THE HP 85070A DIELECTRIC PROBE KIT: TOOL SENSITIVITY, SAMPLE PREPARATION, AND SAMPLING PROCEDURES

by

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INTRODUCTION

Knowledge of dielectric properties of materials is useful for time-to-depth conversion and attenuation prediction of ground-penetrating radar (GPR) data. For log analysis, having dielectric property values from core can provide accurate matching of the core to wireline log electric data. Reported dielectric constant values for common geologic materials (e.g., Daniels, 1996; Davis and Annan, 1989), and minerals (e.g., Olhoeft, 1989; Schon, 1996; Ulaby et al., 1990) may be used in dielectric mixing models to predict bulk dielectric constant values (e.g., Baker, 1991; Knoll, 1996; Ulaby et al., 1986). Mixing models rely on accurate information concerning constituent materials, mineral concentrations, pore geometries and orientations and fluid compositions and their saturations.

While mixing models can help to understand GPR response, dielectric constant values reported in the literature and derived from mixing models may not provide values of sufficient accuracy for calibration of GPR reflection response to petrophysical properties at specific sites. Direct measurement of dielectric properties of rocks provides site-specific data concerning dielectric constants and attenuation. This report summarizes the results of tests performed to determine depth of investigation and best methods for measurement of dielectric properties from rock samples and soil using a Hewlett Packard HP8507A dielectric probe kit (probe). Though the probe Users' Manual contains explicit information concerning operation of the controlling software, it provides no information or guidelines about probe sensitivity, depth of investigation, or sample preparation. Information concerning probe depth of investigation and measurement accuracy for solid and porous media is provided in this report.

THE DIELECTRIC PROBE

The HP85070A dielectric probe measures dielectric permittivity and loss, both of which are parts of complex dielectric permittivity. Complex dielectric permittivity is represented by the relationship (Griffiths, 1989):

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega), \qquad [1]$$

where ω is frequency, $\varepsilon'(\omega)$ is dielectric permittivity (the ratio of electric flux density over the electric field), $\varepsilon''(\omega)$ is dielectric loss (the energy absorbed into a material when applying an AC electric field), and j is the $\sqrt{-1}$. Dielectric constant is calculated from dielectric permittivity using

$$\varepsilon_r(\omega) = \varepsilon'(\omega)/\varepsilon_0, \qquad [2]$$

where $\varepsilon_r(\omega)$ is dielectric constant of a material, and ε_0 is the permittivity of free space (8.85 x 10^{-12} F/m). Dielectric constant values of porous rocks and soils in the near-surface depend primarily on lithology, porosity, moisture content, and frequency. Where pore water is conductive or cation exchange occurs, brine saturations, brine chemistry, and cation exchange capacity will exert significant control on dielectric permittivity.

Measurement repeatability, depth and area of investigation, and probe sensitivity

Measurement repeatability

Repeatability of probe measurement results for rock was tested using samples from the Kansas Geological Survey Wireline Test-hole Core (described in Martinez et al., 1998). The samples range in grain-size from silt (phi = 4.5), to medium-lower fine (phi = 1.75). Repeat probe dielectric constant measurement values of finer-grained materials for the same sampling location (±0.1 cm) exhibited a variance of 0.1 at two standard deviations. Coarse-grained sandstone exhibited a variance in dielectric constant measurement values of 0.2 at two standard deviations. The difference is attributed to effects of probe - rock surface contact (discussed below), and minor variations in the volume measured due to movement of the probe tip of 0.1 cm between measurements.

Probe depth of investigation

The dielectric probe central wave guide is approximately 0.5 mm across. The wave guide is separated from the surrounding ground by a polyethylene insulator that is approximately 1 mm wide. These dimensions control much of the depth and width of investigation of the probe. In homogenous liquids, accurate dielectric values can be obtained irrespective of the probe dimensions, however, in homogeneous and heterogeneous solids, contact of the probe tip with the surface, surface roughness, and the size and distribution of heterogeneities in the sample exert strong control on measured dielectric values. The depth of investigation of the probe controls sample size and design of sampling locations on a solid sample surface. For samples with heterogeneities larger than the probe field of investigation, application of the probe may be unsuitable or interpretation must be made within the context of the nature of the specific material for which the probe is providing data.

The probe's depth of investigation for solid surfaces was determined using a series of measurements on stacked Corning glass plates. These plates are homogeneous amorphous silica and exhibit relatively constant thickness (+/- 0.0005 cm). Two different sets of glass plates, averaging 0.0154 cm and 0.12 cm thick, were used. A series of dielectric constant measurements were performed for successively greater combined thicknesses of glass plates. Combined thicknesses of plates less than 0.25 cm were obtained by stacking the 0.0154 cm thick plates. Greater thickness was obtained by stacking 0.12 cm thick plates. Measured versus calculated stacked thickness values indicated that the thin plates contained very-thin air layers between them (Figure 1), resulting in a stacked series of material (air, glass) with alternate dielectric constant. Sensitivity to the amount of air was observed by noting the differences in values of measured dielectric constant values when pressure was applied to the stacked plates. All reported values were obtained with the glass plates under pressure. To test for the influence of the gap on bulk permittivity between the plates, values were obtained with air and water between the plates.

