

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Federal Center, Denver, Colorado 80225

In reply refer to:

Technical Letter
Special Projects-12
August 17, 1964

DIELECTRIC CONSTANT AND ELECTRICAL CONDUCTIVITY OF
MOIST ROCK FROM LABORATORY MEASUREMENTS

SSN116

By

J. H. Scott, R. D. Carroll, and D. R. Cunningham

Introduction

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In studies of electromagnetic wave propagation in linear isotropic media, three properties of host media are important: dielectric constant, electrical conductivity and magnetic permeability. These parameters are related to attenuation in the following way:

$$\alpha = \omega \left[\frac{\mu \epsilon}{2} \left[\left(1 + \frac{\sigma^2}{\omega^2 \epsilon^2} \right)^{1/2} - 1 \right] \right]^{1/2} \quad (1)$$

where

- α is attenuation constant,
- ω is angular frequency in radians/second,
- μ is magnetic permeability in henrys/meter,
- * ϵ is dielectric permittivity in farads/meter,
- σ is conductivity in mhos/meter.

The attenuation constant, α , can be used to determine the field strength of electromagnetic energy at some distance from its source.

* In this report the dielectric constant of a material is defined as the ratio of dielectric permittivity of the material and the dielectric permittivity of free space: ϵ / ϵ_0 .

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Special Projects-12
August 17, 1964

Capt. W. D. Henderson
AFWL/WLRPE
Kirtland Air Force Base
Albuquerque, New Mexico

Dear Capt. Henderson:

Transmitted herewith are six copies of:

TECHNICAL LETTER: SPECIAL PROJECTS-12

DIELECTRIC CONSTANT AND ELECTRICAL CONDUCTIVITY
OF MOIST ROCK FROM LABORATORY MEASUREMENTS

By

J. H. Scott, R. D. Carroll, and D. R. Cunningham

Additional copies have been distributed as indicated below.

Sincerely yours,

W.S. Twenhofel

for J. H. Scott
Project Supervisor
Special Topical Studies

Enclosures (6)

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In studies of electromagnetic wave propagation in linear isotropic media, three properties of host media are important: dielectric constant, electrical conductivity and magnetic permeability. These parameters are related to attenuation in the following way:

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* In this report the dielectric constant of a material is defined as the ratio of dielectric permittivity of the material and the dielectric permittivity of free space: ϵ / ϵ_0 .

For example, the field strength of a plane wave propagating through a linear, homogeneous and isotropic medium is given by:

$$E_x(z) = E_0 e^{-\alpha z} \cos(\omega t - \beta z) \quad (2)$$

where

$E_x(z)$ is field strength of the x-directed E field propagating in the z direction,

E_0 is field strength of source,

z is distance from source,

ωt is the time dependent part of the phase angle,

β is phase shift constant.

Attenuation of the plane wave in this ideal medium is simply $e^{-\alpha z}$. For more complex media such as a layered earth covered with a layered atmosphere, propagation is less simple and has been investigated theoretically and experimentally by a number of researchers, most recently by Wait (1962) and Fritsch (1962).

The parameters ϵ , σ , and μ for the atmosphere are usually considered equal to corresponding values for free space ($\epsilon_0 = 8.854 \times 10^{-12}$ farads/meter, $\sigma_0 = 0$ mhos/meter and $\mu_0 = 4\pi \times 10^{-7}$ henrys/meter). For earth materials ϵ , σ , and μ are usually determined by making laboratory measurements of representative samples although it is possible, but more difficult, to measure them in situ.

Laboratory measurements of magnetic permeability and electrical conductivity are straightforward and present methods are considered reliable and accurate. However, laboratory measurements of dielectric constant have been controversial for some time. There is no particular

difficulty in measuring the dielectric constant of dry rock; when precautions are taken to remove all moisture, values of dielectric constant, ϵ/ϵ_0 are always quite low, typically 2 to 15, and show only a slight frequency dependence (Keller and Licastro, 1959) and Tarkhov, 1947). Not so with moist rock. Unbelievably high values have been measured at low frequencies by a number of investigators (table 1). These high values are all the more unbelievable when one considers that mixing formulas always give values of ϵ/ϵ_0 less than 80 when applied to rock-water mixtures. For example the soil with 25 percent moisture listed in table 1 would have a relative dielectric constant of only 17 calculated by the logarithmic mixing rule (von Hippel, 1954), if one assumes that the average ϵ/ϵ_0 of dry minerals in the soil is 10 and ϵ/ϵ_0 of water is 80:

$$\left. \begin{aligned} \log (\epsilon/\epsilon_0)_{\text{mix}} &= V_1 \log (\epsilon/\epsilon_0)_1 + V_2 \log (\epsilon/\epsilon_0)_2, \\ \log (\epsilon/\epsilon_0)_{\text{mix}} &= 0.25 \log 80 + 0.75 \log 5, \\ (\epsilon/\epsilon_0)_{\text{mix}} &= 17, \end{aligned} \right\} (3)$$

where

- $(\epsilon/\epsilon_0)_{\text{mix}}$ is relative dielectric constant of mixture,
- $(\epsilon/\epsilon_0)_1$ is relative dielectric constant of water,
- $(\epsilon/\epsilon_0)_2$ is relative dielectric constant of dry minerals,
- V_1 is fractional volume of water,
- V_2 is fractional volume of dry minerals.

However, these mixing formulas were developed for use with dry insulating materials like ceramics and they are not necessarily valid rock-water mixtures.

Table 1.--Some high values of dielectric constant of moist earth materials at low frequencies reported by various investigators

Type of material	Geologic Formation	Location	Moisture content (percent)	Frequency (cps)	Dielectric constant (ϵ/ϵ_0)	Reference
Soil	-----	Middlesex, England	25	50	1×10^5	Smith-Rose (1934).
Mudstone	Morrison Formation	Colorado, USA.	5-1/2	100	7×10^5	Keller and Licastro (1959).
Sandstone	Wilcox ss	(?)	12	100	3×10^3	Howell and Licastro (1961).
Sandstone	Nepean Formation	Ontario, Canada	(?)	100	$>10^5$	Frood and Sharf (1954).

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Attempts have been made to explain the high values of dielectric constant of moist material at low frequencies. Keller and Licastro (1959) have described several mechanisms within the fabric of rock that could account for the abnormal values while Howell and Licastro (1960) have suggested that errors caused by polarization at the sample-electrode interface may be a contributing factor. Tarkhov (1947) states that the high values measured at low frequencies may be explained entirely by inaccuracies in measurements.

The uncertainties regarding the validity of laboratory measurements of dielectric constant of moist rock have led to uncertainties in calculations of propagation of electro-magnetic waves (Wait, 1953). A first step in removing these uncertainties is to determine whether the high measured values of dielectric constant reflect inherent properties of rock or if they are produced artificially by the measuring apparatus. This report describes laboratory experiments designed to test the validity of laboratory methods that have been used in the past to measure the dielectric constant of moist rock. The results of the experiments have led to the development of an improved method for measuring dielectric constant and conductivity. The new method is described in detail and preliminary data are presented for a few rock types.

Equipment

Laboratory equipment consisted of commercially available bridges, oscillators, amplifiers, a sample holder, and an electronic frequency counter (fig. 1). For low frequency measurements (50 cps to 20 kc) a Hewlett Packard Audio Oscillator, Model 201 CR, was used to drive a Wayne Kerr Universal Bridge, Model B-221, operating on the transformer ratio-arm principle. Output of the bridge was monitored on a Rohde and Schwarz Type UBM tunable indicating amplifier which was used as a null indicator. The sample holder was a Wayne Kerr micrometer permittivity jig, Model D-321, with a guard electrode. Since the guard electrode system was found to be ineffective with high conductivity rocks, the samples were cut a little smaller than the diameter of the guarded electrode and a correction was made for the air space. The jig was used for both high and low frequency measurements.

For high frequency measurements (20 kc to 1 Mc) a Hewlett Packard Test Oscillator, Model 650A was used to drive a Wayne Kerr Radio Frequency Bridge operating on the tapped transformer principle. The Rohde and Schwarz indicating amplifier was used to monitor bridge output up to a maximum frequency of 600 kc, the upper limit of the instrument. Above this frequency the tuning stages of a Hallicrafters Model S-108 communications receiver were used to amplify the bridge output, and the 455 kc IF signal from the receiver was amplified by the Rohde and Schwarz tunable indicating amplifier

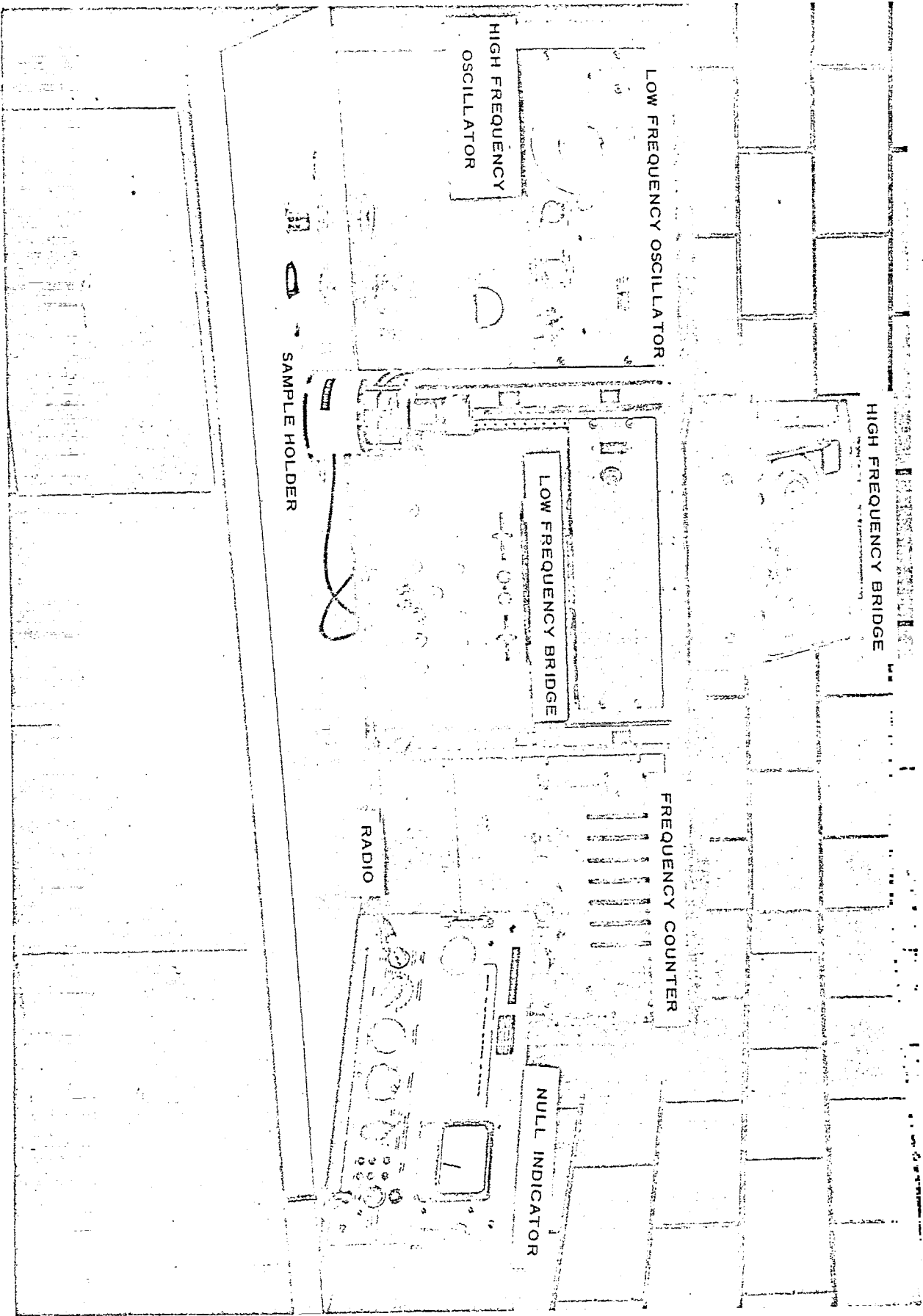


Figure 1. - Equipment used to make measurements of dielectric constant and conductivity.

