



**GRAPHS AND TABLES
USED TO DESCRIBE ELECTRICAL MEASUREMENTS
OF SAMPLES OF UNCONSOLIDATED MATERIAL,
USGS PETROPHYSICAL LABORATORY – DENVER**

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**U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY**

¹Denver, Colorado

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INTRODUCTION

The U.S. Geological Survey Petrophysical Laboratory (PetLab) in Denver CO measures electrical properties of samples of earth materials collected by U.S. Geological Survey personnel. This report describes the standard graphs and tables produced by PetLab to present geoelectrical measurements made on samples of unconsolidated materials.

GENERAL DISCUSSION OF ELECTRICAL PHYSICAL PROPERTIES

Resistivity

Resistivity is an electrical property independent of a material's size and shape that characterizes its opposition to the flow of electric current. Resistivity, in units of ohm-meters (ohm-m) is the numerical inverse of electric conductivity, in units of Siemens/meter or mho/m. Electrical conductivity measures the ability of a material to transport electric charge, and, like resistivity, is independent of the material's size and shape. Note that some field instruments measure electrical conductivity in units of millisiemens/m (for solids) or microsiemens/cm (fluids), and that others measure resistivity in ohm-m. PetLab measurements use resistivity units exclusively.

The resistivity of geological samples depends on several factors. These include the mineral composition of the sample, its porosity, the amount of water present in the pores, and the amount of total dissolved solids (TDS) in that pore water. Of these, the dominant factors that typically determine a sample's resistivity are the amount and TDS of its pore water. Other factors being equal, dry material will be more resistive than wet material, and material saturated with low TDS water will be more resistive than material saturated with high TDS water.

If the sample contains significant concentrations of interconnected conductive metallic minerals, such as pyrite, a low resistivity may be observed. The presence of clay minerals, such as montmorillonite, will similarly result in a low resistivity. Chemical reactions involving different mineral phases of the sample may also effect its resistivity. Sulfide minerals, for example, may react with water to produce dissolved iron and sulfate ions that increase the conductivity of pore water. If the material contains water-soluble minerals (e.g. salt), a low resistivity will result from the addition of water.

Phase

Phase, in general, refers to the angle that an observed sine wave lags or leads a reference sine wave. For PetLab measurements, the phase of the received **voltage** is referred to the **current** sine wave as reference. Phase units are in milliradians (mRad), and by convention are reduced to the first or fourth quadrants. All reported phase values, therefore, will fall in the range between $\pm \text{nil}$ Rad, or about ± 1571 mRad.

Phase is a measure of charge storage or polarization. When electric current is transmitted through a material, a temporary induced polarization (IP) effect is generated. Induced polarization reflects the redistribution from their equilibrium positions of unbound charged particles, such as ions and electrons, due to an applied current. The redistribution of charge is not an instantaneous process, but requires a finite period to develop and dissipate. The time required to develop and dissipate the stored charge produces the phase lag observed between the received voltage and the transmitted current.

Frequency dependency results from different mechanisms of charge redistribution. Some of these mechanisms operate rapidly and are observed at relatively high frequencies, whereas other mechanisms are slow and are observed at lower frequencies. At low frequencies, the electrical properties of typical rocks and minerals may be dominated by charge transport or conduction mechanisms, whereas at higher frequencies charge storage or polarization mechanisms may come into play. Both these mechanisms involve movement of *unbound* charges through distances of at least atomic dimensions. Physicists further distinguish **dielectric** mechanisms, involving the displacement of *bound* charges from their equilibrium positions by distances usually amounting to only a few angstroms (see Pelton and others, 1983). Typical rocks and minerals only begin to display dielectric effects at frequencies above $\sim 10^5$ Hz.

Complex Resistivity

Electrical engineers describe an unknown circuit in terms of its impedance, a complex quantity whose real, or in-phase, component is the resistance of the circuit—or, in our case, the rock sample—and whose imaginary, or out-of-phase, component consists of its capacitance (plus inductance, if any). The phase angle discussed above is the arctangent of the ratio of imaginary to real components of the impedance vector. Zonge and Wynn (1975) introduced the term "complex resistivity" to refer to measurements like those now made in PetLab, which result in a multi-frequency suite of appropriately-normalized impedance vectors. An alternate, equivalent, term is "spectral induced polarization" (SIP).

Measures of Linearity

Most materials obey Ohm's Law, so that the amplitude of the received voltage varies in direct proportion to that of the applied current. Such materials are said to behave linearly. In other words, the calculated electrical properties of linear materials are independent of

the amplitude of the input current. However, some materials have electrical properties that change depending on the amplitude of the input, and so are said to behave non-linearly. A more general statement, of which the above example is a subclass, is that a system is called linear if it obeys **superposition**; that is, if two different inputs (voltages) are applied, the outputs (currents) must be the sum of those that would result had the inputs been applied separately. Non-linear behavior is observed in natural occurring materials actively involved in oxidation-reduction reactions and ion exchange processes (Olhoeft, 1979b).

Hilbert distortion is a measure of non-linear behavior (Olhoeft, 1979b). The real and imaginary parts of the complex resistivity expression are related through the Hilbert transform (Pelton and others, 1983). By applying the Hilbert transform to measured SIP parameters, a "Hilbert resistivity" and "Hilbert phase" can be calculated. Hilbert distortion is the difference between the measured resistivity and phase and the resistivity and phase calculated from the Hilbert transform. These two measures are called "resistivity Hilbert distortion" (RHD) and "phase Hilbert distortion" (PHD), respectively.