Figure 2 shows the average bulk dielectric permittivity for the frequency range of 750-1500 MHz versus thickness of stacked glass plates. The measured dielectric constant values of the dry glass plates asymptotically approached a constant value of approximately 6.5. This value is similar to glass values of 4-7 reported by Griffiths (1989). Glass plate thicknesses of approximately 0.25 cm are within 95% of this value. For thickness values less than 0.25 cm, dielectric constant values increase with thickness. The relationship evident in Figure 2 indicates measurement response is primarily controlled by material within 0.0 – 0.1 cm of the probe tip. Dielectric constant measurement values with water between the plates exhibited greater variability due to slightly differing amounts of water being held between the plates and greater response as a result of the high dielectric constant of water (Figure 2). Measurement values did not vary significantly with position on the plates unless the center of the probe tip was on the very edge of a sample.

From the distribution of probe response exhibited, it is interpreted that the depth and area of investigation of the HP85070A dielectric probe is generally within 0.5 cm, but 99.9% of the response is from within 0.0 – 0.3 mm, approximately the same diameter as the probe central wave guide. Comparison of response versus thickness within 0.3 cm indicates that 50±10% of total response was within 0.00 – 0.03 cm, 70±10% of response is within 0.00 – 0.06 cm, and the remainder of the response occurs from 0.06 to 0.3 cm. Based on these results, minimum sample thickness should be approximately 0.4 cm to avoid significant contribution of air to the response. Appropriate dielectric probe sample sizes include 2.54 cm diameter core plugs and 6.35 cm core slabs. For samples with surface heterogeneities greater than 0.03 cm in size, consideration should be given to effects of heterogeneity on values measured.

Sample/probe tip gap

Based on the relationship between measured dielectric values and sample thickness shown in Figure 2, it is evident that between 85 and 95% of the total probe response is affected by the nature of the material within 0.12 cm of the center of the probe tip. Because of the influence of material within 0.03 cm of the center of the probe and the potential for slight irregularities on rock sample surfaces, a series of measurements were performed to determine the relative influence of air gaps between the probe and the sample surface. With increasing gap the volume of air within the probe range of investigation increases. Response of the probe is non-linear to the distance from the center of the probe tip and is non-linear to the dielectric constants of the materials within the range of investigation. Figure 3 illustrates two repeat measurements of dielectric constant values for quartz, sampled with the probe in contact with a flat quartz surface and for measurements where the probe is separated from the quartz by 0.015, 0.030, and 0.045 cm respectively. Response directly on the flat surface is 4.67, which is within the range of reported values for quartz (Olhoeft, 1989). Figure 3 illustrates that response is significantly reduced within the first 0.015 cm of the probe and diminishes with increases thickness of the air gap. This asymptotic change is consistent with the reverse measurements performed using glass plates discussed above and shown in Figure 2.

To test probe response and the influence of probe – sample contact gap on probe response for sandstones, measurements were performed on core plugs of cores obtained from Tonganoxie Sandstone (T132-P014 and T104-P014 of Beaty and Martinez, 1998). The core plugs were medium to fine grained, quartzose sandstone, and micaceous fine to very-fine grained sandstone. Helium porosities of all samples were measured using a Boyle's Law technique. Measurement results are included in Appendix A. Measurements were also performed on calcite (8.5), gypsum (6.5), and mica (6.4). These measured values are consistent with reported values of 7.8-8.5, 5-11.5, and 6.2-9.3, respectively for these minerals at radio frequencies (Carmichael, 1989). Measured dielectric constant values on rough surfaces of the same samples were a minimum of 5.3, 4.7, and 2.5, respectively. These low values illustrate the potential error introduced by unquantified surface roughness.

The time-propagation (TP) dielectric mixing model was used to determine expected dielectric constant values. The TP model is:

$$(\varepsilon_{TP})^{1/2} = \Sigma\, V_i\, (\varepsilon_i)^{1/2}, \text{ for } i = 1 \text{ to } N, \qquad [3]$$

where ε_{TP} is the bulk, or composite, dielectric constant, V_i is the volume fraction of the i^{th} constituent material, and ε_i is the dielectric constant of the i^{th} constituent material (Knoll, 1996). For a porous material with a matrix of only one mineral, Equation [3] takes the form:

$$\varepsilon_{TP} = [\phi(\varepsilon_\phi)^{1/2} + (1-\phi)(\varepsilon_m)^{1/2}]^2, \qquad [4]$$

where ϕ is the porosity of the measured material, ε_ϕ is the dielectric constant of the material in the pore volume (e.g., 1 for air or 81 for water), and ε_m is the dielectric constant of the matrix of the material (e.g., 4.5 for quartz; Olhoeft, 1989).