to obtain a null. A Beckman Universal EPUT Meter and Timer, Model 7360 was used to adjust the oscillators to the desired frequencies.

Course of Investigation

Since polarization at the sample-electrode interface had been suggested by Howell and Licastro (1961) as a possible source of error in dielectric constant measurements, we decided to isolate the electrodes from the sample by inserting thin layers of insulating material between them. Tarkhov (1948) reported partial success in eliminating polarization errors by coating the sample with shellac and inserting strips of muscovite 0.10 to 0.15 mm thick between the sample and the electrodes. We thought that we might improve on Tarkhov's results by using modern plastic films that have insulating properties far superior to muscovite and shellac and are much thinner than 0.10 mm.

Tarkhov (1948) developed formulas for calculating the resistance and capacitance of a sample separated from electrodes by insulating material. He assumed that the insulators acted as perfect capacitors in series with the capacitance and resistance of the sample and that the equivalent lumped resistance and capacitance of the sample-insulator system was obtained by adjusting a bridge to null.

The equivalent circuit for this arrangement is shown in figure 2, and the equation relating the equivalent circuit of the sample-insulator system to the bridge measurement at null is:

$$\frac{R_x}{1 + j\omega C_x R_x} - \frac{j}{\omega C'} = \frac{R_n}{1 + j\omega C_n R_n} \quad (4)$$

where

R_x is sample resistance,

C_x is sample capacitance,

ω is angular frequency,

C' is series-composited capacitance of the two insulators,

C_n is capacitance measured by bridge at null,

R_n is resistance measured by bridge at null.

When real and imaginary parts of equation (4) are equated the real part gives

$$R_x = \frac{R_n (C' - C_n)}{C' + C_x} \quad (5)$$

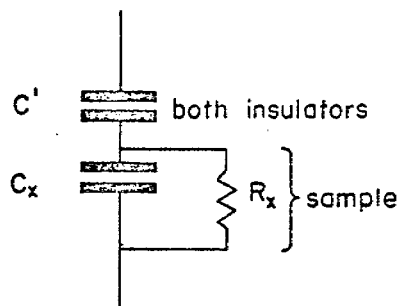
and the imaginary part gives

$$C_x = \frac{C' C_n}{C' - C_n} - \frac{1}{\omega^2 R_n R_x (C' - C_n)} \quad (6)$$

When R_x is eliminated from equation (6) by substituting equation (5), the following equation is obtained:

$$C_x = \frac{C' \left[C_n (C' - C_n) - \frac{1}{\omega^2 R_n^2} \right]}{(C' - C_n)^2 + \frac{1}{\omega^2 R_n^2}} \quad (7)$$

SAMPLE SYSTEM



BRIDGE AT NULL

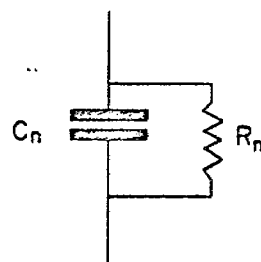


Figure 2.--Equivalent circuits for sample system and bridge at null

We discovered a mistake in Tarkhov's development that resulted in his omission of the term $\frac{1}{\omega^2 R_n^2}$ in the denominator of equation (7).

Since $C' - C_n$ appears in the denominators of equations (6) and (7) one would expect large errors if C' approached C_n causing $C' - C_n$ to approach zero. We thought that Tarkhov's trouble might have been caused by this effect because with his rather thick mica insulators his C' would be quite small and might control C_n , making $C' - C_n$ very small also. To avoid this situation we attempted to increase the value of C' by using very thin plastic insulating films coupled intimately to the rock sample and to the metallic plate of the sample holder. We tried various plastics and various methods of coupling and found that mylar was superior to other plastics because of its extremely low loss and because it can be obtained in sheets as thin as 0.00015 inch. Of various coupling methods tested we found that the most effective one was bonding the plastic to the rock with a thin layer of gelatin and painting the outer surface of the plastic covering the ends of the sample with silver paint, and then clamping the sample in the sample holder.

We obtained some surprising results at low frequencies with the plastic-insulated sample. As we tried thinner and thinner plastic films the capacitance measured at 100 cps steadily increased and remained nearly equal to the calculated series-composited capacitance of the two plastic insulators. Therefore, $C' - C_n$ was always nearly equal to zero, and sometimes it even became negative because of small measurement errors, so that calculated values of C_x were extremely large and subject to tremendous errors.

These results suggested that the fluid near the plastic-rock interface was polarizing and that the high conductivity of the rock had the effect of shorting out the internal capacitance of the sample. In the extreme case, when very moist rocks were measured at very low frequencies, the two plastic insulators behaved like two condensers linked in series by a good conductor. We concluded that we had unwittingly devised a system that enhanced the polarization errors that we were trying to eliminate, and we abandoned the idea of separating the sample from the sample holder with insulating film.

At this point we recognized that problems in measuring the dielectric constant of moist rock are similar to those encountered in measuring the dielectric constant of electrolytic solutions, a subject fairly well covered in the literature on physical chemistry. Chang and Jaffé (1952) give a physical interpretation of the electrode polarization phenomenon in measurements of electrolytic solutions as a piling-up of ions at the electrodes when direct current is passed through the system. The same effect occurs with alternating current if the frequency is low enough to permit ions to migrate. Ions pile up because they cannot enter the electrodes and combine chemically with them, and thus there is a high impedance at the electrode-sample interface. Jaffé and Rider (1952) determined the effects of polarization for electrodes made of platinum, gold, nickel and aluminum immersed in a weak solution of potassium chloride. Figure 3, taken from their report, shows capacitance of various electrodes as a function of frequency. They found that the measured

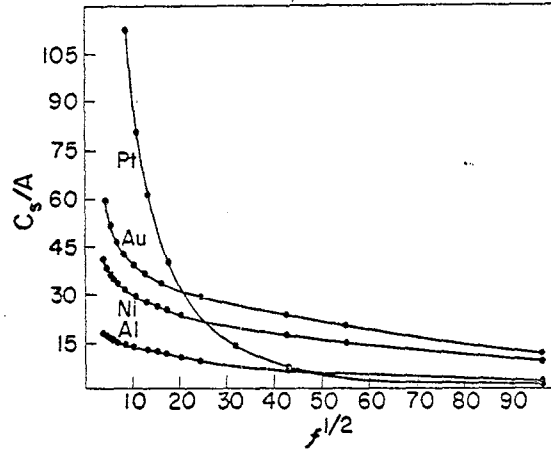


Fig. 3.--Capacitance per square centimeter plotted against the square root of frequency for measurements of potassium chloride solution (0.001 N) made with platinum, gold, nickel and aluminum electrodes (after Jaffé and Rider, 1952)

capacitance was highest with the most inert electrode material, platinum, and lowest with the most active material, aluminum. Brodd and Hackerman (1957) obtained similar results with tantalum, iron, and platinum electrodes.

In studies of electrochemistry various electrode-electrolyte combinations have been devised that are nonpolarizing or to be more exact, only slightly polarizing when electric current is applied to them. For example, when electric current is passed through a copper electrode in contact with a saturated solution of copper sulfate, the system is only slightly polarizing because cupric ions in solution can enter the copper electrodes, drop their electric charge and become atoms of metallic copper, or copper atoms can leave the electrodes and enter the solution as positively charged cupric ions. MacInnes, Shedlovsky, and Longworth (1949) show that a metallic silver electrode with a coating of silver chloride is practically nonpolarizing in a weak solution of potassium chloride when electric current is applied. In this system chloride ions from the solution can combine with silver of the electrodes to form silver chloride, or chloride from the silver chloride coating on the electrodes can enter the solution in ionic form. These electrode-electrolyte combinations are known as reversible electrode systems because chemical reactions between the electrode and the electrolyte are reversible, and, therefore, the contact impedance at the electrode-electrolyte interface is quite low.

We decided to compare measurements of dielectric constant of rocks using different electrodes, some reversible and others nonreversible, to see if electrode polarization error was lower with reversible systems as expected. We cut discs out of blotter paper, saturated them with various weak electrolytes (0.1 N) and placed them against the ends of cylindrically shaped rock samples. We placed electrodes made of various metals in contact with the blotter discs and clamped the 5-layer sandwiches composed of electrode-blotter-sample-blotter-electrode between the sample holder plates.

We then made capacitance measurements at the lowest frequency of interest, 100 cps, where polarization error was expected to be largest.

