THE MOON

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THE MOON
An International Journal of Lunar Studies

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TEMPERATURE DEPENDENCE OF ELECTRICAL CONDUCTIVITY AND LUNAR TEMPERATURES*

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Abstract. Numerous investigations of the electrical conductivity of lunar and terrestrial materials as a function of temperature have been performed to date in an attempt to provide data on which to base lunar interior temperatures from magnetometer-derived lunar conductivity profiles (Schwerer *et al.*, 1971, 1972, 1973; Duba *et al.*, 1972 and others). There are several pitfalls inherent in the extrapolation of lunar temperatures from laboratory measurements of electrical conductivity. These include the choice of representative material for the lunar interior, appropriate environmental conditions (pressure, fugacity, etc.) and the various measurement difficulties.

In the absence of moisture, the electrical conductivity of geological materials is dominated by electronic (metallic or semiconduction) and/or solid electrolytic (ionic) mechanisms. Metallic conduction mechanisms are not likely to be important in lunar materials due to the small amounts of free metal and metallic oxides present. This is confirmed by the extremely low conductivities measured to date and the fact that the conductivity increases with temperature while the opposite is true in metals. Similarly the semiconducting oxide minerals, like ilmenite and the simple iron oxides, which may constitute as much as 20% by weight of some lunar samples, have a minimal contribution to the bulk conductivity due to their fine dispersion in the predominantly silicate matrix. The major conduction mechanism is thus ionic, and this, together with the lesser semiconduction mechanism, is very strongly controlled by temperature, by deviations from stoichiometry, by electric field strengths, and, since the sample may change character by heating in various environments, by oxygen fugacity (see Kofstad, 1972 or Hladik, 1972). We note, however, that some silicates (e.g., pyroxene) have semiconduction as the primary mechanism and ionic conduction as the lesser process.

Silicates are the primary rock forming minerals and are therefore the main phases responsible for the conduction observed in lunar surface materials. In vacuum better

* Presented at the Geophysical and Geochemical Exploration of the Moon and Planets Conference, January, 1973, Lunar Science Institute, Houston, Tex., U.S.A.

TABLE I

Pyroxene analysis
(A. M. Reid, private communication)

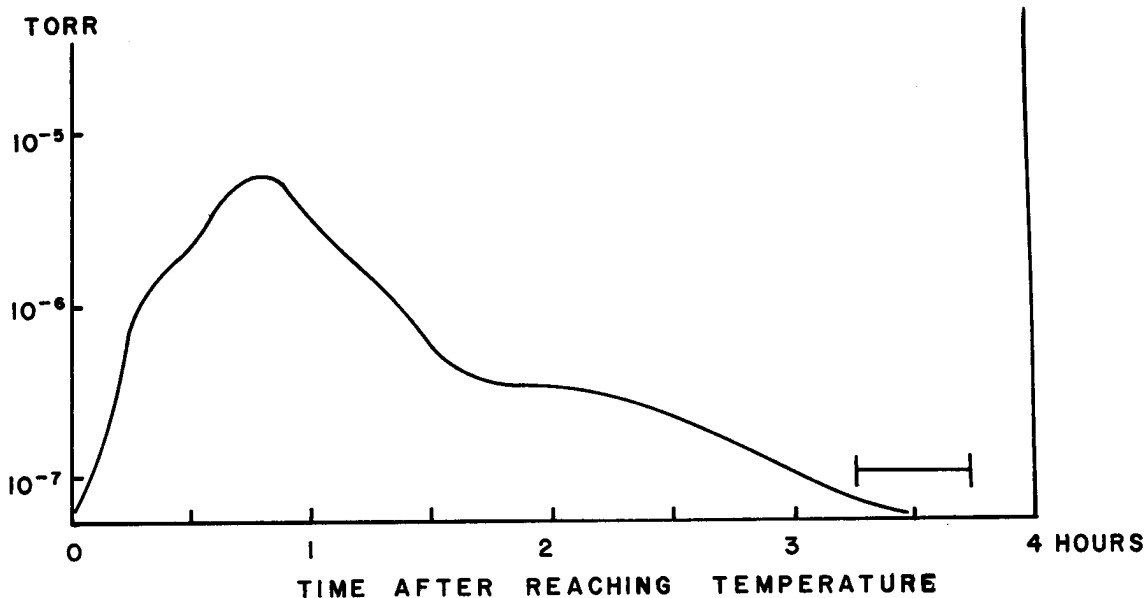|	
SiO$_2$	52.67
TiO$_2$	0.05
Al$_2$O$_3$	0.94
FeO	9.62
MgO	12.04
CaO	23.94
	99.26