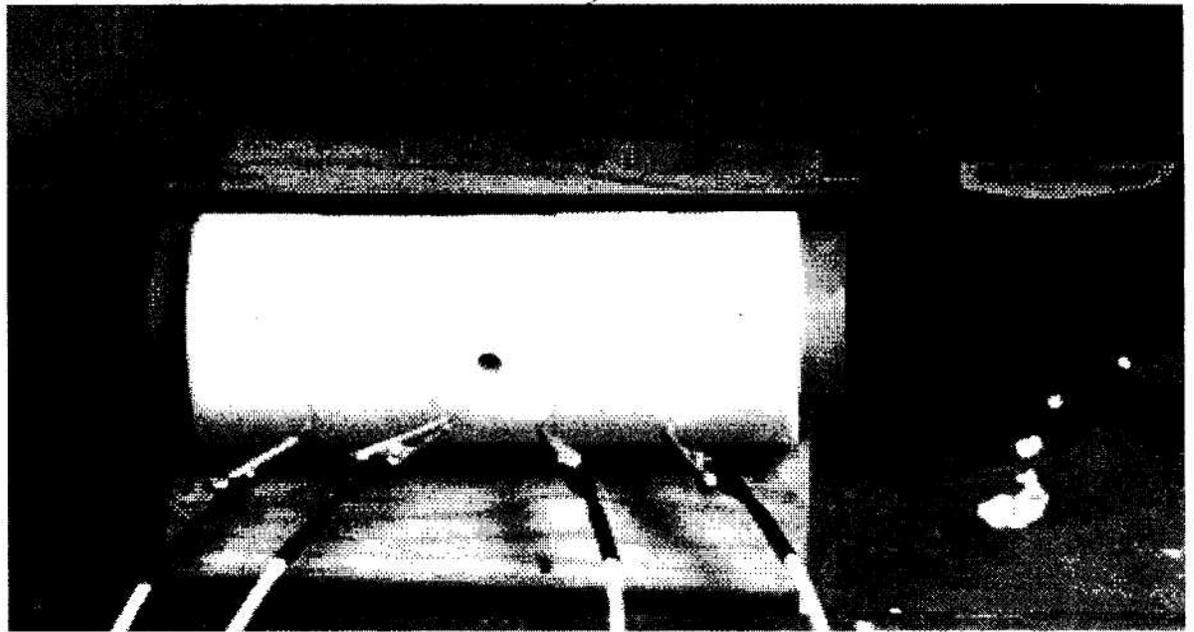
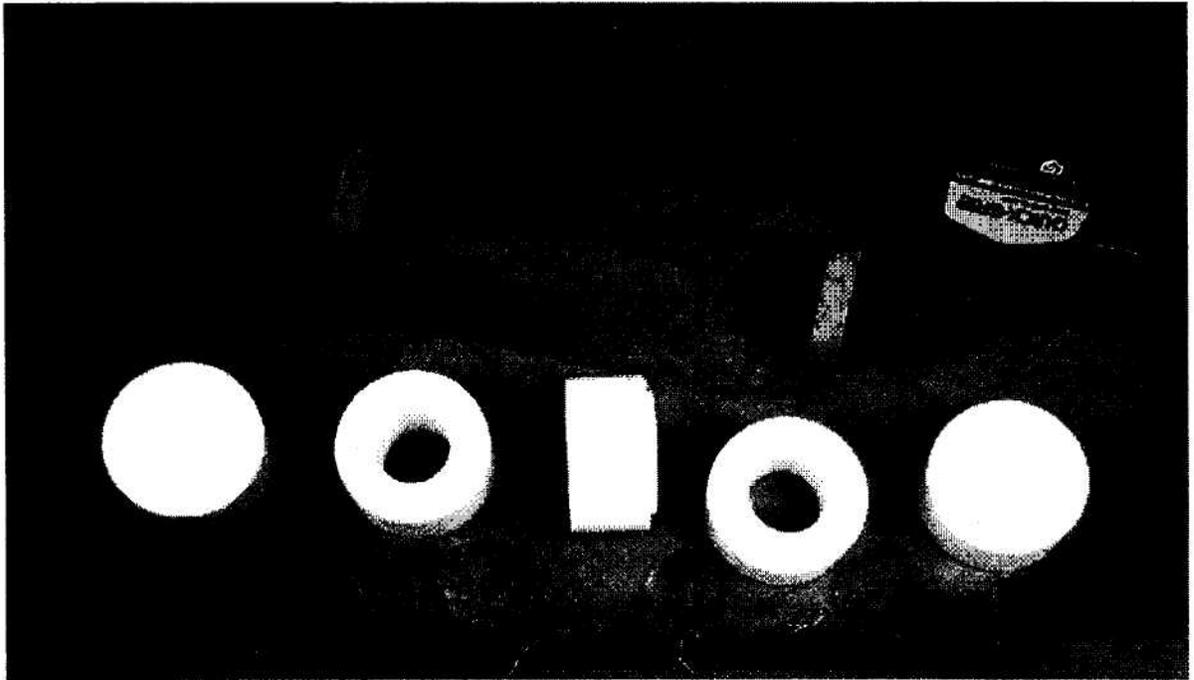
Total harmonic distortion (THD) is another measure of non-linear behavior. In a linear system the harmonic content of the received signal is exactly the same as that of the transmitted signal; in other words, if a pure sine wave is transmitted, a pure sine wave is received. Certain charge transport and storage mechanisms may generate other frequencies in the received signal besides those that were transmitted into it, so that the sample exhibits non-linear behavior. The THD value is the root-mean-square difference between the harmonic content of the transmitted and received wave forms (Olhoeft, 1979b).