We made two sets of capacitance measurements and calculated the apparent dielectric constant for each measurement. For the first set of measurements we prepared the samples in the shape of solid cylinders approximately 1 inch in diameter and 1 inch long. For the second set we cut off the ends of the samples leaving solid cylinders approximately one-half inch long. We were careful to maintain nearly constant water content in the samples for the duration of the experiment by covering the sides of the sample with plastic pressure-bonding tape. Results of the measurements are shown in figure 4 with electrode-electrolyte systems arranged in order of decreasing polarization error from top to bottom. The discrepancy between the dielectric constant determined for the 1-inch samples and the one-half-inch samples is a measure of the electrode polarization error. If no polarization error exists the dielectric constant determined for the two sample

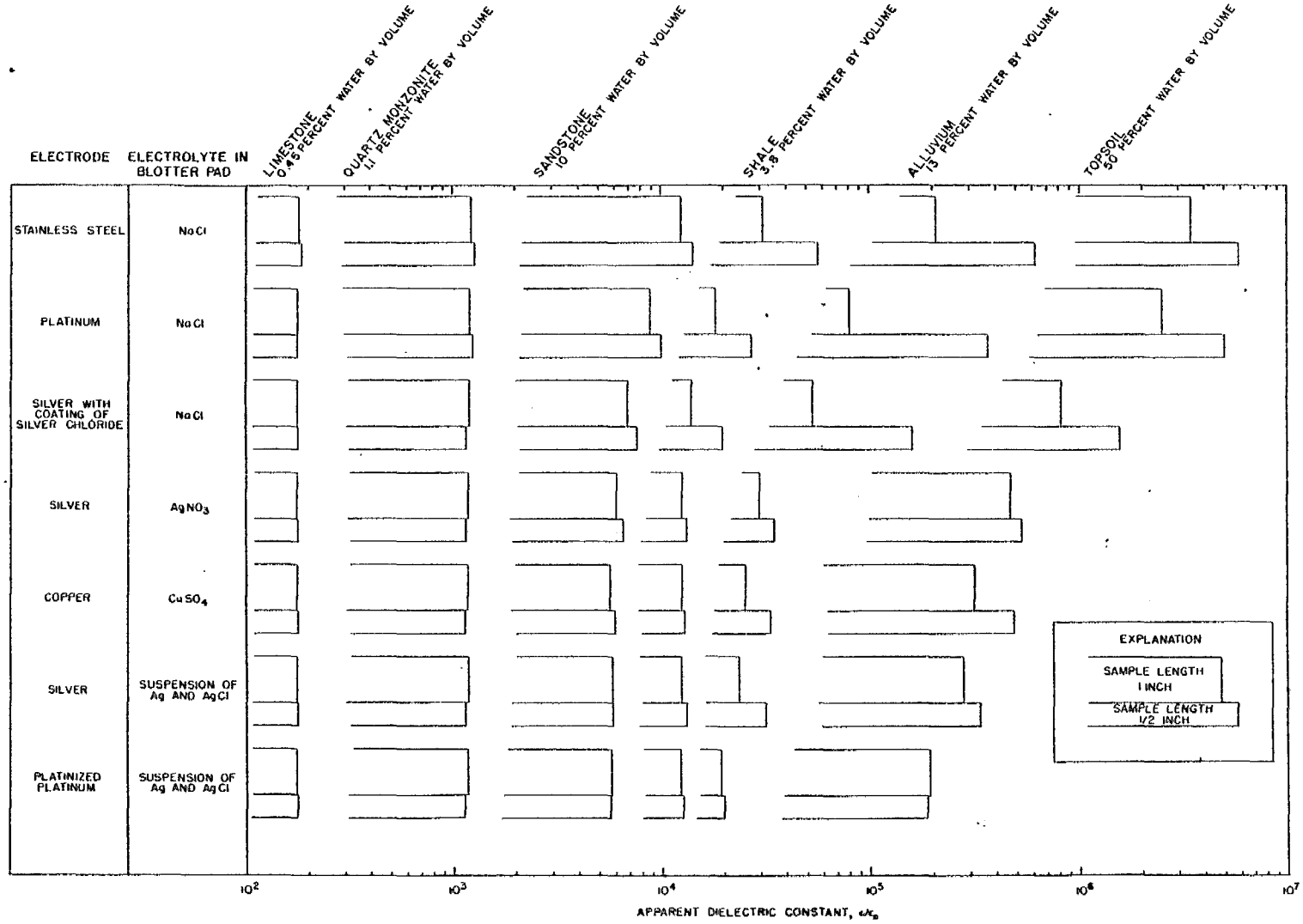


Figure 4.--Bar graph showing apparent relative dielectric constant measured at a fixed frequency of 100cps using various electrode-electrolyte systems and several rock types. Measurements were made on 1 inch long samples first, then repeated after ends were cut off, making samples 1/2 inch long. Wide bars represent measurements of 1 inch samples, and narrow bars represent measurements of 1/2 inch samples. When wide and narrow bars are about the same length, polarization error is negligible.

lengths should be the same allowing for small differences due to sample inhomogeneity.

Detailed descriptions of the samples used in this experiment are given in table 2.

It is interesting to note in figure 4 that when polarization error is large (upper right-hand part of graph) the dielectric constant of the one-half-inch sample is always greater than that of the 1-inch sample. This can be explained by referring to Tarkhov's equations and redefining his variable C' as the electrode polarization capacitance instead of the capacitance of the plastic insulating sheet. We can rewrite equation (6) as follows, solving for C_n , the null capacitance measured on the bridge:

$$C_n = \frac{C' C_x}{C' + C_x} + \frac{1}{\omega^2 R_n R_x (C_x + C')} . \quad (8)$$

Then substituting equation (5) solved for R_n we obtain

$$C_n = \frac{C' C_x}{C' + C_x} + \frac{1}{\omega^2 R_n^2 (C' - C_n)} , \quad (9)$$

and when $C' \gg C_x$ and $C' \gg C_n$,

$$C_n \approx C_x + \frac{1}{\omega^2 R_n^2 C'} . \quad (10)$$

The final term in equation (10) can be considered the error term expressing the effect of electrode polarization. When we cut the ends off a sample and halve its length the value of R_n can be expected to reduce to approximately half its former value, thereby causing the value of the error term to roughly quadruple if ω and C'

Table 2.--Information on samples used for measurements of dielectric constant and conductivity

Sample	Formation	Geologic Age	Location	Description
Topsoil	---	Recent	Central Colorado	Dark gray to dark brown, humic, unctuous, silty to clayey, with few scattered sand grains.
Alluvium	---	Recent	Southern Nevada	Light to dark buff, siliceous to slightly calcareous with detrital fragments of zeolitic and welded tuffs, quartz and feldspar grains, lithics of carbonates and volcanics.
Sandstone	Lyons	Permian	Central Colorado	White to pink to dark red, thinly bedded to laminated, fine to very fine grained, angular quartzose sandstone well cemented with ferro-siliceous cement.
Shale	Mancos	Cretaceous	Eastern Utah	Dark gray to black, thin to thick bedded, carbonaceous, silty.
Quartz monzonite	Climax stock	Mesozoic	Southern Nevada	Fine- to medium-grain, porphyritic, with scattered vein filled and inclusions of pyrite.
Limestone	Goodwin	Ordovician	Southern Nevada	Light to dark gray, thick-bedded very finely crystalline, dolomitic. Fossiliferous, scattered calcite filled fractures.

remain unchanged. Therefore, if the apparent dielectric constant is calculated using the null capacitance of the bridge for the true capacitance of the sample, the value calculated for the one-half-inch sample will always be higher than that of the 1-inch sample when electrode polarization error occurs. Further, the formula for calculating dielectric constant is:

$$\frac{\epsilon}{\epsilon_0} = \frac{C}{\epsilon_0} \cdot \frac{L}{A}, \quad (11)$$

where

ϵ/ϵ_0 is the dielectric constant of the medium,

ϵ_0 is the dielectric permittivity of free space,

C is the capacitance of the sample,

L is the length of the sample,

A is the cross-sectional area of the sample,

so that if polarization error causes the measured value of C to quadruple when L is halved, ϵ/ϵ_0 can be expected to double. Figure 4 indicates that when the shale and topsoil samples are measured with the worst electrodes, stainless steel and platinum, the apparent relative dielectric constant does, in fact, approximately double when the sample is halved, indicating that for these samples the error term in equation (10) is dominant and controls the measured value C_n . Results for the alluvium sample indicate a tripling and quadrupling when the sample is halved, an effect that may be caused by a change in the polarization capacitance, C' , in addition to the change in R_n .

It is interesting to note that equation (10) indicates that the error term increases and, therefore, C_n increases as the polarization capacitance, C' decreases. Conversely, as C' increases toward infinity the error term vanishes. This is an interesting paradox: as capacitance due to electrode polarization becomes smaller the error increases and causes the measured capacitance of the electrode-sample system to become larger. This observation is true under the conditions of approximation of equation (10); that $C' \gg C_x$ and $C' \gg C_n$.

Another interesting result illustrated in figure 4 is that both the dielectric constant and the electrode polarization error decrease with decreasing water content. Polarization error is insignificant for samples with very low water content when stainless steel and platinum electrodes are used even though these electrodes cause very large errors when used on samples with high water content. This observation can also be explained by equation (10). For samples with very low water content, R_n is very large, making the error term in equation (10) very small so that the null capacitance measured on the bridge is nearly equal to the true capacitance of the sample.

The best electrode-electrolyte system in figure 4 appears to be the platinized platinum electrode used with blotters saturated with a dilute aqueous suspension of silver and silver chloride. We discovered this combination in the following way. We decided to try silver electrodes with blotters saturated with silver nitrate because this had been mentioned by Frood and Sharf (1954) as a system that gave negligible polarization even at frequencies as low as 20 cps on some samples. Since we could not see why this

particular electrode-electrolyte combination should be particularly good as a reversible system, we wondered if some unknown chemical reaction between the silver nitrate and the blotter pad might be causing the good results. Organic material of the blotter might reduce the silver nitrate causing finely divided particles of metallic silver to precipitate by the reaction:



Further, there might be soluble chloride compounds in the blotter paper that could combine with silver ions as:



causing finely divided silver chloride to be deposited in the blotter.

As a matter of curiosity we checked the blotter paper for soluble chloride content and found that there was enough to make a 0.007 normal solution of Cl^- when the blotter was saturated with a weak silver nitrate solution.

With small amounts of finely divided metallic silver and silver chloride in the moist blotter paper, we had an electrode system that resembled a reversible reference electrode developed by Brønsted in 1920 and described by Daniels, Mathews, and Williams (1934). Brønsted's electrode consisted of a spiral platinum wire immersed in an aqueous suspension of finely divided silver and silver chloride.

We decided to fortify the suspected chemical reactions with the hope that by doing so we would obtain an improved electrode system more similar to Brønsted's reversible cell. We accomplished this by dipping the blotter discs in a solution of silver nitrate

(0.1 N), drying them slightly by pressing them between layers of absorbent paper, then dipping them in a solution of hydroxylamine hydrochloride (0.1 N), a reducing agent, drying them slightly again, and finally dipping them in a solution of sodium chloride (0.1 N) to supply chloride ions. We found that blotters prepared in this manner and used with silver electrodes were considerably better than blotters saturated with silver nitrate alone, and so we concluded that we had developed an improved electrode-electrolyte system by artificially bolstering the reactions that had occurred naturally when the blotters were saturated with silver nitrate.