Fig. 1.   Pyroxene water vapor outgassing at 167°C; the horizontal bar at approximately 3 hr is the measurement period.

than 1×10^{-7} Torr (typically 2×10^{-8}), we have measured the conductivity as a function of temperature in terrestrial pyroxene (a salite, analysis in Table I, courtesy of A. Reid, NASA/JSC) and two lunar samples (12002,85 basalt and 65015,6 highly recrystallized breccia). A mass spectrometer monitored residual gases in the system. The apparatus and procedure has been described elsewhere (Olhoeft *et al.*, 1972).

A plot of the system total pressure versus time for the pyroxene at 167°C is shown in Figure 1. This represents, for the most part, the outgassing of water vapor from the sample (at each temperature higher than any previously reached temperature, more water was outgassed in similar curve). The electrical properties were measured after temperature stabilization and water outgassing about three hours after the first sign of water vapor on the mass spectrometer (measurement period is shown in Figure 1 as the horizontal bar). The pyroxene showed some water loss at each heating to 800°C. Once a temperature had been reached and the curve of Figure 1 produced, no more water could be driven out without heating to a higher temperature. Lunar sample 12002,85 had been exposed to air for several months and showed water loss up to 250°C.
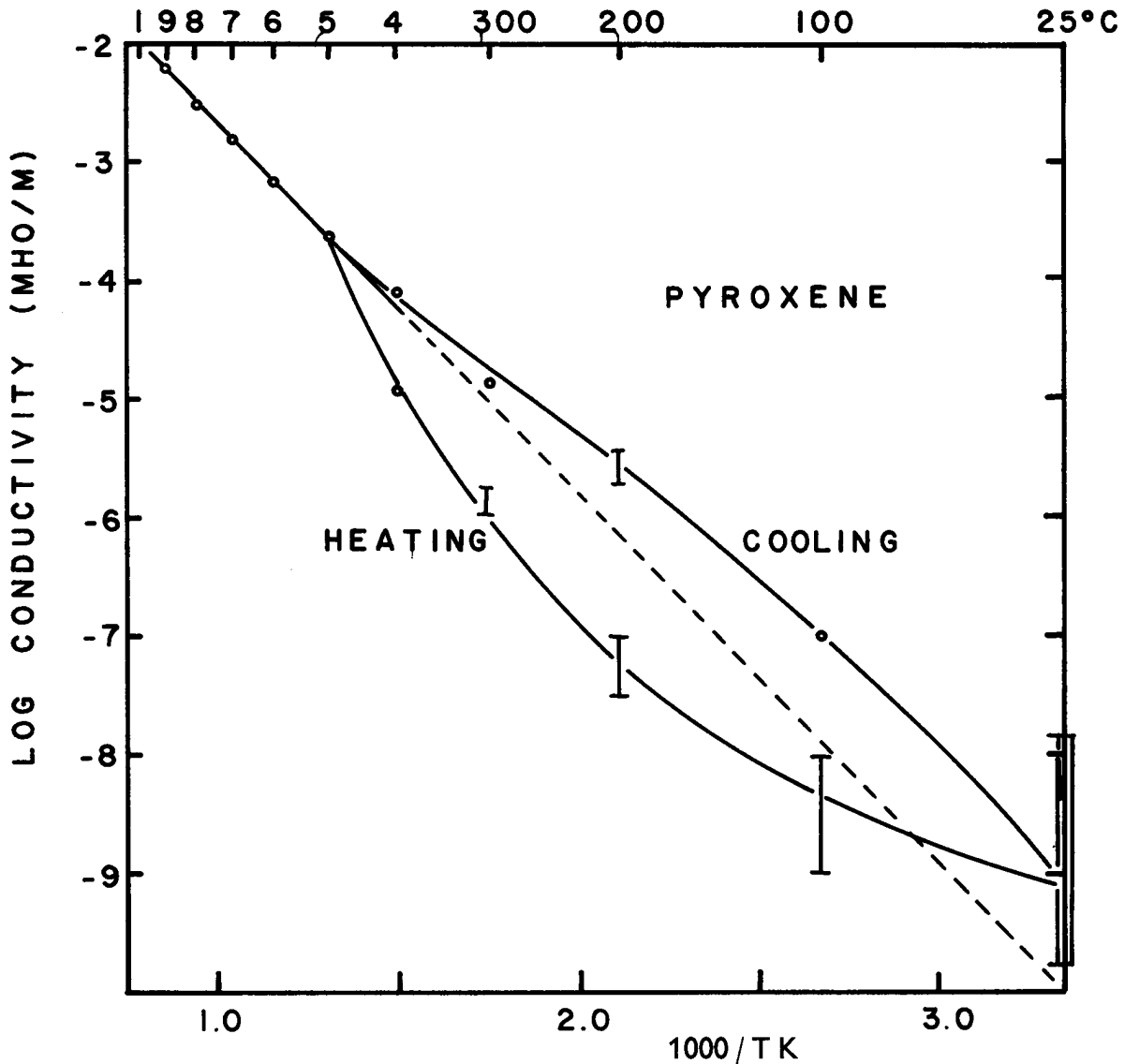
Fig. 2.   Pyroxene conductivity versus temperature in vacuum; the dotted line is the Boltzmann distribution, the solid lines with error bars show the data over many runs.

