MEASUREMENTS OF ELECTRICAL CONDUCTIVITY OF BASALT AT TEMPERATURES UP TO 1500°C AND PRESSURES TO ABOUT 20 KILOBARS

By

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Abstract

The electrical conductivity of basalt was studied by means of the AC technique at temperatures up to 1500°C and pressures to about 20 Kb.

From the sharp changes in the slope of the conductivity curve, melting temperatures were determined. As pressure increases, the melting temperatures of dry basalt increase, and the melting intervals are shorter than those determined for the same sample by differential thermal analysis and the quenching method.

Complete melting of dry basalt increases the electrical conductivity by a factor of about 10 at most not only at atmospheric pressure but also at high pressures up to about 20 Kb. The pressure effect up to about 20 Kb is small compared with the effect of temperature. Water pressure increases the electrical conductivity to a much greater extent than partial melting.

Therefore, structure models of electrical conductivity for western Canada will be interpreted by the difference in water content.

1. Introduction

The electrical conductivity of the lower crust and upper mantle obtained by geomagnetic depthsounding and magneto-tellurics has been discussed by many authors.

There are two alternative interpretations of the petrological models for western Canada; a) partial melting in the lower crust, suggested by Caner *et al.* [1967], b) hydrated lower crustal materials, suggested by R. D. Hyndman and D. W. Hyndman [1968].

The scarcity of data on the electrical conductivity of basalt made the discussions inconclusive. The electrical conductivity of rock depends on temperature and pressure as well as on water pressure and chemical composition.

The present study was undertaken in an attempt to determine the change in the electrical conductivity of dry basalt associated with melting and the effect of pressure.

2. Experimental procedures and results

Electrical conductivity, σ, was calculated from an equation,

$$\sigma = C/Rx, \tag{1}$$

where C is a cell constant, and Rx is an electrical resistance.

The electrical resistances were measured by the AC technique, using a universal bridge (Yokogawa-Hewlett-Pacard, 4255 A) and a tuned null detector (Yokogawa-Hewlett-Pacard, 4403). All the measurements were carried out at a frequency of 1 KHz.

The sample used to determine the electrical conductivity was Yakuno olivine basalt, for which Shimada [1966] determined the melting temperatures at high pressures. The chemical composition of the sample is given in Table 1, which is reproduced from Shimada's paper [1967].

Table 1.   Chemical analysis and norm of Yakuno olivine basalt

SiO_2	49.51	Or	8.5
TiO_2	1.10	Ab	19.0
Al_2O_3	15.75	An	29.8
Fe_2O_3	3.32	Di	7.6
FeO	9.04	En	18.5
MgO	8.72	Fs	7.7
CaO	7.82	Fo	2.5
Na_2O	2.10	Fa	1.1
K_2O	1.47	Mt	3.6
H_2O^+	0.97	Il	1.6
H_2O^-	0.55		
	100.35		99.9

Experiments were carried out in the following three cases; (1) at atmospheric pressure and temperature range from 350°C to about 1200°C, (2) at atmospheric pressure and temperature range from about 1200°C to 1500°C, (3) at high pressures to about 20 Kb and temperature range from 600°C to 1500°C.

(1)   At atmospheric pressure and temperature range from 350°C to about 1200°C

A finely powdered sample was pressed at about 20 Kb, sintered in nitrogen gas at 1100°C for 3 hours, and cut in the shape of a cylinder, 3 mm long and 4 mm in diameter. Both ends of the cylinder were attached to platinum electrodes with platinum alloy paste (DuPont electric grade 8215). The assembly in the furnace is shown in Fig. 1. Measurements were carried out in nitrogen gas to avoid oxidation of the sample. The cell constant, C, was calculated from an equation,