The dielectric constants of the samples were measured both air-dried and fully saturated to determine the range in the gap effect. For air-dried samples, the air-filled gap resulted in measured values being lower than TP modeled values, while for saturated samples the water-filled gap resulted in measurement values being higher than TP modeled values. Assuming the gaps are less than 0.03 cm, and probe response to the gap is linear with gap thickness, the effect of the gap between the probe tip and the sample was treated as the function:

$$\varepsilon_{meas} = G\varepsilon_G + (1-G)(\varepsilon_{TP}), \qquad [5]$$

where ε_{meas} is the measured dielectric constant value, G is the gap factor (ranging from 0 to 1), and ε_G is the dielectric constant of the material in the gap (either 1 for air or 81 for water). Rearranging equation [5] to solve for G yields

$$G = (\varepsilon_{meas} - \varepsilon_{TP})/(\varepsilon_G - \varepsilon_{TP}), \qquad [6]$$

which shows the influence of the gap on the measurement value. Air-dried and saturated gap factors were calculated and averaged for each of the core plug samples. The average gap factors for all samples ranged from 0.25 to 0.55, with a mean of 0.39 and a standard deviation of 0.065. Gap factor generally increased with increasing grain size and corresponding surface roughness. These gap factors correspond approximately with actual gaps of 0.0061 to 0.0133 cm.

For experimental data obtained using the probe, correction for the influence of the gap on the measurement can be made using:

$$\varepsilon_{corr} = (\varepsilon_{meas} - G\varepsilon_G)/(1-G), \qquad [7]$$

where ε_{corr} is the corrected dielectric constant value. Use of the gap correction results in increased dielectric constant values. An average gap factor was calculated for the data set to examine how the gap affects the sandstone measurements. Minimum and maximum gap corrected dielectric constant values, based on a gap of 0.39 +/- 0.13 for air-dried core plug samples, are given in Appendix A.

Probe sampling procedure

Pre-sampling procedure

Prior to measurement of dielectric properties using the probe, the following steps must be performed:

1) Connect the HP 8753D network analyzer (NA) to a PC-computer containing the probe software.
2) Turn on the NA, then the computer, and let them warm up for approximately 10 minutes. Allowing the equipment to warm up prior to calibration reduces electronics-related measurement value drift.
3) Connect the probe cable to a port (either port 1 or 2) on the NA. The cable must be tightly connected to the NA, otherwise significant error can result in measurements. In addition, the cable can be extremely sensitive to its configuration (e.g., coils, etc.). It should be held in the same approximate position during calibration and all measurements.
4) Select an operation frequency range and calibrate the NA with the HP 85033D calibration kit. This should be done at the start of each measurement day. The calibration kit uses a short, loaded circuit, and an open circuit to calibrate the NA.
5) Connect the probe tip to the probe cable. The probe tip must be fastened tightly to the cable, otherwise significant error in measurement results may occur.
6) Start the probe software on the computer. Select a measurement frequency range and step size (this should be the same as the frequency range selected during NA calibration). Operation of the probe software is described in the HP85070A dielectric probe kit manual.
7) Calibrate the probe. Calibration of the probe is done using standards of air ($\varepsilon_r = 1$), a short, and de-ionized water ($\varepsilon_r = 81$).

Once these steps have been performed, the equipment is ready for measurement of dielectric properties. A photograph of the NA and the probe after calibration is shown in Figure 4a. During dielectric measurements, the dielectric constant of air should be measured every few minutes to determine if there has been instrument drift. If there has been significant drift (>+/- 0.2), then the probe should be re-calibrated.

Samples and sampling procedure

Samples appropriate for measurement with the probe include most liquids and solids. The manual does state (HP, 1986, page 1-3) "The probe is compatible with most materials and liquids and is resistant to strong acids. However, these materials will cause degradation and should be avoided: aromatic hydrocarbons, chlorinated hydrocarbons, and ketones." Therefore, the probe should not be used to measure dielectric properties of hydrocarbon-rich samples or liquids where the polyethylene insulator on the probe may become wetted by solvents as these will damage the probe tip. Because there is no gap, measurement values obtained from solid materials, measurement values obtained from liquids do not have to be corrected for a gap factor.

Solid samples should have a smooth, flat measurement surface with surface roughness less than 0.01 cm. One method of obtaining a smooth surface is to cut the sample with a rock saw and then lightly sand the surface. Saw marks must be removed, as they result in undulations on the smooth surface that can significantly affect probe measurements. If a significant amount of fine-grained material coats the surface after sanding, the sample should be cleaned with compressed air. Figure 4b shows the probe being used to take a measurement from an air-dried sandstone sample.

Measurement accuracy for partially saturated samples can vary because of the limited depth of response of the probe (<0.15 cm), and possible non-uniform water distribution in the sample. Water saturation of a sample may not be homogeneous at the sub-centimeter scale, especially at the surface of a sample that is in contact with air. Because of this, bulk water saturation values calculated for samples (such as core plugs) may not be representative of the water saturation of the region being measured by the probe. This is especially true at high water saturations (>~50%) in permeable (>500 millidarcy) samples where water may drain away from the surface. For measurement of dielectric properties from air-dried and partially-saturated samples, small droplets of water on the probe tip can also significantly affect the measurement. No water droplets should be allowed to wet the probe tip.

If a sample is homogeneous in both lithology and porosity at a scale less than ~0.01 cm, then dielectric probe readings from one measurement location are generally sufficient to characterize the dielectric properties of the sample. The small area of investigation of the dielectric probe necessitates different sampling procedures when measured material is heterolithic. To obtain accurate bulk dielectric constant values of a heterogeneous sample, such as argillaceous limestone, several measurements should be made from different measurement locations reflecting the different lithologies in the sample. These dielectric probe readings will then provide general ranges of dielectric constant values for the sample. Fractures and cracks, even in lithologically homogeneous material, must be avoided as they are dielectric heterogeneities.