At about this point we received a suggestion from Dr. L. S. Collett of the Geological Survey of Canada (written communication) to the effect that platinized platinum electrodes would reduce electrode polarization errors when used with blotters saturated with weak electrolytes because of the large effective area of the platinized surface. Polarization error is reduced because migrating ions causing the polarization error are spread out very thinly over the surface of the electrode so that the capacitance of the double layer is very large. If the double layer capacitance is very large the error caused by it is small because, as equation (10) indicates, when C' approaches infinity the error term vanishes.

We tried platinized platinum electrodes and found that they were quite good when used with blotters saturated with any weak electrolyte, but that they were particularly good when used with the blotters saturated with the suspension of silver and silver

chloride prepared by the procedure described previously. We settled on this as the best electrode-electrolyte system.

Both the capacitance and the conductance of the blotter-platinized platinum electrode system were so high that they were beyond the range of measurement of the bridge. It is estimated that both the capacitance and the conductance of two blotters were at least 100 times larger than the capacitance and conductance of 1-inch-long rock samples, so that errors caused by the electrode system were probably less than 1 percent.

Comparison of Nonpolarizing Electrodes and Silver Paint Electrodes

Since many of the measurements of dielectric constant of moist rock reported in the literature in recent years have been made with silver paint electrodes (Keller and Licastro, 1959; and Howell and Licastro, 1961), we decided to compare results obtained with our newly developed electrode system with results obtained on the same samples with silver paint electrodes. We measured capacitance and conductance on the same set of samples used for the tests illustrated in figure 4 but extended the frequency range from 10^2 to 10^6 cps. We calculated the apparent dielectric constant and conductivity and plotted these values against frequency for each of the samples. Results are presented in figures 5 through 10. These figures show that dielectric constant measurements made with silver paint electrodes are in error by as little as a few percent to as much as an order of magnitude.

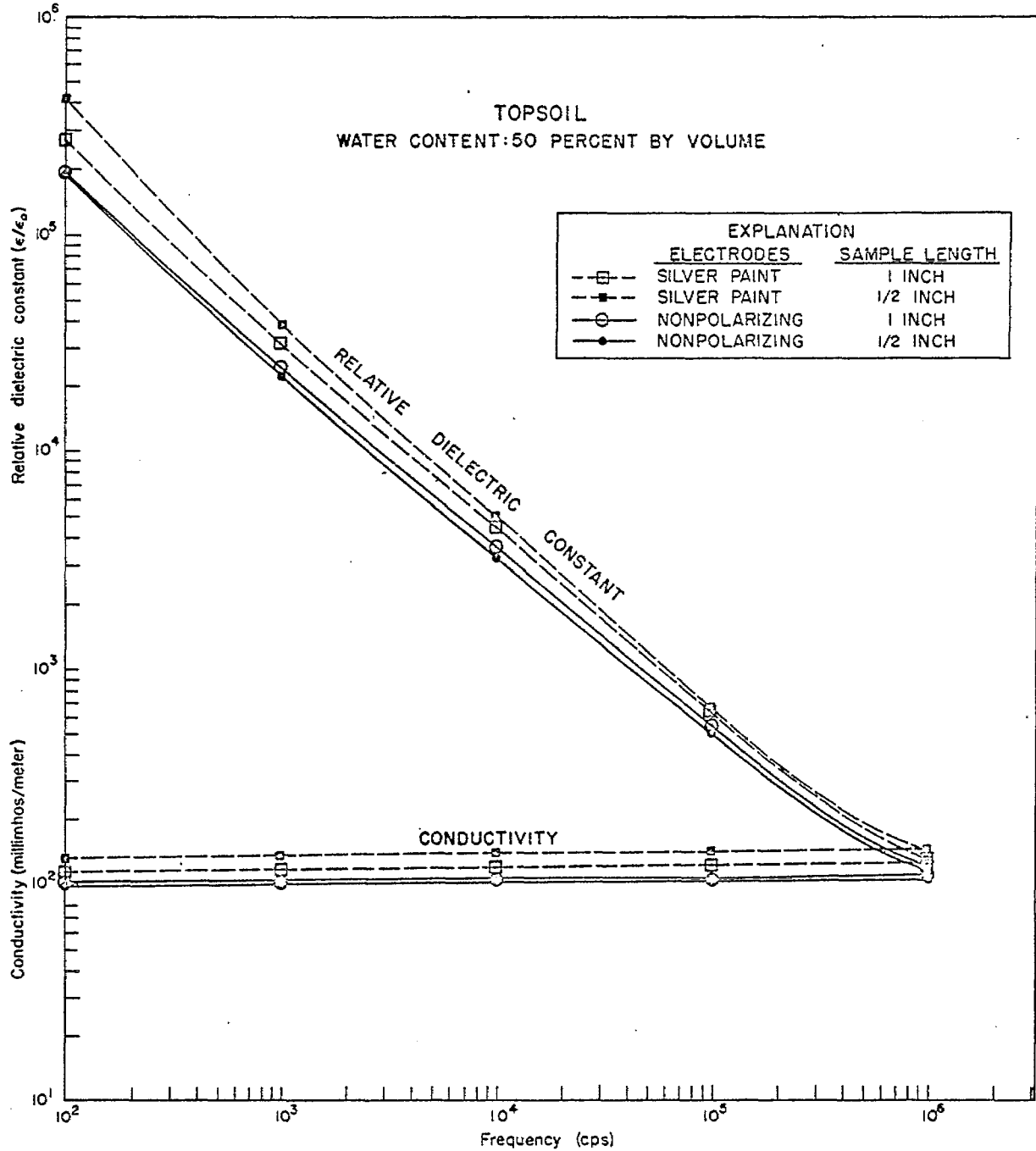


Figure 5.--Relative dielectric constant and conductivity measurements for topsoil showing comparison between nonpolarizing electrodes and silver paint electrodes

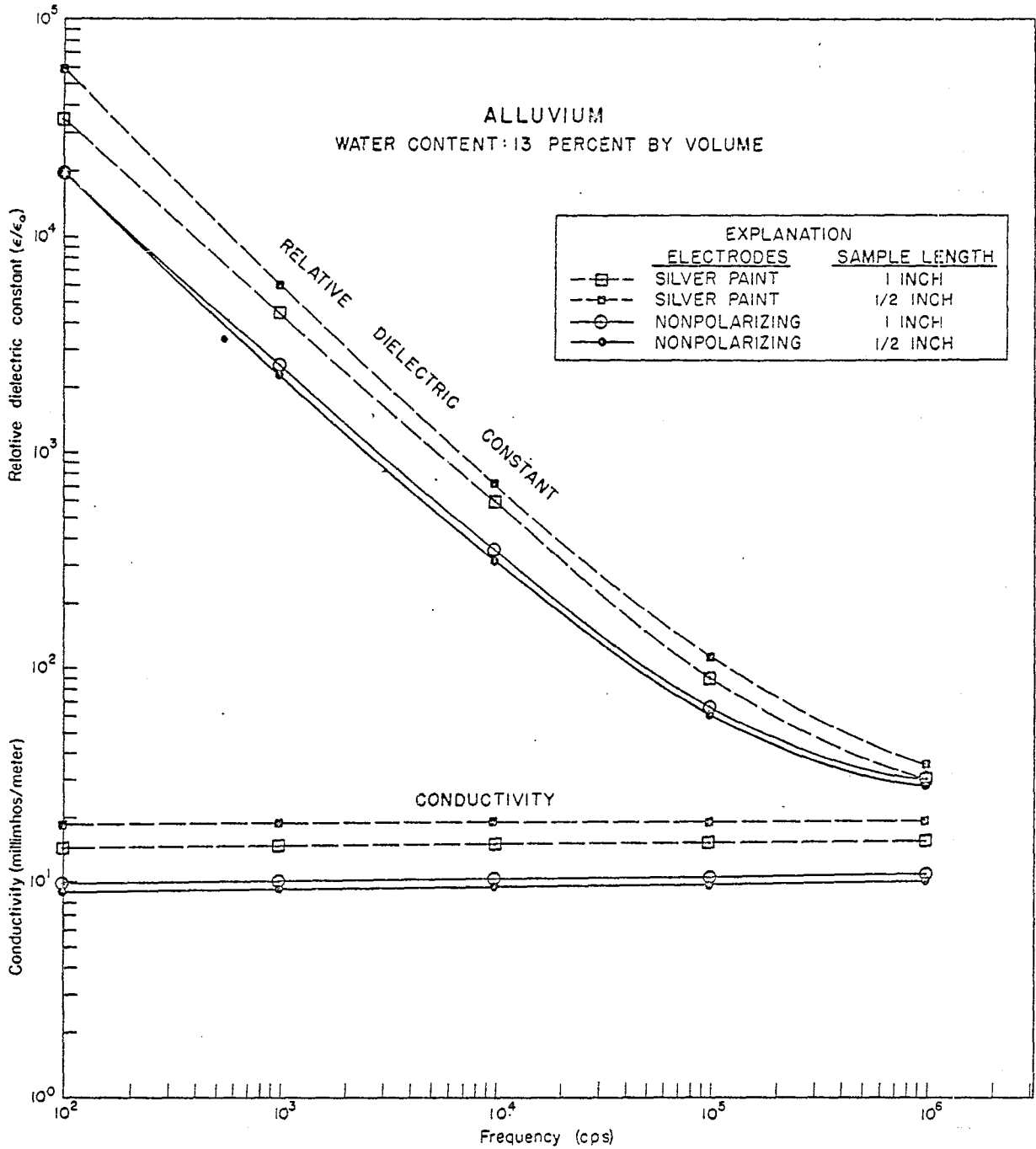


Figure 6.--Relative dielectric constant and conductivity measurements for alluvium showing comparison between nonpolarizing electrodes and silver paint electrodes