$$C = L/S, \tag{2}$$

where L is the length of the sample, and S is the cross-section of the sample. Temperatures were measured with Pt/Pt-Rh 13% thermocouple which was placed very close to the sample. The heating rate was less than 2°C/min at temperatures up to 1000°C, and less than 1°C/min over 1000°C.
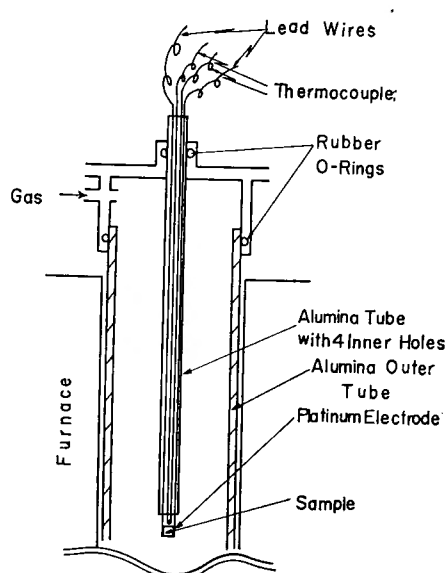

Fig. 1. The assembly in the furnace at atmospheric pressure and temperature range from 350°C to about 1200°C.

(2) At atmospheric pressure and temperature range from about 1200°C to 1500°C

A finely powdered sample, which was dried at 800°C for about 3 hours, was poured into an alumina U-tube and melted at 1300°C and more until the gas confined within the sample bubbled out. After that, platinum electrodes were inserted into the sample and the temperature was reduced to less than 1200°C. After the electrodes were fixed, measurements were begun. The assembly in the furnace is shown in Fig. 2. The cell constant, C, was determined at temperature range from 800°C to 900°C using KCl liquid as the standard substance, and was 55 cm^{-1}. Temperatures were measured with Pt/Pt-Rh 13% thermocouple which was placed very close to the U-tube. The heating rate was about 1°C/min.

The results at atmospheric pressure are shown in Fig. 3. Both results in the cases of (1) and (2) agree well with each other when extrapolated to lower and higher temperatures respectively. From the sharp changes in the slope of the conductivity curve, melting temperatures were determined. Point 'c' in Fig. 3 denotes the start of melting, and point 'b' denotes the end of melting.
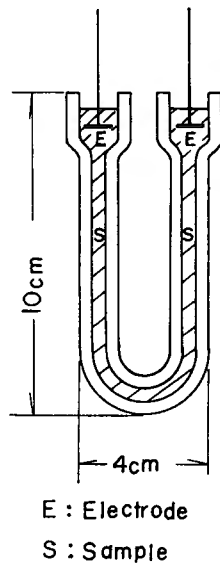
E : Electrode

S : Sample

Fig. 2. The assembly in the furnace at atmospheric pressure and
temperature range from about 1200°C to 1500°C.

The solidus temperature of the sample is 1135 ± 5°C, and the liquidus temperature is 1240°C. The flattening of the conductivity curve near the point 'c' may be due to the loosening of contacts between the sample and the electrodes.

Barus and Iddings's data [1892] for basalt obtained by the DC technique in the cooling run and Levedev and Khitarov's data [1964] for granite by the AC technique are also shown in Fig. 3. Although there are differences in the electrical conductivity by a few powers of ten between present data and Barus and Iddings's, the increase in electrical conductivity of basalt associated with melting is negligible compared with that of granite.

However, the difference in conductivity curves between basalt and granite will be ascribed to the difference in the method of investigation. Nagata's data [1937] for Mihara lava, which are shown in Fig. 4, suggest that, in using a powdered sample at atmospheric pressure, the conductivity curve in the initial heating run is quite different from that in the second heating run. Unfortunately, the method of Levedev and Khitarov's experiment at atmospheric pressure is unknown.