Some kinds of electrochemical processes operating within a sample can give rise to non-linear behavior. In general, the non-linearity due to oxidation-reduction of sulfide minerals is expressed as total harmonic distortion. Cation-exchange reactions involving clay minerals produce Hilbert distortion. However, both reaction types can behave linearly over particular ranges of applied current density. Typically, oxidation-reduction processes become nonlinear at high current densities, whereas cation-exchange processes are nonlinear at low current densities. See Olhoeft (1979b and 1985) for additional information on nonlinear electrical properties.

An important difference between the ways that Hilbert and total harmonic distortions are calculated is that the Hilbert distortions are calculated over the entire ensemble of measurements, whereas total harmonic distortion is calculated separately for each frequency. Consequently, a few bad data points can ruin the Hilbert calculation at many nearby frequencies, but—except at the bad data points themselves—not the calculated harmonic distortions. An example of this is given below.

PETROPHYSICAL LABORATORY PROCEDURE

PetLab measurements are obtained using non-linear complex resistivity (NLCR) impedance spectroscopy instrumentation. These instruments are described by Olhoeft



(1979a) and Jones (1997). Directed by a computer program, the NLCR equipment transmits a sine wave of electric current through a sample and measures the received voltage. Usually, three measurements per decade are made over a band of frequencies ranging from 2×10^{-3} to 10^6 Hz (two millihertz to 1 megahertz). The computer program calculates the resistivity and phase response of the sample at each frequency.

Samples of unconsolidated material are collected in the field in various ways (see Smith and others, 2000, for a description of one particular sampling protocol). Samples that are collected explicitly for PetLab measurement usually consist of unsorted material that is troweled into plastic Zip-lock bags and taped tightly shut so as to keep the natural pore waters intact. Other samples may be prepared differently. Those collected primarily for geochemical analysis, for example, may be dried and sieved to remove particles larger than 2 mm. Separate splits of such samples may be sent for geochemical analysis, for X-ray diffraction analysis, for infrared spectrographic or other mineralogical analysis, and so on, with one of the splits coming to PetLab.

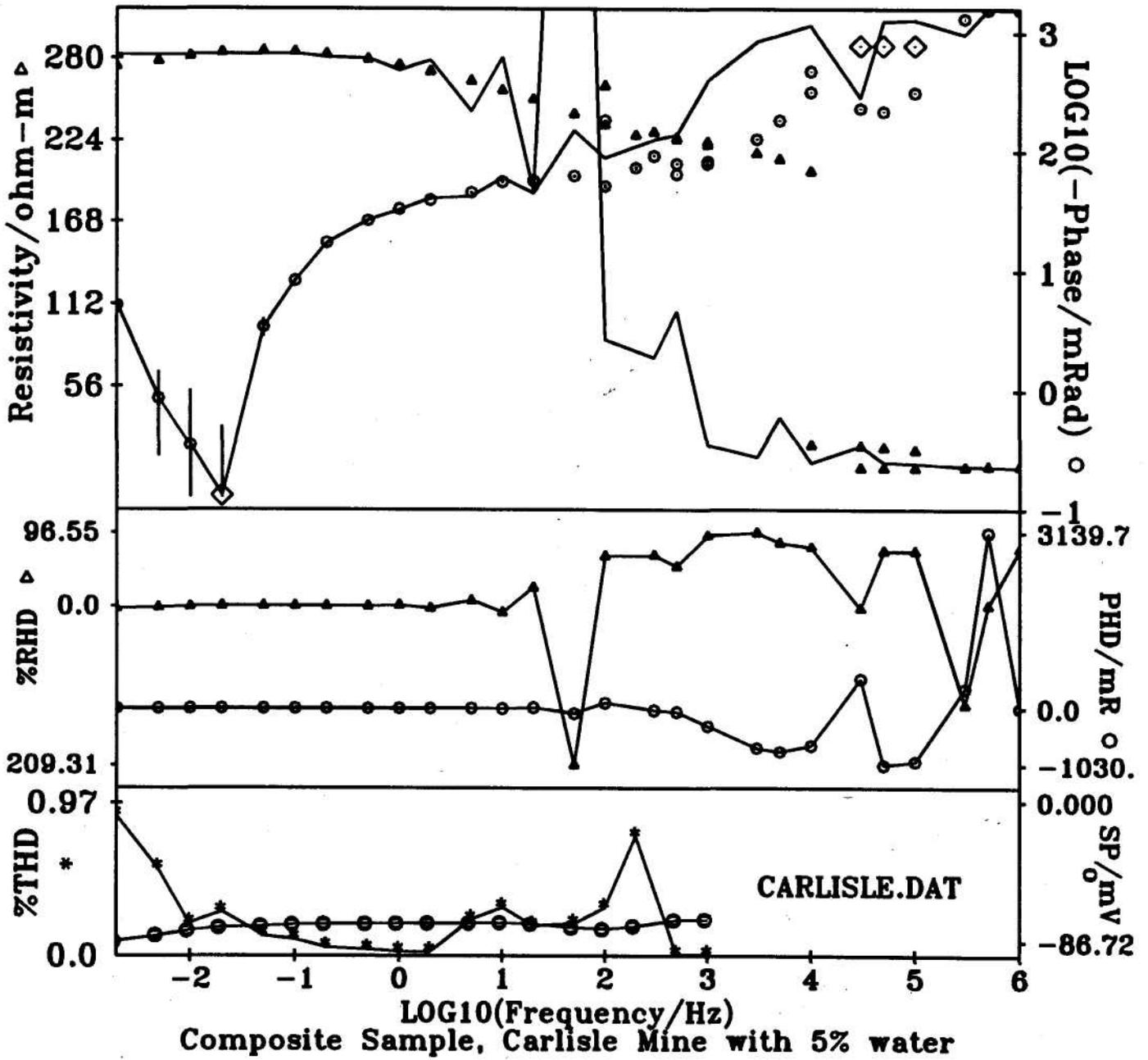
To measure samples of unconsolidated material, we tamp them firmly into a cylindrical sample holder made of white Teflon (fig 1). The sample occupies a space 1 inch in diameter and three inches long, having a volume of 2.356 cubic inches (38.618 cm^3). Four equally spaced electrodes made from bright platinum mesh are emplaced in the sample. Current is transmitted through the sample via two electrodes nearest the ends of the sample holder, and voltage is measured across two electrodes spaced 1 inch apart in the center of the sample holder.

