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Electrical Conductivity of Orthopyroxene and Garnet Single Crystals at High Temperature

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Abstract The electrical conductivities in two orthopyroxene and two garnet single crystals are measured in the temperature range of 600 to 1200°K. Electrical conductivities σ of orthopyroxene and garnet single crystals can be expressed by

$$\sigma = \sigma_0 \exp(-E/KT)$$

where E is the activation energy, K Boltzman constant, σ_0 the pre-exponential factor, and T absolute temperature. The activation energy of two orthopyroxene with approximately the same ferrosilite content is 1.0 ± 0.1 eV and that of two garnets with different almandine content is 1.5 ± 0.1 eV. The electrical conductivities of garnet single crystals largely depend on Fe content; the logarithm of conductivity in garnet increases linearly with increasing almandine content. Slight anisotropy of electrical conductivity in orthopyroxene seems to be present; however, any tendency relating to the lattice orientation was not discovered.

1. Introduction

Recently, the several electrical conductivity structure models in the upper mantle have been estimated from the observed electromagnetic induction (RIKITAKE, 1969; PARKER, 1970; PORATH, 1971; BANKS, 1972; LAUNAY, 1974).

A comparison of the electrical conductivity estimated from observation with that determined in the laboratory will yield further information about chemical composition and mineralogical constitution in the upper mantle. Recently the electrical conductivity of olivine, the most abundant mineral in the upper mantle, has been studied by KOBAYASHI and MARUYAMA (1971) and DUBA (1972). Orthopyroxene and garnet are the second important constituent minerals in the upper mantle. The conductivity of two garnet single crystals has been measured by MIZUTANI and KANAMORI (1967). However, the nature of electrical conductivity in orthopyroxene and garnet, especially the effect of

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chemical composition, is not understood.

The purpose of this paper is to present the new experimental data and to clarify the effect of chemical composition on the electrical conductivity of these rock-forming minerals.

2. Experiment

Brief descriptions of orthopyroxene and garnet single crystals are listed in Table 1.

Table 1. The description of the specimen and the measured electrical conductivity from 600 to 1200°K

Specimen number	Occurrence and locality	Chemical composition (mole %)	Lattice constants (A)	Orientation	Pre-exponential factor σ_0 ($10^{-2}\ \Omega^{-1}\ cm^{-1}$)	Activation energy E (eV)
Bronzite 1	unkown	En 85.5 Fs 14.0 Wo 0.55	a_0=18.27 b_0= 8.86 c_0= 5.20	[100] [010] [001]	5.05 4.40 6.79	0.95 0.96 0.99
Bronzite 2	Isl. Miyake, Japan	En 83.0 Fs 14.7 Wo 2.2			29.4	1.14
Garnet 1	Wada pass, Japan	Sp 60 Al 40			1.54	1.55
Garnet 2	Associated with diatreme rocks, Buhell Park, Arizona, U. S. A.	Py 70.7 Al 16.6 Gr 13.0 Sp 1.3			491	1.47

En : enstatite, Fs : ferrosilite, Wo : wollastonite, Sp : spessartite, Al : almandine, Py : pyrope, Gr : grossularite.

The chemical compositions were determined by electron probe micro-analyzer. The orientation of crystallographic axes was determined by X-ray oscillation photograph. One single crystals of orthopyroxene was cut to give a rectangular prism 3 to 5mm long, each face being parallel or perpendicular to crystallographic axes. The surfaces of the specimen were polished flat. In the case of remaining samples of orthopyroxene and garnet, the crystal orientations were not considered in the present experiment. The shape of specimens is a plate with two opposing flat faces instead of a prism.

Both ends of parallel surfaces of the rectangular prism or plate of the specimens were coated with silver paste to which platinum wires were attached for electric leads. The electrical resistance of the specimens was measured by means of a vacuum tube voltmeter and a D. C. Wheatstone's bridge in argon or nitrogen gas. In order to prevent the effect of polarization by D. C. current, most measurements were made by employing the voltage of rectangular wave form with a period of 0.1 to 0.5 sec. The temperature of the specimen was measured by C-A thermocouples.

