Fo 91) sample was cut normal to the *a* axis and polished, and Pt electrodes were deposited under vacuum as previously described [*Duba*, 1972]. For the high-pressure measurements the experimental procedure of *Duba* [1972] was modified by replacing the Cr-Al thermocouples with Pt-Pt 10% Rh thermocouples and by constructing a filter [*Duba et al.*, 1972] to remove most of the foreign material that plagued earlier experiments. Any hydrocarbons that passed the filtration system were deposited as a thin film in the secondary heater only and did not affect σ measurements, which were performed in the primary heater. The partial pressure of oxygen during the high-pressure experiments is not known.

Electrical conductivity was calculated from conductance measured using either the capacitance bridge or the resistance network described by *Duba* [1972]. Measurements of conductance were made first at 8.0 kbar under conditions of both increasing and decreasing temperature. Gas was then released from the pressure vessel for the 5.0- and 2.5-kbar measurement cycles, followed by repressurization to 8.0 kbar in order to check reproducibility. Constant pressure was maintained by releasing gas from the pressure vessel during the temperature increase portion of the cycle (600°–1440°C) and by pumping during the temperature decrease portion of the cycle. Temperatures were corrected for the effect of pressure on thermocouple emf by using the values of *Getting and Kennedy* [1970]. The temperature corrections for the pressure-temperature range of this study do not differ significantly from those indicated by *Hanneman et al.* [1971] and *Lazarus et al.* [1971].

Figures 1*a*–1*c* include the σ data collected at the three pressures at temperatures above 560°C. Below this temperature, leakage conductance in the sample assembly affected the measurement. Inspection indicates a negligible pressure effect over the range 2.5–8.0 kbar. The scatter for any given pressure encompasses the scatter for all other pressures. However, the σ obtained on temperature decrease at each pressure appears to be consistently higher than that measured for temperature increase. The reasons for this slight hysteresis are possibly related to a reaction between olivine and the high-pressure atmosphere. The decreased conductivity during the second 8-kbar cycle (Figure 1*a*) may be the result of the slightly different atmosphere (i.e., a change in f_{O_2}) in the vessel

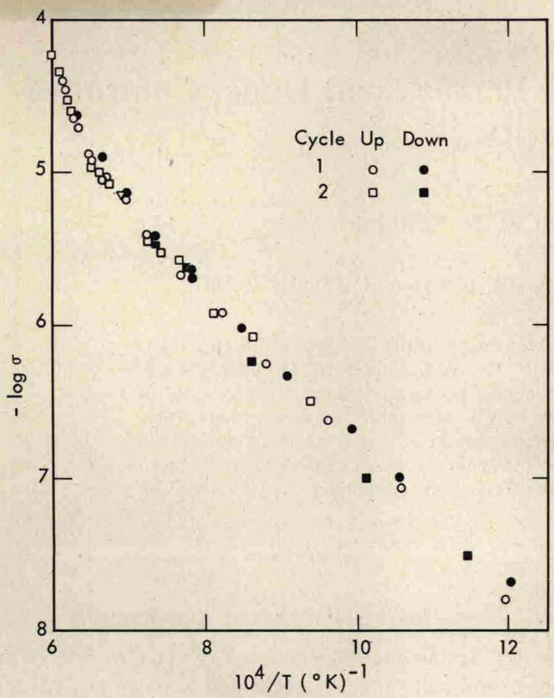

Fig. 1*a*.

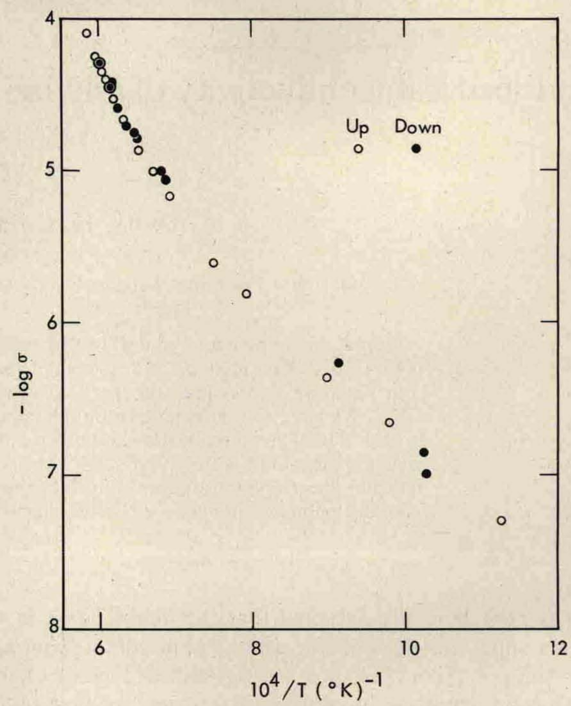

Fig. 1*c*.