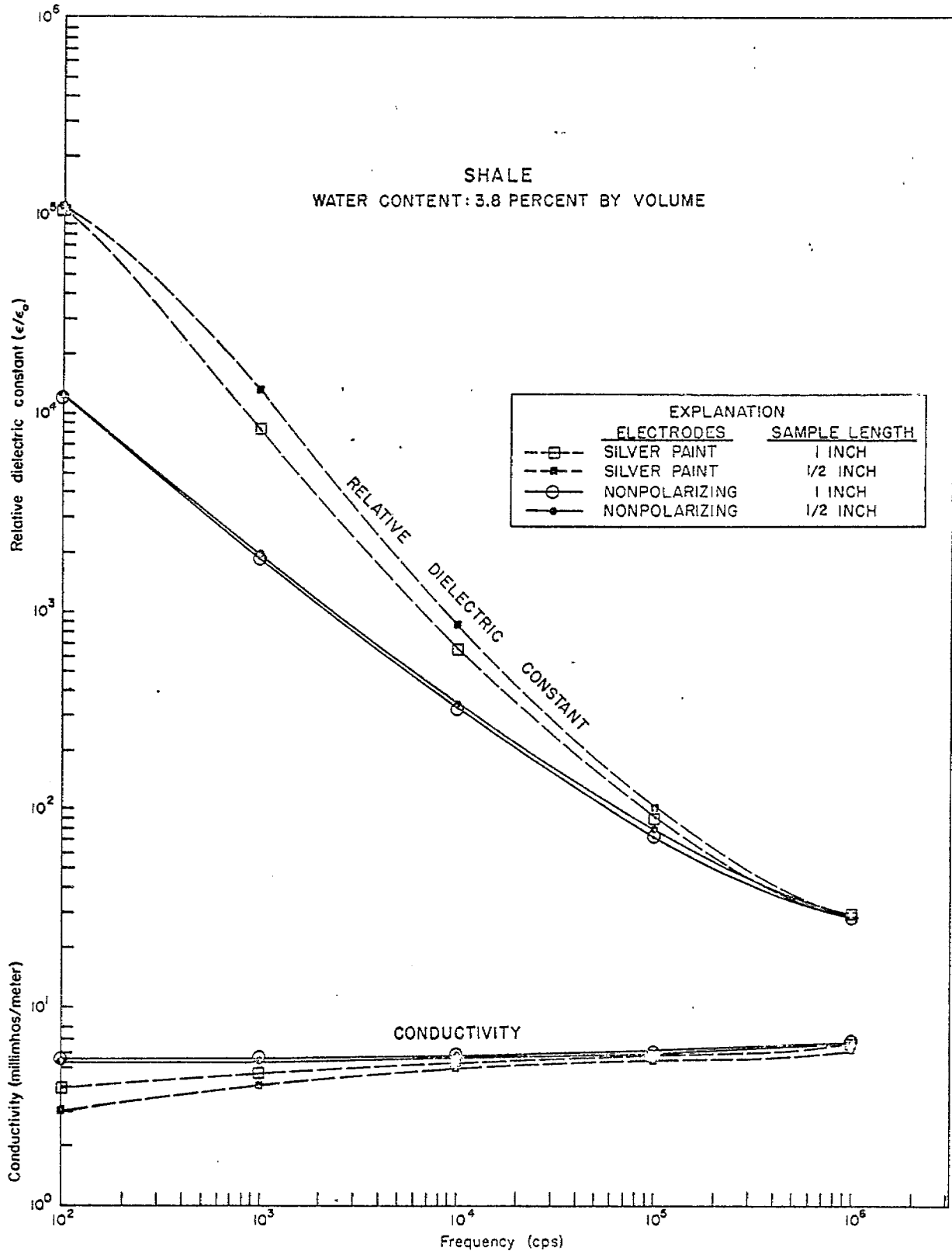


Figure 7.--Relative dielectric constant and conductivity measurements for shale showing comparison between nonpolarizing electrodes and silver paint electrodes

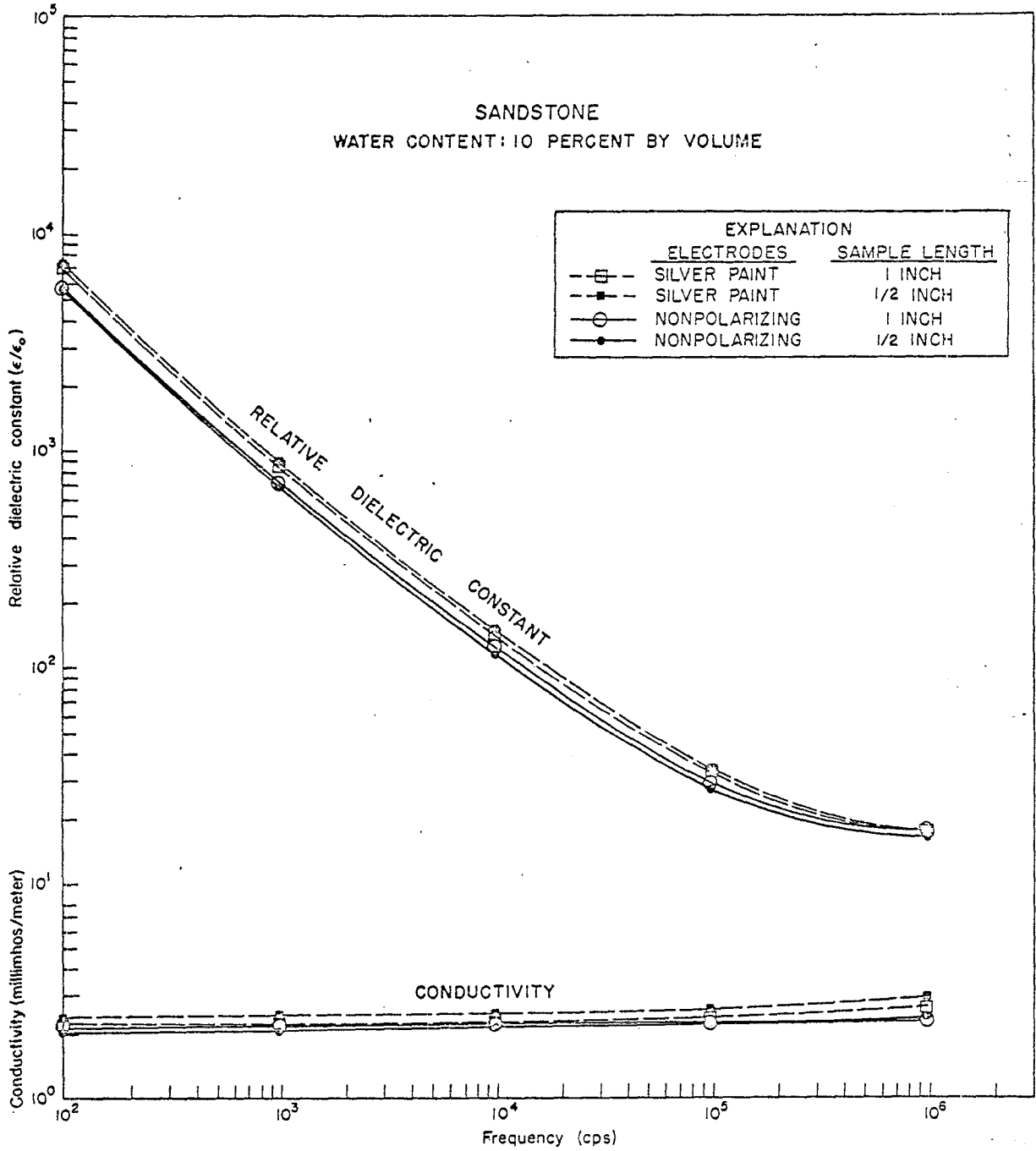


Figure 8.--Relative dielectric constant and conductivity measurements for sandstone showing comparison between nonpolarizing electrodes and silver paint electrodes

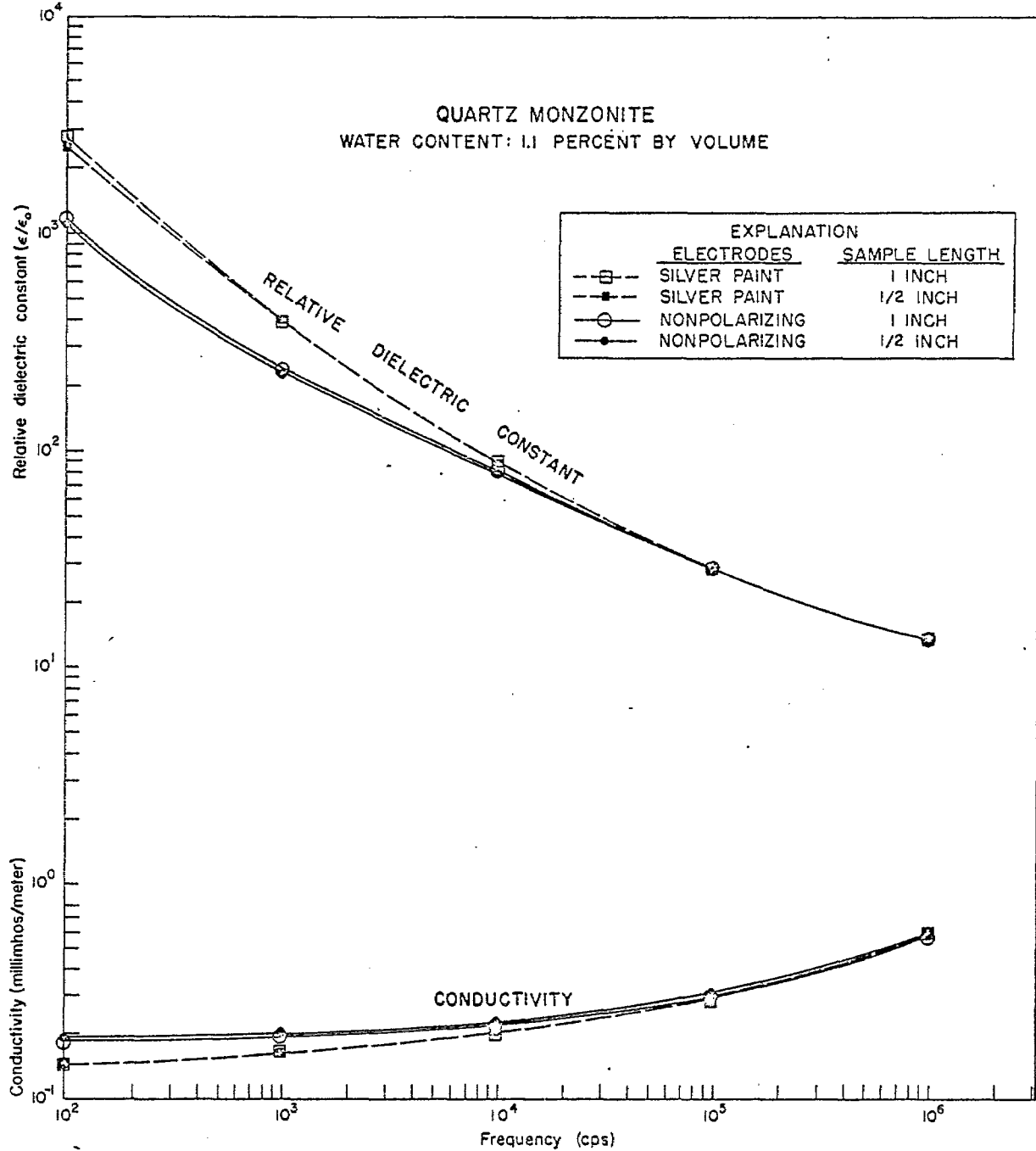


Figure 9.--Relative dielectric constant and conductivity measurements for quartz monzonite showing comparison between nonpolarizing electrodes and silver point electrodes