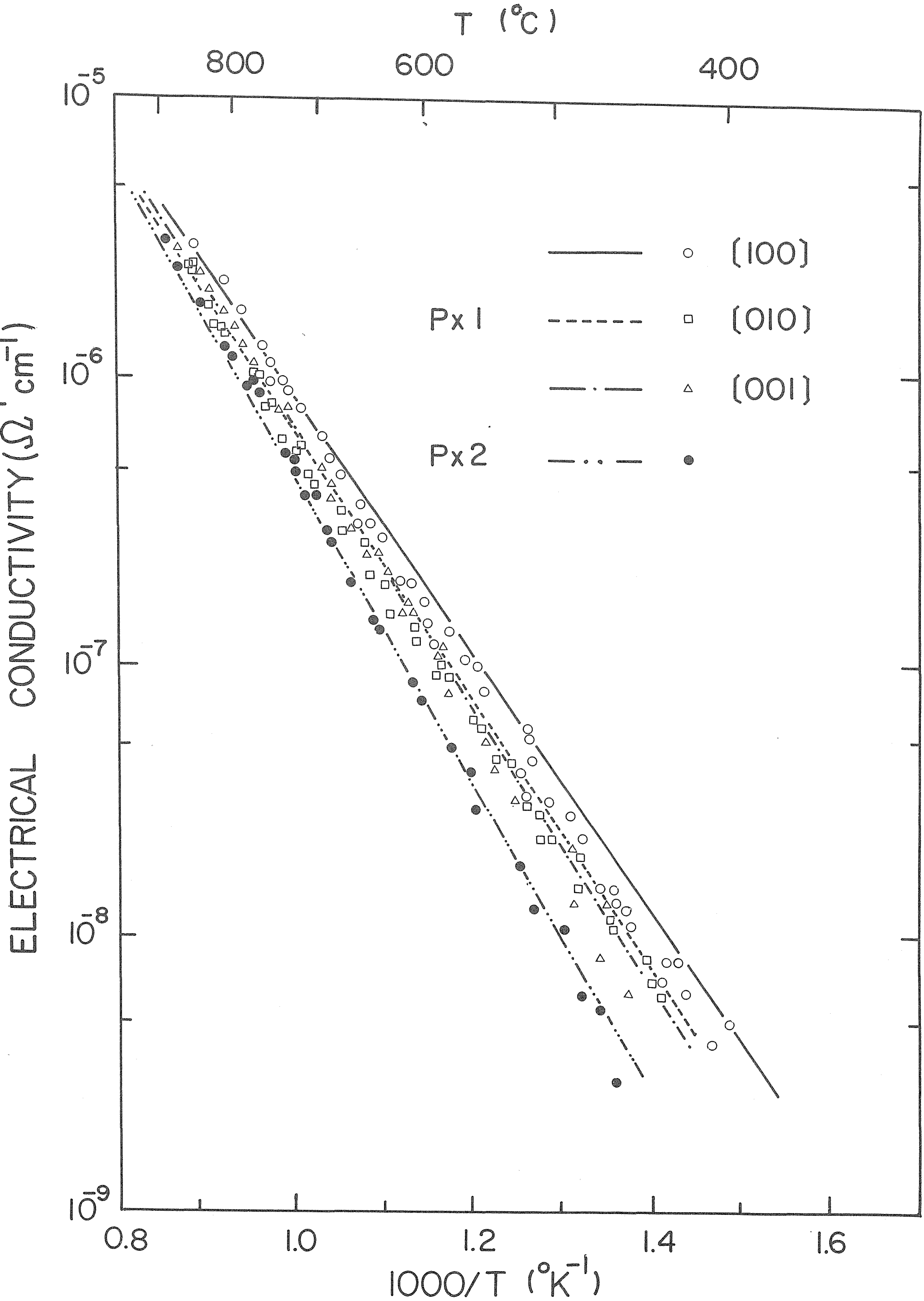

Fig. 1 Log σ versus $10^3/T$ for orthopyroxene (bronzite) 1 and 2.