Sample 65015,6 had been processed in dry nitrogen and transferred under dry nitrogen to the vacuum system, and it exhibited water loss for less than five minutes at 25 °C only (probably due to residual water vapor in the system before pumpdown).

Figure 2 shows the resultant pyroxene conductivity versus temperature, following a typical Boltzmann temperature distribution (which plots as a straight line on log conductivity versus reciprocal temperature axes). The sample conductivity reversibly and repeatably followed the lower curve marked 'heating', during both heating and cooling to maximum temperatures below 500 °C; heating above 500 °C resulted in the conductivity following the upper curve during cooling. Similar behavior has been observed in other materials (ice, von Hippel, 1969) and has no explanation as yet. The dotted line in Figure 2 is a theoretical Boltzmann distribution expressed by

$$\sigma = 1.4 \, e^{-0.54/kT} \text{ mho m}^{-1},$$

where T is expressed in K.

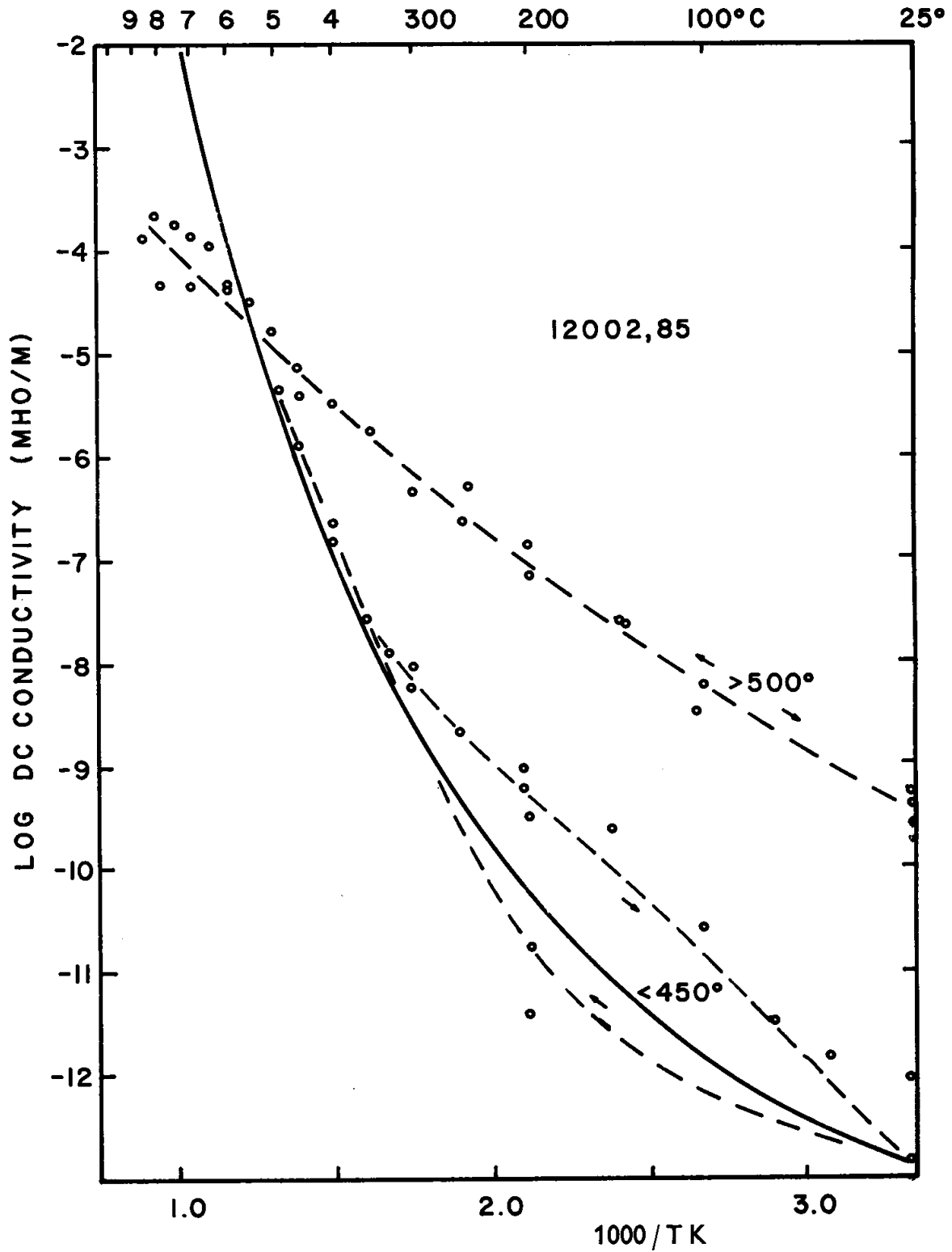Fig. 3. Lunar sample 12002,85 (basalt) electrical conductivity versus temperature in vacuum; the solid line is the theoretical exponential distribution, the dotted lines are the data with circles showing typical scatter.

The solid lines with error bars represent the scatter in several cycles of data measurement.

Figures 3 and 4 show the results for the two lunar samples. Unlike the terrestrial pyroxene both lunar samples have a conductivity that is exponentially-temperature dependent upon heating (the solid line in each figure is a theoretical exponential fit to the data). Similar exponential temperature dependence has been observed in amorphous materials (Adler, 1971). This can be interpreted as the result of an activation energy which is temperature-dependent and decreases with temperature. The effect is to give an apparent activation energy (given by the slope of the plot) which is temperature dependent and increases with temperature. The real activation energy is defined in terms of the Fermi energy and the valence band mobility edge, whereas the apparent activation energy is the derivative of the electrical conductivity with respect to reciprocal kT (Boltzmann constant times temperature). This type of behavior is particularly noticed in regions where transitions occur (phase changes, crystallization or recrystallization, etc.).

In addition, both lunar samples exhibited different conductivity versus temperature curves on heating and cooling, in the case of 12002 after the temperature exceeds 450–500 °C, and in the case of 65015, after it exceeds 200–300 °C. As indicated in Figure 3, 12002 has a small region of hysteresis below 250–300 °C behaving like the pyroxene already discussed. After heating to 450–500 °C the electrical properties undergo an irreversible change. The thermal hysteresis is such that the heating and cooling curves are the same. The dots are representative data points with the dotted lines representing the smoothed data. The solid line is an exponential theoretical fit to the data below 600 °C as described by

$$\sigma = 1.7 \times 10^{-18} \, e^{+0.037T} \text{ mho m}^{-1}.$$

As in the pyroxene case the hysteresis below 250–300 °C cannot be explained. The 450–500 °C breakpoint appears to be a chemical or mineralogical change in the sample, but the exact nature of the change is as yet unknown.