If possible, samples are first measured in their "as received" condition. Some "as received" samples, however, can be very dry and too resistive for the NLCR system to measure. When the contact resistance is greater than about 10^6 ohms, the NLCR system generates extremely noisy data or is unable obtain a reading

Whether or not we were able to measure the samples "as received", almost all samples are measured "wet", after adding a small amount of laboratory grade de-ionized water. The sample is weighed after adding water and its electrical properties are then measured immediately. It takes about 30 minutes to run a complete set of measurements covering all the standard frequencies. After the measurements are done the sample is dried in an oven and its dry weight is then used to calculate total weight percent of water that it contained during the measurement. Typical samples will contain 5-10 weight percent water. If possible, the sample is measured with several different weight percents of water.

THE BASIC PETROPHYSICS GRAPH

Our standard graph of the PetLab measurements (e.g., fig. 2) consists of three vertically-stacked panels which plot various quantities versus a common frequency abscissa. The upper panel shows the variation with frequency of resistivity (left legend, triangular symbols) and of phase (right legend, circle or diamond symbols). If the phase is negative (the usual situation), its sign is reversed and the value is plotted as a circle. If the phase is



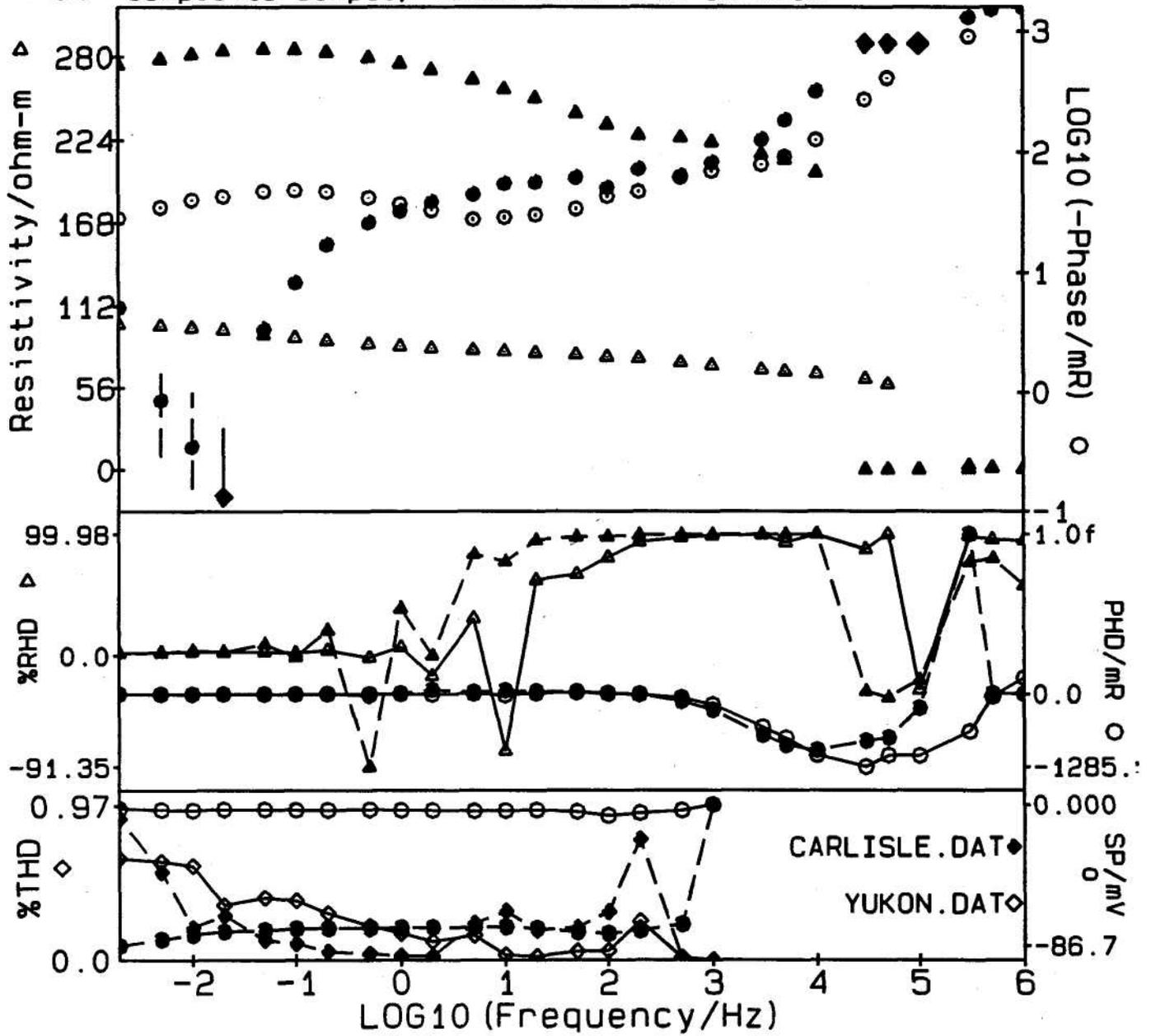
The RHD, PHD, and THD panels on the basic petrophysics graph are scaled automatically. It is useful, therefore, to note the *amplitude* of the distortions. Some values will be shown, after all, even if the distortions are trivial. If the distortions are substantial, it is useful to note the frequencies at which they occur, for these can help indicate the kinetic rate of the process that is giving rise to the distortion.