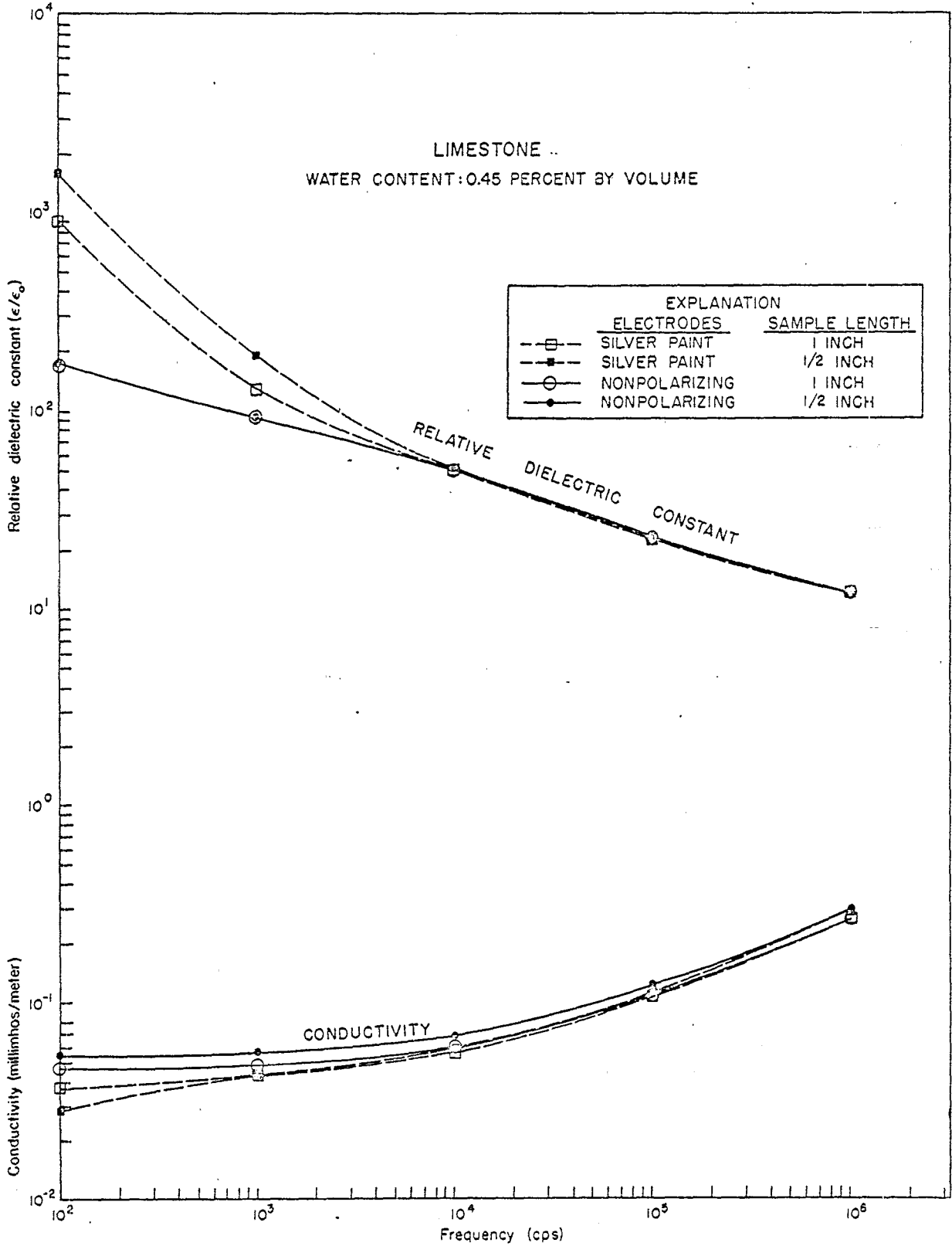


Figure 10.--Relative dielectric constant and conductivity measurements for limestone showing comparison between nonpolarizing electrodes and silver paint electrodes

Errors caused by silver paint electrodes are surprisingly large for samples with very low water content (fig. 10). Errors appear to depend on sample length and frequency, being most severe for short samples and low frequencies.

Electrode polarization may not have been the only source of error when silver paint was used on porous samples. Silver paint penetrating into the pores of the rock would have the effect of shortening the sample which would explain the apparent increase of conductivity of topsoil, alluvium and sandstone samples. The apparent decrease of conductivity of shale, quartz monzonite and limestone samples with silver paint electrodes may be caused by evaporation of moisture leaking through the silver paint.

Desaturation Measurements

It is well known that water content has a great effect on the conductivity and dielectric constant of rock. We made measurements to obtain quantitative relationships between water content and conductivity and dielectric constant by measuring fully saturated samples, then allowing them to dry at room temperatures for 15 hours and repeating the measurements, and finally allowing them to dry for 21 additional hours before repeating the measurement again. Results are illustrated in figures 11 through 16 for topsoil, alluvium, sandstone, shale, quartz monzonite and limestone samples measured at 10^2 , 10^3 , 10^4 , 10^5 , and 10^6 cps. Measurements were difficult to make because moisture was absorbed into the

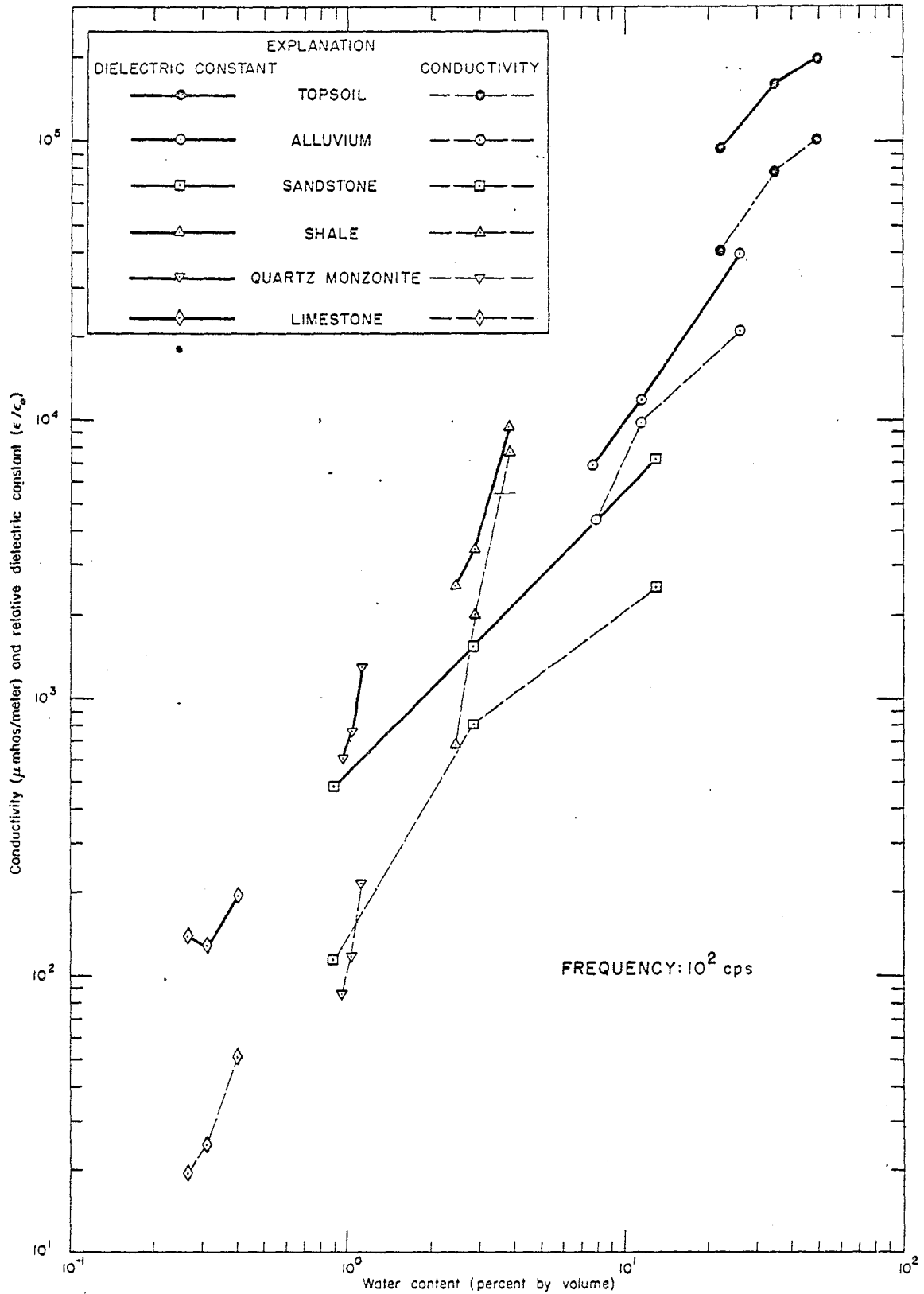


Figure 11.--Values of relative dielectric constant and conductivity measured at 100 cps for several rock types and plotted as a function of water content. Samples were fully saturated when first measurements were made, air dried for 15 hours before second measurements were made, and air dried for 21 additional hours before third measurements were made.