CONCLUSION

The HP85070A dielectric probe provides a method of measuring dielectric property values from rock samples. The probe has a primary depth of investigation of approximately 0.15 cm, though sample volumes out to 0.5 cm are incorporated in the reading. Probe response within this range of investigation is non-linear. Approximately 50±10% of the response is within 0.00-0.03 cm, and approximately 70±10% is within 0.00-0.06 cm. Because such a small region is investigated, samples can be relatively small. The small area of investigation necessitates a smooth, flat, sample measurement surface with less than 0.01 cm variation in surface roughness. Care must be taken to insure good probe – surface contact. Measurement values obtained from solid samples, even those with smooth surfaces, should be corrected for the gap that occurs between the probe tip and sample surface. Consideration must be given to the sample heterogeneities larger than 0.01 cm in scale. This would include sandstones or soils with grain sizes greater than lower fine grained (> 177 μ; >2.0 phi).

For these samples, multiple measurements may be required and a sampling plan should be designed to measure the properties of regions within the heterogeneous media. Table 1 summarizes problems and possible causes and fixes that may occur when using the probe.

Dielectric Probe Measurement Pitfalls	
Problem	*Possible causes; fixes*
NA will not calibrate	Poor probe cable or calibration kit connection; tighten connections if necessary.
Probe software will not start	Poor connection between NA and computer; reattach connecting cable. Restart computer if this persists.
Probe will not calibrate	Poor probe cable or probe tip calibration; tighten connections if necessary.
Probe readings anomalously low	Rough measurement surface; smooth surface as much as possible. Check the dielectric constant of air; recalibrate if significant instrument drift has occurred.
Probe readings are anomalously high	Water droplets or moisture on the probe tip; dry the probe tip if moist. Check the dielectric constant of air; recalibrate if significant instrument drift has occurred.

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REFERENCES

Baker, P. L., 1991, Fluid, lithology, geometry, and permeability information from ground-penetrating radar for some petroleum industry applications: *in* Proceedings of the Society of Petroleum Engineers Asia-Pacific Conference, Perth, Western Australia, SPE paper no. 22976, p. 277-287.

Carmichael, R.S., 1989, Practical handbook of physical properties of rocks and minerals, CRC Press, Boca Raton, FL, 741 p.

Daniels, D. J., 1996, Surface-penetrating radar: IEE Radar, Sonar, Navigation and Avionics Series 6, E. D. R. Sharman and P. Bradsell (eds.), Short Run Press Ltd., Exeter, United Kingdom, 300 p.

Davis, J. L, and A. P. Annan, 1989, Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy: Geophysical Prospecting, **37**, 531-551.

Griffiths, D. J., 1989, Introduction to electrodynamics, second edition: Prentice hall, Englewood Cliffs, New Jersy.

Hewlett Packard, 1986. HP 85070A dielectric probe kit: Hewlett Packard.

Knoll, M. D., 1996, A petrophysical basis for ground-penetrating radar and very early time electromagnetics, electrical properties of sand-clay mixtures: unpublished Ph. D. dissertation, University of British Columbia, 316 p.

Martinez, A., D. S. Beaty, J. Stiles, and T. R. Carr, 1998, Comparison of ground-penetrating radar reflectivity and rock properties in a sandstone-dominated incised valley-fill deposit: *in* Proceedings from the 7th International Conference on Ground-Penetrating Radar, May 27-30, Lawrence, KS, University of Kansas Center for Research, Inc., 693-698.

Olhoeft, G. R., 1989, Electrical properties of rocks: *in*, Touloukian, Y., S., W. R. Judd, and R. F. Roy (eds.), Physical Properties of Rock and Minerals, 257-329.

Schon, J. H., 1996, Physical properties of rocks: fundamental and principles of petrophysics: Elsevier Science, Inc., Tarrytown, New York.

Ulaby, F. T., R. K. Moore, and A. K. Fung, 1986, Microwave remote sensing, active and passive: Volume III – From theory to applications: Artech House, 2017-2119.

Ulaby, F. T., T. H. Bengal, M. C. Dobson, J. R. East, J. B. Garvin, and . L. Evans, 1990, Microwave dielectric properties of dry rocks: IEEE Transactions on Geoscience and Remote Sensing, **28**, No. 3, 325-336.

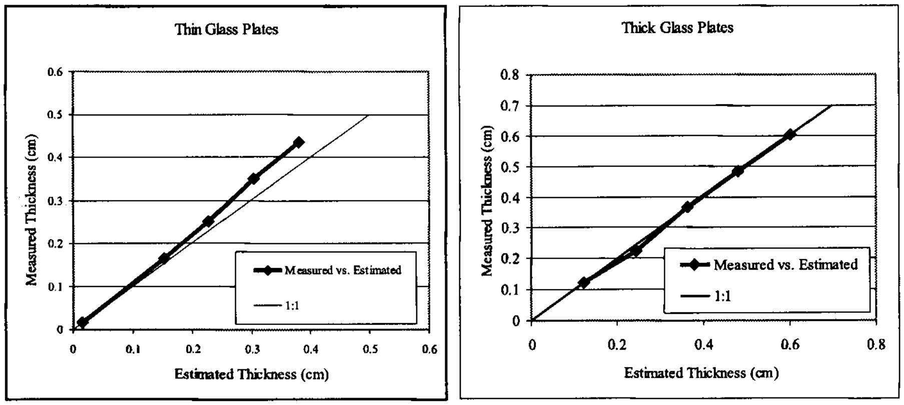

Figure 1. Measured versus calculated thickness values of stacked glass plates.