Fig. 2 is a plot of fairly mediocre data, illustrating some particular (mostly instrumental) problems to be aware of. First, notice that two measurements are made for the frequencies 1×10^2 , 5×10^2 , 1×10^3 , and for 1×10^4 , 3×10^4 , 5×10^4 , and 1×10^5 Hz. This happens because the NLCR instrumentation consists of three subsystems that overlap at those frequencies. Those frequencies are near the ends of the proper ranges of operation for the subsystems, so that the values they find there may be unreliable. If at least one subsystem finds values that smoothly fit the curve determined by adjacent frequencies, the NLCR computer program is able to choose those "good" values. It does so by calculating the Hilbert resistivity and phase for the entire ensemble of measurements (plotted as solid lines in the upper panel). If it happens, however, that neither subsystem can find good values, the Hilbert calculation goes awry. We can see that that is the case here by the way that the calculated Hilbert curves oscillate unstably for frequencies above about 1×10^2 Hz. In turn, this means we can ignore the apparent Hilbert distortions at those frequencies that are shown in the middle panel. In particular, the %RHD value at 5×10^1 Hz happens to be very bad, and the calculated PHD values at high frequencies are extreme. Because the PHD scale shows the *difference* between calculated and measured phase values, it is possible to get PHD values beyond the ± 1571 mR range, as happens here. Such artifacts reflect poor data quality, and serve to alert us of it. Similarly, the higher %THD at 3×10^2 Hz in the lower panel may also be an artifact of a bad data point (the "best" measured phase value at that frequency is still too low compared with its likely correct value from nearby frequencies).

DOUBLE PLOTS

It is often useful to compare petrophysical measurements of two samples by plotting them together on the same graph. Figure 3 shows an example of such a double plot. In this plot values for the first sample are indicated by open symbols, and those for the second by filled symbols.

▲●◆ Composite Sample, Carlisle Mine with 5% water
 ▲○◇ Composite Sample, Yukon Mine with 5% water



the lowest frequency used in a frequency-domain IP survey—and "percent frequency effect" (PFE), the percentage change between resistivity at this lowest frequency and that at some higher frequency. The particular frequencies one uses generally are those measured by the field equipment one has, typically about 0.1 Hz for the lowest frequency and 1 or 10 Hz for the higher one. By analogy, then, we define the following simple indices to characterize petrophysical curves that can be calculated from measured values of resistivity, R, and phase, P:

LowRes (low resistivity) = $R(0.1 \text{ Hz})$. LowRes typically is less for wet samples than dry ones, and is lower for samples containing conducting minerals, such as clays or most sulfides.

PRE (percent resistivity effect) = $100 \times [R(0.1 \text{ Hz}) - R(1.0 \text{ Hz})] / R(1.0 \text{ Hz})$. PRE is a specific version of PFE, mentioned above (different geophysicists have defined PFE in different ways; see Sumner, 1976). PRE is usually positive in sign, meaning that resistivity values **decrease** with frequency, as they typically do. PRE values can be quite high (above 30, say) for sulfide samples.

LowPhz (low phase) = $-P(0.1 \text{ Hz})$. The leading negative sign is to accommodate the fact that measured phase values are almost always negative. LowPhz typically is positive in sign, and higher (above 100 mR, say) for sulfide samples.

PPE (percent phase effect) = $-100 \times [P(0.1 \text{ Hz}) - P(1.0 \text{ Hz})] / P(1.0 \text{ Hz})$. This definition is parallel to that for PRE, except that a leading negative sign is inserted to accommodate the fact that measured phase values are usually negative. This sign convention leads to positive PPE values when phase **increases** with frequency over the 1-decade frequency range from 0.1 to 1.0 Hz, as commonly happens. Note, however, that PPE can be negative in sign. Sulfide-rich samples typically have low or negative (<10) PPEs.