(3)　At pressures up to about 20 Kb and temperature range from 600°C to 1500°C

The high pressure apparatus used for this study was a single-stage piston cylinder type. The diameter of the cylinder was 20.0 mm. In order to study
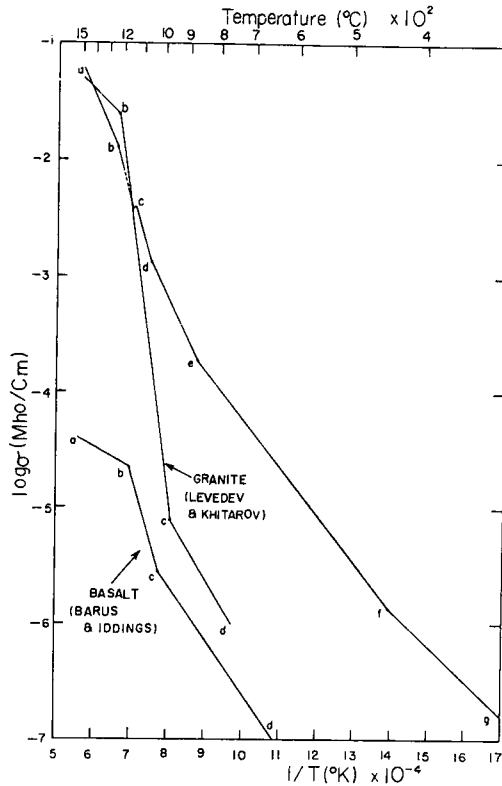
Fig. 3. Electrical conductivity as a function of temperature at atmospheric pressure. Sections b-c of the curves are melting intervals.
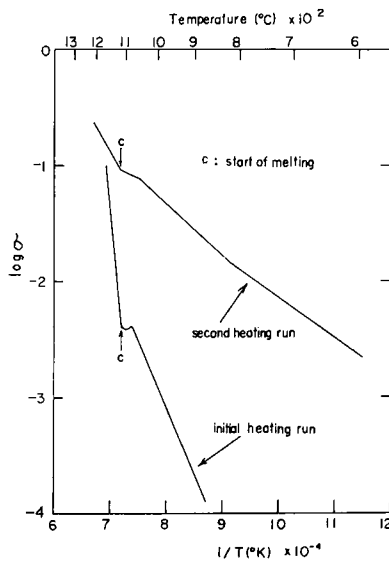

Fig. 4. Difference in conductivity curves between in the initial heating run and in the second heating run from Nagata's [1937] AC-data for Mihara lava.

the effect of water pressure, two kinds of experimental assembly were examined; (a) glass assembly, and (b) non-glass assembly.

(a)   Glass assembly

The glass assembly is shown in Fig. 5. The sintered sample in the shape of a cylinder, 3 mm long and 4 mm in diameter, was inserted into a fused quartz tube, attached to platinum electrodes at both ends of the cylinder and fixed by boron nitride caps. The boron nitride caps and pyrophyllite rods inside a graphite heater were previously heat-treated at 800°C for 1 hour. To receive the H_2O produced by the dehydration of a talc sleeve, a pyrex glass was placed between the heater and the talc sleeve, which were previously dried at 110°C for more than 24 hours.
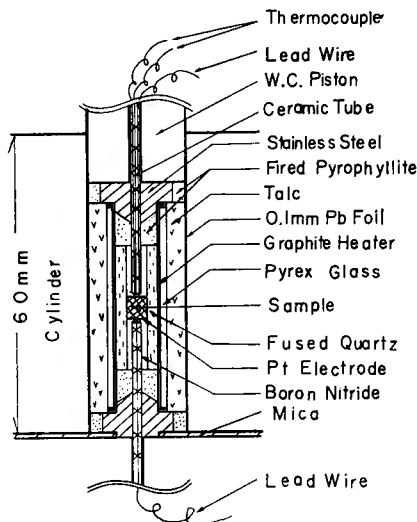

Fig. 5. Glass assembly in the high pressure chamber.

Electrical resistances were measured after maintaining the experimental temperature at a constant for about 10 minutes. Temperature was raised by steps at intervals of from 30°C to 50°C by manually controlling the electric power. Temperatures were measured with Pt/Pt-Rh 13% thermocouple attached to one side of the electrodes. When a sample was placed at the center of the heater, the temperature difference in the sample was about±10°C at 1000°C. No correction was made for the effect of pressure on *emf* of the thermocouple. The cell constant, C, was calculated from the equation (2), and also no correction was made for the change of volume of the sample.