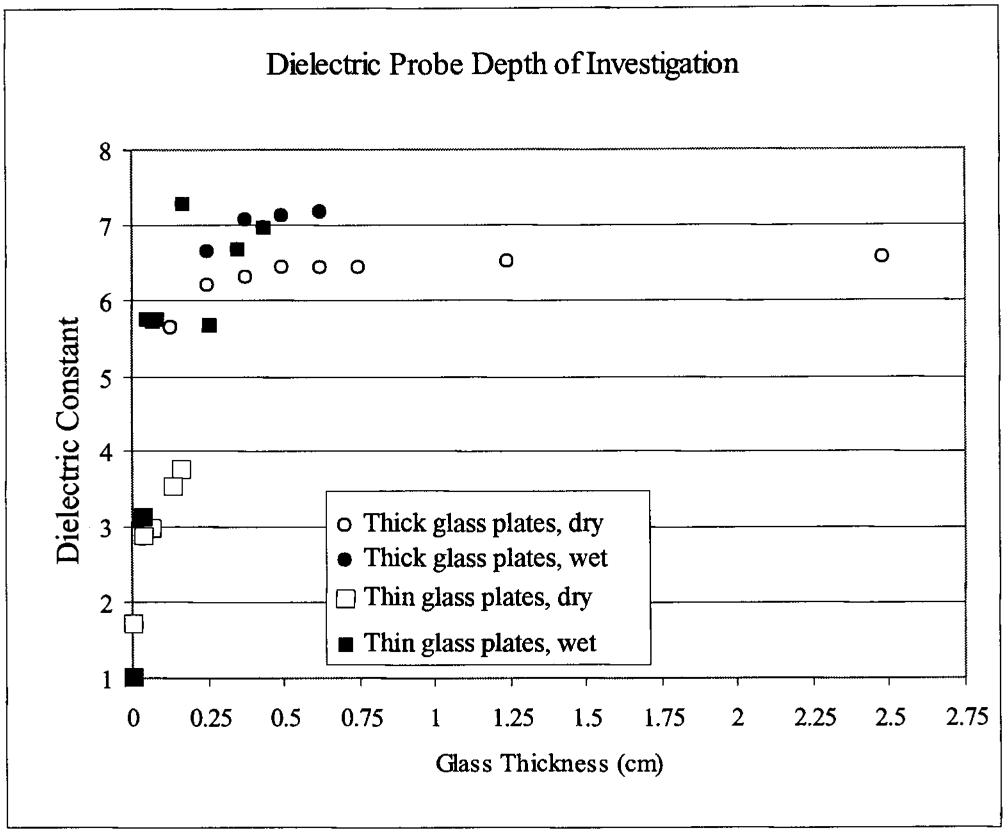

Figure 2. Average bulk dielectric constant for the frequency range of 750-1500 MHz versus thickness of stacked glass plates with air-filled and water-filled gaps. For thickness values less than 0.25cm, dielectric constant values increase with thickness. The relationship shown in the figure above indicates measurement response is controlled by material within 0.0-0.25 cm of the probe tip. Dielectric constant measurement values with water between the plates exhibited greater variability due to slightly differing amounts of water being held between the plates and greater response as a result of the high dielectric constant of water.

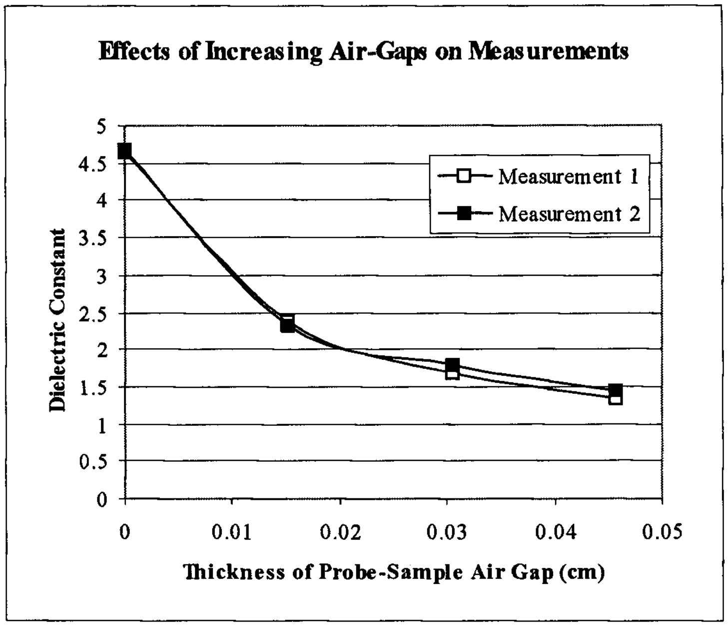

Figure 3. Repeat measurements of measured dielectric constant values for quartz, measured with the probe in contact with a flat quartz surface and for measurements where the probe is separated from the quartz by 0.015, 0.030, and 0.045 cm, respectively. The figure illustrates that response is significantly reduced within the first 0.015 cm of the probe and diminishes with increases thickness of the air gap. This asymptotic change is consistent with the reverse measurements performed using glass plates discussed in the text..