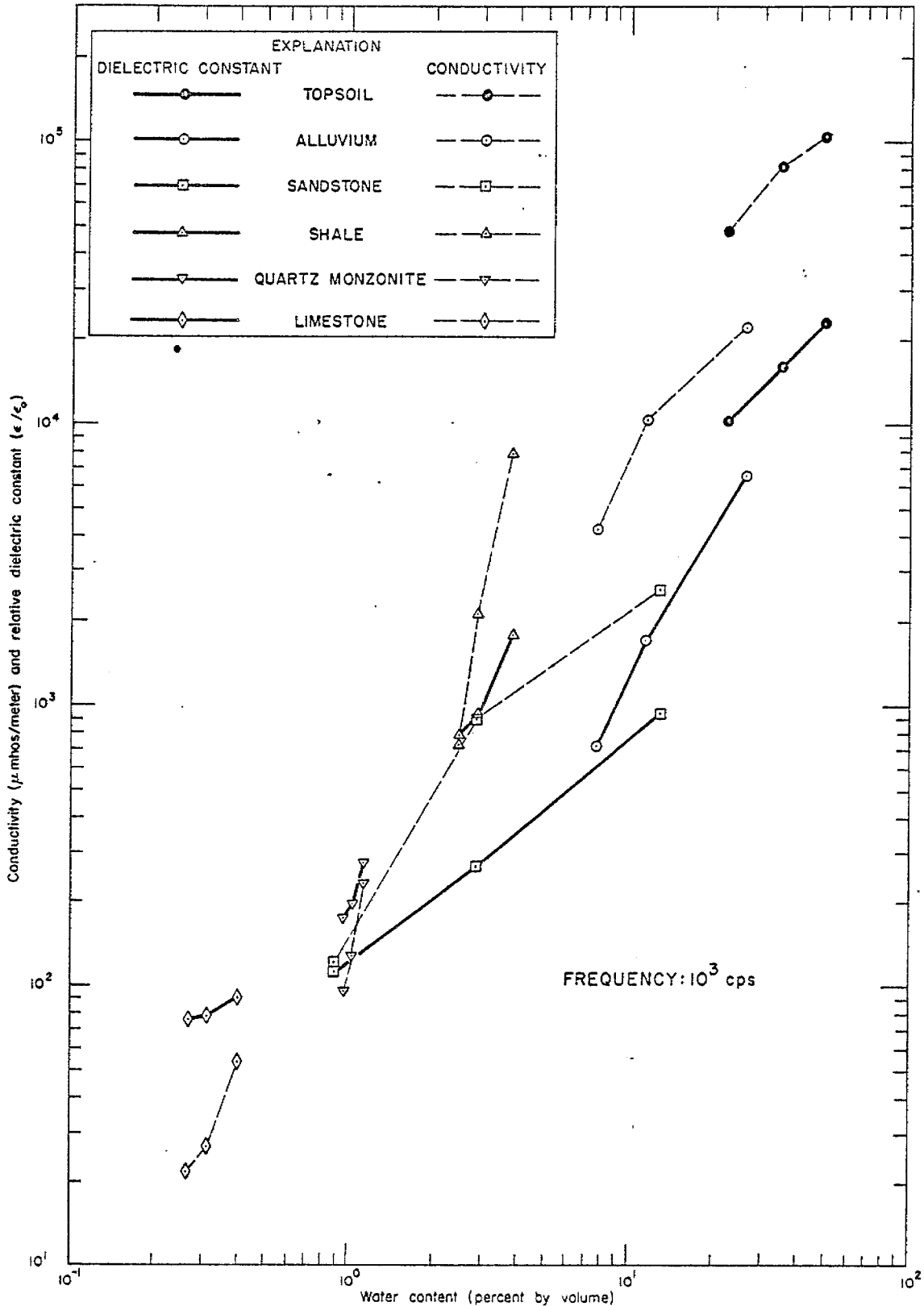


Figure 12--Values of relative dielectric constant and conductivity measured at 1,000 cps for several rock types and plotted as a function of water content. Samples were fully saturated when first measurements were made, air dried for 15 hours before second measurements were made, and air dried for 21 additional hours before third measurements were made.

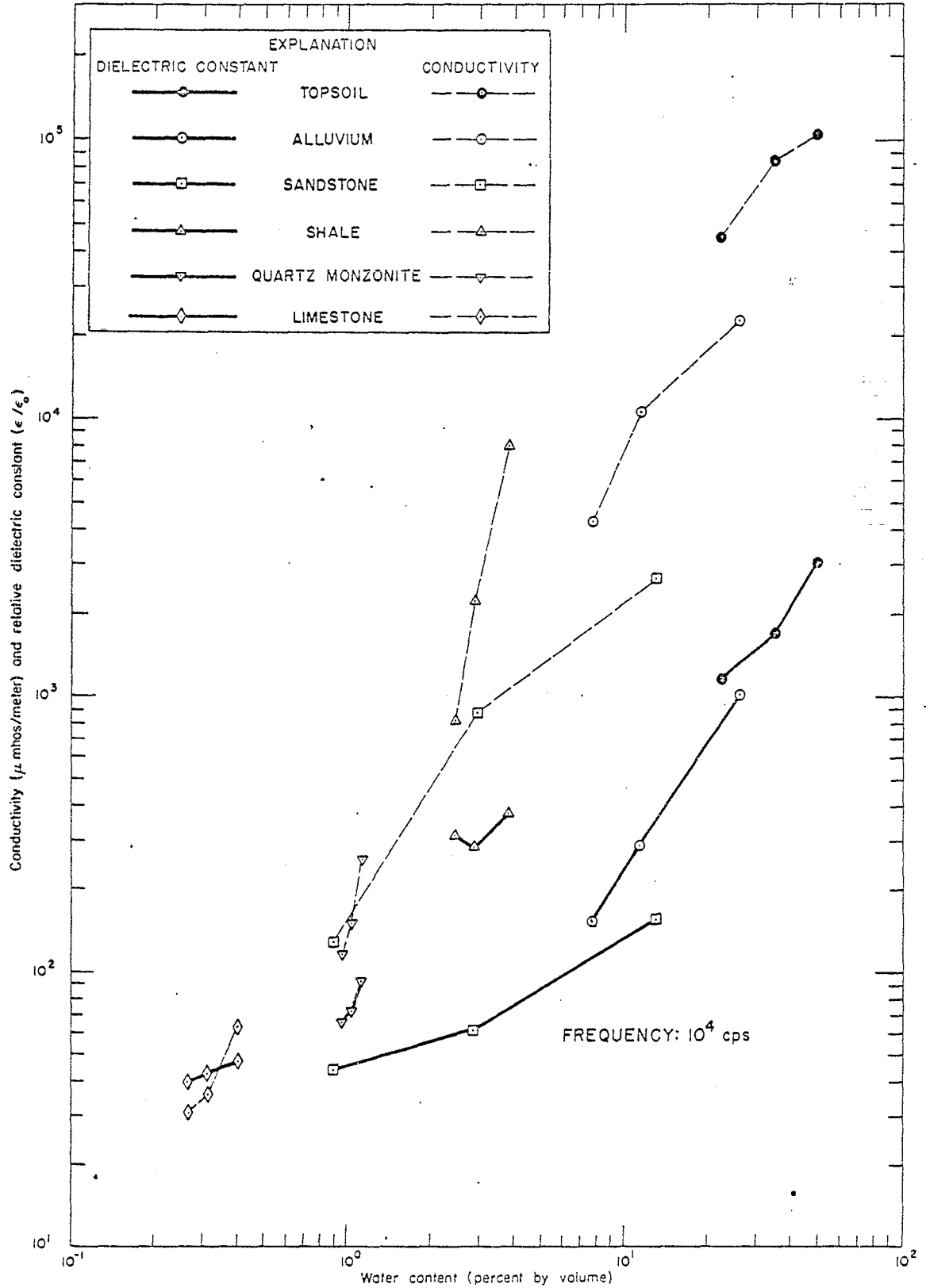


Figure 13.--Values of relative dielectric constant and conductivity measured at 10,000 cps for several rock types and plotted as a function of water content. Samples were fully saturated when first measurements were made, air dried for 15 hours before second measurements were made, and air dried for 21 additional hours before third measurements were made.

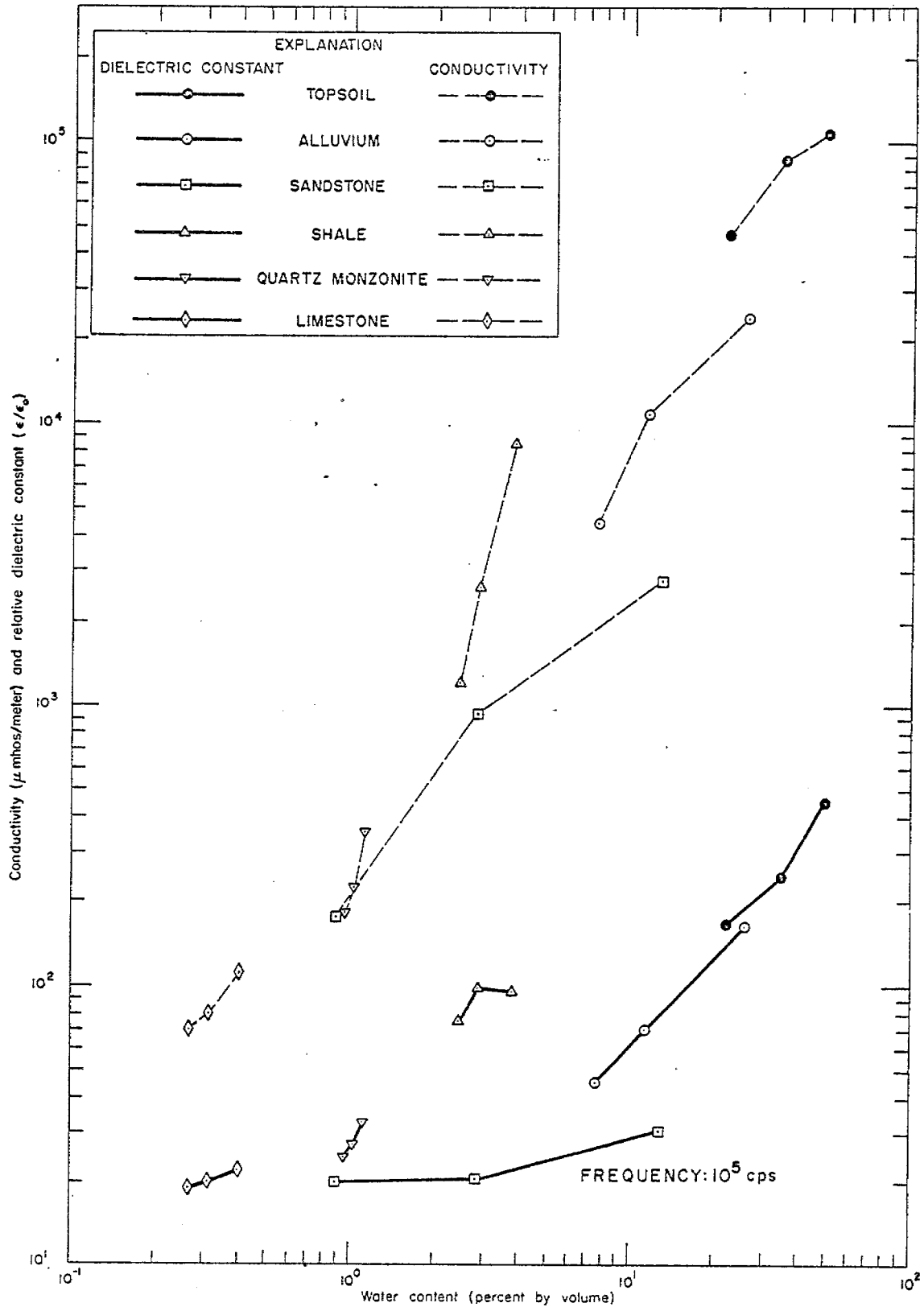


Figure 14.—Values of relative dielectric constant and conductivity measured at 100,000 cps for several rock types and plotted as a function of water content. Samples were fully saturated when first measurements were made, air dried for 15 hours before second measurements were made, and air dried for 21 additional hours before third measurements were made.

