The Electrical Conductivity of Gabbro at High Temperature and High Pressure*

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Abstract: The electric conductivity of gabbro has been measured at 1.0– 2.0 GPa and 320–700℃, and the conduction mechanism has been analyzed in terms of the impedance spectra. Experimental results indicated that the electric conductivity depends on the frequency of alternative current. Impedance arcs representing the conduction mechanism of grain interiors are displayed in the complex impedance plane, and the mechanism is dominated at high pressure. These arcs occur over the range of $10^2 - k \times 10^5$ Hz (k is the positive integer from 1 to 9). On the basis of our results and previous work, it is concluded that gabbro cannot form any high conductivity layer (HCL) in the middle-lower crust.

Key words: high temperature and pressure; gabbro; conduction mechanism; electrical conductivity; HCL

Laboratory *in-situ* measurement of the electric conductivity of materials in the Earth's interior at high temperature and high pressure is one of the most effective methods to study the Earth's interior, which provides not only important information about the composition and structure of the crust, but also the important basis for the explanation of the microscopic physical mechanism of HCL in the middle-lower crust (Zhu Maoxu et al., 2001). In recent years, with the development of field magnetotelluric sounding and the chemistry of the Earth's interior, great progress has been made in the measurements of electrical properties of the Earth's interior at high temperature and high pressure to study the materials of the Earth's interior and their movement state. In general, it is reported that the four-electrode direct current method (Kobayashi and Maruyama, 1971; Bradley et al., 1964; Lacam, 1983) and the alternative current method (Cemic, 1980; Hirsch and Wang, 1986) were used, and the high temperature and high pressure apparatuses including the piston cylinder of fluid and solid medium (Shankland et al., 1997), multi-anvil press (Zhu Maoxu et al., 2001; Wang Duojun et al., 2001), diamond cell (Li Xiaoyuan and Raymond Jeanloz, 1991) and the shock wave cell were used on the trial basis. As far as the measuring methods are concerned, serious polarization effect of the samples is involved in the direct current method. Moreover, there exist grain-boundary electric capacity, interface electric capacity between the samples and the electrodes and electric capacity between the two electr-

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odes in the single frequency alternative current method, which leads to dependence of the electric conductivity on frequency.

Early in the 1990's, people realized the weak effect of pressure on the electrical conductivity, but it is not possible to distinguish effect of pressure on the electric conductivity of grain interior from that of the grain boundary until the impedance spectra have been introduced to determine sample's conductance. We have reported new measurements of electric conductivity of gabbro over the frequency range of 12– 10^5 Hz, the temperature range of 320– 700℃ and the pressure range of 1.0– 2.0 GPa, and discussed the microscopic physical mechanism of HCL in the middle-lower crust on the basis of the experimental results and previous studies.

Sample Preparation and Experimental

Sample preparation

The samples used in our experiments are fresh gabbro, and its chemical composition (wt%) is SiO_2 45.48%, Al_2O_3 14.64%, TiO_2 0.8%, FeO and Fe_2O_3 12.10%, MnO 0.21%, MgO 11.7%, CaO 10.0%, Na_2O 1.95%, K_2O 0.5%, H_2O^+ 1.62%, P_2O_5 0.08% and CO_2 0.70%. The gabbro was cut and ground into cylinders measured at 5.8 mm and 5.6 mm in diameter, and 6.60 mm and 5.60 mm in length, respectively. The samples were soaked in acetone to get rid of grease and were baked at 100– 120℃ for 12 h to eliminate adsorbed water.

Experimental

The sample assembly was described by Wang Duojun et al. (2001). The cubic pyrophyllite used as pressure medium and spacers were baked at 500℃ to eliminate the potential effects of the dehydration of pyrophyllite in the process of experiment. The insulating tube, which is made of Al_2O_3, was placed in the center of the heater to avoid the effect of temperature gradient. The electrodes are made of copper, 5.3 mm in diameter, and the traverse is made of dual-wick screened wire. The heater, which is made of dual-layer stainless steel foil, was connected to the ground in order to shield outer electromagnetism noise. Temperatures of the samples were monitored by a NiCr-NiAl thermocouple, placed closely against the sample, with an error of ±10℃.