Table 1 is an example of a table written by the computer program that calculates the above-listed simple indexes. After the heading, the table gives two lines of information for each sample. The first line lists the name of the data file for that sample, followed on the same line by an echo of the title line from its data file. The second line lists the values of the simple indexes. This particular table shows results of a linearity test run on the "Tucson lobe 3" sample, with applied voltage values of 0.1, 0.2, 0.3, 0.4, and 0.5 volts. It appears that this particular sample behaves fairly linearly, at least insofar as its simple indexes are concerned (it is linear at frequencies of 0.1 and 1.0 Hz, in other words).

Table 1.—Simple IP Indexes for samples from the Tucson mine dump. PRE and PPE are calculated between 0.1 and 1.0 Hz.

	LowRes	PRE	LowPhz	PPE
tucson1.txt	tucson lobe 1 with about 10% water			
	100.24	7.31	38.49	49.54
tucson2.txt	tucson sulfide sample from lobe 3 as rec'd			
	0.94	18.99	102.25	6.99
Tucson3.txt	Tucson lobe 3 no water added			
	4.15	26.52	156.00	-9.30
Tucson10.txt	Tucson lobe 3, current test .1			
	3.29	25.57	147.62	-6.37
Tucson9.txt	Tucson lobe 3, current test .2			
	3.12	25.81	149.73	-7.09
Tucson8.txt	Tucson lobe 3, current test .3 volts			
	3.12	25.81	149.63	-7.03
Tucson7.txt	Tucson lobe 3, current test .4 volts			
	3.13	25.70	149.73	-7.33
Tucson6.txt	Tucson Lobe 3, current test .5 volts			
	3.15	26.00	147.19	-5.56
Tucson4.txt	Tucson lobe 4 with 10% water			
	73.80	2.34	8.56	75.08
Tucson5.txt	Tucson lobe 5 with 10% water			
	90.28	6.10	18.96	73.97
Compst5.txt	Composite Sample, Tucson with 6% water			
	167.40	4.21	31.36	3.00

Cole-Cole fits

The simple indices defined above are useful for making gross comparisons between petrophysical curves, and for correlating such curves with field data. However, they gloss over details of the curves, particularly the phase curves, that can reflect grain size and textural properties, mineralogical compositions, and geochemical reactions that may be taking place. The latter may reflect interactions between grains and pore waters, and so can be of particular interest for studies of geochemical processes.

Suppose a particular physical or chemical process operates in our sample that results in the freeing-up or movement of charged particles. To be concrete, consider ions in pore waters, although the underlying principle is more general than just that. When voltage is

applied across the sample, the cations will begin to drift towards the anode, and the anions toward the cathode. If that voltage is then reversed, cathode and anode switch roles, and the ions change their drift direction. As long as the frequency with which the voltage changes is low, the ions will be able to respond, and a constant value of resistivity and zero phase will be seen. As the frequency increases, however, the ion response will not be so perfect, and the current due to these ions will begin to lag the impressed voltage. The phase value will become finite and (since our convention specifies the phase of the voltage with respect to that of the current) *negative*. As the frequency gets still higher, there comes a time when the ions will not be able to respond at all. At that point it doesn't matter how much higher the frequency goes—no further response is possible for this particular mechanism, and the apparatus measures "saturated" values of resistivity and phase, usually that are less than the low-frequency ones.

This example describes a single relaxation mechanism, due to a particular process. If the process happens over a range of frequencies (imagine ions drifting through a matrix of different grain sizes so that the pore channels are variously clogged), or if there are several different processes happening over a range of closely-spaced frequencies, then the relaxation curve will be distributed over that frequency interval and will be flattened accordingly. Such a relaxation curve can be fit numerically using the Cole-Cole formula (Cole and Cole, 1941; Pelton and others, 1978):

$$\text{Complex impedance } Z(\omega) = R_0 \{ 1 - m [1 - 1 / (1 + i\omega\tau)^c] \}$$

The above equation is written in the form of Major and Silic (1981). Its inverse is

$$\text{Complex admittance } Y(\omega) = \{ 1 + m [(i\omega\tau)^c / (1 + (1 - m)(i\omega\tau)^c)] \} / R_0$$

In these equations ω represents angular frequency and $i = \text{SQRT}(-1)$. The above formula is used to describe diffusion of charges through a material. To include dielectric effects, another and separate relaxation distribution term should be included (see Olhoeft, 1979a). For most materials this dielectric relaxation comes into play at frequencies greater than about 100 kHz; frequencies, that is, that are not well investigated using PetLab apparatus. To approximate this dielectric effect we add one constant term, $+i\omega\epsilon_0 K_{oo}$, to the complex admittance. When that is done, the equation for $Y(\omega)$ has 5 adjustable parameters:

R_o , *low frequency resistivity*, sets the low frequency asymptotic value for the resistivity curve.

K_{oo} , *the high-frequency dielectric value*, sets the high frequency asymptotic values for both resistivity and phase curves. (Actually, K_{oo} represents the *low*-frequency asymptote of the possible, but un-modeled, dielectric dispersion.) Between them, R_o and K_{oo} specify the amplitude of the overall drop in the resistivity curve between low and high frequencies and of the frequency (typically, about 100 kHz) at which the highest-frequency knees in the resistivity and phase curves will be located.

The remaining parameters specify an auxiliary down step in resistivity and hump in phase response (Pelton and others, 1983; Jones, 1997).