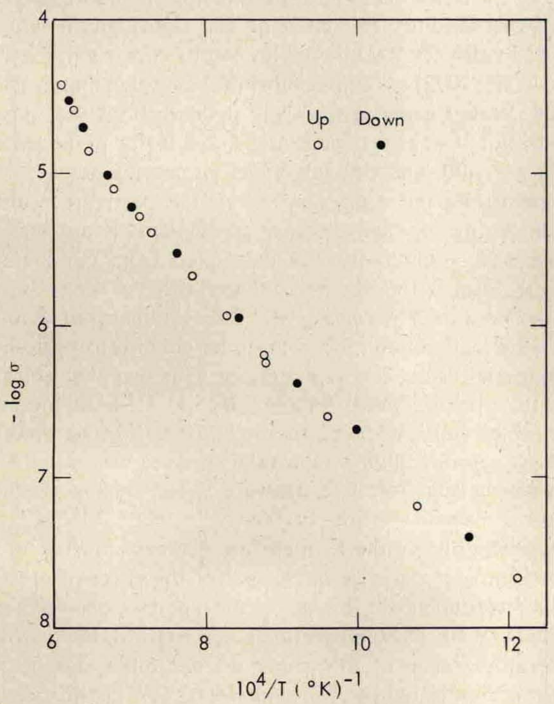

Fig. 1*b*.

Fig. 1. Conductivity (Ω^{-1} cm^{-1}) of Red Sea olivine [100] to 1440°C at various pressures: (*a*) 8.0 kbar, cycle 1, 2 (second cycle data taken after 5.0- and 2.5-kbar cycles), (*b*) 5.0 kbar, and (*c*) 2.5 kbar.

after repressurization or some change in the sample. After the four cycles were completed and the sample was removed from the pressure vessel it was observed to have one central fracture. It is not known when the sample was fractured or how the fracture affected σ. All of the data in Figures 1*a*–1*c* are replotted in Figure 2 along with a linear regression fit of the data to (1) in the high- and low-temperature regions. Analyses of each data set shown in Figures 1*a*–1*c* are summarized in Table 1.

Six months later we measured the σ of the same sample under controlled f_{O_2} using mixtures of H_2 and CO_2 as described by *Duba and Nicholls* [1973]. Below 1200°C, σ was initially as much as 10 times greater than that determined at high pressure. However, σ decreased rapidly with time and approached the high-pressure values previously determined at temperatures above 1200°C (Figure 3). We infer that this low-temperature behavior is the result of adsorbed water in the crack. Similar observations have been reported for cracked pyroxenes [*Duba et al.*, 1974]. After the sample was allowed to remain at 1252° ± 10°C for about 15 hours at $f_{O_2} = 10^{-8.4}$ bar (referenced to 1200°C), σ had decreased about one-half order of magnitude to point A indicated in Figure 3. When no further change in σ was noted at 1244° ± 3°C for 1.5 hours, data were collected at the lower temperatures as shown. Heating and cooling rates during cycling were 50°–100°C per hour.

On temperature increase, f_{O_2} was readjusted to 10^{-8} bar (1200°C). This mixture of CO_2 and H_2 follows a *T-f* path (indicated at the top of Figure 3) close to the quartz-fayalite-magnetite equilibrium curve and within the olivine stability field [*Duba and Nicholls*, 1973]. After 30 hours at 1060° ± 10°C a small decrease in σ was observed as indicated in Figure 3 (point B). Following σ measurement to 1475°C, equilibration of the sample with the experimental atmosphere was indicated by the absence of any change in σ after 15 hours at approximately 1400°C. During the next 6 hours, σ was measured as the temperature was increased from 1400°C to 1660°C and then decreased to 1440°C. The data on the temperature decrease portion indicate an irreversible increase in the conductivity of the sample below 1500°C. Repeat measurements over an identical cycle during the succeeding 5 hours yielded a curve displaced to higher σ by about 0.1 order of magnitude from the previous temperature increase portion and practically identical with the decrease portion. After 15 hours at about 1400°C, no change in σ was observed. Repeat of the above temperature cycles a third time yielded conduc-