Our experiments were carried out in a cubic anvil apparatus on an YJ-3000T pressure machine. The details of the apparatus were described by Xu Ji'an et al. (1995). Pressure, with an error of ±0.1 GPa, was increased slowly to a desired value and then kept constant; the temperature was increased step by step. Various temperatures selected at a pressure maintained constant long enough to ensure the equilibrium state before measurement. The modulus $|Z|$ and phase angles ϕ were recorded simultaneously at a given frequency with a ZL-5 LCR meter (measurement accuracy: 0.05%) at every temperature point. The measurement voltage is 1V and the frequencies are within the range of 12– 10^5 Hz.

Results and Discussion

The impedance spectra of gabbro were measured at 1.0 GPa, 320– 620℃ and 2.0 GPa, 350– 700℃, respectively. The results obtained at two pressure ranges were quite similar. Previous wave velocity data (Kern et al., 1999) indicated that the interstices and cracks of the dry rock would close up when the pressure was higher than 0.2 GPa, so the interstices and cracks would not affect the electric conductivity of gabbro at 1.0 and 2.0 GPa, and the factors concerned can be omitted. Previous studies (Hirsch and Wang, 1986) indicated that the electric properties of rocks and minerals depend on frequency when they are measured with the AC method, and such dependency can be seen from the effect of frequency on each part of the complex impedance. The real parts (Z_r) follow the same law, and they tend to decrease with increasing frequency, especially at low temperatures [Fig. 1 (a)]. Imaginary parts ($-Z_i$) increase to the biggest value as frequencies increase, then they decrease as frequencies increase [Fig. 1 (b)]. Phase angles (Φ) depend on frequency, and such dependency becomes weak at elevated temperature, and phase angles decrease while frequencies increase [Fig. 1 (c)]. From these results, we know that the frequency influences the real and imaginary parts and the phase angles, that is, the frequency influences the complex impedance, indicating that the electrical properties of rocks and minerals depend on frequency.

It can be seen from Figs. 2 and 3 that arc iv occurs in the complex plane at each temperature, over $10^5 - k \times 10^2$ Hz (k is the positive integer from 1 to 9), it becomes more and more complete with the rise of temperature. According to the principle of impedance spectra, this semicircle represents the conduction mechanism of the interior of gabbro, which only occurs over a high frequency range. The values of real and imaginary parts decrease drastically with the rise of temperature at the same pressure, demonstrating that the resistance of gabbro strongly depends on temperature. It is suggested that arc iv will shift toward higher frequencies with the rise of temperature. This phenomenon is in consistency with the results reported by Duba et al. (1993).

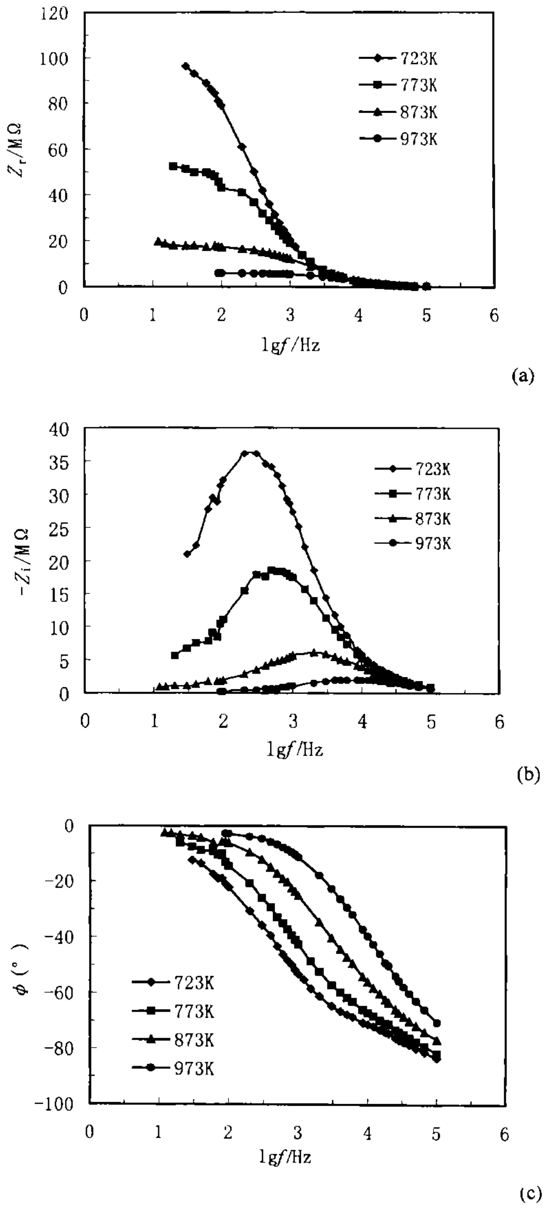

Fig. 1. The relationship between real part (a), imaginary part (b), phase angle (c) and frequency at 2.0 GPa and 623- 973 K.