3. Result and Discussion

Orthopyroxene (Bronzite)

The logarithm of the electrical conductivity for two orthopyroxene single crystals is plotted against the reciprocal of the absolute temperature in Fig. 1. As shown in Fig.1, the logarithm of the electrical conductivity of the specimens is represented by a straight line in the temperature range of 700 to 1200°K. Therefore, the electrical conductivity σ is represented by the following equation:

$$\sigma = \sigma_o \exp(-E/KT)$$

where E is the activation energy, σ_o the pre-exponential factor, K Boltzman constant, and T absolute temperature. The numerical values of activation energy E and pre-exponential factor σ_o are calculated and shown in Table 1.

The anisotropy of electrical conductivity is definitely present. However, the anisotropy of the electrical conductivity for the orthopyroxene is very small as olivine (KOBAYASHI and MARUYAMA, 1971).

The two specimens of orthopyroxene measured have nearly the same contents of ferrosilite molecule ($FeSiO_3$) and the small difference in contents of wollastonite molecule ($CaSiO_3$). It is found that the electrical conductivities for the two orthopyroxenes with the same ferrosilite contents have almost the same conductivity values in the temperature range of 600 to 1200°K.

Garnet

The logarithm of the electrical conductivity in the two garnet single crystals with different composition is plotted against the reciprocal of the absolute temperature in Fig. 2. The logarithm of the electrical conductivity of the specimens is represented by a straight line as in orthopyroxene. The numerical values of activation energy E and pre-exponential factor σ_o are calculated and shown in Table 1.

Although the two samples of garnet have the different chemical composition, the values of activation energy E are approximately the same values. The electrical conductivity of a garnet with higher almandine content (40 mole %) is larger than that of a garnet with lower almandine content (16.6 mole %) in the temperature range of 700 to 1200°K.

Fig. 2 also shows the comparison of the electrical conductivities between the present results and those by MIZUTANI and KANAMORI (1967). The activation energy of the present results is slightly different from that of MIZUTANI and KANAMORI (1967). The electrical conductivities for the garnets with the same almandine content have the almost same values, while the electrical conductivity increases with increasing almandine content. It is shown in Fig. 3 that the logarithm of electrical conductivities at constant temperature increases linearly with increasing almandine content. An empirical relation is given by a formula:

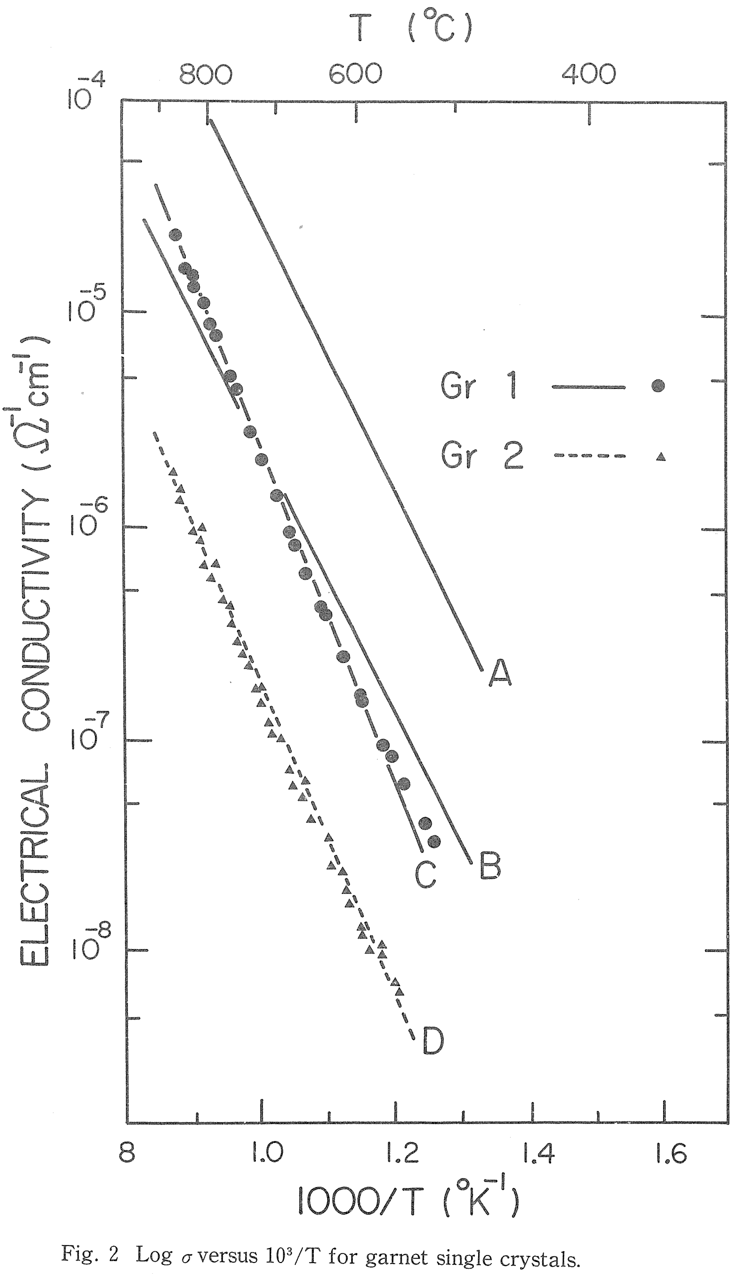

Fig. 2 Log σ versus 10^3/T for garnet single crystals.
A : 50 % almandine by MIZUTANI and KANAMORI (1967)
B : 40 % almandine by MIZUTANI and KANAMORI (1967)
C : garnet 1. 40 % almandine.
D : garnet 2. 16.7 % almandine.

$$\log \sigma = -(0.60 + 16.82 \times 10^3/T) + 0.06C$$

where C is almandine mole %.

As shown above, we conclude that the electrical conductivity in garnet single crystal is strongly controlled by the Fe content as in olivine single crystal (KOBAYASHI and MARUYAMA, 1971), and the logarithm of electrical conductivities of these minerals increases linearly with increasing the Fe content.

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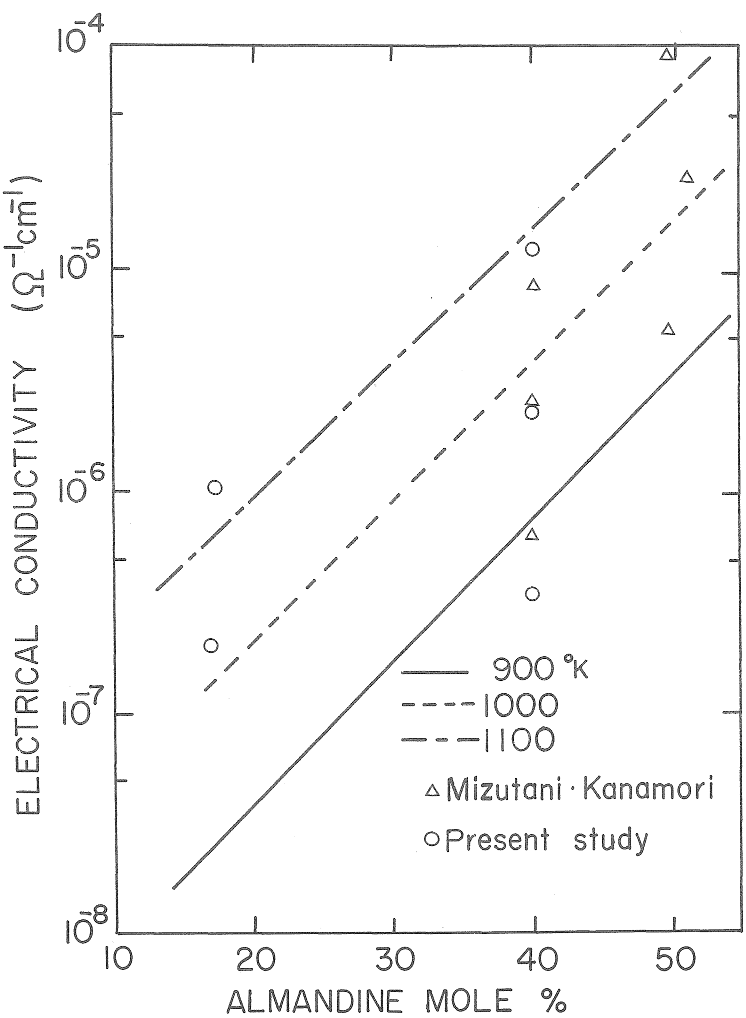

Fig. 3 Electrical conductivity of garnet at constant temperature as a function of almandine mole %.

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