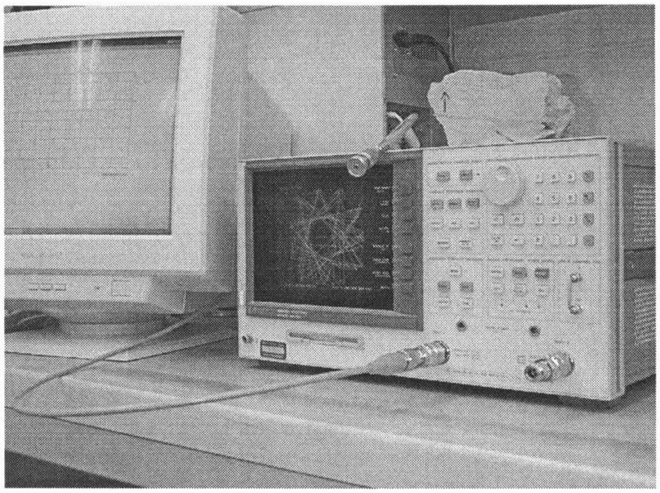

Figure 4a. Photograph of the network analyzer, dielectric probe cable and tip, and the probe software GUI.

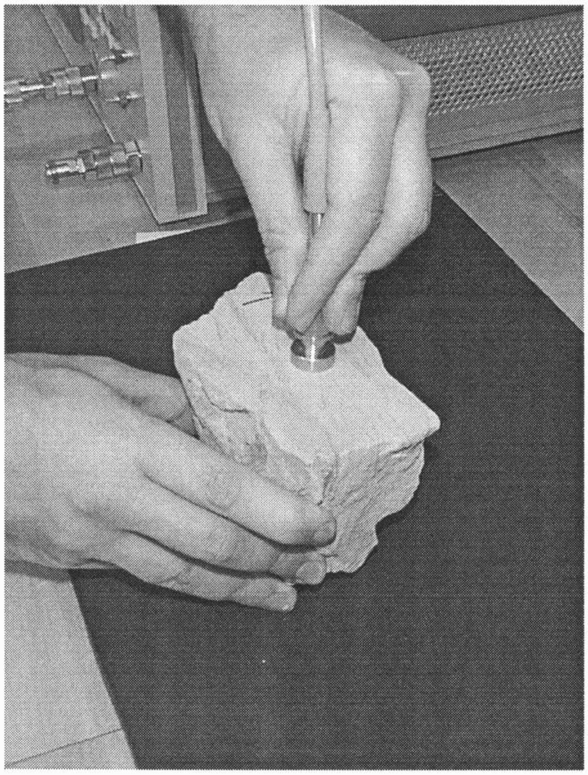

Figure 4b. Photograph of the dielectric probe being used to take a measurement from a sandstone sample. In preparation for the probe measurement, the sample was cut, sanded, and dried.

APPENDIX A

K7 Study Site - Petrophysical Measurement Results
Cores W1 (T132-P014) and W2 (T104-P014); NE SW NW, S13, T11S, R23E