Our experiment indicated that the total electrical conductivity is mainly due to the grain interior. Using the methods reported by Huebner and Dillenburg, we established Fig. 4 and Table 1.

Perfectly linear relations are recognized between electrical conductivities and reciprocal temperature at 1.0 (a) and 2.0 GPa (b). In these fits the squares of correlation coefficients are 0.9577 and 0.9871, respectively. Conductivities are fit to the Arrhenius equation:

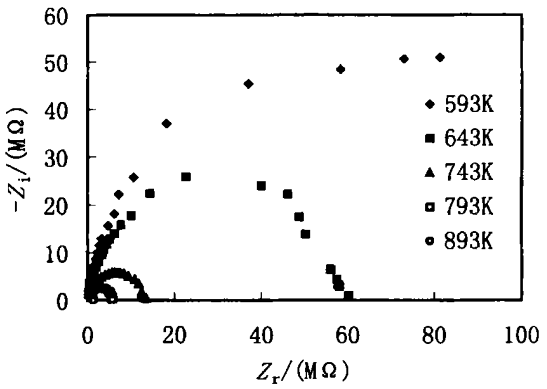

Fig. 2. The impedance spectra of gabbro at 593– 893 K and 1.0 GPa.

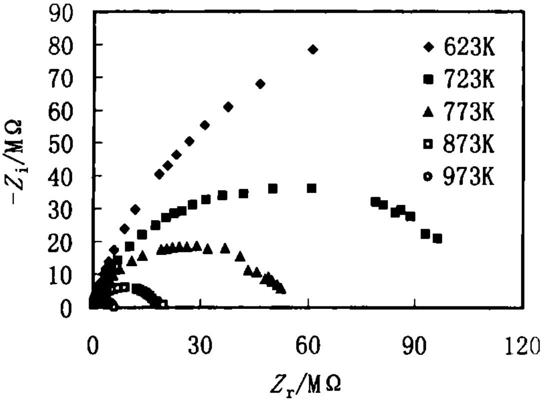

Fig. 3. The impedance spectra of gabbro at 623– 973 K and 2.0 GPa.

$$\sigma = \sigma_0 \exp(-\Delta H/kT)$$

where σ_0 is a pre-exponential factor, T is the absolute temperature, k is Boltzmann constant, and ΔH is the activation enthalpy. The linear relations shown in Fig. 4 imply that the conductivity is likely to be dominated by a single mechanism under the condition of temperature and pressure of our experiment.

From Table 1, the gabbro, which is almost of insulation at room temperature, processes the characteristics of a semiconductor under the condition of conduction ability is greatly enhanced.

Since the discovery of the first crust HCL in the south of eastern Siberia, the HCL in the middle-lower crust has been found all over the world, and geophysicists have been centered on the microscopic physical mechanism of HCL and proposed four mechanisms as follows (Zhu Maoxu et al., 2001; Jones, 1992): (1) fluids in the crust's interior; (2) solid high-conductivity phases at mineral grain boundaries, such as graphite; (3) dehydration of minerals; and (4) partial melting of rocks.