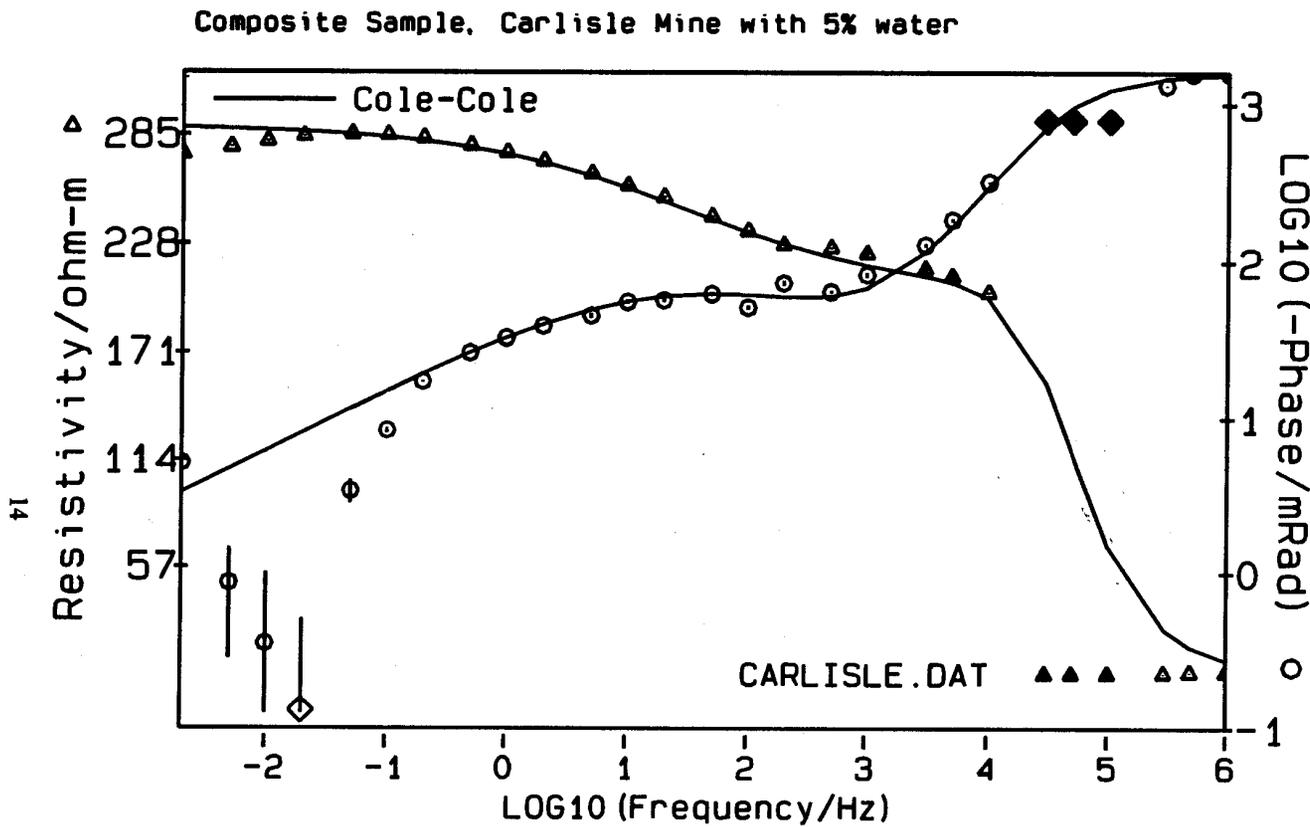
τ *the time constant*, is related to a characteristic frequency where the phase curve hump has its maximum and where down step in the resistivity curve has bottomed out. Higher τ means lower characteristic frequency.

m , *the chargeability*, reflects the size of the down step in the resistivity curve and the value of the peak of the phase curve. Higher m means greater step size and peak value. Practical limits: $0 < m < 1$. For some fits, $m < 0$. If $m = 0$, the Cole-Cole term vanishes.

c reflects the steepness of the resistivity step and width of the phase hump. Higher c , steeper step and narrower hump. Small values of c imply the described process takes place over a wider frequency band. Practical limits: $0 < c < 2$. The value $c=1$ implies a sharp single-frequency relaxation.

Most spectra display more than one relaxation, so that a number of Cole-Cole terms (the quantity inside the curly brackets of the above admittance equation) must be used to adequately describe the shape of the complete spectrum. Either sums or products of Cole-Cole terms may be used. According to linear systems theory, a **sum** of such terms is appropriate if the component relaxations happen independently of one another. If, on the other hand, the relaxations interact with one another - if, for example, the first relaxation produces conditions that effect how well the other can proceed - then it is appropriate to use **products** of terms. However, Major and Silic (1981) show that in using Cole-Cole terms, products and sums are equivalent as long as the relaxation time constants, τ_1 and τ_2 differ by a factor of 10 or more. To translate a product fit to a sum fit, one need only make an appropriate modification of the chargeability constants, m_1 and m_2 , in the component terms, and subtract R_0 from the result. Unless we explicitly say otherwise, PetLab uses the **sum** of Cole-Cole terms.