Lunar sample 65015 on heating, exhibited the exponential temperature dependence discussed above. However the sample was irreversible at temperatures as low as 200 °C. In addition, below 400 °C there were non-linear voltage-current relations exhibited (to be discussed below). The solid curve in Figure 4 is an exponential temperature distribution fitted to the data above 300 °C by

$$\sigma = 3.0 \times 10^{-14} \, e^{+0.023T} \text{ mho m}^{-1}.$$

The dotted lines are smoothed data points with several representative points to show the scatter. The heating and cooling irreversibility in this sample is such, that during the initial heating, the conductivity follows the exponential distribution and during cooling, the conductivity is higher than during heating. On reheating, the heating conductivity follows the previous cooling curve until it intersects the exponential
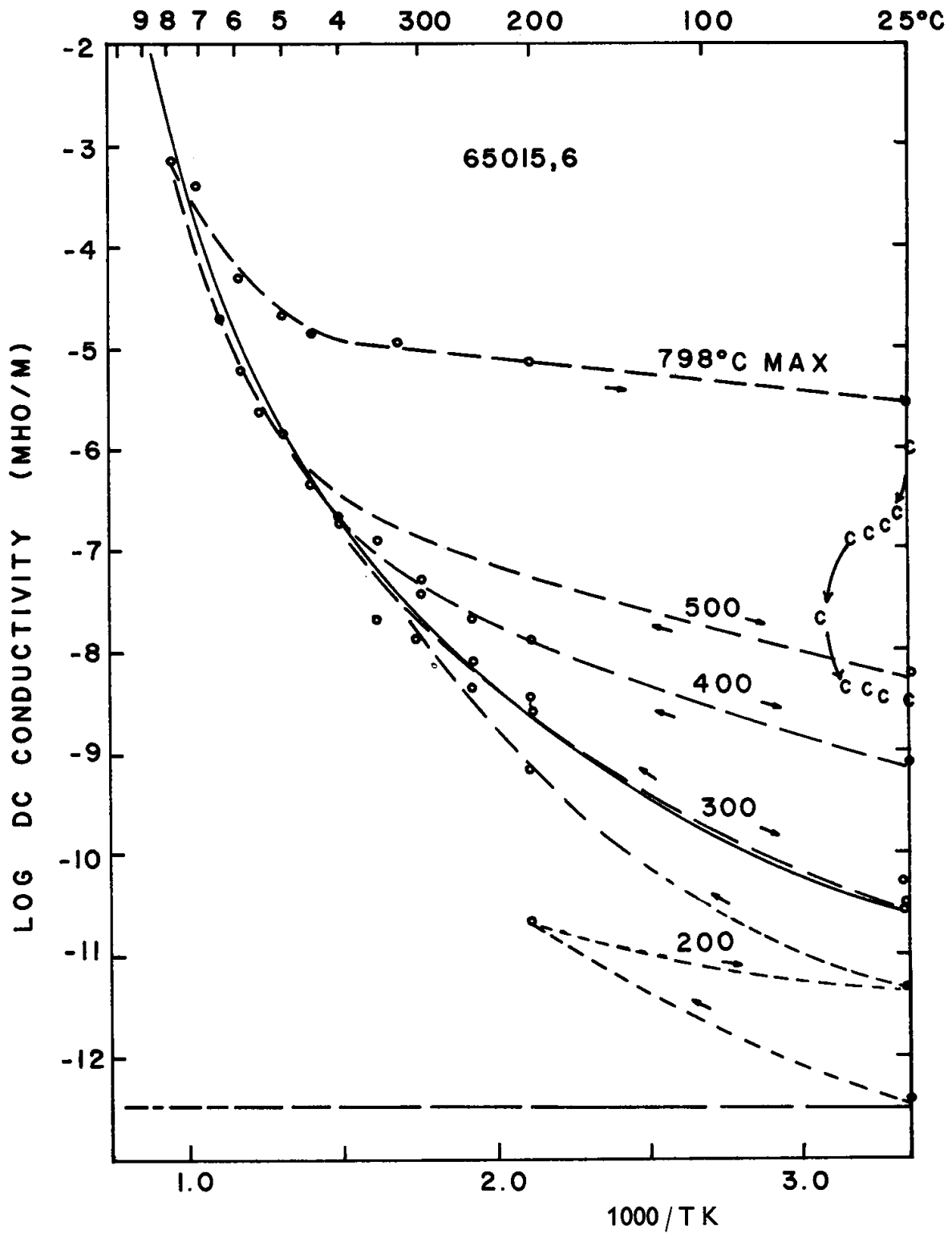
Fig. 4. Lunar sample 65015,6 (highly recrystallized breccia) electrical conductivity versus temperature in vacuum; the solid line is the theoretical exponential distribution, the finely dotted lines below log-10 show the region of constant-current behavior, coarse dotted lines are the data with circles showing the typical scatter; the 'c' data points are 100μ pressure air recovery (see text).