												Dielectric Constant							
Core ID	**Sample ID No.**	**Depth (ft)**	**Permeability (md)**	**Porosity (%)**	**Grain Density (g/cc)**	**Avg. Qtz. Grain Size (mm)**	**Lithology other than Qtz.**			**Saturation (%)**		*measured*				*corrected*			
							Mica (%)	*Clay (%)*	*Fe Cement (%)*	*wet 1*	*wet 2*	*dry*	*wet 1*	*wet 2*	*sat*	*dry*	*wet 1*	*wet 2*	*sat.*
W1	3	2.9	2621.81	0.35	2.70	0.17	2.00	0.50	4	65	58	1.90	13.89	3.72	39.16	2.47	—	5.43	13.33
W1	4	4.1	2805.16	0.36	2.69	0.15	2.25	0.75	2	57	50	2.33	6.37	4.21	39.20	3.18	9.76	6.24	13.39
W1	5	5.2	2344.89	0.35	2.67	0.14	4.00	1.00	4	35	52	2.14	3.23	4.02	40.73	2.87	4.64	5.94	15.89
W1	6	6.15	1203.56	0.35	2.70	0.11	4.75	1.00	3	29	54	2.33	3.85	4.49	35.13	3.17	5.65	6.70	—
W1	7	7	1295.80	0.35	2.69	0.12	6.25	1.50	3	29	58	2.38	3.91	5.36	37.68	3.25	5.75	8.12	10.91
W1	8	7.9	655.89	0.33	2.67	0.11	8.50	2.00	3	27	57	2.43	4.14	5.63	39.29	3.34	6.12	8.56	13.54
W1	9	8.9	1590.04	0.33	2.68	0.14	2.50	1.50	4	33	67	2.65	4.21	5.28	36.69	3.70	6.23	7.98	9.30
W1	10	10	1641.07	0.34	2.68	0.14	2.75	2.00	3	31	61	2.41	3.99	4.54	35.68	3.31	5.88	6.78	7.65
W1	11	10.9	1637.42	0.33	2.68	0.12	2.00	3.00	4	37	60	2.23	4.20	5.07	36.45	3.00	6.22	7.65	8.91
W1	12	11.9	1672.42	0.31	2.67	0.15	1.75	2.00	4	27	56	2.47	3.75	5.16	35.65	3.40	5.49	7.79	—
W1	13	12.9	1349.99	0.31	2.67	0.14	4.25	3.00	5	38	66	2.34	4.22	5.26	34.16	3.18	6.26	7.95	—
W1	14	14	899.66	0.30	2.68	0.09	5.25	5.00	3	31	59	2.59	4.52	5.28	31.54	3.59	6.74	7.99	—
W1	15	15	1375.02	0.33	2.68	0.14	4.25	5.00	3	34	56	2.77	4.03	4.48	34.31	3.89	5.95	6.68	—
W1	17	17	168.29	0.44	2.76	0.17	1.25	4.00	40	29	58	2.61	3.60	5.99	—	3.63	5.24	9.15	—
W1	18	18	79.99	0.47	2.79	0.14	0.75	6.00	50	25	62	2.87	5.56	6.50	—	4.05	8.45	9.98	—
W1	19	19	0.02	0.04	2.66	0.15	1.38	3.00	40	6	32	5.65	—	6.67	10.06	8.60	—	10.25	—
W2	3	2.8	1766.78	0.36	2.66	0.12	2.25	2.00	2	30	56	2.27	4.41	4.28	40.62	3.07	6.57	6.35	15.71
W2	4	3.8	1022.91	0.36	2.66	0.11	6.25	4.00	5	31	60	2.05	3.47	4.89	52.88	2.72	5.04	7.35	—
W2	5	4.8	1455.23	0.34	2.66	0.12	3.75	2.50	2	30	59	2.52	3.88	5.84	41.49	3.48	5.70	8.90	17.14
W2	6	5.8	1292.19	0.34	2.67	0.12	6.25	4.00	3	27	63	2.48	4.07	5.13	41.55	3.42	6.02	7.74	17.23
W2	7	6.8	2088.31	0.34	2.67	0.15	1.50	2.00	5	31	61	2.33	3.54	3.79	38.11	3.17	5.15	5.55	11.61
W2	8	7.8	1691.83	0.35	2.65	0.14	1.25	4.00	3	32	60	2.08	3.20	3.49	39.42	2.76	4.60	5.07	13.75
W2	9	8.8	1644.46	0.35	2.66	0.14	3.00	3.00	2	24	60	2.43	3.39	4.27	37.73	3.34	4.90	6.35	11.00
W2	10	9.8	2003.15	0.36	2.67	0.15	2.25	4.00	3	31	62	2.20	3.13	3.53	39.44	2.96	4.48	5.13	13.79
W2	12	11.9	1213.17	0.35	2.68	0.14	1.50	5.00	12	26	61	2.27	3.09	4.33	38.63	3.07	4.42	6.44	12.46
W2	13	12.8	2592.30	0.37	2.67	0.15	1.13	2.00	2	29	63	2.35	3.04	4.94	39.89	3.21	4.33	7.42	14.52
W2	14	13.8	136.37	0.35	2.73	0.12	3.00	4.00	20	27	63	2.52	4.02	4.04	—	3.48	5.94	5.97	—
W2	15	14.7	0.04	0.08	2.71	0.14	1.13	2.00	40	15	23	5.32	5.32	5.48	12.90	8.05	8.05	8.31	—
W2	16	15.9	0.04	0.04	2.66	0.12	0.75	6.00	45	13	29	5.55	5.29	4.79	13.50	8.43	8.01	7.18	—
W2	17	16.7	0.58	0.12	2.71	0.14	0.63	8.00	35	13	26	4.62	4.74	4.72	14.33	6.92	7.10	7.08	—
W2	18	18.1	1383.89	0.33	2.67	0.11	1.13	2.00	4	31	65	2.76	3.88	5.43	30.44	3.87	5.69	8.23	—
W2	19	18.9	1562.42	0.32	2.66	0.12	0.88	2.00	4	38	59	2.53	4.11	5.18	35.22	3.49	6.08	7.82	—
W2	20	19.9	1102.28	0.30	2.69	0.11	0.75	2.00	5	47	58	2.67	4.32	4.80	32.14	3.73	6.42	7.21	—

K7 Study Site - Petrophysical Measurement Results
Cores W1 (T132-P014) and W2 (T104-P014); NE SW NW, S13, T11S, R23E