Figures 4 and 5 show two- and three-term Cole-Cole fits, respectively. Figs. 4 and 5 are examples of another standard PetLab plot, wherein the solid lines represent curves calculated from Cole-Cole equation using the parameter values given in the panel at right. Notice on figs. 4 and 5 that the observed values are apparently in error for frequencies 2×10^4 , 5×10^4 , and 1×10^5 —not only are the phase values negative (large diamonds), but neither phase nor resistivity values for those frequencies fall on the fairly smooth curve defined at adjacent frequencies. Consequently, the observed values at these three frequencies were dropped in making the Cole-Cole fits, and the dropped values are indicated by plotting their resistivity (triangle) and phase (diamond) symbols as filled in. Note also that the third relaxation has a value of " m " that is negative. Negative " m " values are not physically realistic, but they sometimes can give better, albeit strictly formal, fits to the observed resistivity and phase values. Actually, though, in this case the chi-squared and least square fit errors are not really improved by adding the third relaxation.



Cole-Cole Parameters	
$R_0 = 290.00,$	$K_i = 2500.0$
$m_1 = 0.060$	$t_1 = 9.00E-006$
$c_1 = 0.210$	
$m_2 = 0.280$	$t_2 = 6.00E-003$
$c_2 = 0.440$	
$\chi_n^2 = 1.44E-001$	
fiterr = 3.20E+000	

Figure 4. A 2-term Cole-Cole fit to the data shown in fig. 2.

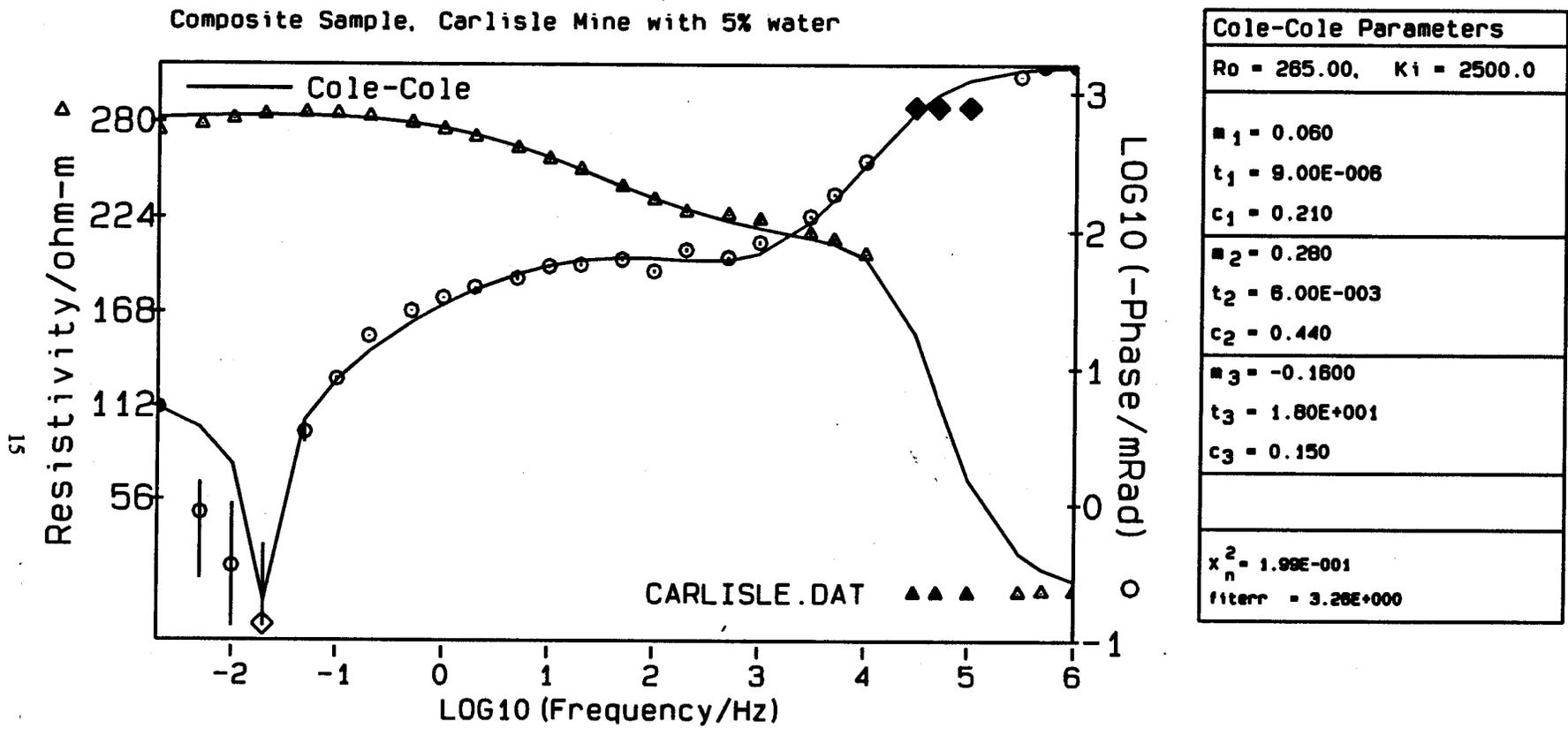


Figure 5. A 3-term Cole-Cole fit to the data shown in fig. 2. The third term has a negative m-value, and this is physically unrealistic. m_3 was allowed to be negative in hopes that the fit might be improved, but that did not happen.

Note that the Cole-Cole form is strictly phenomenological—that is, it provides numbers that describe the shape of a relaxation curve, without elucidating the underlying electrochemical or physical processes that are responsible for the relaxation. Of course, if we somehow know what the mechanism actually is, then the Cole-Cole parameters may help supply useful information about it (e.g., reaction rates).

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