distribution curve. It then follows the exponential curve, but on cooling the conductivity is again higher. The whole process repeated at each thermal cycle. This behavior is similar to the effect of annealing and devitrification on electrical conductivity as reviewed by Adler (1971) in amorphous materials and is similar to the behavior observed by Schwerer *et al.* (1972) in lunar samples. The similarity of the former is particularly suggestive when considering that Albee *et al.* (1973) described 65015 as a glassy agglutinate of mineral and lithic fragments cemented by 'KREEP' glass which was extensively recrystallized with incipient melting of interstitial K-rich material. The other important characteristic of 65015 is that it has undergone partial, but extensive sub-solidus recrystallization and reequilibration at a relatively low temperature (Albee *et al.*, 1973).

The mass spectrometer indicated that above 450 °C, the sample started to outgas oxygen and nitrogen. After the last cycle to 798 °C, the sample was exposed to air and reheated to 65 °C in 100 μ, of atmospheric air with the results shown as '*c*' in Figure 4. The outgassing and partial recovery upon heating in low pressure air, suggest that reduction of the sample may be an alternative explanation of the irreversible behavior in vacuum.

In addition to the above irreversible effects upon heating in vacuum, sample 65015 exhibited non-linear voltage-current behavior below 400 °C as shown in Figure 5. Constant-current versus voltage curves were found which bear a strong resemblance to some space-charge phenomena (the effect was also observed in the dielectric data, to be reported elsewhere). The behavior at 195 °C and above, showing constant-current versus voltage relation below 20 V and a constant impedance versus voltage above 50 V is that expected if the breakdown voltage for the sample-electrode system due to space-charge or other interfacial polarization (von Hippel, 1966) is in the 20–50 V range (which is about 63 V cm^{-1} for the sample).