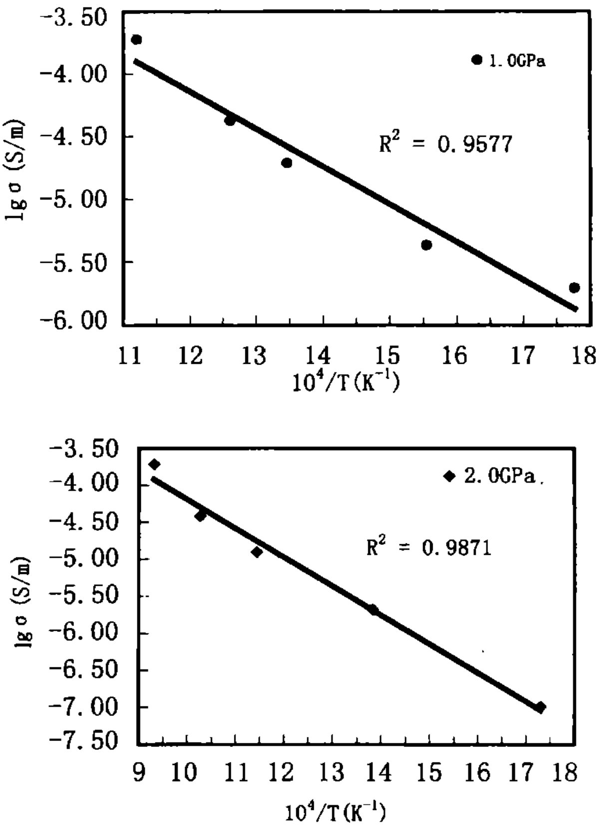

Fig. 4. The relationship between $\lg\sigma$ and $1/T$ at 1.0 GPa (a) and 2.0 GPa (b) for gabbro.

Because the area where there exists the HCL is high in heat flow value, the formation of HCL used to be thought to connect genetically with only partial thermal diffusion, but the temperature within the crust is generally less than 600℃ (Sha Shuqing, 1991). Our experiment indicated that the electrical conductivity of dry gabbro is several orders of magnitude lower than that of HCL in the middle-lower crust. So, we don't think that dry gabbro with no solid high-conductivity phase at the grain boundary is responsible for the formation of the HCL. In addition, previous measurements (Glover and Vine, 1995; Shankland and Ander, 1983) of the electrical conductivity of rocks with no solid phase in the middle-lower crust at high temperature and high pressure indicated that the electrical conductivity of the rocks in the middle-lower crust is almost several orders of magnitude lower than that of the HCL in the middle-lower crust. As for some representative rocks such as gneiss, granulite and eclogite, their electrical conductivity values are within the range of $n \times 10^{-2} - n \times 10^{-3}$ Sm^{-1}. So the temperature is not the exclusive factor leading to the formation of HCL in the crust, and partial melting of the gabbro cannot lead to the formation of the HCL. Furthermore, dehydration of minerals and solid high-conductivity phases could not lead to the formation of the HCL either because pyroxene and plagioclase are not hydrous minerals, so they cannot dehydrate. Some individual thin graphite layers (Glover, 1996) have been found in the middle-lower crust at present, but statistical probability like jewellery is still an open question. There are two graphite resources in the crust: (1) organic matter which has experienced metamorphism; and (2) graphite that comes from CO_2 in the reductive medium. In fact, very thin graphite layers can lose their consistency. Moreover, tectonic displacement on the thin graphite layer order can destroy their electrical conductivity completely. The electrical conductivities of rocks will increase on the orders of magnitude if they contain a little amount of free water. Gabbro is not a kind of rock with such particularities.

Table 1. Fitting parameters of the electrical conductivity of gabbro to Arrhenius equation at 1.0 GPa and 2.0 GPa

P/GPa	T/K	$\log(\sigma_0)$	σ_0(S/m)	ΔH (eV)
1.0	593-893	-0.084	0.824	0.670
2.0	623-1173	0.161	1.452	0.808

In general, gabbro cannot form the HCL.

Glover et al. (1995) considered that the HCL in the middle-lower crust is generally normal, and the assemblage of special rock types and fluids may constrain the formation and forming depth of the HCL. Gu Zhijue et al. (1995) and Gao Ping et al. (1998) thought that the dehydration of hydrous minerals is closely connected with the formation of the HCL.

Therefore, on the basis of previous studies and our experimental results, it can be concluded that any rock that is responsible for the formation of HCL must contain one or several kinds of hydrous minerals, and the hydrous minerals can dehydrate under the condition of temperature and pressure in the middle-lower crust. As dehydration can accelerate partial melting of the rock, and when the rock began melting, the melted materials would form a continuous conductivity film, which causes the electrical conductivity of the rock to decrease by several orders of magnitude, thus forming the HCL in the middle-lower crust.

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