The results obtained by using the glass assembly at high pressures are

shown in Fig. 6. Point 'c' in Fig. 6 again denotes the start of melting, and point 'b' denotes the end of melting. The melting temperatures of the sample increase with increasing pressure. Complete melting of dry basalt increases the electrical conductivity by a factor of about 10 at most at pressures up to about 20 Kb as well as at atmospheric pressure. As pressure increases, the electrical conductivity increases, but the effect of pressure within the pressure interval studied is not striking compared with the effect of temperature.
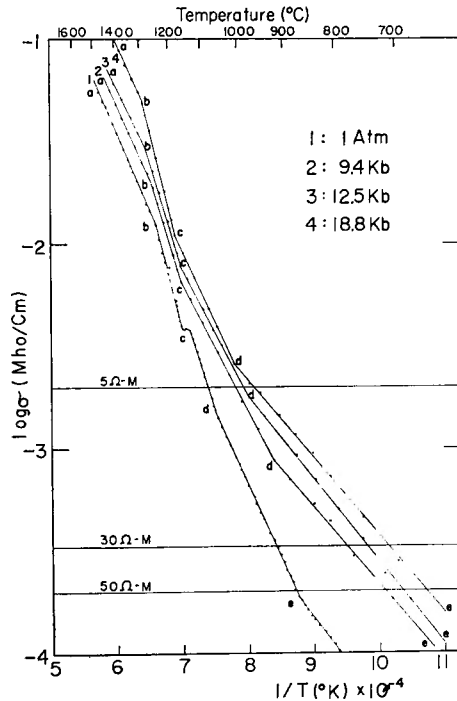

Fig. 6. Effects of pressure and melting on the electrical conductivity of dry basalt. Sections b-c of the curves are melting intervals.

Khitarov and Slutskiy [1965] also studied the effect of pressure on the melting temperatures of basalt based on electroconductivity measurements, but their results, which are shown in Fig. 7, show negative pressure effect on the electrical conductivity, which is contrary to the present results.

As shown on the graphs in Figs. 3 and 6, $\log \sigma$ varies linearly with $1/T$ throughout the experimental temperature range. Therefore, the electrical conductivity of a polycrystalline material such as rock can be expressed by an equation similar to that for a single crystal (Parkhomenko [1967]),

$$\sigma = \sigma_1 \exp\left(-E_1/kT\right) + \sigma_2 \exp\left(-E_2/kT\right) + \cdots, \tag{3}$$
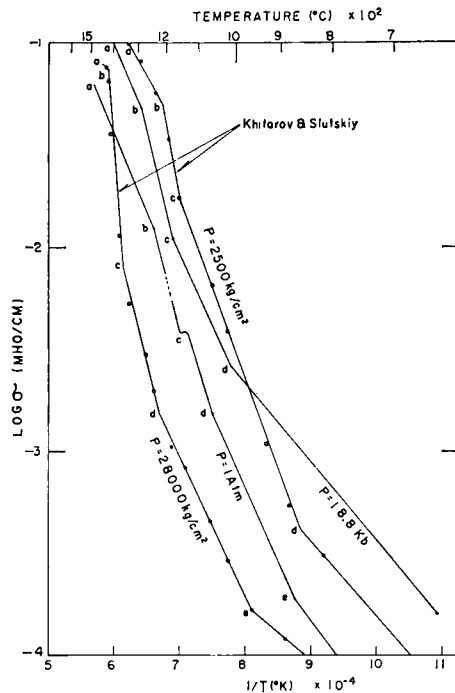
Fig. 7. Difference in pressure effect between present results and Khitarov
and Slutskiy's [1965]. Sections b-c of the curves are melting intervals.

where E_i's are the activation energies, k, the Boltzmann constant, and σ_i's
are the proportionality constants. The first term corresponds to low tempera-
ture conductivity, and the second corresponds to high temperature conductivity.

On the other hand, the electrical conductivity of a silicate melt can be
expressed by the Rasch-Hinrichsen law [1908],

$$\sigma = A \exp(-E/RT), \tag{4}$$

where A is a proportionality constant, and R is the gas constant.

From a relation,

$$k = R/N, \tag{5}$$

where N is Avogadro's number, the equation (4) can be shown as,

$$\sigma = A \exp(-E'/kT). \tag{6}$$

Therefore, the electrical conductivity can be expressed by the equation (3)
throughout the temperature range studied. From the conductivity curves in
Figs. 3 and 6, the values of σ_i and E_i are calculated and listed in Table 2.