We are not sure what material should be chosen to represent the lunar interior composition. It is unlikely to be represented by the lunar surface samples we have measured, but there is a possibility that it is pyroxene-rich (Ringwood and Essene, 1970; Solomon, 1973). If we consider the sample data reported here to at least be representative of the lunar interior and if we assume that the electrical conductivity of the interior is 0.01 mho m^{-1} following Dyal *et al.* (1972), then deep lunar interior temperatures in the range from 700 to 1400 °C are predicted from laboratory electrical conductivity measurements. The 700 °C value is based upon the highest conductivity measured on a lunar sample while the 1400 °C value is based upon the lowest conductivity lunar sample data obtained by extrapolating the data measured below 450 °C before irreversible effects occur. The pyroxene data falls in the middle of this range at 1000 °C for 0.01 mho m^{-1}. These extrapolations need to be accepted with considerable reservation since we do not understand either (a) the reason for the low temperature thermal hysteresis or (b) the irreversible change at higher temperatures. Further efforts need to be made to understand these effects. The uncertainty of choosing an appropriate composition for the lunar interior will remain a difficult problem (Anderson, 1973).
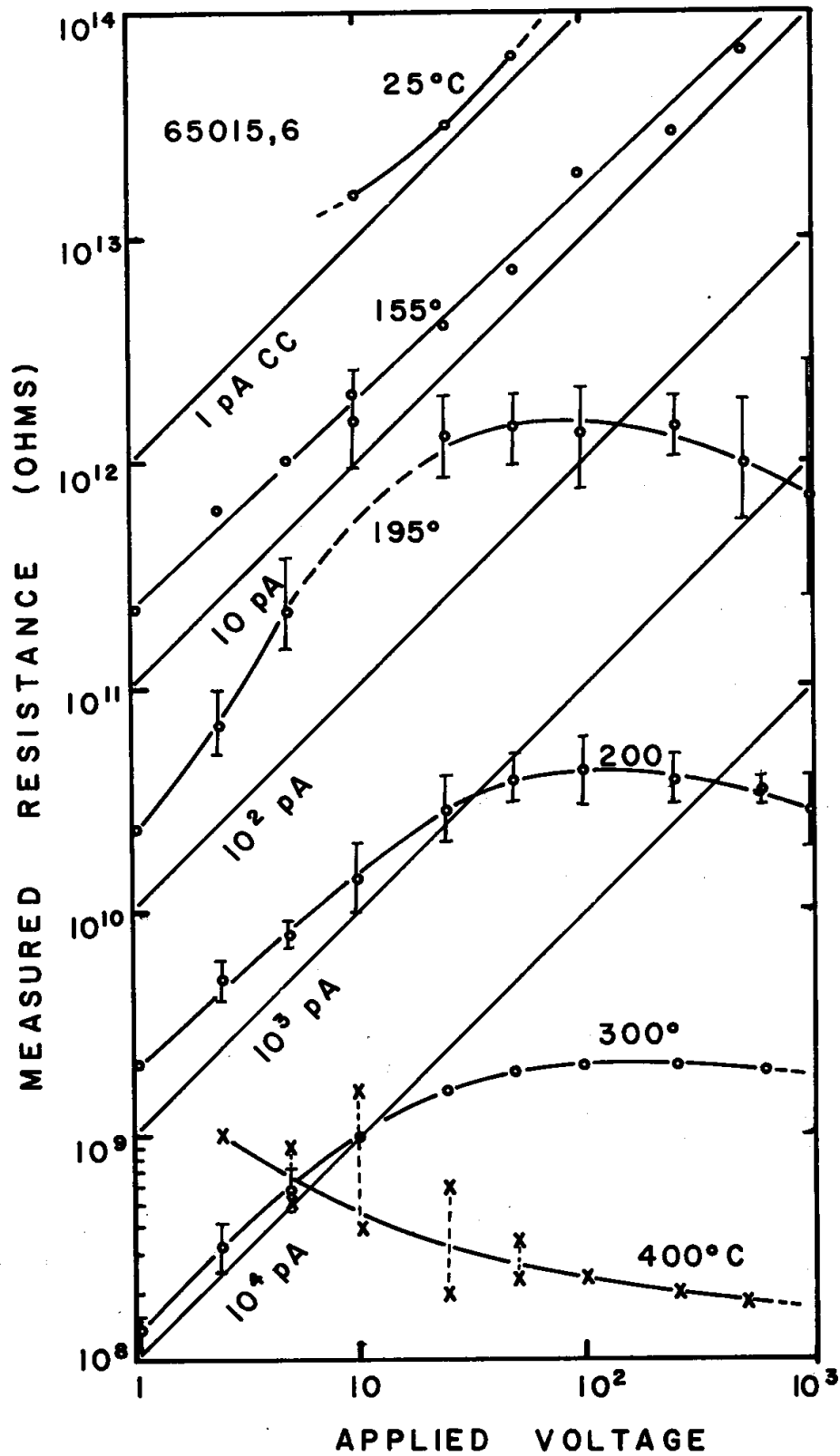
Fig. 5. Lunar sample 65015,6 constant-current behavior; the solid lines with slope of 1.0 are constant-current profiles with values as marked; the solid lines with circles are data below 400° exhibiting constant-current behavior (see text); the 400 °C data is represented with crosses to show the transition to linear current-voltage relations. Error bars are indicated where known.

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