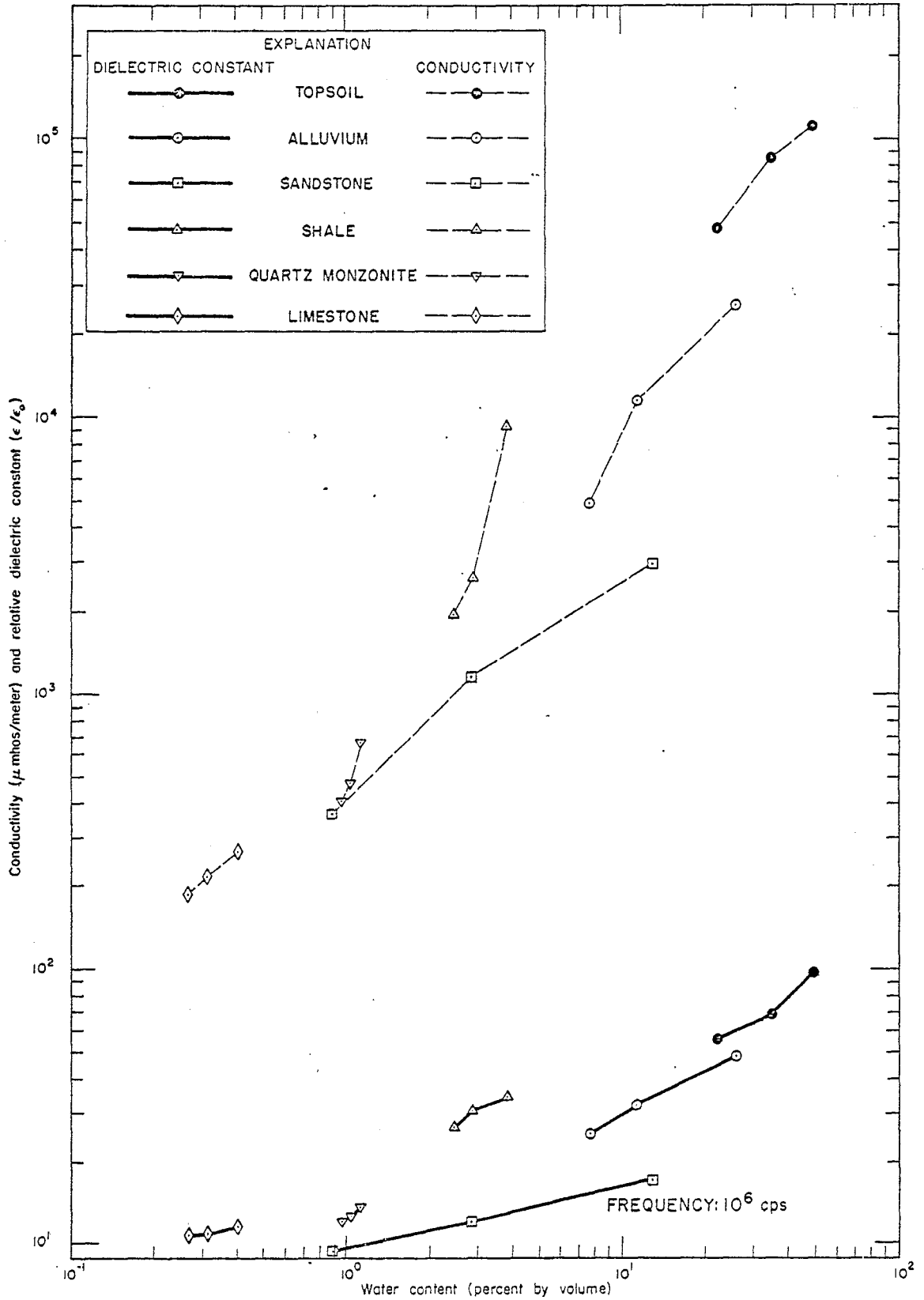


Figure 15.--Values of relative dielectric constant and conductivity measured at 1,000,000 cps for several rock types and plotted as a function of water content. Samples were fully saturated when first measurements were made, air dried for 15 hours before second measurements were made, and air dried for 21 additional hours before third measurements were made.

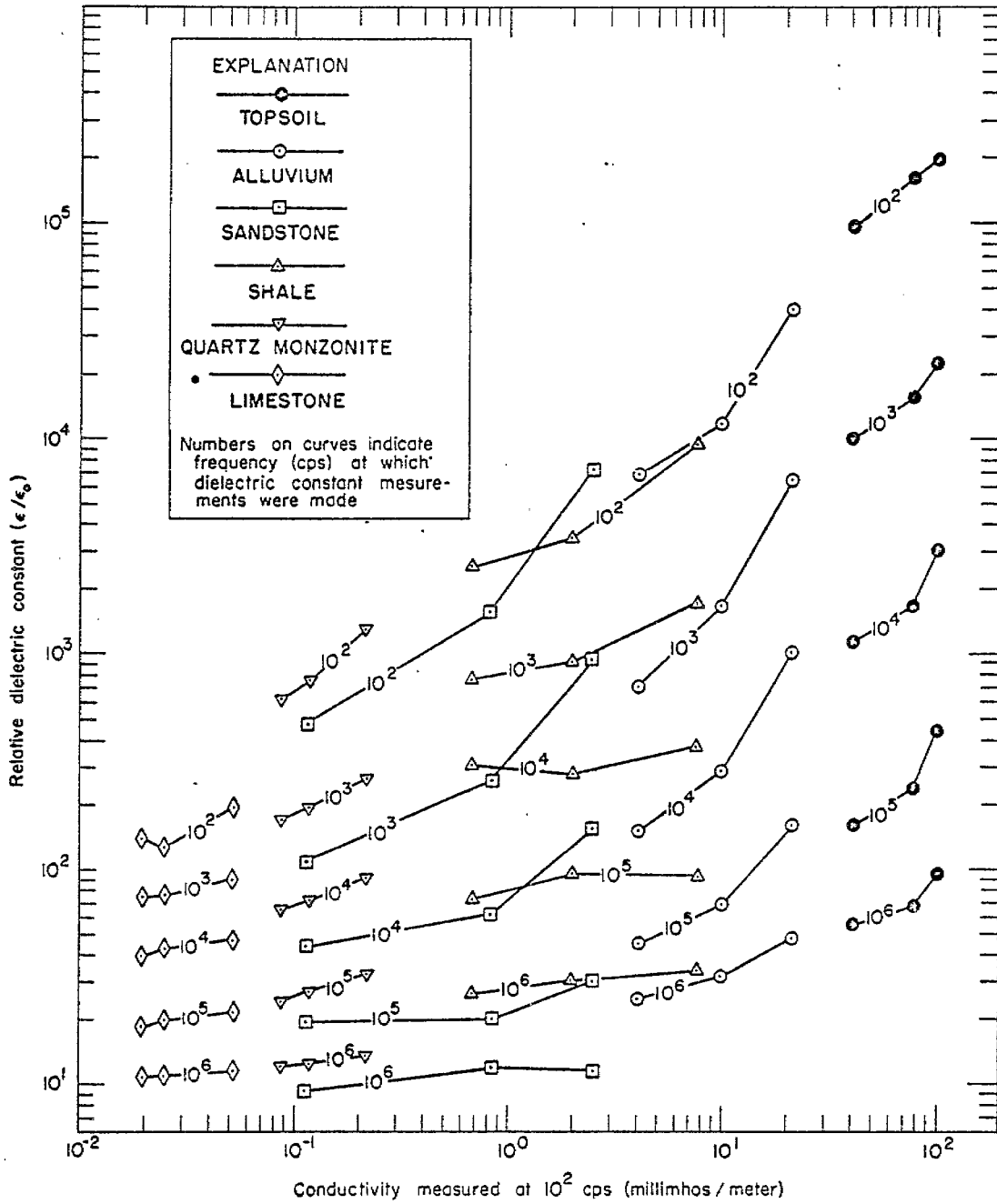


Figure 16.-- Values of relative dielectric constant measured over the frequency range 10^2 to 10^6 cps plotted against conductivity measured at 10^2 cps

partially desaturated samples from the blotters. This caused drift, making it difficult to obtain a null and introducing errors that may be 100 percent or larger. Nevertheless we attempted, with a computer, to fit a mathematical surface to the data obtained from these measurements so that dielectric constant and conductivity could be expressed as functions of water content and frequency. First the variables were all transformed logarithmically as follows:

<u>Transformed variable</u>	<u>Operator</u>	<u>Original variable</u>	<u>Original units</u>
F	= \log_{10}	Frequency	Cps
W	= \log_{10}	Water content	Percent by vol.
K	= \log_{10}	Conductivity	Millimhos/meter
D	= \log_{10}	Rel. Diel. Const.	ϵ / ϵ_0 .

First, second, and third degree polynomials were fitted to the data. For the conductivity-frequency-water content correlation a first degree surface appeared to represent the data sufficiently well:

$$K = -0.9033 + 0.08306 F + 1.491 W, \quad (12)$$

Sum of squares of residuals = 7.24,

Standard error = 0.288,

and for the dielectric constant-frequency-water content correlation a second degree surface appeared best:

$$D = 4.246 - 0.7957 F + 1.631 W + 0.04648F^2 - 0.2520FW + 0.1725W^2, \quad (13)$$

Sum of squares of residuals = 3.88,

Standard error = 0.215.

Another correlation was made between dielectric constant, frequency, and conductivity to provide a relationship that could be used to estimate dielectric constant from field measurements of electrical resistivity of rock in place. Since field measurements are usually made at dc or very low ac frequencies, the correlation study was made using conductivity measured at 100 cps which would be approximately the same as conductivity measured at dc. The second degree polynomial surface appeared to provide a satisfactory fit to the data:

$$D = 5.027 - 0.914 F + 1.079K_{100} + 0.046F^2 - 0.149 FK_{100} + 0.077K_{100}^2 \quad (14)$$

where K_{100} is \log_{10} of conductivity measured at 100 cps.

Sum of squares of residuals = 1.88

Standard error = 0.15

Future Work

It is recognized that variables other than frequency and water content influence dielectric constant and conductivity measurements. Temperature, pressure, salinity of pore fluid, mechanical structure and mineralogy can all be expected to play important roles. It is recommended that future laboratory measurements be directed toward quantifying the effects of these parameters.

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