(b) Non-glass assembly

Non-glass assembly is shown in Fig. 8. A sample was cut from a natural

Table 2. Values of activation energy, E_i, and proportionality constant, σ_i, calculated from the conductivity curves in Figs. 3 and 6

| Pressure	Temperature range, °C	Activation energy, eV		Proportionality constant, Mho/cm		Section of the curve
1 Atm	350– 545	E_1	0.37	σ_1	2.05×10^{-2}	f–g
	545– 870	E_2	0.79	σ_2	7.0×10^{-1}	e–f
	870–1060	E_3	1.43	σ_3	4.9×10^{2}	d–e
	1060–1135	E_4	2.17	σ_4	5.0×10^{5}	c–d
	1135–1240	E_5	2.67	σ_5	9.5×10^{6}	b–c
	1240–1500	E_6	1.46	σ_6	1.42×10^{3}	a–b
9.4 Kb	600– 920	E_1	0.74	σ_1	1.35	d–e
	920–1160	E_2	1.26	σ_2	2.22×10^{2}	c–d
	1160–1260	E_3	2.13	σ_3	2.15×10^{5}	b–c
	1260–1450	E_4	1.39	σ_4	1.10×10^{3}	a–b
12.5 Kb	600– 975	E_1	0.79	σ_1	3.40	d–e
	975–1165	E_2	1.24	σ_2	2.18×10^{2}	c–d
	1165–1275	E_3	2.29	σ_3	9.2×10^{5}	b–c
	1275–1435	E_4	1.30	σ_4	6.4×10^{2}	a–b
18.8 Kb	600–1015	E_1	0.77	σ_1	2.70	d–e
	1015–1180	E_2	1.37	σ_2	1.10×10^{2}	c–d
	1180–1290	E_3	2.58	σ_3	1.52×10^{7}	b–c
	1290–1400	E_4	1.39	σ_4	2.55×10^{3}	a–b
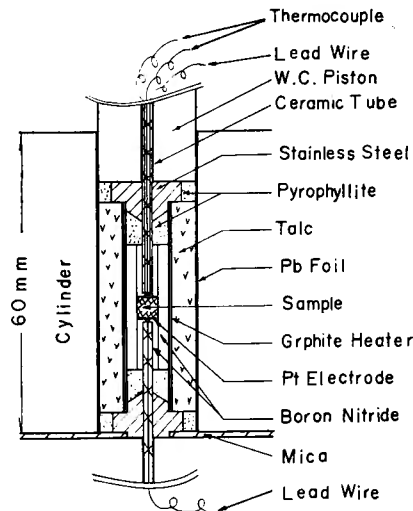
Fig. 8. Non-glass assembly in the high pressure chamber.

rock in the shape of a cylinder, 3 mm long and 4 mm in diameter, and was dried at 800°C for more than one hour, but the sample is considered to have

still contained a small quantity of water. A boron nitride capsule was used instead of the fused quartz tube. All the experimental materials were previously dried at 110°C for more than 24 hours.

Experimental results are shown in Fig. 9. The tendency of increasing conductivity with temperature is different from that obtained by using the glass assembly. This difference is due to H_2O produced by the dehydration of the sample and the pressure medium such as talc, pyrophyllite and boron nitride.
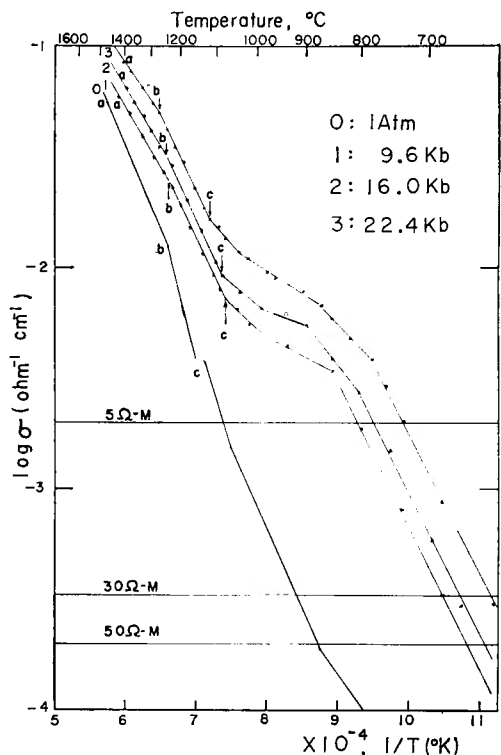

Fig. 9. Effects of pressure and water on the electrical conductivity of basalt. Sections b–c of the curves are melting intervals.