							Gap factor							**Gap Factor Error****	
Core ID	**Sample ID No.**	**Depth (ft)**	**TP Model Dielectric Constants**				calculated*		*sample average*	*sample range*	*total average*	*total minimum*	*total maximum*	*Dielectric Constant*	
			dry	*wet 1*	*wet 2*	*water*	*air*	*water*						*min. dry*	*max. dry*
W1	3	2.9	2.98	12.60	11.11	20.43	0.55	0.47	0.51	0.08	0.39	0.25	0.52	2.20	2.88
W1	4	4.1	2.95	11.13	9.91	20.99	0.32	0.47	0.39	0.15	0.39	0.25	0.52	2.78	3.79
W1	5	5.2	2.98	7.32	10.19	20.44	0.42	0.49	0.46	0.07	0.39	0.25	0.52	2.53	3.39
W1	6	6.15	3.00	6.38	10.30	20.08	0.34	0.42	0.38	0.08	0.39	0.25	0.52	2.78	3.78
W1	7	7	2.98	6.43	11.30	20.51	0.30	0.45	0.38	0.15	0.39	0.25	0.52	2.85	3.89
W1	8	7.9	3.07	6.04	10.47	19.13	0.31	0.47	0.39	0.16	0.39	0.25	0.52	2.92	4.00
W1	9	8.9	3.08	6.87	12.33	18.99	0.20	0.44	0.32	0.23	0.39	0.25	0.52	3.21	4.46
W1	10	10	3.04	6.62	11.43	19.48	0.31	0.42	0.37	0.12	0.39	0.25	0.52	2.89	3.96
W1	11	10.9	3.06	7.36	11.12	19.21	0.40	0.43	0.42	0.03	0.39	0.25	0.52	2.64	3.57
W1	12	11.9	3.16	5.98	9.82	17.79	0.32	0.42	0.37	0.11	0.39	0.25	0.52	2.97	4.08
W1	13	12.9	3.16	7.28	11.48	17.76	0.38	0.40	0.39	0.02	0.39	0.25	0.52	2.79	3.80
W1	14	14	3.20	6.33	10.07	17.16	0.28	0.37	0.32	0.09	0.39	0.25	0.52	3.12	4.32
W1	15	15	3.07	6.90	10.32	19.00	0.15	0.41	0.28	0.26	0.39	0.25	0.52	3.37	4.70
W1	17	17	2.65	6.89	13.33	26.19	0.02	-0.03	0.00	0.06	0.39	0.25	0.52	3.16	4.37
W1	18	18	2.54	6.41	15.39	28.42	-0.21	-0.03	-0.12	0.18	0.39	0.25	0.52	3.50	4.90
W1	19	19	4.31	4.39	4.75	5.73	-0.40	0.08	-0.16	0.48	0.39	0.25	0.52	7.23	10.73
W2	3	2.8	2.96	6.58	10.97	20.83	0.35	0.49	0.42	0.14	0.39	0.25	0.52	2.70	3.66
W2	4	3.8	2.95	6.84	11.88	20.97	0.46	0.65	0.55	0.19	0.39	0.25	0.52	2.41	3.20
W2	5	4.8	3.04	6.55	10.99	19.57	0.26	0.50	0.38	0.24	0.39	0.25	0.52	3.03	4.18
W2	6	5.8	3.01	6.13	12.04	19.95	0.26	0.50	0.38	0.24	0.39	0.25	0.52	2.99	4.10
W2	7	6.8	3.04	6.55	11.44	19.53	0.35	0.46	0.40	0.11	0.39	0.25	0.52	2.78	3.78
W2	8	7.8	3.00	6.91	11.46	20.23	0.46	0.47	0.47	0.01	0.39	0.25	0.52	2.45	3.26
W2	9	8.8	2.98	5.81	11.52	20.51	0.28	0.45	0.36	0.18	0.39	0.25	0.52	2.92	4.00
W2	10	9.8	2.96	6.77	12.12	20.76	0.39	0.47	0.43	0.08	0.39	0.25	0.52	2.61	3.51
W2	12	11.9	2.97	6.05	11.87	20.56	0.36	0.46	0.41	0.11	0.39	0.25	0.52	2.70	3.66
W2	13	12.8	2.93	6.51	12.47	21.34	0.30	0.48	0.39	0.18	0.39	0.25	0.52	2.81	3.83
W2	14	13.8	2.97	6.17	12.32	20.60	0.23	-0.04	0.10	0.27	0.39	0.25	0.52	3.04	4.18
W2	15	14.7	4.11	4.52	4.74	7.26	-0.39	0.12	-0.14	0.51	0.39	0.25	0.52	6.78	10.04
W2	16	15.9	4.30	4.49	4.72	5.84	-0.38	0.12	-0.13	0.50	0.39	0.25	0.52	7.09	10.52
W2	17	16.7	3.93	4.43	5.00	8.82	-0.24	0.14	-0.05	0.37	0.39	0.25	0.52	5.85	8.58
W2	18	18.1	3.08	6.57	11.92	18.94	0.15	0.36	0.25	0.20	0.39	0.25	0.52	3.35	4.68
W2	19	18.9	3.11	7.38	10.61	18.54	0.28	0.42	0.35	0.14	0.39	0.25	0.52	3.04	4.19
W2	20	19.9	3.20	8.39	9.99	17.18	0.24	0.38	0.31	0.14	0.39	0.25	0.52	3.24	4.50

*Calculated using dielectric constants of 1 (air), 80 (water), and 4.5 (quartz)

**Calculated using mean (0.39) +/- standard deviation (0.1345) of the gap factor sample population.