At temperatures ranging from 800°C to 1000°C, the slope in the conductivity curve decreases; therefore, the boron nitride capsule may serve as a passage for H_2O.

The conductivity curves at temperatures up to about 800°C suggest the effect of absorption of water. Although the water pressure could not be determined, it will be lower than the total pressure.

These results show that the effect of water pressure on the electrical conductivity is remarkable compared with the effects of pressure and partial melting.

Melting temperatures determined by the electrical conductivity measurements are shown in Fig. 10. Good agreement between the melting temperatures at atmospheric pressure and those at high pressures is shown in the case of the glass assembly. Therefore, these temperatures give the melting temperatures for dry basalt, of which melting intervals are shorter than Shimada's determination [1966] for the same dry basalt by differential thermal analysis and the quenching method.

Melting temperatures obtained by using the non-glass assembly are lower than those by using the glass assembly. Therefore, the former gives the melting temperatures under slight water pressure.
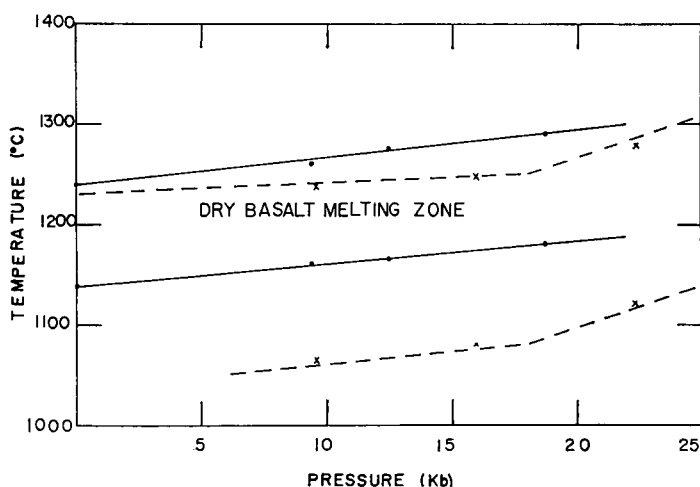

Fig. 10. Melting zone of dry basalt determined by electrical conductivity measurements. Circles illustrate melting temperatures obtained by using a glass assembly and cross points illustrate melting temperatures obtained by using a non-glass assembly. Broken lines illustrate Shimada's melting zone [1966] for the same dry basalt determined by differential thermal analysis and the quenching method.

3. Geophysical discussions

Caner [1970] constructed structure models of electrical conductivity for western Canada by geomagnetic depthsounding and magneto-tellurics. Caner's models show that in south-western Alberta, the electrical resistivity at depths ranging from 30-35 km to 110 km is 30-50 Ω-m, and in the western region, at depths ranging from 10-15 km to 40 km and more is 5 Ω-m. The three horizontal lines in Figs. 6 and 9 represent the three electrical resistivities.

Assuming dry basalt for the lower crust and upper mantle materials, it is suggested from Fig. 6 that: a) the temperature at a depth of 35 km is at

least 700°C in south-western Alberta, and b) the temperature at a depth of 15 km exceeds 1000°C in the western region. These temperatures are too high compared with the geotherms in western Canada as suggested by Caner [1970]. So, the dry rock assumption can not be valid.

Water pressure increases the electrical conductivity remarkably as shown in Fig. 9. Therefore, the assumed temperatures might be reduced if the regions are under any water pressure. In the case of water pressure lower than the total pressure, it is suggested from Fig. 9 that: a) the temperature at a depth of 35 km is about 600°C in south-western Alberta, and b) the temperature at a depth of 15 km is about 800°C in the western region. Much more water pressure will decrease the temperature in western region.

Therefore, the present study suggests that the difference in water content accounts for the difference in the electrical conductivity in both regions, as suggested by R. D. Hyndman and D. W. Hyndman [1968].

Acknowledgement

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